GEOLOGY OF THE SOUTHERN PORTION
OF THE
DULUTH COMPLEX

By

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ABSTRACT

The Duluth Complex (Middle Proterozoic - 1,099 Ga) is a large intrusive body that contains numerous smaller intrusions that collectively comprise the Complex. Recent work has shown that igneous stratigraphic sections can be delineated within these intrusions through detailed relogging of drill core, e.g., for the Partridge River intrusion (Severson and Hauck, 1990; Severson, 1991) and the South Kawishiwi intrusion (Severson, 1994). This report pertains to the igneous geology of the South Complex area. More than 140 drill holes are located in the "South Complex" area. Most of these holes are relogged (112 holes, 88,000 feet of core) and are correlated into several troctolitic to gabbroic stratigraphic units for several specific areas in the South Complex that have abundant drill holes. While each individually drilled area exhibits good correlative units, these correlative units do not extend into an adjacent drilled area that is located only a few miles distant. This lack of large-scale continuity suggests: 1) the South Complex study area constitutes an area that actually includes several smaller intrusive bodies; 2) drilling is not detailed enough to delineate large-scale correlative units; 3) because most of the drill holes are located close to the basal contact, the effects of contamination to the magma, via assimilation of footwall rocks, hampers large-scale correlations; or 4) combinations of the above.

Most of the holes within the South Complex were drilled during exploration for Cu-Ni sulfide mineralization. Only weak sulfide mineralization is present in these drill holes. However, many of the holes intersect small plug-like bodies of Oxide-bearing Ultramafic Intrusions (OUIs) that are intrusive into the troctolitic rocks of the Complex. The OUIs are characterized by coarse-grained to pegmatitic clinopyroxenite, picrite, peridotite, and dunite. Oxide content in the OUI varies from disseminated (15%-20%) to thick massive oxide zones. Ilmenite is the dominant oxide in some OUIs; whereas, titanomagnetite is dominant in others. In almost all instances, the OUIs are

spatially arranged along linear trends, suggesting that structural control was important to their genesis. At some localities (northern end of the South Complex), an empirical link between iron-formation assimilation near the basal contact and OUI formation is apparent. This relationship suggests that the OUIs were initially formed at depth followed by upward injection of OUI material along fault zones. However, other OUI (southern end of the South Complex) are situated within, or immediately below, layered oxide-rich gabbroic rocks, suggesting that the OUIs formed from a differentiated iron-rich melt that drained down into the cumulate pile along fault zones. These two different OUI groups (north and south) also show some corresponding differences in chemistry. The north OUIs are characterized by relatively higher chromium contents and the south OUIs have relatively higher vanadium contents. All of the OUIs contain titanium mineralization and some sulfide mineralization. A model of origin for the OUIs involving metasomatic replacement of pre-existing igneous rock is not considered to be plausible.

Also present within the South Complex area are fine-grained granular rocks that are hornfelsed inclusions of basalt and troctolitic-gabbroic-noritic rocks. One of these inclusions, referred to as the FN Unit, is only observed in drill holes in the southern half of the South Complex area. The unit exhibits vesicle-like features in drill core and has often been referred to as a hornfelsed basalt. However, several features argue against a basalt protolith for the FN Unit. These features include the presence of abundant footwall hornfels inclusions within the unit, common gradations into medium-grained intrusive rock, and a "rind-like" overall pattern of the unit at the basal contact at Water Hen. These characteristics suggest that the FN Unit represents an earlier pulse of magma (chilled?) into the footwall rocks that was later hornfelsed by subsequent intrusions of the Complex. The Bear Lake Inclusion, present in numerous outcrops and one drill hole, probably represents a large inclusion of magnetic basalt. The inclusion is a massive rock with no distinct volcanic features, but is similar to magnetic basalt inclusions described elsewhere in the

Complex (Colvin Creek Inclusion, and "INCL" unit within the South Kawishiwi intrusion; Severson and Hauck, 1990; Severson, 1994; Patelke, 1996). The Bear Lake Inclusion is over 500 feet thick and dips gently to the southeast. It is located well into the interior of the Complex and is not related to the basal contact (as is the FN Unit).

Geochemical plots are constructed for many of the igneous units of the South Complex area. These plots are not particularly instructive in discriminating between the units because many of the spider profiles are fairly similar, and in the X-Y plots only a few units cluster within distinct fields. However, some conclusions can still be drawn from these data. First, similarities in geochemistry indicate that some units of the nearby Partridge River intrusion are present as far south as Water Hen. Second, the FN Unit is chemically similar to both troctolitic to gabbroic rocks, even in the same drill hole. This relationship supports an earlier intrusive protolith rather than a basalt protolith. Third, the north and south OUI can be separated into two groups based on similarities in spider diagram profiles. However, the profiles for the north OUI show similar profiles that alternate with geographic location. The reason for this "leap frog" alternation in profiles is unknown at this time, but may be related to more than one OUI-forming event along a fault zone. Last, rocks of the Bear Lake Inclusion are chemically similar to rocks of the Colvin Creek inclusion (Severson & Hauck, 1990; Patelke, 1996) and the "INCL" unit of the South Kawishiwi intrusion (Severson, 1994); all of which have been inferred to be magnetic basalts.

A sample of a semi-massive oxide horizon (0.8 ft. thick), associated with subhorizontal, ultramafic layers (picrite, peridotite, etc.) near the Water Hen area (drill hole SL-19A) has been found to contain anomalous PGE and chromium values (Pt = 737-786 ppb, Pd = 63-106 ppb, Cr = 46,000 ppm). This semi-massive oxide horizon is similar in many respects to PGE- and Cr-enriched semi-massive to massive oxide horizons located elsewhere within the Duluth Complex (Birch Lake and Fish Lake areas). The data suggest that the PGE in SL-19A are magmatic and have not been redistributed by hydrothermal fluids, as has been suggested for other areas within the Complex. Additional targets of vein-like PGE-enriched Cu-Ni ore are also present in the Skibo and Water Hen areas. These targets could potentially have formed via fractional crystallization of a sulfide melt in a vein-like setting.

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INTRODUCTION

BACKGROUND

The Duluth Complex (Complex) is a large intrusive body comprised of numerous smaller individual intrusions. Recent studies have shown that igneous stratigraphic sections can be delineated within these intrusions through detailed relogging of drill core. To date, igneous stratigraphic sections have been correlated in drill core and documented for the Partridge River intrusion and South Kawishiwi intrusion (Fig. 1; Severson and Hauck, 1990; Severson 1991, 1994). The stratigraphic packages of these two intrusions are remarkably different. Definition of the stratigraphy provides a framework by which mineralized zones (containing elevated values of Cu, Ni, and precious metals) can be traced with increased accuracy. Contained within the Partridge River and South Kawishiwi intrusions are several known Platinum Group Element (PGE) occurrences associated with Cu-Ni mineralization. Often, these PGE occurrences closely correspond to a subzone within the igneous stratigraphic section. Thus, knowledge of the stratigraphy can aid in defining favorable zones of PGE mineralization that can be utilized by mining companies in their exploration endeavors. However, similar large-scale stratigraphic studies are lacking for drilled portions within the southern portion of the Complex - this area is the subject of this investigation, and is herein referred to as the South Complex (Fig. 1). It encompasses a north-south corridor of exploratory drilling (more than 140 drill holes) situated between the Wyman Creek Cu-Ni Prospect (to the north) and the Boulder Lake area (to the south). Also, the South Complex contains a number of late Oxide-bearing Ultramafic Intrusions (OUIs) that are intruded into the troctolitic rocks of the Complex. The OUIs represent potential Fe-Ti±V resources that have not been collectively studied in detail.

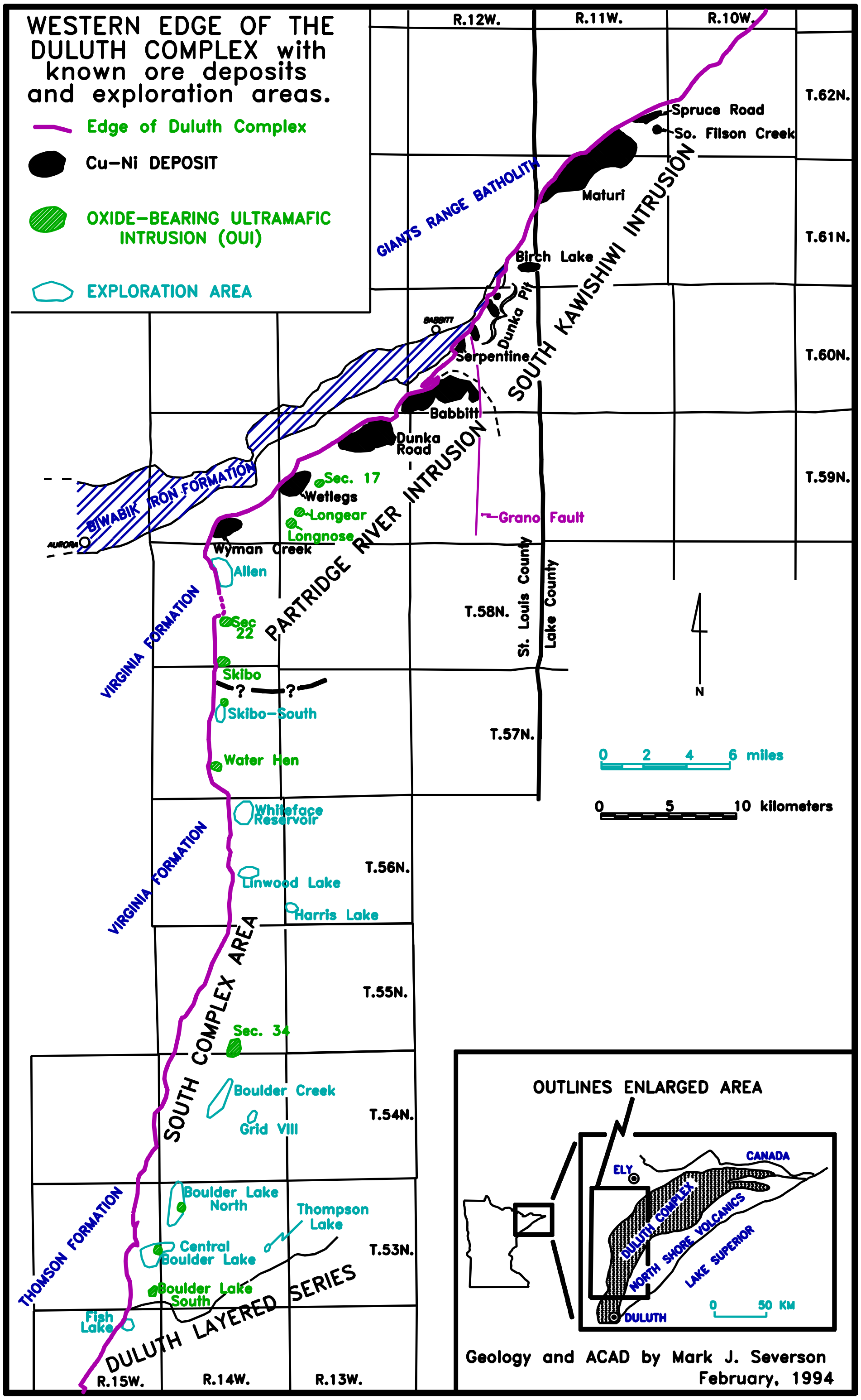

Figure 1. Location of Cu-Ni deposits, Fe-Ti±V deposits, and other exploration areas within the Partridge River intrusion, South Kawishiwi intrusion, and South Complex areas, Duluth Complex, northeastern Minnesota.

The objectives of this study are to: 1) extend the igneous stratigraphy of the Partridge River intrusion southward from the Wyman Creek area; 2) locate the southern limit/edge of the Partridge River intrusion; 3) establish new igneous stratigraphies for the South Complex, including the various late OUI bodies; 4) compare the South Complex stratigraphy to the Partridge River intrusion (PRI), South Kawishiwi intrusion (SKI), and Duluth Layered Series stratigraphy; 5) determine the geochemical and mineralogical composition of the igneous units defined in the South Complex through use of previously collected, and newly collected samples; 6) determine possible structural and magmatic controls on Cu-Ni-PGE and Fe-Ti-V mineralization within the South Complex; and 7) provide additional data in the form of cross-sections to aid in understanding the origin of the Duluth Complex and its related mineral deposits. This report is the culmination of a 1.5 year investigation involving relogging of almost all existing drill holes and conducting limited geochemical sampling and reconnaissance geologic mapping.

GEOLOGIC SETTING

The Duluth Complex (Fig. 1 - inset) 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 exposed in an arcuate belt extending a distance of about 150 miles (240 km) 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 Thomson/Virginia Formations (argillite and graywacke sequence) 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) granite and greenstone. East from the Gunflint trail, at the basal contact are Lower Proterozoic Gunflint Iron-formation and overlying 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, 1975).

Rocks of the Duluth Complex are varied and include a series of anorthositic, troctolitic, gabbroic, granodioritic, and granitic intrusive bodies. Generally, these rocks are 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 the Troctolitic and Anorthositic Series rocks have indistinguishable crystallization ages of about 1,099 Ma (Miller, 1992; Paces and Miller, 1993). Age dates are also available on several of the smaller intrusions that collectively comprise the Complex. These intrusions, and their relative age, are formally and informally referred to as: Logan Sills - 1,109 Ma (Davis and Sutcliffe, 1985); Nathan's Layered Series - 1,107 Ma (Paces and Miller, 1993); 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 (Paces and Miller, 1993); and various intrusions of the Beaver Bay Complex (Miller, 1989) - 1,096 Ma (Paces and Miller, 1993). Many of these intrusions, and several additional unnamed intrusions, of the Complex are delineated by Chandler (1990) on the basis of aeromagnetic and gravity signatures. The range in age data suggest that the multiple intrusions of the Duluth Complex were emplaced within a 11-13 Ma range.

Two of the intrusions of the Duluth Complex, the South Kawishiwi intrusion (SKI) and Partridge River intrusion (PRI), have been extensively drilled for Cu-Ni mineralization. Substantial drilling also took place in the South Complex, but only weak Cu-Ni mineralization was encountered. These intrusions/areas 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. Also shown on Figure 1 are Exploration Areas and Oxide-bearing Ultramafic Intrusions (OUIs). Exploration areas are defined as areas with minor drilling that intersected weak Cu-Ni mineralization (at best). OUIs are late pod-like bodies with Fe-Ti±V±Cu±Ni potential.

Rock outcroppings are extremely scarce within the study area. The topography of the area is related to thick glacial deposits. Major glacial features within the South Complex area are depicted in Figure 2. Glacial features in the northern portion of Figure 2 are related to the Rainy lobe; whereas, features in the southern portion, e.g., Toimi Drumlin Field, are related to the Superior lobe.

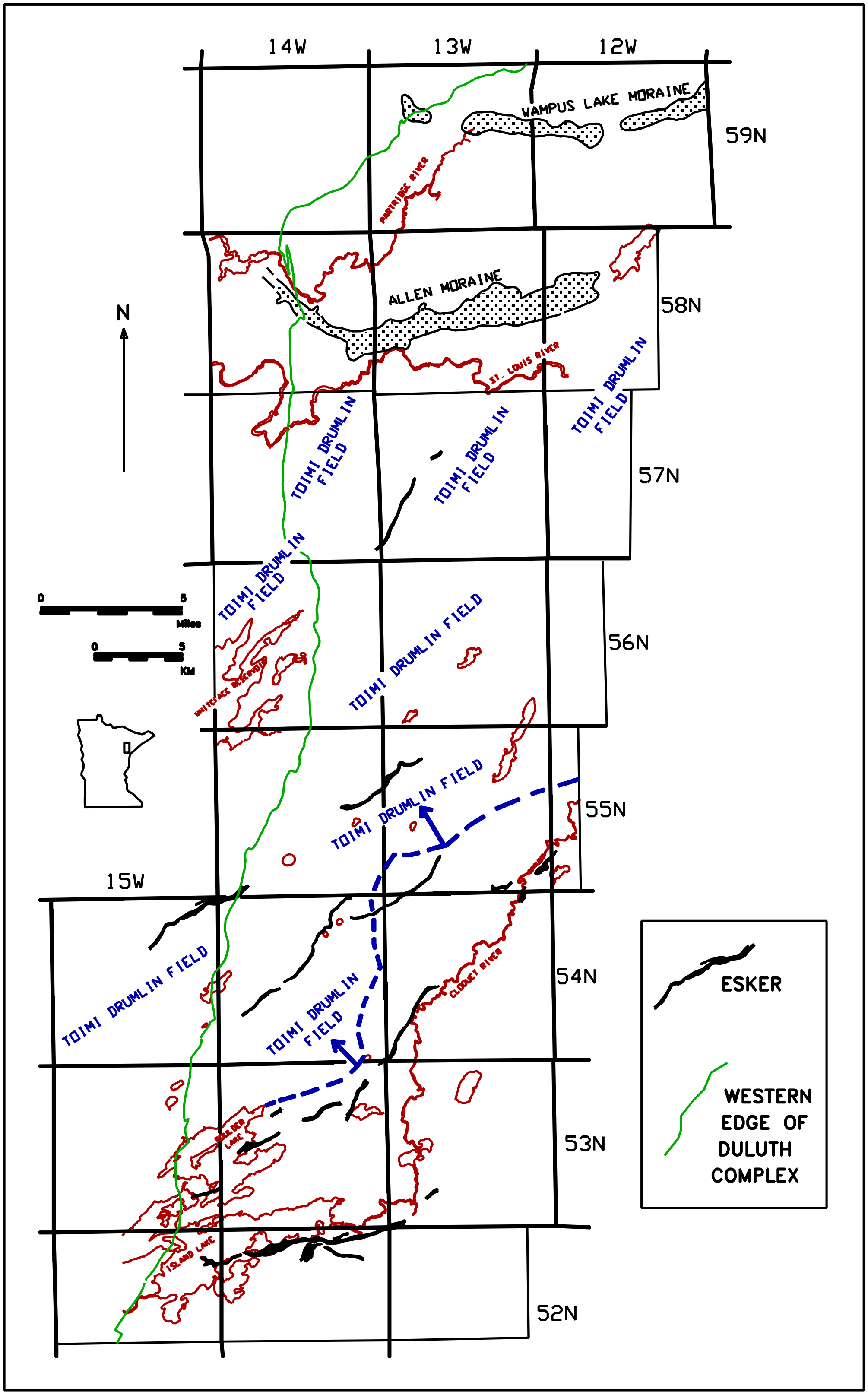

Figure 2. Major glacial features within the South Complex area.

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Within the area of this investigation, 149 drill holes were drilled in search of Cu-Ni and/or Fe-Ti±V mineralization. Out of this set, 123 holes are preserved intact, plus 7 skeletonized holes, and can be utilized to define the stratigraphy present within the South Complex. Unfortunately, very little detailed work, in the form of relogging and correlating units in drill core, was conducted prior to this investigation. Bonnichsen (1972) briefly described the geology of two drilled areas (Water Hen and Boulder Lake Reservoir) within the South Complex area. Mainwaring (1975) and Mainwaring and Naldrett (1977) logged and correlated several units in 17 drill holes associated with the OUI body at Water Hen (referred to by them as the Water Hen Intrusion). Ross (1985) compared drill core samples from two holes at Water Hen to exposures of the Bardon Peak peridotite at Duluth. Strommer et al. (1990) correlated 30 drill holes at Water Hen and established that it was similar to OUI bodies in the Partridge River intrusion described by Severson and Hauck (1990). Sassani (1992) looked at two drill holes (FHL-1 and FHL-2) to the immediate south of the South Complex area within the Duluth Layered Series. Jeff Feenstra started an MS thesis (University of Minnesota - Duluth) that compared OUI bodies at Boulder Lake North, Water Hen, and Skibo. Jeff Seitz (Washington University, St. Louis, Missouri) also initiated an MS thesis pertaining to a drill hole in the OUI body at Skibo. A brief geologic summary of his data were presented in Seitz and Pasteris (1988). Geochemical support was provided by the NRRI for this study and the results are included in this report.

Previous investigations to the north of the South Complex have documented stratigraphic igneous packages for the Partridge River intrusion (Severson and Hauck, 1990; Geerts, 1991; Severson, 1991; and Severson, 1994) and for the South Kawishiwi intrusion (Severson, 1994; Zanko et al., 1994). These stratigraphic packages are described in detail and referred to as the Partridge River Troctolite Series (PRTS) and South Kawishiwi Troctolite Series (SKTS). Previously acquired geochemical results (whole rock, etc.) collected from drill holes scattered throughout the South Complex, are included in: Sellner et al., 1985; Dahlberg, 1987; Dahlberg et al., 1987; and Dahlberg et al., 1989. These geochemical data are also included in this report.

Reconnaissance mapping in the South Complex is limited due to a general lack of outcrop. Bonnichsen (1971) included outcrops from the South Complex area in his overall reconnaissance geology map of the Duluth Complex. Detailed geologic mapping was recently completed to the south of this investigation in the Duluth area and is referred to as the Duluth Layered Series (Miller et al., 1993). Brown (1988) studied glacial esker morphology and conducted a study regarding heavy mineral prospecting over a large area that includes the South Complex area.

Adams (1990) and Loukili (1990) conducted research using geophysical techniques to map the rocks near the basal contact of the Complex along specific traverses, which included portions of the South Complex. While their work was more regional in nature, they showed the probable existence of north-south trending faults that parallel the western contact of the Complex within the study area of their investigation.

PRESENT INVESTIGATION

To date, 111 drill holes (88,423 feet of drill core) were relogged in detail from the South Complex area (note that some of these holes are located within the southern portion of the Partridge River intrusion). An additional 16 holes at Water Hen were scanned for major lithologic breaks. In essence, almost all drill holes (all but three holes) that were drilled into the South Complex area, and are still preserved in some form, were examined for this study. A listing of all known holes drilled within the South Complex area is included in Appendix 1 and the SOCOMP.WK1 data file (back pocket). Major lithologic breaks within each drill hole are also listed in the appendix and data file. All drill hole locations, in addition to bedrock outcrops located during reconnaissance mapping, are shown on Plate I.

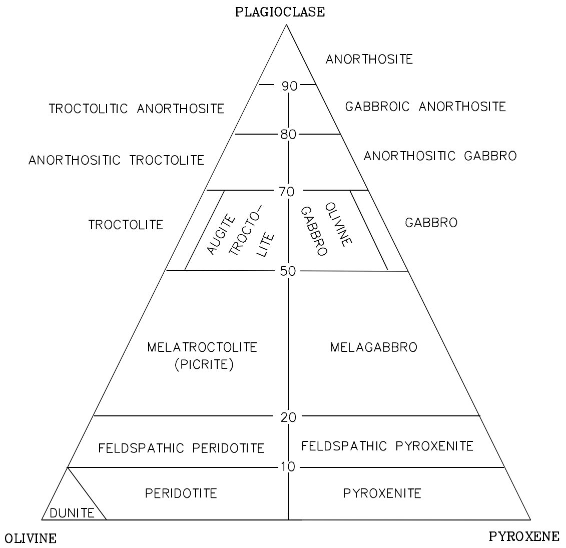

Figure 3. Rock classification scheme (after Phinney, 1972).

Drill core for holes within the South Complex area are stored at three localities: Minnesota Department of Natural Resources

(MDNR) in Hibbing, Minnesota; USX Corp. storage building at the Coleraine Minerals Research Laboratory (CMRL) of the Natural Resources Research Institute (NRRI) facilities in Coleraine, Minnesota; and American Shield Corp. core storage in Duluth, Minnesota. Rock types of the Duluth Complex are classified, in drill core, according to Figure 3. The igneous rock names are based on visually estimated modal percentages of plagioclase, olivine, and pyroxene.

Several of the major igneous units, including the various OUIs, defined in this investigation were sampled for geochemistry. Nineteen samples were collected for whole rock, base metal, trace element, and REE analyses. The samples were analyzed by X-ray Assay Laboratories in Don Mills, Ontario, Canada. Platinum Group Element (PGE) scans were conducted at the University of Quebec at Chicoutimi. The data for these 19 samples are included in the SCOMCHEM.WK1 data file (back pocket). Also, all previously collected geochemical data, sampled from drill core, are assembled and included in the SOCOCHEM.WK1 data file (back pocket). Base metal analyses (Cu, Ni, S) that were originally conducted by the exploration companies that drilled the holes 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 either: Minnesota Department of Natural Resources - Hibbing, Minnesota; United States Steel - Mt. Iron, Minnesota; or American Shield Corporation - Duluth, Minnesota. TiO_2 values, for the OUIs only, are assembled from all available private and public sources and are included in the SOCOTI.WK1 data file (back pocket).

Petrographic study was conducted on sections (thin sections, polished thin sections, and polished sections) prepared from 750 sampled drill hole intervals. These sections are on file at either the MDNR or NRRI.

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GEOLOGY OF THE SOUTH COMPLEX AREA

INTRODUCTION

Within the South Complex area, there are 16 individual subareas where exploratory holes were drilled in search of Cu-Ni and/or Fe-Ti±V mineralization (Fig. 1). The igneous stratigraphy present in each of these subareas is often vastly different from the igneous stratigraphy in an adjacent subarea. Because of these differences, there are **no** large-scale continuous units within the South Complex. Thus, each of the subareas must be described separately, starting at the north end of the study area and progressing south. These individual subareas, along with respective drill hole locations, are depicted on Plate I.

Within the majority of the explored areas are Oxide-bearing Ultramafic Intrusions (OUIs) that intrude the troctolitic rocks of the Duluth Complex. The OUIs are characterized by coarse-grained olivine-rich rock (picrite, peridotite, dunite) and coarse-grained to pegmatitic clinopyroxene-rich rock (melagabbro and pyroxenite). All of these rock types are present within a particular OUI body, and often even in an individual drill hole, and exhibit both large- and small-scale alternations between specific rock types. All OUI rock types contain >10% disseminated oxides; massive oxide horizons are common to some OUIs. Ilmenite is generally the dominant oxide; however, in some OUIs, ilmenite is greatly subordinate to magnetite. The OUIs always contain disseminated sulfides in amounts that range from trace to a few percent (visual estimation). Pyrrhotite is the dominant sulfide, with lesser amounts of chalcopyrite, cubanite, and pentlandite. Net-textured sulfide with massive sulfide zones (>90% pyrrhotite) are present in some OUIs. Primary minerals in the OUI rock types include varying amounts of olivine, clinopyroxene, and oxides; plagioclase is a minor constituent and always occurs as intercumulus material. Biotite is present in all OUI rock types. Hornblende and interstitial calcite are also locally present in all OUI rock types. Known analyses for TiO_2 in the various OUIs of the South Complex area are listed in the SOCOTI.WK1 data file (back pocket).

In the South Complex area, almost all of the OUIs, and in some cases subhorizontal peridotitic layers in the troctolitic sequence, exhibit rusty-brown, Cl-rich, liquid drops that have accumulated on the drill core via a deliquescent process. Intervals of drill core that are coated by these Cl-rich drops are graphically designated on the plates of this report. The most common drop-coated minerals in drill core are serpentinized olivine and/or sulfide grains. The presence of the Cl-rich drops suggests that the rocks of the Duluth Complex were subjected to invasion by Cl-bearing syn- to post-magmatic hydrothermal solutions.

ALLEN EXPLORATION AREA

The most northern exploration area within the study area is the Allen area, which is located immediately south of the Wyman Creek deposit (Fig. 1). Twelve holes were drilled by Bear Creek Mining Co. (1958-1960) and Exxon Minerals Co. (1976-1979). The holes encounter troctolitic rocks that are roughly correlative with units of the Partridge River Troctolite Series (PRTS) that are present to the north in the Wyman Creek deposit. Plate II illustrates a rough correlation of the igneous units in 5 holes within the Allen area relative to units at Wyman Creek. Many of the PRTS marker beds that are present at Wyman Creek begin to "lose their identity" to the south toward the Allen area, and correlation of units becomes progressively more difficult in a southerly direction. The mapped contact of the Complex with the Virginia Formation, in the Allen area (Plate I), is based on the distribution of rock types intersected in the collars of drill holes (ledge rock type).

It is important to note that the Wyman Creek/Allen area marks a dramatic change in the trend of the western contact of the Complex. In this area, the contact exhibits a rapid change from a northeasterly trend at Wyman Creek to a nearly north-south trend in the Allen area (Fig. 1). Drill hole data at this inflection point indicate that the attitude of the basal contact beneath the Complex steepens from a 15E-25E dip at Wyman Creek to 60E or more in the Allen area (Severson, 1988). Since the configuration of the basal contact is almost cliff-like in the Allen area, the entire section of troctolitic rocks intersected in drill holes is in close contact with footwall rocks and is probably contaminated via assimilation of the country rocks. Thus, correlation of igneous units is hampered by a thick package of contaminated and heterogeneous rocks in close contact with the footwall.

Troctolitic Rocks

Troctolitic rocks in the lower portions of drill holes in the Allen area are texturally heterogeneous, sulfide-bearing, and presumably correlative with Unit I of the PRTS (these low troctolitic rocks are referred to as Unit I? in Plate I). The thickness of Unit I? in the Allen area is highly variable, depending on the placement of the drill hole relative to the cliff-like basal contact, and ranges from 300 feet thick (drill hole W-5) to >970 feet thick (drill hole W-4). Cu-Ni mineralization is common to Unit I? in the Allen area; however, the extent of visual mineralization is highly variable in the drill holes. Maximum Cu values of 0.65%-0.78% are present in 3 of the 12 drill holes, but overall, Cu values are less than 0.40%. Unit II of the PRTS is present at Wyman Creek, but cannot be traced with certainty to the south of drill hole W-5. Unit V of the PRTS is also present in the Allen area where it is greater than 2,500 feet thick in drill hole W-15 (the hole is collared and terminated within Unit V).

SECTION 22

Core from six holes is available for the Section 22 area (Fig. 4). One hole is collared in the Virginia Formation, and the remaining holes are collared in the Duluth Complex; presumably in Unit I of the PRTS. Three of these holes also intersect OUI rocks that are present over both thick and thin intervals. Drill hole data suggest that the basal contact is not as steep as at the Allen area to the north. A shallow dip of 35E is suggested for the basal contact at Section 22 (see Plate VI).

Oxide-Bearing Ultramafic Intrusion (OUI)

The cross-sectional relationships of four drill holes in the Section 22 area are shown in Plate VI. Unique to this cross-section are the thick intervals of OUIs intersected in holes A-4 and A-6. Drill hole A-4 is inferred to have been drilled into the center of a plug-like OUI body; whereas, A-6 is inferred to have been drilled near the margin of the OUI body. The abundant OUI lenses intersected in A-6 represent apophyses off of the main body. Minor thin OUI lenses are also present in A-2 at 215-274 feet. Rock types of the OUI consist of medium- to coarse-grained, oxide-bearing picrite and oxide-bearing peridotite, with gradations to oxide-bearing troctolite. Oxide content is generally 5%-15% and rarely is as high as 30%. Ilmenite is dominant, and magnetite is only rarely present as composite patches within the ilmenite. Composite patches of chromium titanomagnetite are common along the periphery of some ilmenite grains. Overall, the OUIs in Section 22 average about 10.74% TiO_2 (without considering thickness) with a maximum of 28.72% TiO_2 (see data in SOCOTI.WK1). The best TiO_2 values (>15%) are present in thick intervals in the bottom portions of drill holes A-4 and A-6 (60 feet + 20 feet thick, respectively).

Cu-Ni mineralization is common to the OUIs in all drill holes, but the various analyses only average 0.14% Cu (maximum of 0.25% Cu) and 0.08% Ni (maximum of 0.12% Ni). Within the troctolitic rocks, the Cu-Ni mineralization is generally much weaker and is rarely >0.10% Cu, with the following exception. Drill hole A-2 intersects slightly stronger mineralized rocks, with a maximum of 0.91% Cu (over 10 ft.). Overall, Cu-Ni mineralization in both the OUI and troctolitic rocks in the Section 22 area is weak and sporadic. Maucherite, a nickel arsenide, is associated with both OUI and sulfide-bearing troctolitic rocks. It is present in 8 out of 53 petrographic sections. Parkerite, a nickel-bismuth sulfide, is present within some maucherite grains.

Troctolitic Rocks

Drill holes A-2 and A-5 intersect fairly thick sequences of troctolitic rocks that can be correlated with PRTS units in the Partridge River intrusion. Hole A-5 is unique in that it contains abundant hornfelsed sedimentary inclusions and abundant thin OUI lenses (Fig. 5). Near the bottom of A-5, a thin interval of mottled troctolitic anorthosite, with unique olivine oikocrysts, is present at 486-504 feet. This mottled troctolitic unit is extremely similar to Unit III of the PRTS to the northeast at the Wetlegs deposit. There, Unit III is a distinctive marker bed, due to olivine oikocrysts that give it a unique texture in drill core. The presence of a Unit III-like rock in only one hole at Section 22 suggests that Unit III is present as an inclusion. Geochemical plots, to be discussed latter, suggest that most of the sampled troctolitic rocks in the Allen area correspond to Units I and V of the PRTS.

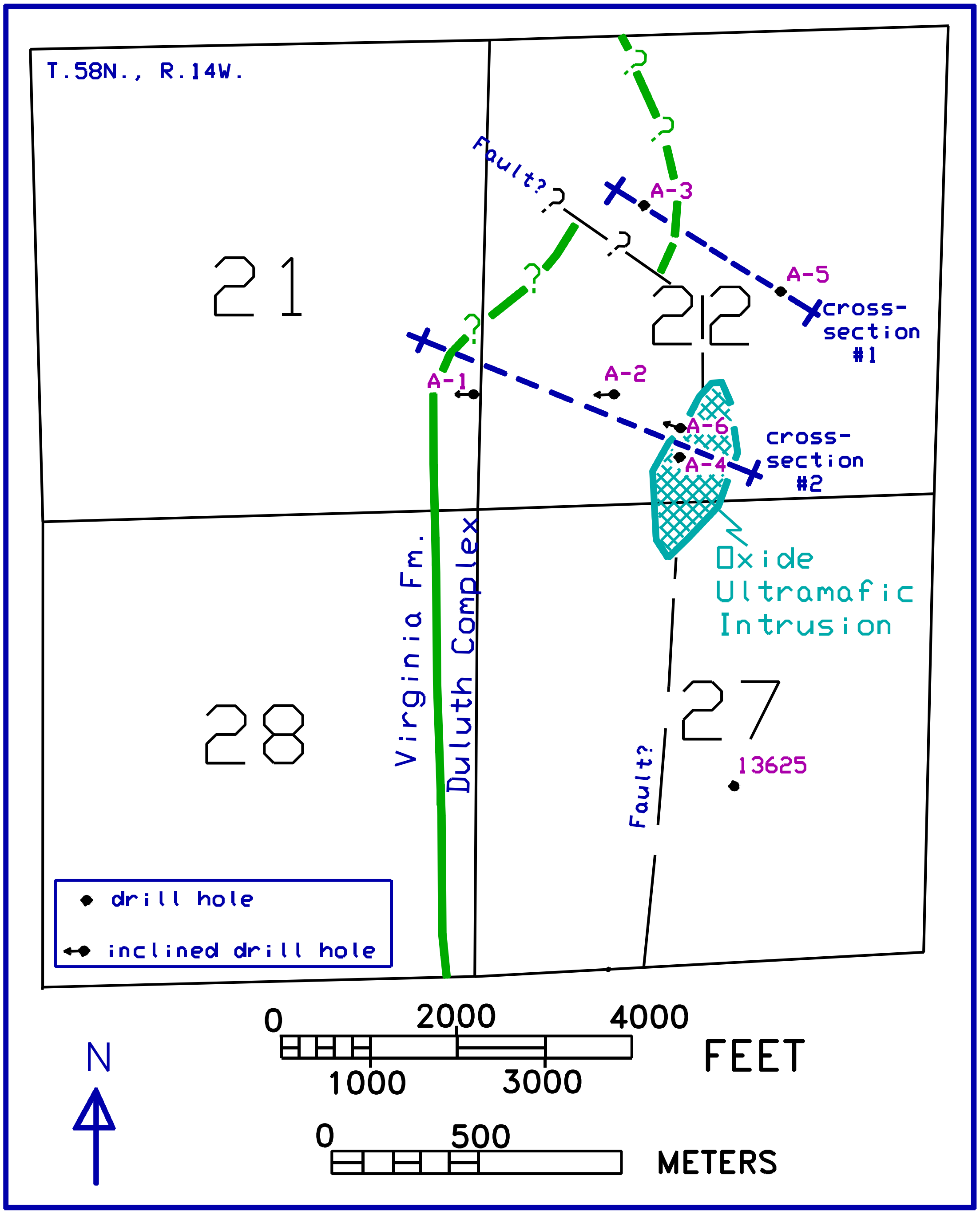

Figure 4. Drill hole location map and general geology for the Section 22 area. Cross-sections #1 and #2 are shown on Figure 5 and Plate VI, respectively.

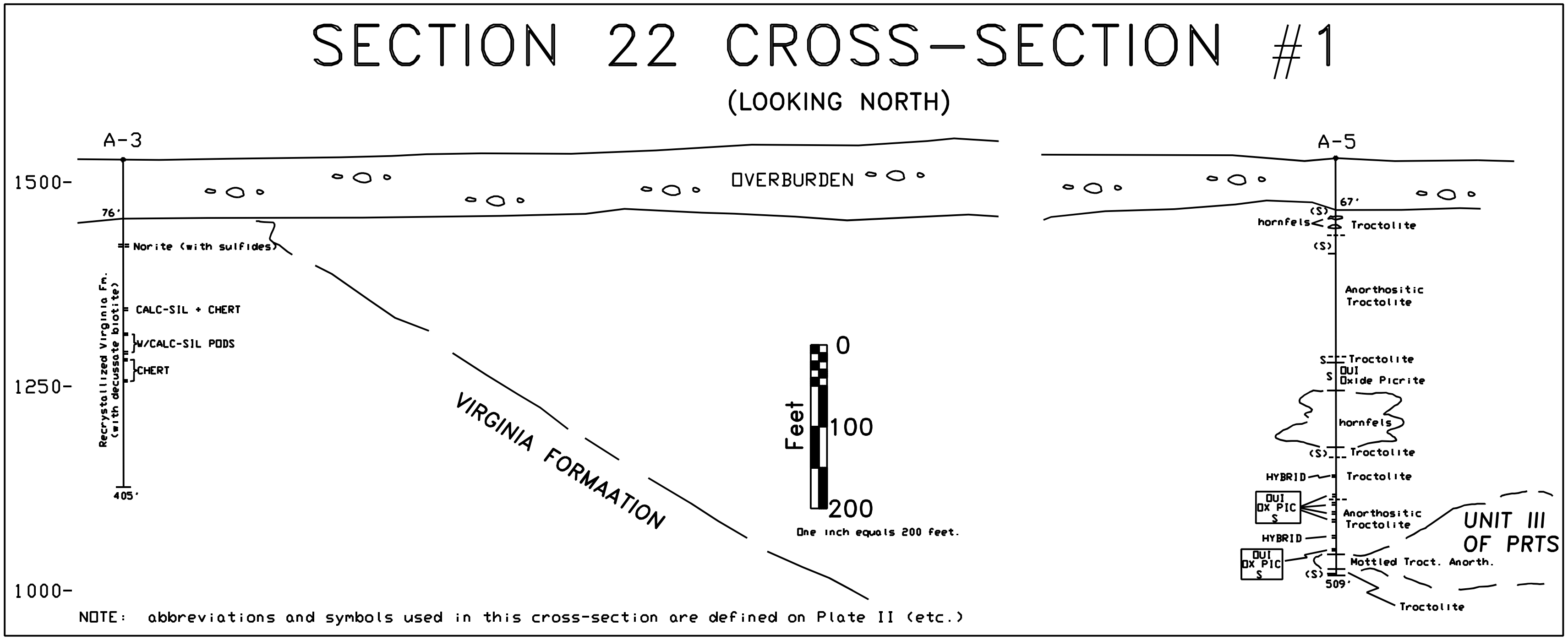

Figure 5. Cross-section #1 of the Section 22 area (see Fig. 4 for location of cross-section).

Footwall Rocks - Virginia Formation

Figure 5 illustrates the cross-sectional relationship of holes A-3 and A-5. In drill hole A-3, the Virginia Formation consists of a totally recrystallized argillite characterized by decussate medium-grained biotite set in a rock that is now totally devoid of any bedding plane features. This rock type is informally referred to as the RXTAL unit of the Virginia Formation (Severson and Hauck, 1990; Severson, 1991; Severson, 1994; Severson et al., in prep.). Mixed within the RXTAL rocks are thin zones of chaotically-bedded argillite with common micro-faults, micro-folds, and partial melt lenses. This rock type is informally referred to as the DISRUPTED unit of the Virginia Formation (Severson, 1994; Severson et al., in prep.) Both RXTAL and DISRUPTED units are common to the Virginia Formation only in close proximity to the basal contact of the Complex. More detailed descriptions of the DISRUPTED and RXTAL units, including photographs of outcrops, are presented later in this report (see Linwood Lake section, page 43).

SKIBO

Twenty drill holes were drilled in the Skibo area (Fig. 6). INCO drilled 18 of the holes during 1956-57 and 1969; none of the core for these holes remains for examination. Drill hole DDH-3 was drilled by an unknown company (INCO?) and only skeletonized core remains for this hole (at the MDNR). United States Steel Corp. drilled hole 27016 in 1982. This hole represents the only complete core available for the Skibo area. On Plate II, the rock units of drill hole 27016 are correlated with rock units in adjacent areas within the South Complex. The cross-sectional relationships of major rock units intersected in hole 27016 and several INCO holes is shown in Plate VI. This cross-section is constructed by comparing the rock types intersected in drill hole 27016 to the rock types described in the INCO drill logs and reinter-

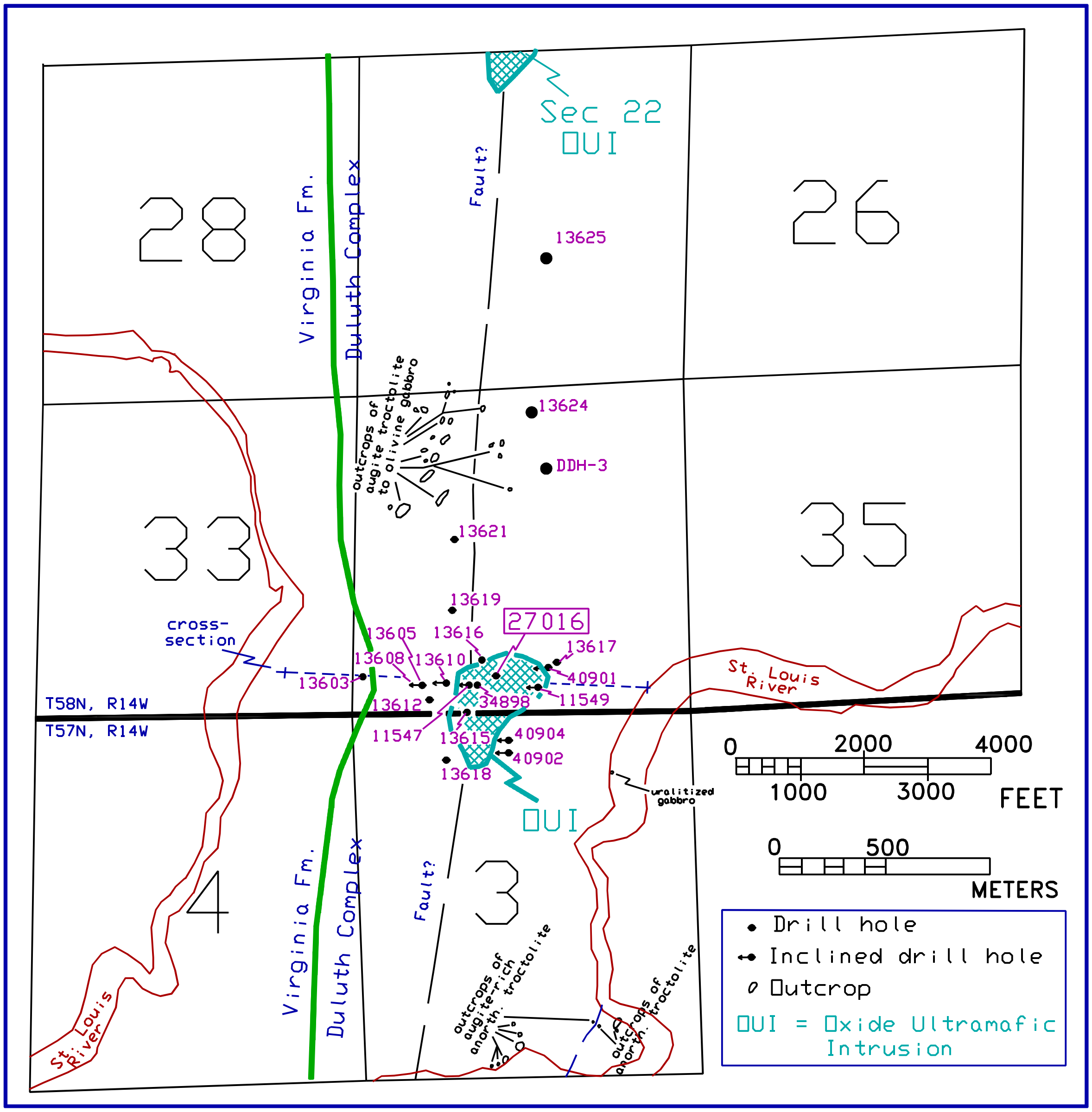

Figure 6. Drill hole location map and general geology of the Skibo area. Cross-section shown in Plate VI.

preting them accordingly. The basal contact of the Complex at Skibo is also shallow, as at Section 22, and appears to dip at about 35E-40E to the east (see Plate VI).

Oxide-Bearing Ultramafic Intrusions (OUI)

A highly irregular-shaped OUI body is intersected in the top portions of at least 10 holes in the Skibo area (see Plate VI). The OUI rocks are characterized by coarse-grained peridotite with 5%-20% plagioclase (intercumulus), 5%-10% augite, 70%-85% olivine, minor amphibole and biotite, 5%-15% oxides (locally up to 40%), and trace-8% sulfides (locally net-textured). Zones of massive graphite, or graphite-rich rocks, are described in the INCO logs. These rocks are interpreted to be associated with the OUI-like rocks. A graphite-bearing peridotite, with 1% graphite, is also present in drill hole 27016.

Ilmenite is the dominant oxide in the Skibo OUI where it occurs as interstitial, skeletal, and rounded lobate grains. Seitz and Pasteris (1988) believe that the oxide textures are suggestive of oxide-liquid immiscibility. Magnetite is present, but occurs only as thin cracks within olivine grains; it is the product of a serpentinization event. Along the margins of some ilmenite grains are small, composite patches of chromium titanomagnetite. Overall, the TiO_2 content of the Skibo OUI averages about 14.33% with a maximum of 25.28% at 251-257 feet (SOCOTI.WK1 data file - from drill hole 27016 only). Cu-Ni mineralization associated with the OUI is weak and rarely greater than 0.3% Cu. An average of 0.19% Cu (maximum of 0.34%) and 0.10% Ni (maximum of 0.31%) is present in the OUI of drill hole 27016. Some evidence of pre-glacial weathering in the Skibo area is indicated by an abnormally thick weathered zone of both troctolitic rocks and OUI in the top of hole 27016 (at 94-135 feet). A "magnetite-ilmenite sand" is reported in an INCO drill log for hole 13616 (see Plate VI). Iverson (1991) suggests that the sand may have been produced during the

Cretaceous and that some black sand potential exists in an area extending from the Section 22 area south through the Water Hen area.

Troctolitic Rocks

Because only one drill hole is preserved for the Skibo area, little is known about the overall nature of the troctolitic rocks that host the OUI. In drill hole 27016, the troctolitic rocks consist of both troctolite (center of the hole) and augite troctolite (top and bottom of the hole). These rocks can be correlated with rocks of the Partridge River intrusion, specifically with Unit I (in the lower half of the drill hole) and Unit V (in the top half of the hole). The troctolitic rocks are mineralized only in close proximity to the basal contact. Cu-Ni mineralization in the troctolitic rocks at Skibo is weak and is rarely greater than 0.25% Cu. However, several Cu-Ni-rich zones, associated with strongly mineralized troctolite and massive sulfide veins, are reported as scattered occurrences in the INCO drill logs for holes 13605 and 13615. Drill hole intervals and the percentage of high Cu and Ni values for these two holes are listed in Table 1.

Table 1. Strongly mineralized zones reported in INCO drill holes in the Skibo area.

Drill Hole	Interval (ft.)	Rock Type	Cu Wt. %	Ni Wt. %
13605	31.7-35.6	Mass. Sulfide	11.23	0.48
13615	378.0-379.0	Troctolite	0.83	1.04
13615	462.0-472.0	Troctolite	1.21	0.46
13615	861.0-861.8	Mass. Sulfide	3.44	3.54
13615	907.4-909.3	Troctolite	1.17	0.35
13615	921.3-922.0	Troctolite	2.82	0.35
13615	933.9-934.5	Troctolite	1.15	0.15
13615	971.0-971.3	Troctolite	1.60	0.68
13615	1130.5-1131.3	Mass. Sulfide	3.80	6.42

These high values may be associated with progressive Cu-Ni enrichment related to fractional crystallization of a sulfide melt within a vein-like system. A similar mechanism of Cu-enrichment, along with PGE-enrichment, is envisioned for footwall sulfide veins at the Strathcona Mine of the Sudbury Intrusion (Naldrett et al., 1992). The high-grade sulfide veins at Skibo may also be PGE-enriched, but no core material remains of these zones for geochemical analysis.

Footwall Rocks - Virginia Formation

In drill hole 27016, the Virginia Formation contains a unique interbed of graphite-bearing argillite with conspicuous thin sulfide-rich lamellae that parallel the bedding. Pyrrhotite is the dominant sulfide, but minor chalcopyrite and sphalerite are locally present. This unit is also present elsewhere in the Virginia Formation at the Babbitt, Serpentine, and Dunka Pit deposits (Fig. 1), where it is referred to as the BDD PO unit (Severson, 1994; Severson et al., in prep.; and Zanko et al., 1994). One grain of clausthalite (PbSe) is present in a polished section collected from the BDD PO unit at Skibo.

SKIBO-SOUTH

A total of seven drill holes are present in the Skibo-South area (Fig. 7), or the Grid II area, as referred to by the Phelps Dodge Corporation. One hole is collared in the Virginia Formation (II-2), one hole intersects a thick OUI body (SR-1), and the remaining five holes intersect weakly-mineralized troctolitic rocks. The nature of the basal contact of the Complex at Skibo-South is unknown as only one hole encountered footwall rocks.

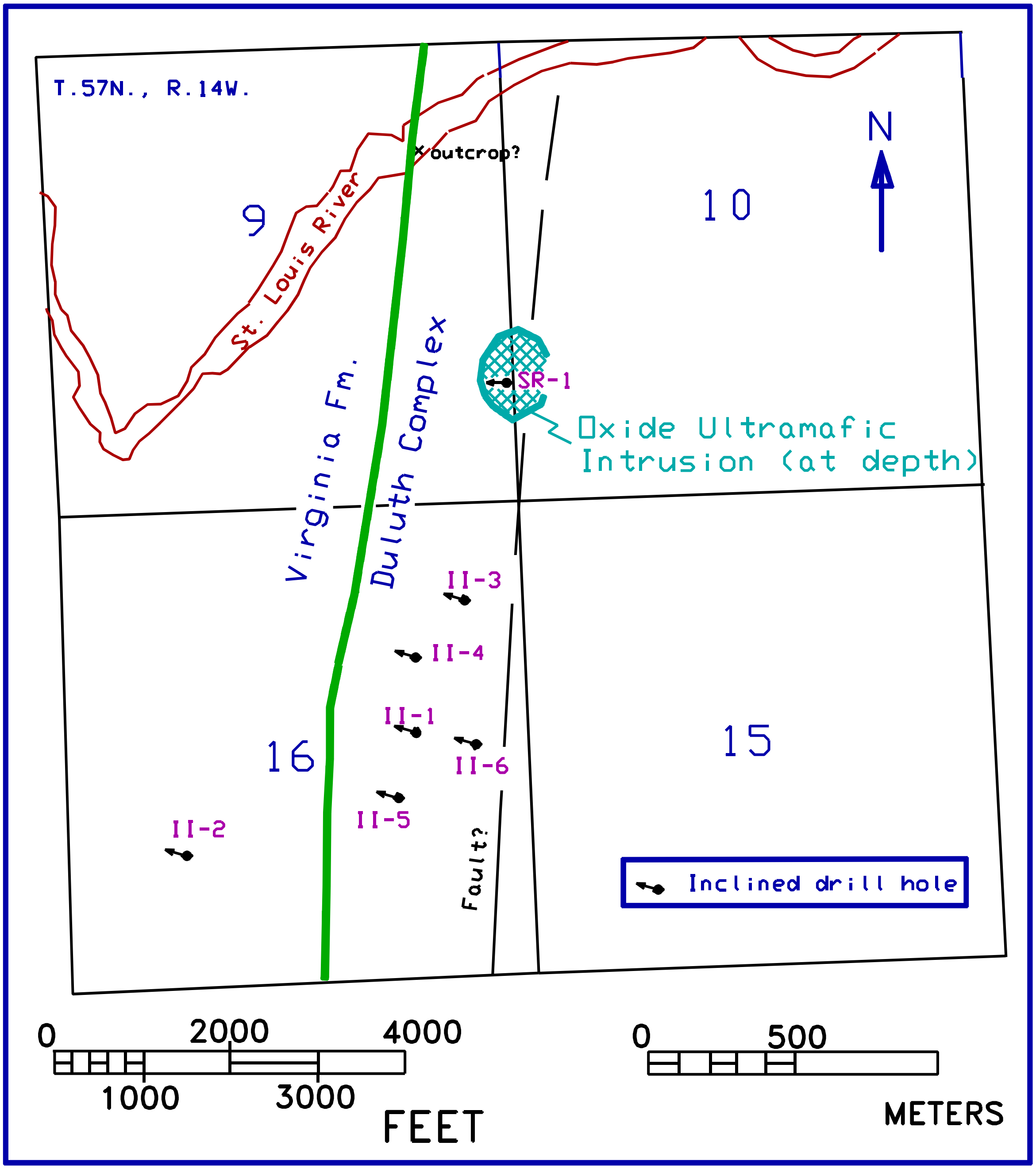

Figure 7. Drill hole location map and general geology of the Skibo-South area.

Oxide-Bearing Ultramafic Intrusion (OUI)

The OUI, in drill hole SR-1, is characterized by coarse-grained rocks consisting of picrite, peridotite, and pyroxenite. All OUI rock types contain 10%-15% oxides (locally up to 25%) and trace to 0.5% sulfides. Ilmenite is dominant and occurs as round (cumulate?) grains that exhibit straight to weakly lobate boundaries with other ilmenite grains. Magnetite is rare, and occurs as bands between the ilmenite grains. Internal patches of chromium titanomagnetite are present in some ilmenite. The TiO_2 content of the OUI at Skibo-South is unknown - sampled intervals in drill hole SR-1 were never analyzed for TiO_2. Cu and Ni data for the OUI in drill hole SR-1 are unknown as the data are not open-filed. The sulfides in the OUI are dominantly pyrrhotite, with lesser amounts of chalcopyrite, cubanite, and pentlandite, and rare sphalerite. One grain of maucherite (a nickel arsenide) is present in one polished section.

Troctolitic Rocks

The troctolitic rocks at Skibo-South cannot be correlated in drill holes (see Plate II) and are characterized by both texturally-homogeneous and texturally-heterogeneous troctolite and anorthositic troctolite. Serpentinized picrite zones are minor and may be present as discontinuous layers. Scattered throughout the troctolitic rocks are thin lenses/apophyses and patches of OUI and hybrid rocks. The hybrid rocks consist of olivine/augite-rich rocks with oxide (<10%), net-textured to semi-massive sulfide, and local graphite. All of these rock types rarely contain >0.1% Cu, except the hybrid zones that contain up to 0.6% Cu. Pyrrhotite is the dominant sulfide, with lesser amounts of chalcopyrite, cubanite, and pentlandite. Mogessie et al. (1991) report safflorite, cobaltite-gersdorffite, oxides, spinels, and V-Cr spinel associated with a graphite-rich hybrid zone.

FN Unit

Most of the drill holes of the Skibo-South area terminate in a heterogeneous mess of variable rock types and textures that are collectively referred to as the FN Unit. On Plate II, the drill holes within the Skibo-South area are hung on the top of the FN Unit. Rock types of the FN Unit consist of: 1) medium-grained heterogeneous to homogeneous troctolite; 2) gradational olivine-rich troctolite zones; and 3) fine-grained, granular, troctolitic to gabbroic rocks that exhibit a purple sheen in drill core. The latter rock type is the most unique of this group because of their fine-grained nature (<1.0 mm diameter grains), and a localized presence of vesicle-like features (plagioclase-filled clots and wisps) in an otherwise featureless and massive rock. Because of these features, the fine-grained rocks could easily be classified in drill core as hornfelsed basalt inclusions. However, this same rock package is also present 2 miles to the south at the Water Hen deposit where relationships suggest that the FN Unit is not hornfelsed basalt, but rather, hornfelsed and/or chilled early intrusive rocks near the basal contact (for a more detailed description see the discussion below pertaining to the FN Unit at Water Hen).

Footwall Rocks - Virginia Formation

Over 1,600 feet of the Virginia Formation are intersected in drill hole II-2, which is inclined at -45E. Rock types consist of well-bedded argillite with abundant thin (<26 feet) BDD PO horizons (see Plate VIII). Also present are cordierite-rich argillite, RXTAL zones, and rare thin interbeds of calc-silicate and quartzite.

WATER HEN

Since the late 1950s, 37 holes have been put down into the Water Hen deposit (Fig. 8) by various companies. Most of these holes intersect an OUI body within troctolitic rocks, and only four holes intersect the footwall Virginia Formation below the basal contact (see Appendix 1). A crude igneous stratigraphy of the Water Hen area relative to other areas in the South Complex is portrayed on Plate II. Plate VII includes four cross-sections that display the

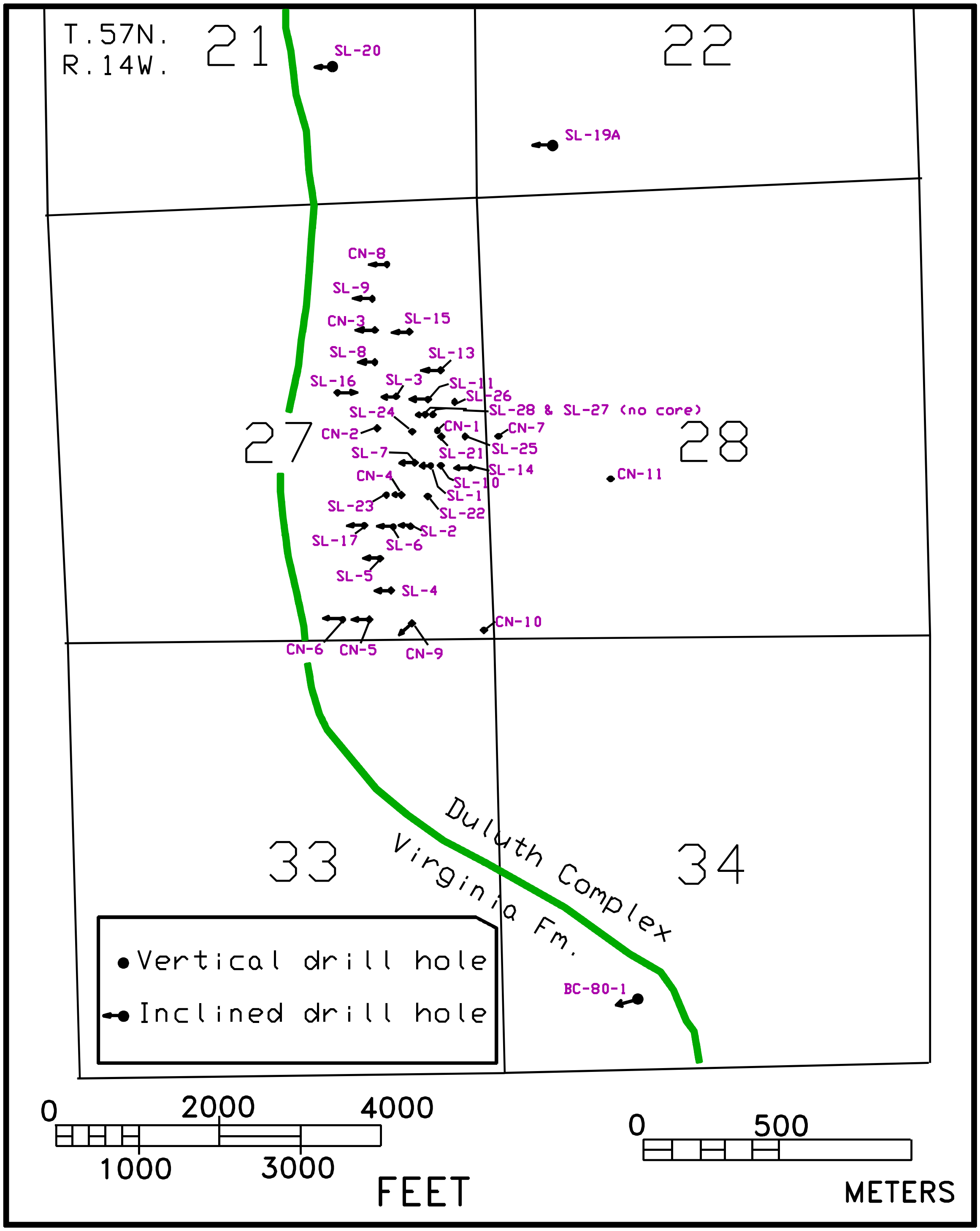

Figure 8. Drill hole location map of the Water Hen area (north at top of figure).

correlative igneous stratigraphy within the Water Hen area. These data update and supercede some of the cross-sections of Strommer et al. (1990). The basal contact along the western edge of the Complex at Water Hen appears to be very steep (cliff-like) as deduced from scattered drill hole information (see Plate VII). However, toward the interior of the Complex (toward the east), the basal contact appears to flatten out at depth (see Plate VII - drill hole CN-11 in Cross-Section #3). A description of the major rock units intersected in drill hole at Water Hen follows.

Oxide-Bearing Ultramafic Intrusion (OUI)

Thick intervals of an irregular OUI body are intersected in 16 out of 34 holes at Water Hen. The OUI intervals often alternate with troctolitic rocks (see Plate VII) and exhibit sharp contacts with the enclosing troctolitic rocks. Drill holes that are collared in the main OUI body are shown in Figure 9-A. Toward the margins of the main OUI body, another 11 holes intersect abundant apophyses (or thin lenses) of OUI mixed with the troctolitic country rock. The apophyses exhibit highly variable thicknesses of 2 inches to 10 feet. Contacts with the troctolitic rocks are sharp and often highly irregular; in some cases, they exhibit interpenetrating crystals that cross the contact boundary. The contacts also vary from subhorizontal to vertical, and some OUIs appear to occur as irregular-shaped patches within the troctolitic rocks. In some drill holes, the OUI apophyses are so abundant and chaotic that they appear to be arranged in a networked pattern (as in the drill holes of Cross-Section #4 on Plate VII). The chaotic configuration, as well as contact relationships, suggest that the apophyses and the main OUI body were emplaced while the troctolitic rocks were not fully crystallized. Note on Plate VII the main OUI body is shown with a root or feeder zone at depth. The root zone has not been confirmed by drilling, and a certain amount of "artistic license" is utilized in preparing the Water Hen cross-sections.

Rocks of the Water Hen OUI consist of: coarse-grained peridotite, feldspathic peridotite, dunite, and picrite; coarse-grained to pegmatitic clinopyroxenite; and minor medium-grained

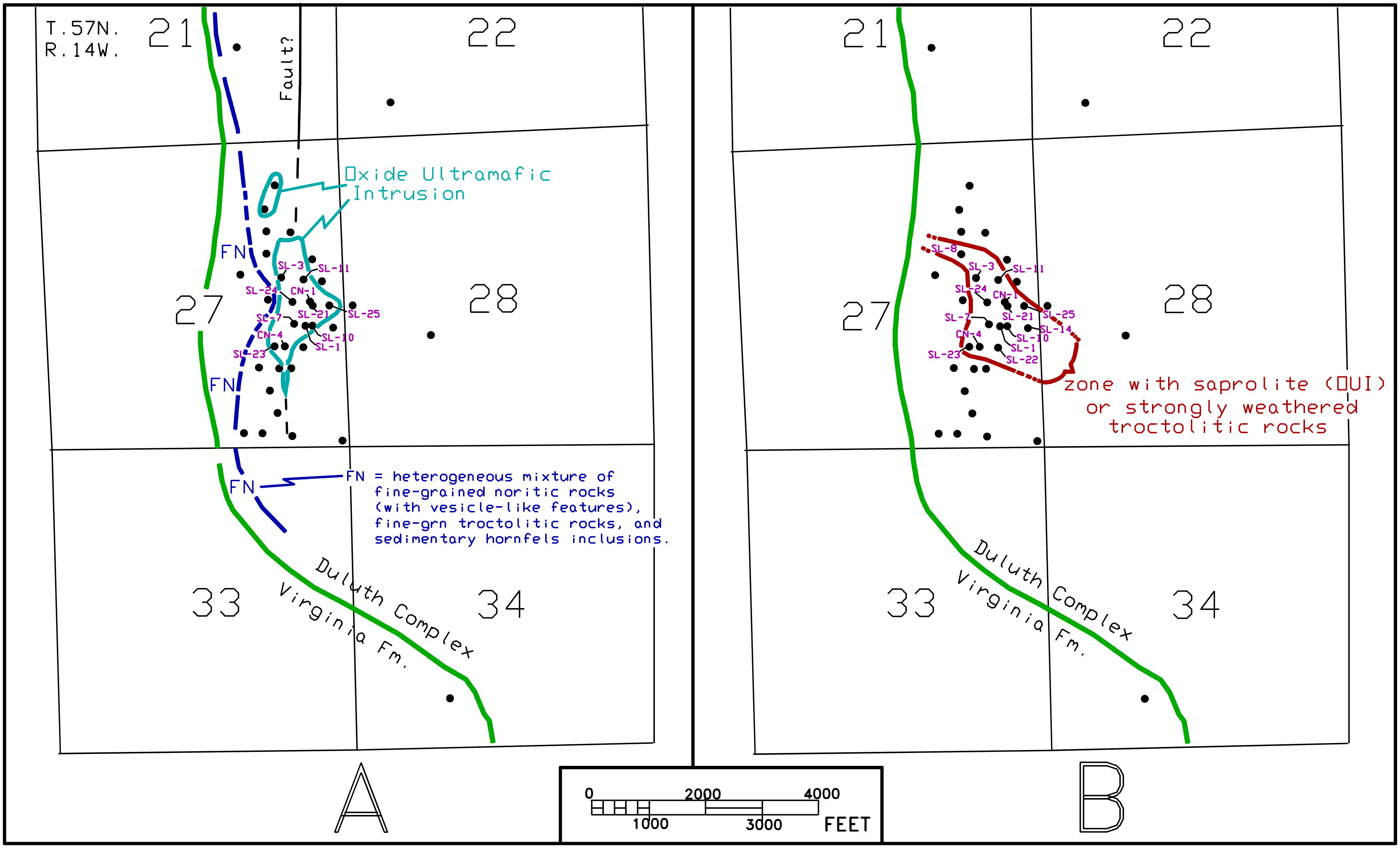
T.57N.
R.14W.
21
22
27
28
33
34
Fault?
Oxide Ultramafic Intrusion
FN
FN = heterogeneous mixture of fine-grained noritic rocks (with vesicle-like features), fine-grn troctolitic rocks, and sedimentary hornfels inclusions.
SL-3
SL-11
SL-24
CN-1
SL-7
SL-21
SL-25
CN-4
SL-10
SL-1
SL-23
SL-8
SL-14
SL-22
zone with saprolite (OUI) or strongly weathered troctolitic rocks
Duluth Complex
Virginia Fm.
A
B
0
1000
2000
3000
4000
FEET

Figure 9-A. General geology of the Water Hen area as determined from rock types present in the collars of drill holes.
Figure 9-B. Distribution of saprolite (derived from the OUI) and strongly weathered troctolitic rocks where intersected in the drill hole collars.

orthopyroxenite. All, but the latter rock type, contain 5%-20% oxides (dominantly ilmenite). Up to 40% oxides are locally present in thin intervals, and massive oxide zones are rare. The main OUI body at Water Hen is crudely zoned. Clinopyroxenite is generally the most common rock type in the upper portion of the main OUI body, i.e., top 50-500 feet. Olivine-rich rocks (peridotite, dunite, picrite) are almost exclusively the only rock type present in the lower two-thirds of the main OUI body. Orthopyroxenite is present as rare and extremely localized thin intervals (<30 feet) in the bottom portions of the main OUI body. The apophyses of OUI peripheral to the main OUI body also are zoned - clinopyroxenite is the most common rock type in the tops of drill holes; whereas, peridotite is more common with depth. The Water Hen OUI is unique in that it contains abundant graphite-rich zones associated with both pyroxenitic and olivine-rich rocks. The occurrences of graphite range from disseminated round blobs (up to 1.5 cm across), to semi-massive graphite zones, to massive graphite zones up to 2 feet thick. Graphite-bearing rocks are confined to the upper one-third to one-half of the main OUI body. Mainwaring and Naldrett (1977) concluded that the graphite and sulfides of the OUI may be due to contamination of the magma by assimilation of carbon and sulfur from the footwall rocks.

Wherever the OUI is collared immediately at the glacial/bedrock ledge, a thick oxide-bearing saprolite zone is present, which extends downward into the main OUI body for depths up to 250 feet (see the cross-sections of Plate VII). Figure 9-B displays the area where saprolite and highly-weathered troctolitic rocks occur. The presence of the saprolite indicates a period of extensive weathering prior to Quaternary glaciation. Weathering appears to have been more pronounced in the OUI relative to the troctolitic rocks - in some drill holes saprolitic lenses of OUI (vertical lenses?) are separated by non-weathered to weakly weathered troctolite (see SL-14 in Plate VII - Cross-Section #3). Because most of the saprolite drill core was consumed during metallurgical testing, very little core is preserved for inspection. The saprolite core that remains consists of clayrich, crumbly, and iron-stained core with some coarse clinopyroxene crystals and common massive graphite zones. Probably most of the saprolite was derived from weathering of dominantly pyroxenitic OUI. With depth, the saprolite progressively grades into moderately weathered OUI and then into non-weathered (fresh) OUI.

Strommer et al. (1990) estimated that the overall size of the main OUI body to be approximately 1,600 feet long x 500 feet wide x 700 feet deep. Mainwaring (1975) believed that the OUI (referred to as the Water Hen Intrusion) consisted of an upper "layered zone" and a lower "basal dunite" (see drill hole CN-7, Cross-Section #2, Plate VII). However, Strommer et al. (1990) determined that Mainwaring's "layered zone" is a mixed zone of the host troctolite with abundant thin apophyses of OUI (as is confirmed in this investigation and depicted as such on Plate VII). Strommer et al. (1990) felt that the OUI lenses are marginal apophyses extending outward from a main OUI body, e.g., the "basal dunite" of Mainwaring (1975). They also determined that **some** of Mainwaring's "layered zone" rocks are a series of cyclically layered troctolitic rocks, each cycle consisting of an ultramafic base that grades upward to anorthositic troctolite. These cyclic layers are referred to as the Troctolitic Layered Series (TL unit) by Strommer et al., 1990. However, whole rock and trace element geochemistry for the ultramafic layers (collected by Strommer et al., 1990) indicate that the material that they sampled is actually OUI material. Furthermore, geochemistry for the upper troctolitic portions of these cyclic layers suggests that they are differentiated equivalents of the OUI rather than the host troctolitic rocks (to be further discussed in the Geochemistry section of this report). In conclusion, the overall data indicates that: 1) many of Mainwaring's "layered zone" rocks consist of the host troctolitic rocks with abundant late OUI apophyses - in some areas the OUI apophyses are so abundant and chaotic that they are interpreted in this report to be networked; 2) some of the apophyses may be internally cyclically layered (as the geochemistry suggests); and 3) the TL unit of Strommer et al. (1990) may not be as prevalent as originally believed, and in some cases, it is difficult to ascertain whether the cyclic layers are related to the late OUI or troctolitic host rocks.

Within the OUI, the oxides (>95% ilmenite) occur in a variety of forms that include subhedral grains, round grains, coalesced groups of round grains with weakly embayed edges, skeletal grains, blades, and intercumulus grains. Composite patches of chromium titanomagnetite are common on the edges of some ilmenite grains. TiO_2 content of the OUI averages about 11% with a maximum of 29.3%. Chromium-enriched zones are present in drill hole CN-7 where Cr contents >3,000 ppm are common from 1,145-1,200 feet (Dahlberg et al., 1989) with a maximum of 4.9% Cr at 1,151 feet (Dahlberg, 1987). Cu and Ni average about 0.23% and 0.11% with maximums of 1.97% and 0.64%, respectively. Thick zones (>15 feet) with >0.5% Cu are rare and are restricted to three drill holes (CN-7, SL-1, and SL-3). Sulfides in the OUI are generally disseminated in amounts less than 2% and occur as round drop-like interstitial blebs. Sulfide-rich zones (>10%), consisting of net-textured sulfides with alternating intervals of massive sulfide, are locally present in 8 holes (CN-1, SL-3, SL-8, SL-9, SL-10, SL-13, SL-15, and SL-26). The sulfide-enriched zones are generally located near the base of the main OUI or in the lowermost OUI apophyses; however, similar sulfide-enriched zones are also present in the host troctolitic rocks at about the same horizon (see Cross-Sections #1 and #2 - Plate VII). Pyrrhotite is the dominant sulfide in both disseminated sulfide and massive sulfide. Associated with the pyrrhotite are lesser amounts of chalcopyrite, cubanite, and pentlandite with rare sphalerite, bornite, mackinawite, and maucherite. Thin magnetite-filled cracks, the product of a serpentinization event, are common in some disseminated sulfides. Locally, pyrite replaces pyrrhotite in five drill holes (CN-1, CN-7, SL-2, SL-6, and SL-17).

Troctolitic Rocks

The troctolitic rocks that host the OUI at Water Hen are characterized by texturally-homogeneous troctolite and anorthositic troctolite in the upper portion of the sequence and texturally-heterogeneous troctolite in the lower half of the sequence. Geochemistry plots, discussed later, suggest that all of the troctolitic rocks at Water Hen may be correlative with Unit V of the Partridge River intrusion. Minor picrite layers are also locally present and may be correlative with the TL unit of Strommer et al. (1990). Sulfide mineralization in the troctolitic rocks is generally weak (average of 0.16% Cu and 0.11% Ni), except for zones with net-textured sulfides (maximum of 0.97% Cu). The net-textured sulfides in the troctolitic rocks are similar to those in the OUI. Sulfide mineralogy is also essentially the same except that maucherite (nickel arsenide) is much more common in the troctolitic massive sulfides (up to 28 individual maucherite grains are present in a single polished thin section!). Maucherite occurs in a variety of forms that include ovoids and long slender blades generally <0.1 mm, but can be up to 0.3 mm. Sulfide-enriched zones associated with the troctolitic rocks are intersected in 5 holes (CN-1, CN-7, SL-8, SL-9, SL-11, and SL-26).

FN Unit

In the Water Hen area, an assortment of fine-grained granoblastic rocks with local vesicle-like features are present in a zone immediately above the basal contact of the Complex with the footwall Virginia Formation. This unit is referred to as the FN Unit because all the rock types are dominantly fine-grained (<1 mm) and equigranular regardless of mineralogy. The FN Unit constitutes an enigmatic rock unit that has been previously interpreted to be: 1) hornfelsed sedimentary footwall rocks (listed in some drill logs); 2) hornfelsed troctolitic rocks (Mainwaring, 1975); and 3) hornfelsed basalt and/or troctolite (Strommer et al., 1990). In this report, the FN Unit is interpreted to be hornfelsed intrusive rock with common sedimentary hornfels inclusions and local vesicle-like features. It is present throughout the South Complex in an area that extends from the Skibo-South area to the Fish Lake area.

The FN Unit is characterized by fine-grained, granular gabbroic, troctolitic, and noritic rock types that commonly grade into, and alternate with, medium-grained rocks of similar mineralogy. In drill core, all of the fine-grained rock types appear to be aphanitic and display a purple sheen. In some drill holes, the entire FN Unit is represented by a monotonous sequence of fine-grained rocks, with only minor changes in grain-size and mineralogy. However, in other drill holes, the FN Unit consists of a heterogeneous mess of widely varying mineralogy and grain-size where both fine-grained and medium-grained variations are common. In both instances, the FN Unit also contains common inclusions of hornfelsed cordierite-bearing Virginia Formation. In addition, the FN Unit contains scattered thin zones (<20 feet thick) with vesicle-like features characterized by ovoids and wisps filled with coarse-grained plagioclase, clinopyroxene, orthopyroxene, and/or olivine. In thin section, the FN Unit is characterized by fine-grained, granular grains of plagioclase and clinopyroxene with variable amounts of granular orthopyroxene (inverted pigeonite) and granular to oikocrystic olivine; triple point junctions are ubiquitous. The dominant rock type of the FN Unit, based on examination of 31 thin sections of the fine-grained rocks, is olivine gabbro (15 thin sections), but troctolite (9 thin sections) and norite (7 thin sections) are also common.

The presence of vesicle-like features suggested to Strommer et al. (1990) that these rocks represent either a hornfelsed basalt of the North Shore Volcanic Group or a chilled and later hornfelsed troctolitic rock positioned near the basal contact. If the FN Unit represents a hornfelsed basalt, then the presence of abundant Virginia Formation inclusions in it are difficult to reconcile. Also, relative to a cliff-like basal contact, the FN Unit is positioned immediately alongside it. In essence, the FN Unit occurs as peripheral zone, or rind, on the extreme outer margin of the Duluth Complex. Even where the basal contact is steep, the FN Unit also occurs as a steeply-dipping parallel band on the margin of the Complex (see Cross-Sections #1 and #2 - Plate VIII). This rind-like configuration of the FN Unit is more easily explained if it is considered to be related to intrusive rocks of the Complex rather than a basalt flow. For all of these reasons, the FN Unit is interpreted to be an earlier, chilled equivalent of the Duluth Complex that was emplaced before the overlying troctolitic rocks. Subsequent emplacement of the troctolitic rocks produced the granoblastic textures that are evident in the FN Unit. Inclusions of the FN Unit are also found in the overlying troctolitic rocks and further support an early-Complex age for the FN Unit.

Orthopyroxenite dikes and dikelets are also common within the FN Unit. The dikes range in thickness from <3 inches to 8 feet. The orientation of these dikes are generally subvertical; however, for the most part, the dike orientations are unknown and are difficult to deduce from split drill core. In core, the smaller dikelets (<6 inches thick) almost look like magmatic segregations or "sweat-outs" from the enclosing rocks (Strommer et al., 1990). Most of the dikes are sulfide-enriched (0.5% to 2% sulfides) relative to the FN Unit. In most instances, chalcopyrite is the dominant sulfide. Anomalous PGE values (>3 ppm combined Pt-Pd-Au) are documented for one orthopyroxenite dike (680-683 feet) in drill hole SL-1 (Morton and Hauck, 1987). Mineralization in this dike includes chalcopyrite, pyrrhotite, cubanite, pentlandite, bornite, maucherite, native bismuth, nickeline, parkerite, native silver, and tetradymite (Morton and Hauck, 1987). The true relationship of the dikes and the enclosing FN Unit rocks is poorly understood at this time. However, because the FN Unit represents an early (chilled?) and hornfelsed intrusive rock, it may have acted as a "footwall" unit during formation of the orthopyroxenite dikes. In this manner, the orthopyroxenite dikes could be crudely compared to sulfide- and PGE-enriched footwall ore zones at the Sudbury Igneous Complex (SIC). In the SIC, a fractional crystallization of a sulfide melt in a closed vein system is envisioned to explain Cu- and PGE-enrichment in footwall veins (Naldrett et al., 1992).

Footwall Rocks - Virginia Formation

Only four drill holes intersect footwall rocks of the Virginia Formation in the Water Hen area (CN-3, CN-6, CN-10, and CN-11). Near the basal contact, the Virginia Formation is generally characterized by cordierite-bearing hornfels, the RXTAL unit, and the DISRUPTED unit. Well-bedded argillite and graywacke become dominant with distance below the basal contact (drill hole CN-10). In drill hole CN-6, a poorly-sorted, immature, recrystallized quartzite is intersected immediately below the basal contact at 676-698 feet. The quartzite is presumably present as an interbed within the Virginia Formation.

Drill Hole SL-19A

Drill hole SL-19A is described separately because of the unique geologic units intersected in the hole. The hole is isolated relative to the rest of the Water Hen drill holes and is located well to the north of the Water Hen OUI body (Fig. 8). Within the drill hole, layered ultramafic rocks (picrite, peridotite, etc.) interlayered with troctolitic rocks are intersected from 336-374 feet. Another package of interlayered ultramafic and troctolitic rocks are also intersected lower in the hole from 455-481 feet. Contact relationships and serpentinization foliation suggest that both of the ultramafic packages are subhorizontal with shallow dips to the east or southeast. Such subhorizontal ultramafic horizons are rarely intersected in drill holes in the Water Hen area. Both of the ultramafic packages intersected in SL-19A are interpreted to be correlative with an olivine-rich troctolite layer in the top of drill hole CN-11 (see Plate II). However, this correlation is somewhat speculative due to the limited number of drill holes that intersect subhorizontal ultramafic layers in the Water Hen area.

An unusual oxide-rich horizon is present between the two ultramafic packages from 446-446.7 feet. In drill core, the oxide-rich horizon consists of about 50%-70%, fine-grained oxide that is poikilitically enclosed in medium-grained plagioclase (25%-45%) and olivine (5%). Similar oxide-to-plagioclase textures are observed in drill core within the South Kawishiwi intrusion, where it is referred to as a "2-in-1" texture (Alapieti, pers. comm., 1991; Severson, 1994) because the texture looks to be the result of two entirely different thin sections (anorthosite and semi-massive oxide) superimposed on each other. Wherever this "2-in-1" texture has been noted, geochemical analyses indicate high Cr values that exceed 2%-5% (drill holes Du-15 and Du-9 in the South Kawishiwi intrusion; and drill hole FHL-2 at Fish Lake). Anomalous PGE values (>1 ppm combined Pt + Pd) are also common to these zones (Du-15 and Du-9), or anomalous PGEs are present in zones immediately below the oxide-rich zone (as at Fish Lake - Sassani, 1992). For these reasons, the oxide-rich horizon in SL-19A was sampled for geochemical analysis. Geochemistry for this horizon (see SCOMCHEM.WK1 data file) indicates that it also contains anomalous values for Cr (46,000 ppm), Pt (737-786 ppb), and Pd (63-106 ppb). Concentrations of Os, Ir, Ru, and Rh are elevated as well (see SCOMCHEM.WK1).

In thin section, the oxide-grains consist of dark-colored magnetite (because it is Cr-bearing), with minor amounts of composite ilmenite and ubiquitous small blebs of pleonaste (also Cr-bearing). The magnetite occurs in a variety of forms that include: 1) round grains; 2) subhedral grains; 3) embayed round grains; 4) hook-shaped and embayed round grains; and 5) masses of coalesced round grains. The pleonaste occurs within the magnetite as: 1) semi-circular blebs on the periphery of

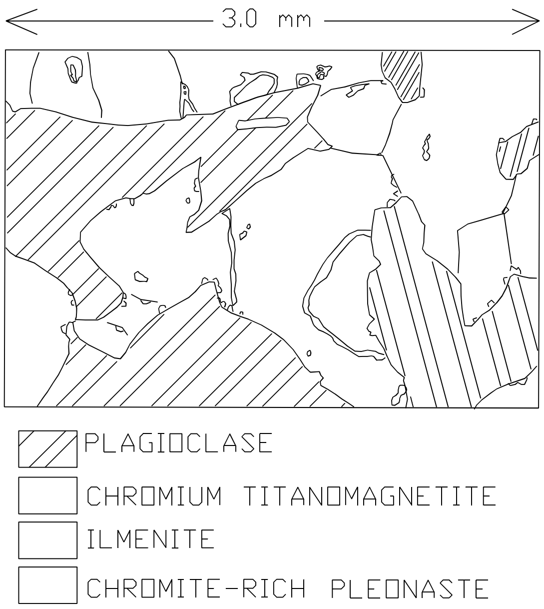

Figure 10. Sketch of textures in a polished thin section from a semi-massive oxide zone with "2-in-1" texture in drill hole SL-19A (446-446.7 ft) at Water Hen.

magnetite grains; 2) round blebs in the interior of magnetite grains; and 3) as bands between, and separating, composite magnetite and ilmenite grains. All of these textures are depicted in the sketch drawing in Figure 10. Rare amounts of sulfide are also present within the oxide-rich zone of SL-19A. The sulfides consist of varying amounts of pyrrhotite, chalcopyrite, cubanite, pentlandite (with mackinawite), and late pyrite replacing pyrrhotite. All of these sulfides occur as: 1) interstitial sulfides; 2) sulfide inclusions in plagioclase; and 3) as sulfide-filled micro-cracks in the magnetite grains.

Microprobe analyses were performed on the oxides and spinels in one polished section collected from the oxide-rich zone in SL-19A. Analyses were conducted using an updated MAC 400 electron microprobe equipped with a Krisel Control Model 2003 package. Operating conditions were 15kv and 20 nanoamps. Results of the microprobe analyses are listed in Table 2 (analyses with oxide totals <97% and >102% were discarded). The analyses indicate that the magnetite is actually chromium titanomagnetite and the internal blebs are chromite-rich pleonaste. The chromium-rich pleonaste is difficult to analyze because of its very small grain size. For this reason, only three analyses with good totals are listed in Table 2. Additional microprobe results, with totals between 90% and 95%, are listed for the chromium-rich pleonaste in Table 3.

Table 2. Mineral compositions (in wt. %) of coexisting ilmenite (ILM), chromium-titanomagnetite (Cr TiMT), and chromium-rich pleonaste (Cr PLEO) from a semi-massive oxide zone in drill hole SL-19A (446.3 ft.) at Water Hen.

Sample	SL-19A ILM	SL-19A ILM	SL-19A ILM	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr TiMT	SL-19A Cr PLEO	SL-19A Cr PLEO	SL-19A Cr PLEO
MgO	4.29	4.33	4.44	3.25	2.96	3.30	3.00	3.12	3.33	3.05	3.25	3.05	2.94	8.50	6.94	8.91
FeO	37.11	37.99	38.12	40.09	42.38	40.18	43.24	38.02	41.14	41.51	41.66	40.76	41.26	24.72	27.53	25.00
MnO	0.39	0.39	0.42	0.52	0.27	0.28	0.46	0.34	0.45	0.18	0.21	0.40	0.23	0.15	0.21	0.09
ZnO	0.07	0.17	0.05	0.39	0.00	0.18	0.08	0.33	0.00	0.00	0.37	0.27	0.21	0.00	0.40	0.62
Al_2O_3	0.02	0.07	0.00	6.90	8.03	8.07	7.12	8.89	7.98	7.23	6.21	7.93	7.80	31.21	30.08	40.71
Cr_2O_3	0.06	0.22	0.14	13.95	14.37	15.41	14.58	19.27	15.30	15.88	18.14	19.51	12.52	25.89	31.10	17.44
Fe_2O_3	4.85	2.82	3.03	18.13	14.08	17.93	16.23	18.62	16.26	17.29	15.36	16.17	17.63	6.28	2.97	6.31
TiO_2	50.28	51.44	51.71	15.10	16.21	14.17	16.64	11.39	15.22	14.88	15.65	13.77	15.34	1.65	1.80	0.98
Total	97.07	97.43	97.91	98.33	98.30	99.52	101.35	99.98	99.68	100.02	100.85	101.86	97.93	98.40	101.03	100.06
ti	0.953	0.970	0.970	3.273	3.496	3.018	3.503	2.411	3.234	3.171	3.318	2.874	3.330	0.308	0.333	0.173
mn	0.008	0.008	0.009	0.127	0.066	0.067	0.109	0.081	0.108	0.043	0.050	0.094	0.056	0.032	0.044	0.018
fe	0.782	0.797	0.795	9.664	10.163	9.517	10.123	8.949	9.722	9.837	9.822	9.461	9.961	5.131	5.668	4.920
zn	0.001	0.003	0.001	0.083	0.000	0.038	0.017	0.069	0.000	0.000	0.077	0.055	0.045	0.000	0.073	0.108
mg	0.161	0.162	0.165	1.396	1.265	1.393	1.252	1.309	1.402	1.288	1.365	1.262	1.265	3.144	2.546	3.124
al	0.001	0.002	0.000	2.346	2.716	2.696	2.351	2.951	2.660	2.417	2.065	2.596	2.656	9.137	8.736	11.300
fe_3	0.092	0.053	0.057	3.934	3.040	3.823	3.421	3.946	3.459	3.689	3.260	3.379	3.832	1.173	0.551	1.118
cr	0.001	0.004	0.003	3.180	3.259	3.452	3.228	4.290	3.419	3.559	4.045	4.283	2.859	5.082	6.056	3.246
Total	2.000	2.000	2.000	24.004	24.004	24.004	24.004	24.004	24.004	24.004	24.004	24.004	24.004	24.007	24.007	24.007

Note: Cation proportions normalized to 3 (for ILM) or 32 oxygen atoms.

Table 3. Mineral compositions (in wt. %) of chromium-rich pleonaste from SL-19A (446.3 ft.) at Water Hen (poor totals).

Sample	SL-19A Cr PLEO	SL-19A Cr PLEO	SL-19A Cr PLEO	SL-19A Cr PLEO	SL-19A Cr PLEO	SL-19A Cr PLEO
Mg	6.47	7.70	7.97	6.50	7.41	6.99
FeO	27.30	23.64	22.47	25.74	25.68	24.38
MnO	0.29	0.19	0.10	0.15	0.18	0.35
ZnO	0.26	0.38	0.74	0.26	0.00	0.51
Al_2O_3	32.40	32.16	29.84	28.29	32.45	29.56
Cr_2O_3	22.79	18.65	18.39	20.91	19.04	18.22
Fe_2O_3	6.58	8.64	9.36	9.57	7.66	9.52
TiO_2	1.43	1.27	1.85	1.91	1.93	2.06
Total	97.52	92.63	90.72	93.33	94.35	91.59

As described previously, oxide-rich zones with a "2-in-1" texture are seen in several drill holes including SL-19A, FHL-2, Du-15, and Du-9. In all these occurrences, there is an enrichment in Cr, Pt, and Pd in either the oxide-rich zone and/or in zones immediately adjacent to the oxide-rich zone. Similar looking oxide grains are also present in a polished section collected near the base of the main OUI in drill hole CN-7 at 1,193 feet (10,418 ppm Cr from 1,190-1,200 feet - Dahlberg et al., 1989). However, this oxide-rich zone is different from the other "2-in-1" occurrences in that: 1) the oxide-rich horizon is associated with an OUI rather than subhorizontal ultramafic horizons; and 2) PGE values are **not** elevated in CN-7 (Dahlberg, 1987; Dahlberg et al., 1989). Although no microprobe analyses were conducted on the CN-7 1,193 foot occurrence, Mainwaring (1975) described and analyzed similar oxides and spinels from a nearby zone in CN-7 at 1,159 feet. All microprobe analyses from rocks with the "2-in-1" texture are plotted in Figure 11. All of the spinels in Figure 11 exhibit similar chemistries for the oxide-rich zones in drill holes SL-19A, FHL-2, and CN-7. Similar spinel chemistries are also present in the oxide-rich zones of drill holes Du-15 and

Du-9; however several additional spinel varieties (including hercynite) are present. The wide variation in spinels for the Du-holes may be related to geologic setting. The oxide zones in the Du-holes are related to a footwall-contaminated igneous unit (U3 Unit of Severson, 1994) that contains abundant massive oxide zones associated with intruded and assimilated Biwabik Iron-formation. Contamination of the magma, by assimilation of iron-formation, is not envisioned to be a possible source for the oxide-rich zones in the SL-19A and FHL-2 occurrences.

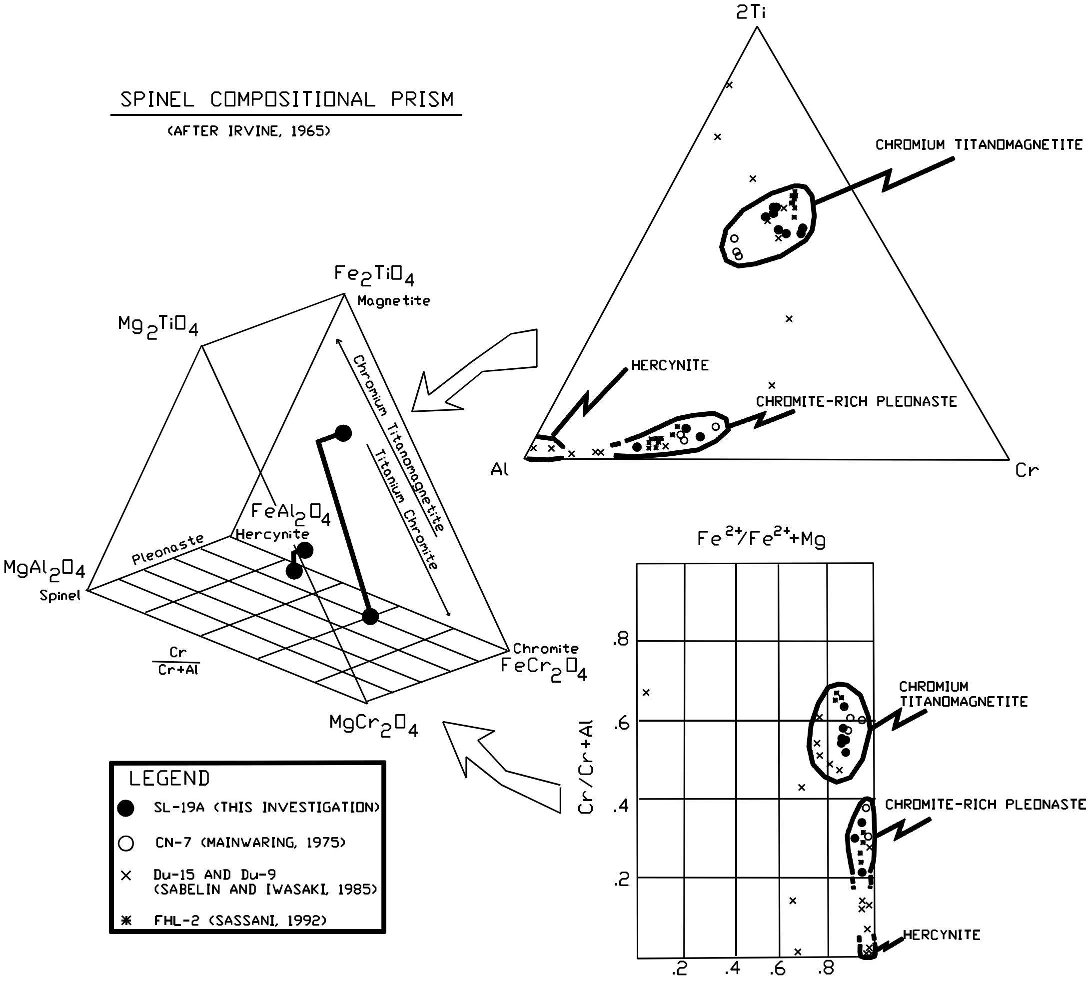

Figure 11. Spinel compositional prism plot.

WHITEFACE RESERVOIR

Four core holes were drilled into rocks of the Duluth Complex in the Whiteface Reservoir area (Fig. 12) by United States Steel Corp. (USSC). An additional two holes were drilled into geophysical conductors within the Virginia Formation to the west of the Complex by Amax (drill hole BC-80-1) and by W.S. Moore Co. (drill hole CL-3). The drilling was not detailed enough to provide any information on the attitude of the basal contact in the Whiteface Reservoir area.

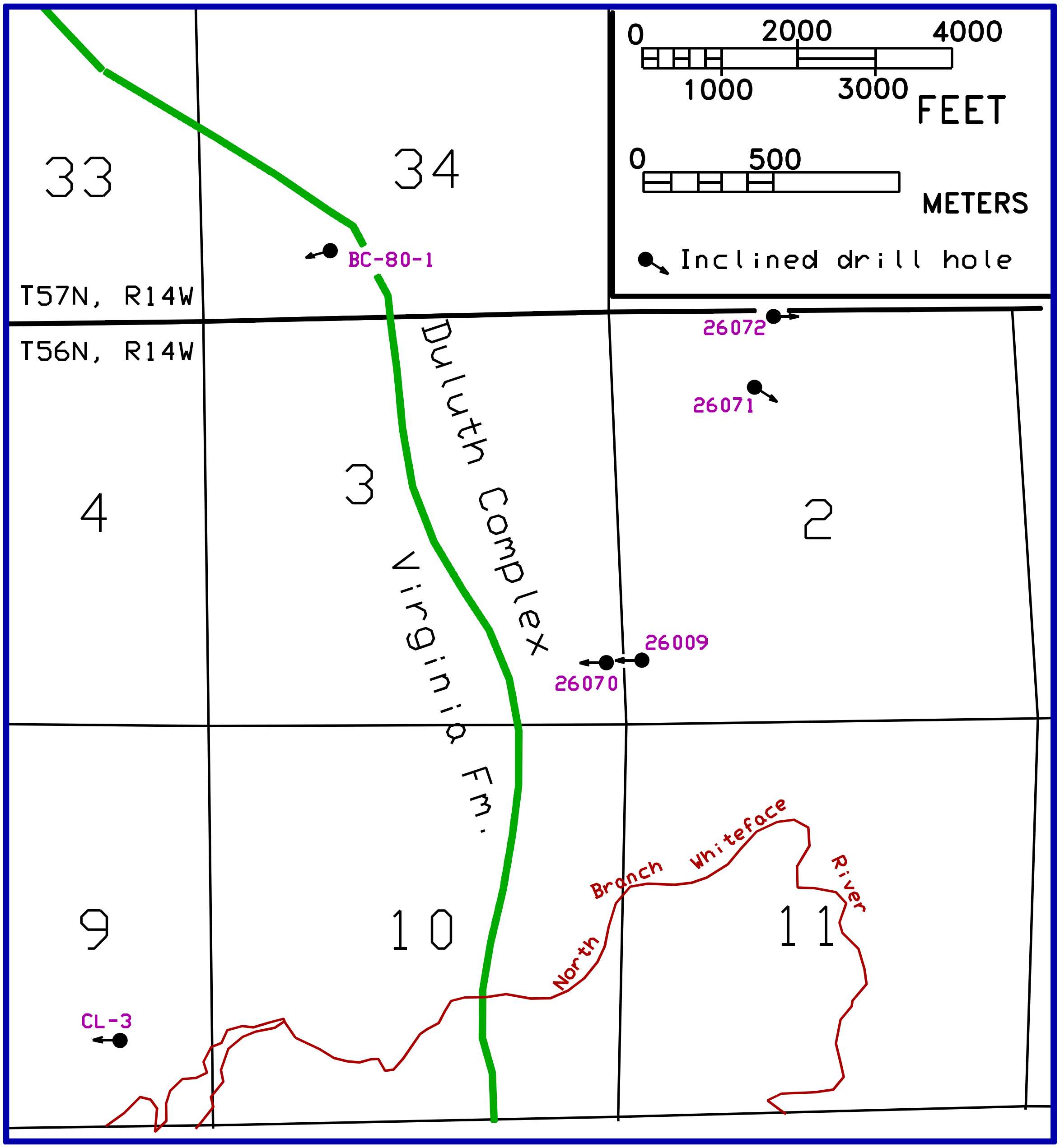

Figure 12. Drill hole location map of the Whiteface Reservoir area.

Troctolitic Rocks

A diverse package of troctolitic rocks are intersected in the four USSC drill holes. The igneous units in these holes are correlated in Plate III (right side of the plate) by hanging the holes on the top of a highly heterogenous troctolitic unit (Heterogeneous Zone in Plate III). The Heterogeneous Zone is unique and can be used as a stratigraphic marker horizon because it contains: 1) graphite-sulfide-bearing hybrid rocks; 2) picrite and olivine-rich troctolitic layers (or pods); 3) oxide-bearing (5%-15%) ultramafic rocks (layers or pods?); and 4) thin semi-massive to massive sulfide intervals. The hybrid rocks contain highly varying amounts of pyroxene and olivine, with lesser amounts of plagioclase, graphite, biotite, chlorite, diopside, sulfides, and quartz. All other troctolitic rock units are correlated in Plate III according to their position above or below the Heterogeneous Zone. An oxide-bearing picrite (stratabound OUI?) is present in drill hole 26009 from 663-766 feet.

Several intervals with sulfide mineralization are present in two of the holes from the Whiteface Reservoir area. Drill holes 26009 and 26070 encounter thick intervals with 0.5%-5.0% sulfides (pyrrhotite-dominant) and scattered thin intervals with massive sulfide (pyrrhotite dominant) up to 2 feet thick. Drill hole 26009 exhibits more sulfides than 26070, but was not as heavily sampled for Cu-Ni analyses as was 26070. Results from these two holes indicate that Cu values of 0.1%-0.2% are common, but are rarely greater than 0.3% Cu. Ni values range from 0.04% to 0.08%. Inspection of polished thin sections collected from these two holes indicates that pyrrhotite and cubanite are present in near equal amounts (pyrrhotite is generally more dominant), with lesser amounts of chalcopyrite, pentlandite, mackinawite, sphalerite, and chalcopyrite-magnetite-filled micro-cracks that cross-cut silicate grains. In one section, late pyrite almost completely replaces the pyrrhotite.

Footwall Rocks - Virginia Formation

Rocks of the Virginia Formation intersected in two holes in the Whiteface Reservoir area consist of interbedded argillite and graywacke. In some zones, these two sedimentary rock types are present as rapidly alternating interbeds; whereas, in other zones one rock type may predominate over the other for thicknesses of tens of feet. The argillite is well-bedded, with shallow bedding plane dips in drill core, and is characterized by light gray sequences and dark-gray to black carbonaceous sequences. The graywacke is characterized by massive- to finely-bedded sequences with plane parallel laminae (Bouma B and/or D). Also present are local thin laminae, up to 2.0 inches thick, with cross-bedding (Bouma C). In drill hole BC-80-1, located close to the contact of the Complex, the Virginia Formation also contains scattered intervals of the BDD PO, DISRUPTED, and RXTAL units.

LINWOOD LAKE

Three core holes are available for the Linwood Lake area (Fig. 13) and include: 26012 - drilled by U. S. Steel Corporation; CL-1 - drilled by W.S. Moore Co.; and SL-1B - drilled by the MDNR. All of the holes are collared in rocks of the Duluth Complex. Several outcrops of the Virginia Formation are also present in the Linwood Lake area (Fig. 13). These outcrops show a progressive increase in the amount of deformation and metamorphism towards the basal contact of the Complex. Both drill hole and outcrop data suggest that the basal contact of the Complex in the area is near vertical at the surface. This condition is indicated by: 1) bedding planes in the Virginia Formation that become progressively steeper and more north-trending closer to the contact; and 2) drill hole SL-1B, located approximately 700 feet from the contact, does not intersect the Virginia Formation at a total drilled depth of 1,008 feet.

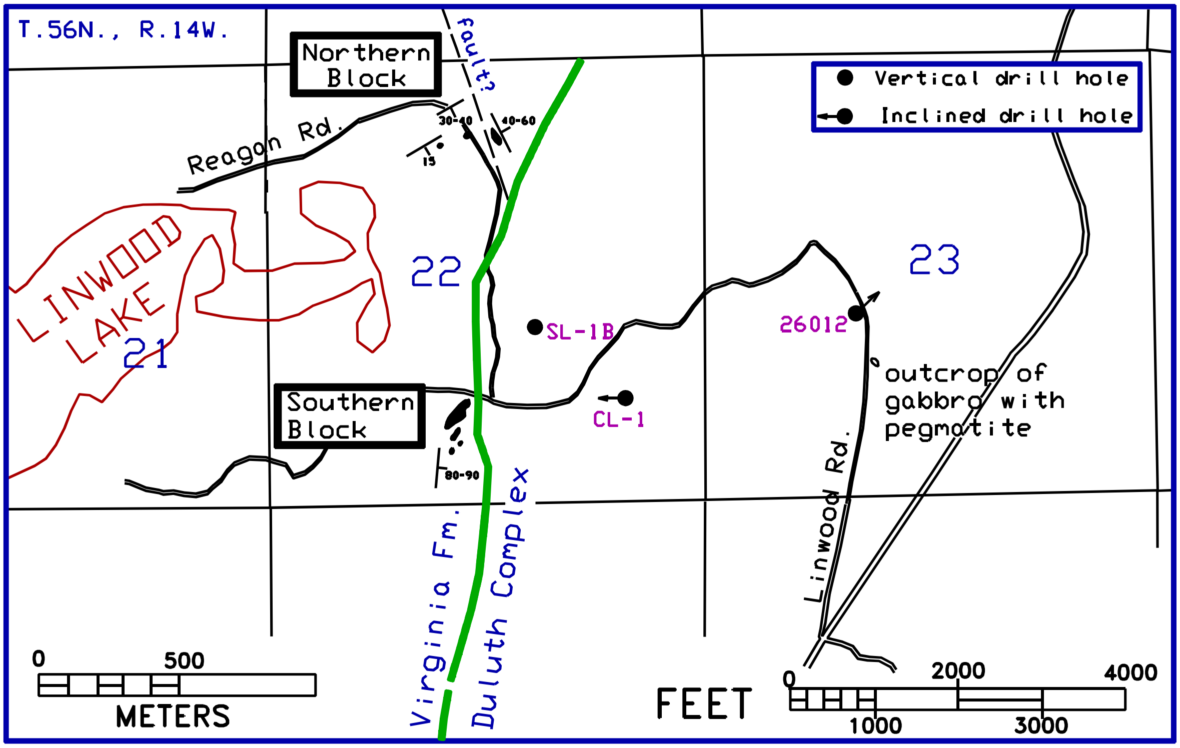

Figure 13. Map showing drill hole locations, outcrop locations, and general geology of the Linwood Lake area.

Troctolitic Rocks

Anorthositic rock types are dominant in drill hole 26012; whereas, troctolitic rock types are dominant in drill holes CL-1 and SL-1B. The various rock types present in these holes are diagrammatically shown in Plate III. Unfortunately, there are no correlative stratigraphic units in the Linwood Lake area based on the information from these three holes. Several thin OUI horizons, varying from 1 to 4 feet thick with 15%-30% oxides, are present in portions of 26012 and CL-1 (see Plate III). Drill hole SL-1B intersects numerous sedimentary hornfels inclusions and noritic rocks at many intervals - it is presumed to be very close to a steeply dipping basal contact.

Sulfide mineralization is rare in the Linwood Lake area. Sulfides are associated with some of the thin OUI horizons in both 26012 and CL-1 (0.5% to 3.0% visually estimated sulfides). Sulfides associated with the troctolitic rocks are present in: 1) a 6 inch net-textured pyrrhotite zone (20% sulfide) in 26012 at 519 feet; and 2) a 2 foot thick zone in CL-1 from 242-244 feet with a 6 inch pyrrhotite-dominated semi-massive sulfide.

FN Unit

Fine-grained granular gabbroic, troctolitic, and noritic rocks with common sedimentary hornfels inclusions are intersected from 18-76 feet and 145-306 feet in drill hole SL-1B. These rocks are very similar to rocks of the FN Unit in the Skibo-South and Water Hen areas. Geochemistry for rocks of the FN Unit (to be discussed later) indicates that they are almost identical to medium- to coarse-grained augite troctolite present from 76-145 feet.

Footwall Rocks - Virginia Formation

Outcrops of the Virginia Formation are characterized by interbedded argillite and graywacke (Bouma B and/or D with minor C). The rock types are very similar to the rocks intersected in drill holes to the immediate north in the Whiteface Reservoir area (see above discussion). What makes these outcrops unique is that they record a progressive increase in the amount of deformation, metamorphism, and partial melting toward the contact with the Complex. In Figure 13, the outcrops in the Linwood Lake area are broken down into two areas - a northern block and a southern block.

Outcrops in the northern block consist of gently southward dipping sediments that show a gradual increase in the amount of dip toward the contact. Outcrops farthest away from the contact display normal dips of 5E-10E to the south; whereas, outcrops that are closest to the contact show an increase in dip to about 40E-50E (locally 60E-75E) to the east beneath the Complex. Also at this locale, the sedimentary rocks contain thin wisps of leucocratic partial melts that parallel the bedding plane trend.

Outcrops in the southern block exhibit north-trending bedding-planes that are highly deformed and recrystallized adjacent to the Complex. Consistent dips of 80E-90E toward the east are present within the deformed rock. Rock types can be divided into two categories - the DISRUPTED unit and the RXTAL unit of the Virginia Formation. Both of these units have been noted elsewhere, in drill core, along the margin of the Duluth Complex, e.g., at the Babbitt, Dunka Road, Water Hen deposits. Photographs of outcrops of both the DISRUPTED and RXTAL units at Linwood Lake are shown in Figures 14 and 15, respectively. The DISRUPTED unit is characterized by bedding-plane foliated and sheared sedimentary rocks with rotated and discontinuous micro-folds. Superimposed on this chaotic bedding are anastomosing patches, lenses, and wisps of bedding-parallel leucocratic partial melts. In some areas, the partial melts also appear to have been deformed (folded and sheared) either during or after their formation. The overall texture of the DISRUPTED unit appears to be the result of a combination of partial melting coupled with intense micro-folding, micro-faulting, micro-brecciation, and shearing in response to emplacement of the Duluth Complex. Still closer to the contact of the Complex (toward the east), the DISRUPTED unit passes into the RXTAL unit (Fig. 15). The RXTAL unit is characterized by a medium-grained rock with biotite flakes that are arranged in a decussate manner, which at first glance gives the rock an igneous appearance. Bedding planes are completely obliterated within the RXTAL unit. Floating within this recrystallized matrix are sedimentary clasts that are often well-bedded, and in some cases, internally folded. At an outcrop scale, these clasts appear to represent "boudined" blocks of structurally more competent interbeds that are now randomly set within a totally recrystallized rock. In drill core (elsewhere), both the DISRUPTED and RXTAL units grade back and forth

Figure 14. Photograph showing textures of the DISRUPTED member of the Virginia Formation, Linwood Lake area (see next page).

Figure 15. Photograph showing textures of the RXTAL member of the Virginia Formation, Linwood Lake area (see next page).

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into each other, with the RXTAL unit most commonly present nearest to the basal contact. Such a gradation is not evident in the limited outcrops of Linwood Lake.

In thin section, the DISRUPTED unit is characterized by beds of very-fine grained quartz-rich sandstone (graywacke) and siltstone (argillite), with variable amounts of quartz, feldspar, biotite, and sericite. The partial melts are distinguished by slightly coarser-grained laminae (fine- to medium-grain size with the same mineralogy as in the surrounding sedimentary rocks) and decussate-arranged medium-grained biotite. The RXTAL unit is similar to the partial melts in mineralogy and texture.

HARRIS LAKE

U. S. Steel Corporation leased state lands in the vicinity of Harris Lake on the basis of a coincident magnetic high and strong airborne electromagnetic (EM) anomaly. After conducting geophysical surveys in the area, they drilled three vertical holes in 1967-68. Because the holes intersected mainly serpentinized ultramafic rocks with no visible sulfide mineralization, USSC dropped the state leases. Shortly after this period, Phelps Dodge Corp. leased the same lands and subsequently drilled two inclined holes into the same magnetic-EM conductor in 1971. The locations of all five holes in the Harris Lake area are shown in Figure 16. These holes are located approximately 2.5 miles east of the basal contact (Plate I). No footwall rocks are present in these holes. The glacial overburden ranges from 85 to 143 feet thick in the area.

Troctolitic Rocks

All of the holes within the Harris Lake area intersect a thick subhorizontal package of serpentinized ultramafic rocks. Anorthositic and troctolitic rocks are also present as internal

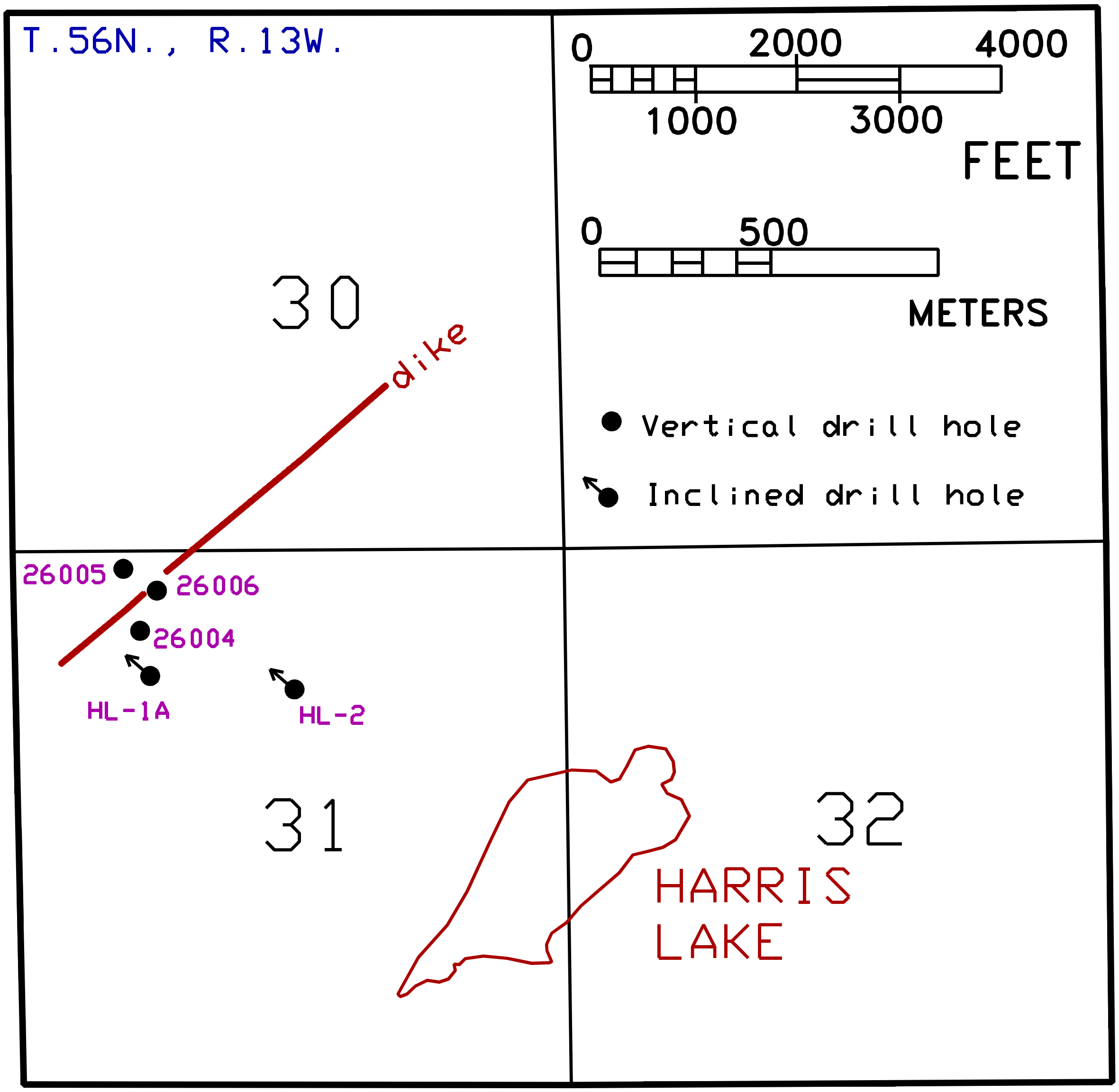


Figure 16. Drill hole location map of the Harris Lake area. Dike orientation based on intersections in HL-1A a

layers within the ultramafic package, and as thick packages at depth below the ultramafic rock package. The correlative igneous units in two of the holes at Harris Lake are displayed in Plate III (**Note:** These two holes are placed at an arbitrary distance above the basal contact in Plate III). The igneous units present in all five drill holes are displayed in a cross-section in Plate VI.

The subhorizontal ultramafic rock package consists of serpentinized peridotite, feldspathic peridotite, and picrite layers that range from <1.0 foot to over 50 feet thick. Internal layers of troctolite, anorthositic troctolite, and anorthosite are also common within the ultramafic package and range from a few inches to 5 feet thick. Contacts between the ultramafic and troctolitic rocks are generally sharp and subhorizontal (70E-80E to the core axis). A primary igneous foliation, defined by aligned coarse plagioclase laths and blebs and rare troctolitic inclusions, is present in both ultramafic and troctolitic rocks. The foliation is also subhorizontal (60E-80E to the core axis). Serpentinization of the ultramafic rocks is pervasive, but variable in intensity so that some drill hole intersections have a banded appearance due to alternating strongly and weakly serpentinized zones. The serpentinization foliation is also subhorizontal (70E-80E to the core axis). Magnetite seams and stringers, a product of serpentinization, are common to the serpentinized ultramafics (10%-15% magnetite stringers in thin section) and occur up to 1.0 cm thick in drill core. In most instances, the intensity of serpentinization decreases with depth in drill hole into very-weakly serpentinized rocks. All the ultramafic rocks contain primary ilmenite grains in amounts of 1%-10% (locally up to 30%). In thin section, the ilmenite grains commonly contain composite patches of chromium titanomagnetite. Sulfides (pyrrhotite and chalcopyrite) are also present in thin section, where they occur in trace amounts as interstitial grains and as partial fillings in the magnetite stringers.

Below the ultramafic rock package, a thick package of dominantly anorthosite is intersected in four drill holes at Harris Lake (Plate VI). The anorthosite is typically coarse- to very coarse-grained and exhibits a subhorizontal primary igneous foliation defined by aligned plagioclase laths

(70E to the core axis). Also included within the top portion of the anorthositic rock package are thin intervals of anorthositic troctolite, troctolite, and picrite (see Plate VI). A primary igneous foliation is also present within the first two rock types. Some thin intervals with weak sulfide mineralization are present within the anorthositic rock package. Two intervals are present in drill hole HL-1A from 528.5-530 feet (1%-2% sulfides with chalcopyrite >pyrrhotite) and from 800-850 feet (rare sulfides).

Troctolitic rocks are intersected below the anorthositic rock package in only one drill hole (HL-1A, Plate VI). Augite troctolite, with minor picritic layers, is the dominant rock type. It also exhibits a subhorizontal primary igneous foliation as do the overlying rock packages.

A fine-grained, northeast-trending, dark gray basaltic dike with chilled margins is present in two holes in the Harris Lake area (drill holes: HL-1A from 850-907 feet; and 26006 from 442-461 feet). Contacts in the drill core indicate the dike to be near vertical. Rocks immediately adjacent to the dike in drill hole HL-1A are strongly saussuritized and uralitized.

SECTION 34

U. S. Steel Corporation drilled six core holes into a magnetic high in the Section 34 area (Fig. 17). Three of the holes intersect an Oxide-bearing Ultramafic Intrusion (OUI) that is present throughout the entire length of the holes. The remaining three holes intersect numerous apophyses of OUI that alternate with anorthositic host rocks. The igneous units intersected in four of the holes are diagrammatically correlated with other rocks of the South Complex area in Plate III (**Note:** On Plate III, the holes in the Section 34 area are placed at some arbitrary distance above the basal contact). The cross-sectional relationship of all six holes is shown in Plate VI. On Plate VI, the OUI is interpreted to be present as two separate bodies on the basis of USSC ground magnetic surveys. The limited drilling into both OUI bodies suggests that they may be crudely zoned, and thus on Plate VI, both are diagrammatically portrayed as consisting of a peridotite-picrite core surrounded by a pyroxenite outer rind. The linear distribution of the two OUI bodies at Section 34, coupled with the distribution of additional OUI bodies to the south, suggests that they are fault controlled. This inferred fault, shown in Figure 17 and Plate I, trends approximately N15E-20EE. Because the Section 34 drill holes are located well within the interior of the Complex (almost 3 miles east of the basal contact - Plate I), no footwall rocks are intersected in the holes.

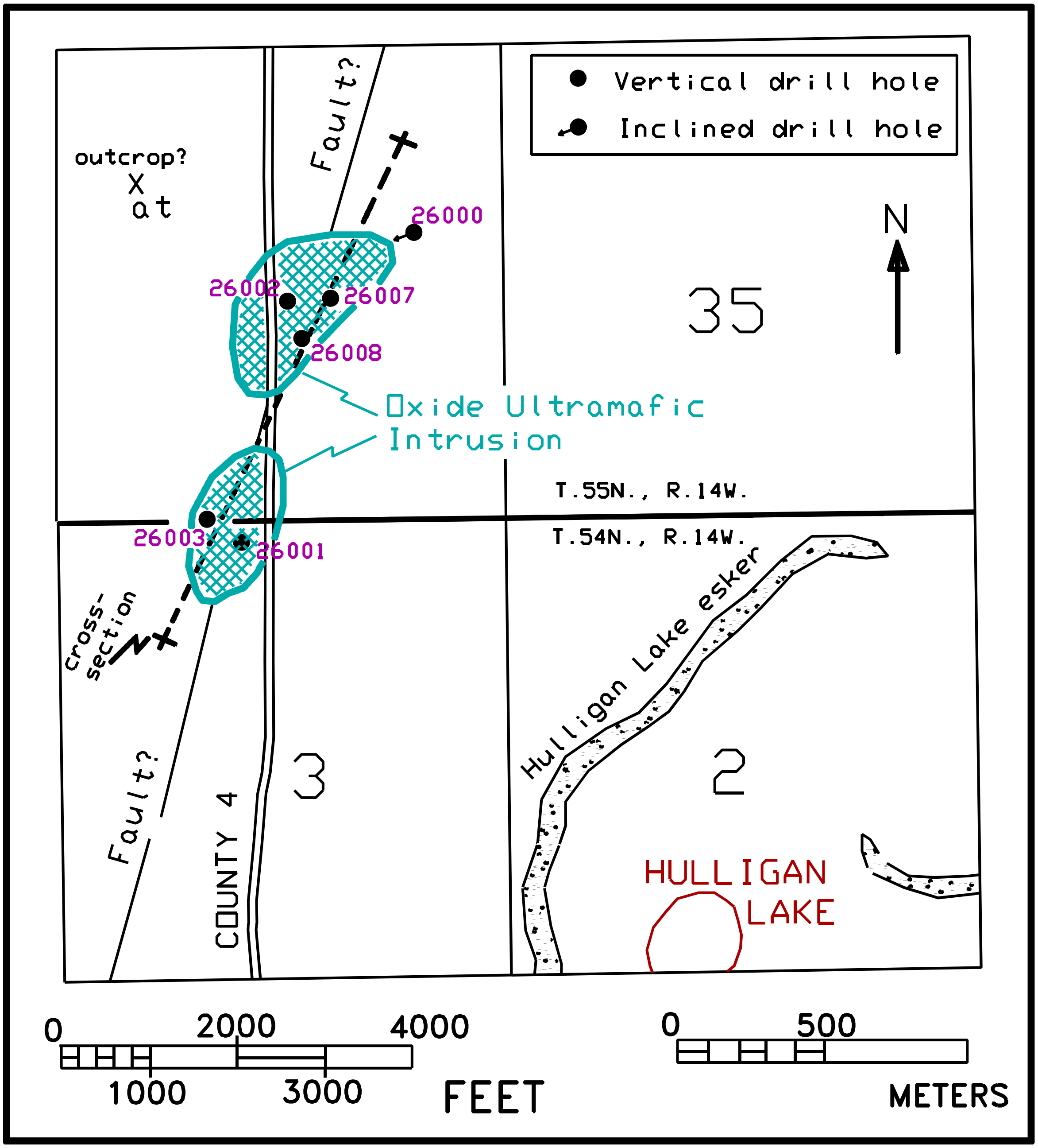


Figure 17. Drill hole location map and inferred outline of OUI bodies in the Section 34 area. Cross-section sho
VI.

Oxide-Bearing Ultramafic Intrusion (OUI)

Rocks of the Section 34 OUI are characterized by oxide peridotite and oxide pyroxenite that, in drill core, often alternate over both thin (<1-10 feet) and thick (>10 feet) intervals. Massive oxide zones/pods are also a major constituent in some drill holes. Oxide peridotite is the dominant olivine-rich rock type, but it commonly grades into oxide feldspathic peridotite and oxide picrite. Similarly, the oxide pyroxenite also contains portions of oxide melagabbro and oxide gabbro due to local changes in modal percentages of minerals. Oxide content in the OUI is generally higher than most other OUIs in the South Complex area. The content ranges from 10%-40% in both the oxide peridotite and oxide pyroxenite. In addition, semi-massive oxide intervals (60%-80% oxides) and massive oxide intervals (80%-100% oxides) are commonly present. The amount of oxide in the peridotitic versus the pyroxenitic rocks varies drastically even between drill holes. For example, in drill hole 26001, the peridotitic rocks contain a higher percentage of oxides relative to adjacent alternating intervals of pyroxenitic rocks (likewise the TiO_2 content is higher in the peridotitic rocks). However, in drill hole 26007, the pyroxenitic rocks have a higher oxide content (and TiO_2 content) relative to the adjacent peridotitic rocks.

Several intervals of massive to semi-massive oxide are present in drill hole 26002 (Plates III and VI). In this hole, the massive oxide intervals are up to 136 feet thick and make up about 60% of the upper 593 feet of drill core. Coarse titanomagnetite grains, up to 2 cm across with ilmenite oxy-exsolution lamellae visible in drill core, are present in much greater quantities than ilmenite grains. In thin section, the massive oxide zones consist of: 1) titanomagnetite grains with oxy-exsolution ilmenite lamellae parallel to the (111); 2) composite, round ilmenite patches in titanomagnetite grains; 2) ilmenite grains; and 3) green pleonaste grains at titanomagnetite grain junctions. Morphology of the titanomagnetite is as: 1) round grains; 2) coalesced round grains (±

embayed edges); 3) subhedral grains; 4) skeletal blades; and 5) material that is interstitial to round olivine grains.

Generally, titanomagnetite is present in greater quantities than ilmenite in the peridotitic and pyroxenitic rock types at Section 34. However, in polished sections collected from the top portion of drill hole 26002, ilmenite rather than titanomagnetite is dominant in both the peridotitic and pyroxenitic rocks. Conversely, in the same drill hole at depth, titanomagnetite is always much greater than ilmenite in the massive oxide horizons. Still deeper in the hole, titanomagnetite is greater than ilmenite in the peridotitic and pyroxenitic rocks. Overall, titanomagnetite is dominant over ilmenite in the massive oxides at Section 34; whereas, titanomagnetite is only slightly greater than, if not locally subordinate to, ilmenite in the peridotitic and pyroxenitic rocks.

The OUI rocks at Section 34 average about 15.66% TiO_2 and 2,610 ppm V with maximums of 26.74% TiO_2 and 4,035 ppm V. The highest TiO_2 contents are generally associated with the massive to semi-massive oxide zones (20%-26% TiO_2); however, even some of the peridotitic and pyroxenitic rocks, with only 20%-40% oxides, have TiO_2 contents that are only slightly lower (15%-20% TiO_2). This difference in TiO_2 content in the latter rock type is instructive in that even at a lower oxide content these rocks contain near equal amounts of TiO_2 contents relative to massive oxide zones. A possible explanation for this phenomenon is that ilmenite is equal to, or greater than, titanomagnetite in the peridotitic and pyroxenitic rocks; whereas titanomagnetite is much greater than ilmenite in the massive oxides. Since the ilmenite in the peridotitic and pyroxenitic rocks occurs as coarse composite patches and coarse unit grains, rather than as dominantly oxy-exsolution lamellae, in the massive oxides, the former rock type may be more amenable to mechanical separation and ore processing for titanium. Some metallurgical processing research was conducted by U. S. Steel Corporation on Section 34 material for Ti and V (pers. comm. - Pete Niles, CMRL, Coleraine, MN, 1995).

In addition to the high oxide content, the OUI in the Section 34 area is well mineralized with respect to sulfide content. The peridotitic and pyroxenitic rocks contain trace amounts to 2.0% sulfides, while the massive oxides contain only trace quantities of sulfides. In comparison, the host anorthositic rocks have only minor sulfide zones that are thin and extremely localized. Chalcopyrite, not pyrrhotite, is the dominant sulfide in the OUI. It often contains internal patches of cubanite, bornite, pentlandite, and sphalerite (stars). Most of the chalcopyrite is cut by thin stringers of magnetite that were produced during a serpentinization event. Minor pyrite is seen replacing pyrrhotite. Very few intervals of the Section 34 OUI have been analyzed for Cu and Ni. To date, these limited analyses indicate a maximum of 0.16% Cu and 0.03% Ni.

Troctolitic Rocks

Variable amounts of troctolitic rocks are intersected in three drill holes in the Section 34 area (Plate VI). Anorthosite is the dominant rock type, but the anorthosite commonly grades into troctolitic anorthosite and gabbroic anorthosite. Generally, the anorthosite ranges from medium- to coarse- to very coarse-grained, and the other anorthositic rocks are medium- to coarse-grained. Local thin zones with subhorizontal primary igneous foliation, defined by aligned plagioclase laths, are present in the anorthosite in two drill holes. These rocks contain very few sulfide-bearing zones in contrast to the OUI. Wherever the anorthositic rocks are weakly mineralized, they are usually "sandwiched" between sulfide-bearing OUI apophyses. Faint pink heulandite veins are common to both the anorthositic and OUI rocks.

In addition to the anorthositic rocks, several subhorizontal ultramafic layers are present in drill hole 26008 (Plates III and VI). These layers are generally picrite with some troctolite and olivine-rich troctolite layers/zones. At the bottom of hole 26008, a picrite layer grades down into feldspathic peridotite. Both the top and bottom contacts of the picrite layers are always sharp and subhorizontal. Internal contacts, with troctolitic bands, are also subhorizontal and sharp. The picrite layers are not serpentinized. These layers are distinguished from apophyses of OUI, present in the same drill hole, by their finer grain size (medium-grained) and low oxide content (1%-3%). Occasionally, the picrite layers exhibit an internal fabric characterized by variably oriented, coarse plagioclase laths (subhorizontal).

BOULDER CREEK

In 1969, Phelps Dodge Corporation drilled 12 core holes (Fig. 18) in an area they referred to as Grid I. Igneous units intersected in these holes consist of heterogeneous troctolitic rocks, troctolitic to gabbroic rocks with a well developed plagioclase lamination, and a disjointed, stratabound OUI that is associated with a large inclusion of the FN Unit. These units are correlated in Plate IV for the holes of the Boulder Creek area. In Plate IV, all the drill holes are hung on the top of the laminated troctolite-gabbro package, and the other igneous units are correlated accordingly. The cross-sectional relationships of these units are also portrayed in Figure 19. This cross-section suggests that rocks in the area dip toward the east at about 15E-20E. No footwall rocks are present in these holes because the area is located more than 2 miles east of the basal contact. The linear distribution of the OUI at Boulder Creek may be related to an inferred north-trending fault zone (Fig. 18). Another fault zone, shown in the southern portion of Figure 18, is intersected in drill hole I-8 (see Plate IV).

Oxide-Bearing Ultramafic Intrusion (OUI)

The OUI body at Boulder Creek is unique relative to all the other OUIs in the South Complex area in that it is apparently stratabound, with weak cross-cutting features. It is found at the same stratigraphic level within a package of Heterogenous Troctolitic Rocks (Plate IV), and it is often closely associated with large and small inclusions of the FN Unit (also at the same stratigraphic level - Plate IV). The Boulder Creek OUI is also unique in that it contains a lower percentage of oxides relative to all the other OUIs, and portions of the OUI contain graphite (as at the Skibo and Water Hen OUI bodies). The thickest portions of OUI are intersected in drill holes I-2 and I-4 (Plate IV). There, cross-sectional relationships (Fig. 19) suggest that the OUI locally cross-cuts the stratigraphy and a feeder zone for the OUI may be located in this area. To the north and south of the inferred feeder zone, the OUI becomes disjointed and is expressed by several irregular and bifurcating zones that probably represent stratigraphically-controlled apophyses (Plate IV). OUI distribution and contact relationships in the inferred feeder zone suggest that the OUI originated via a magmatic intrusive event. However, OUI distribution and contact relationships away from the feeder zone suggest that the OUI may have originated via a combination of magmatic and metasomatic replacement events.

The OUI rock types that are located in, and away from, the inferred feeder zone are all moderately serpentinized. This condition is expressed by chlorite-serpentine laminae (1-5 mm thick) that are either randomly oriented or parallel at regular spacings (1-5 cm, up to 30 cm). Magnetite seams, up to 1.0 mm thick, are present in some of the laminae. The dip of these laminae cannot be systematically determined in the inclined drill holes.

In the inferred feeder zone area (drill holes I-2 and I-4), the OUI intervals range from 6 inches to 66 feet thick. Country rocks that host the OUI are both troctolitic rocks and the FN Unit (the FN Unit also occurs as thick inclusions in the feeder zone area). Contacts between the OUI and FN Unit, and the OUI and troctolitic rocks, are always abrupt to sharp. The sharp contacts and thick OUI intervals suggest that the OUI originated from intrusion of an ultramafic magma. Because the OUI does not change in rock type or texture, regardless of the host rock, an in situ metasomatic replacement origin in the feeder zone is not substantiated. The dominant rock type is oxide peridotite, with gradations into picrite, feldspathic peridotite, and dunite; no oxide pyroxenite is present. Oxide content is generally low (1%-15%). The oxides are not evenly distributed throughout the rock and are often more heavily concentrated in zones less than 1 foot thick; no massive oxide zones are present. Sulfides are present in only the feeder zone OUI in amounts that commonly range from 0.5% to 2.0%; the entire range of sulfide content is trace amounts to 5.0%. Graphite is also locally present in amounts that range from trace to 10%. The graphite occurs as rounded blebs (up to 3 cubic inches in core) and as highly irregular and branching blebs. Locally, in drill hole I-2, the peridotite contains small secondary vugs that are partially filled with a chlorite-uralite mixture and rimmed by white feldspar that is 1.0 mm thick.

To the north and south of the inferred feeder zone, the OUIs are different in that they: 1) are present as bifurcating lenses (apophyses) and irregular patches that range from 2 inches to 13 feet thick; 2) no sulfide mineralization is present; 3) no graphite is present; 4) oxide content is elevated (10%-30%) at the north end of the drilled area; and 5) at the south end of the drilled area, a 1 foot thick semi-massive oxide is present in drill hole I-12. Oxide peridotite is the dominant rock type as in the feeder zone. In some drill holes, the OUIs occur as numerous patches and zones that are chaotically distributed throughout the troctolitic rocks. The shape, orientation, thickness, and contacts of these patches are also chaotic. Contacts with the troctolitic rocks are abrupt, with coarse interpenetrating crystals. The troctolitic rock immediately surrounding an OUI patch contains randomly scattered medium- to coarse-grained

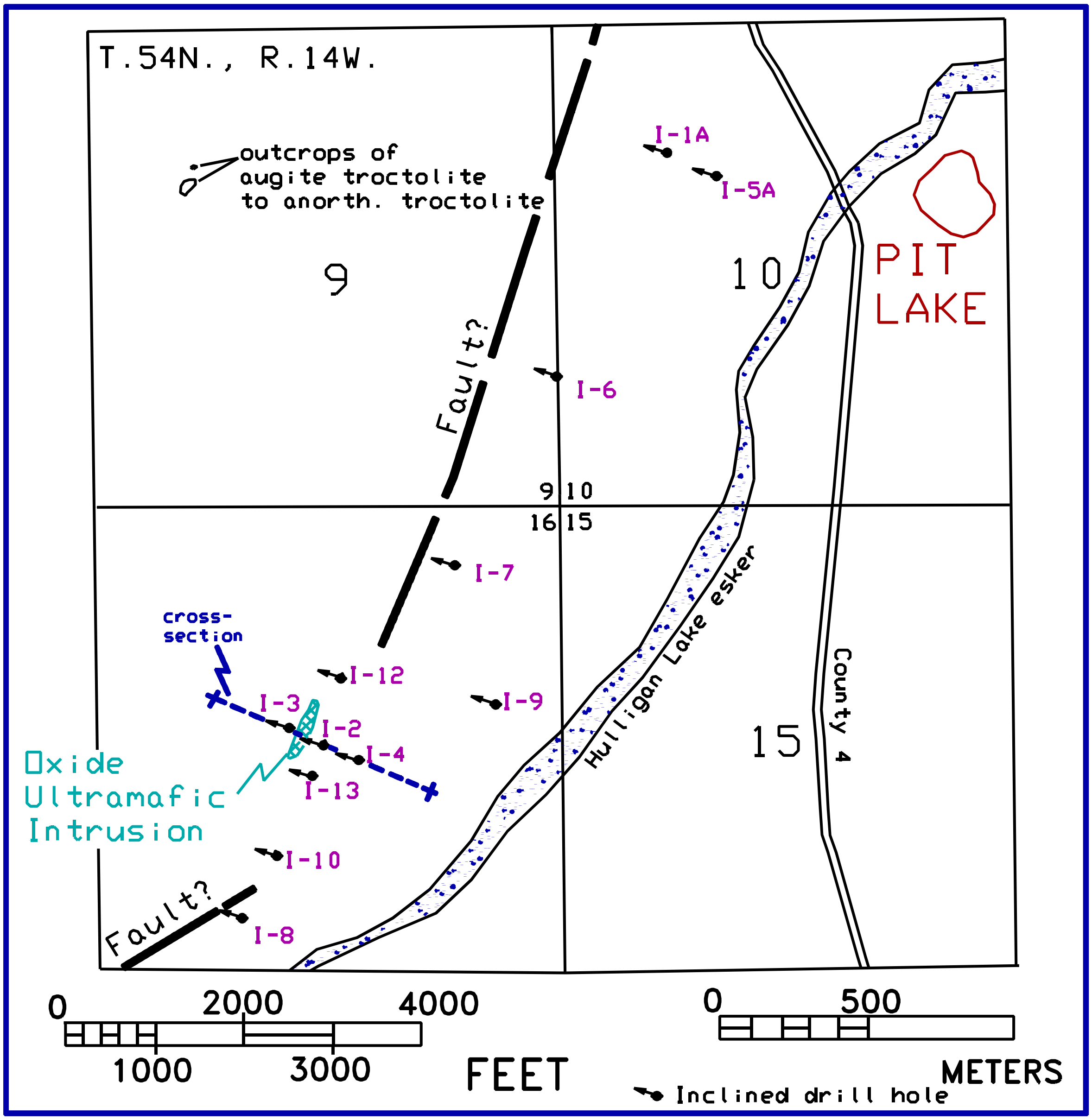
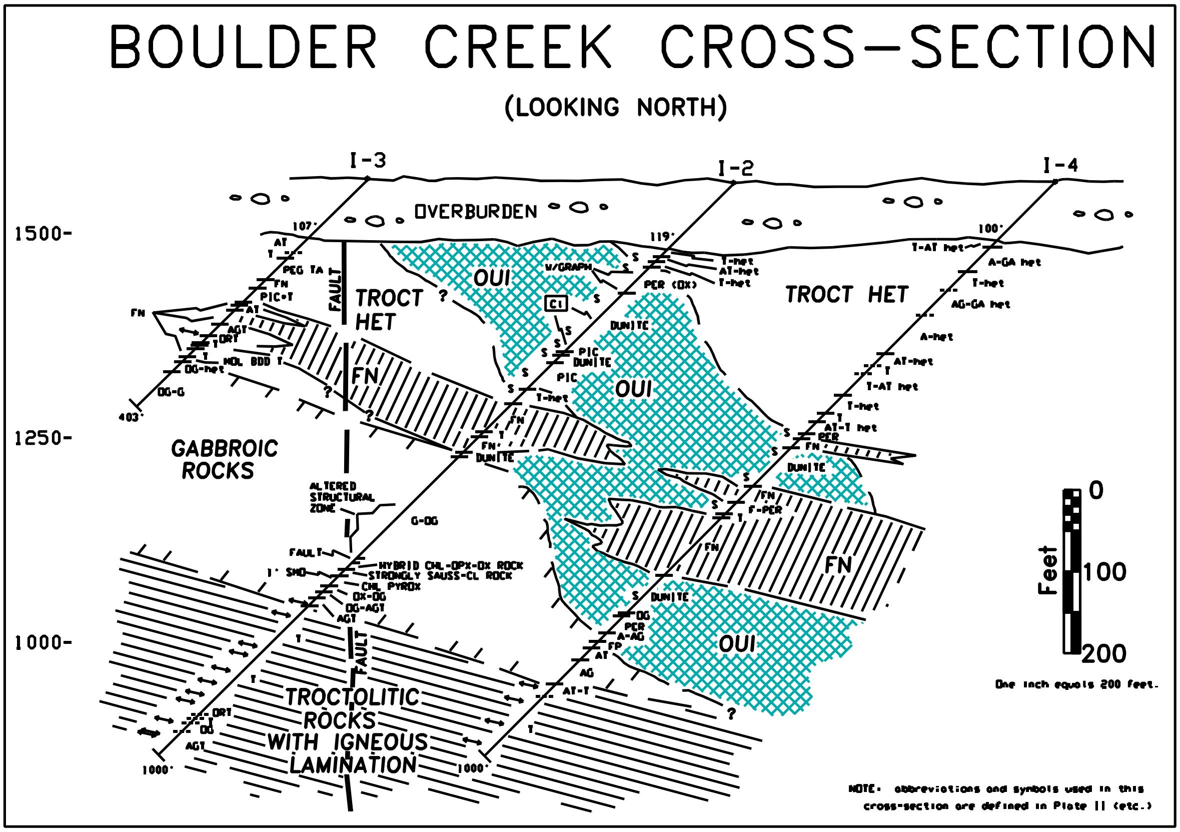


Figure 18. Drill hole location map of the Boulder Creek area. Cross-section is portrayed on Figure 19.



NOTE: abbreviations and symbols used in this cross-section are defined in Plate II (etc.)

Figure 19. Cross-sectional relationship of igneous rock units in the central portion (inferred feeder zone?) of the area (see Fig. 18 for location of cross-section).

olivine grains that are similar to the olivine in the OUI patch. All of these features suggest that some of the OUI patches may have originated as metasomatic replacements. Contact relationships of the thicker OUI lenses are generally sharp and not as chaotic. The thicker lenses probably originated via a combination of magmatic and metasomatic replacement mechanisms.

The OUI at Boulder Creek has been inadequately sampled and analyzed for TiO_2. Only eight analyses are available (see SOCOTI.WK1), and even these analyses are composite samples collected from intervals that contain thin OUI patches intermixed with troctolitic rocks; the samples were collected by the MDNR in 1977 (MDNR open files, Hibbing, MN). There are no TiO_2 data for the OUI material in the inferred feeder zone. Notwithstanding, this highly select data set indicates maximum values of 19.09% TiO_2 and 8,125 ppm V. Iron contents (Fe%) are extremely high for these same samples (56%-59% Fe), considering that the Boulder Creek OUI is not particularly enriched in oxides. Either the analyses are suspect or olivine in the Boulder Creek OUI are more fayalitic than olivine in the other OUI. Polished thin section inspection (only 6 sections - none from the feeder zone) reveals that magnetite is greater than ilmenite (>90% magnetite). Sulfides in the OUI material consist of varying amounts of chalcopyrite, cubanite, pyrrhotite, and pentlandite, with local bornite and sphalerite.

Troctolitic Rocks

At Boulder Creek, the troctolitic rocks can be correlated into two groups: an upper package of Heterogeneous Troctolitic Rocks (with a basal gabbro subgroup in the feeder zone area); and a lower package of Troctolitic to Gabbroic Rocks, with well-developed plagioclase lamination. Each group is correlated in the drill holes of Boulder Creek in Plate IV. They are individually described below.

Heterogeneous Troctolitic Rocks (HTR)

The upper package of Heterogeneous Troctolitic Rocks (HTR) consists of near equal amounts of troctolite and anorthositic troctolite, with slightly lesser amounts of troctolitic anorthosite and anorthosite. Also present are local, thin gradational zones of augite troctolite, olivine-rich troctolite, and picrite. All of the rocks are medium- to coarse-grained, with common gradations into very coarse-grained to pegmatitic zones. Typically, the more plagioclase-rich rocks are coarse- to very coarse-grained. Both texturally-heterogeneous and texturally-homogeneous zones are present in all rock types. Primary igneous foliation, defined by aligned plagioclase laths, is present locally. Inclusions of the FN Unit are common in the HTR. These inclusions are especially thick and numerous in the vicinity of the OUI feeder zone. Rocks of the HTR rarely have sulfide-mineralization, and even when they are mineralized, they contain only rare to trace amounts of sulfides. A 1 foot thick zone with 30% pyrrhotite is intersected in drill hole I-10 (502-503 feet).

In the vicinity of the OUI feeder zone, a gabbro subzone is present at the base of the HTR. This gabbro subzone is shown in Figure 19. It is not shown in Plate IV, but is present in drill holes I-2, I-3, I-4, I-12, and I-13. Rocks of the gabbro subzone are dominantly gabbro and olivine gabbro that locally grade into augite troctolite and anorthositic gabbro. All rock types are medium-grained with 5%-10% oxides.

Troctolitic to Gabbroic Rock

Beneath the HTR is a lower package of rocks that all exhibit a well-developed primary igneous lamination and local modal bedding. Rock types are variable, consisting of troctolite, augite troctolite, and olivine gabbro; all grade into each other. Locally present are anorthositic gabbro, anorthositic troctolite, and picrite. Most of the rocks are texturally-homogeneous. The lamination, defined by aligned plagioclase laths, exhibits a 50E-80E orientation to the drill core axis (all the holes are inclined at -45E). Modal bedding, defined by subtle increases and decreases in olivine and clinopyroxene content (locally oxide content as well), subparallels the lamination. Inclusions of the FN Unit are present, but rare, within these rocks at Boulder Creek.

FN Unit

The FN Unit consists of fine-grained (0.5-2 mm), granular augite troctolite. It is always in sharp contact with the enclosing rocks and often contains internal bands of troctolitic rocks with sharp contacts. In drill core, it is generally a massive rock with a faint purple sheen. It contains features that could be interpreted as vesicles (plagioclase-rich clots up to 1.5 cm across) in only one drill hole (I-4, 611-617 feet). However, the FN Unit looks remarkably similar to the FN Unit intersected in drill holes elsewhere. Contact relations in some of these other areas, e.g., Water Hen, suggest that the FN Unit is not a basalt, but rather an inclusion of earlier chilled intrusive material of the Duluth Complex. The FN Unit at Boulder Creek is also inferred to be the latter.

GRID VIII

Only two holes were drilled by Phelps Dodge Corporation on their Grid VIII (Plate I). These holes intersect moderately magnetic, oxide-bearing troctolitic and gabbroic rocks that correspond to a north-northeast-trending aeromagnetic high.

Troctolitic Rocks

Rocks in the Grid VIII area are characterized by medium-grained, oxide-bearing (5%-10%; magnetite dominant), troctolite, augite troctolite, and olivine gabbro, with local gradations into oxide-bearing, coarse-grained anorthosite, anorthositic gabbro, and anorthositic troctolite. Most contacts between these rock types are gradational due to subtle changes in modal percentages. All of these rocks display a subhorizontal fabric that is related to aligned plagioclase laths and elongate cumulus olivine and clinopyroxene grains. Numerous thin beds and irregular patches of oxide picrite and oxide peridotite are present in all rock types. The beds are parallel to the internal fabric of the adjacent troctolitic rocks. Oxide content in the picrite-peridotite beds is elevated (up to 30%) relative to the troctolitic rocks. Rare sulfides are present locally in the rocks at Grid VIII. Only Cu and Ni analyses are available for the drill holes. The Cu content of these rocks is rarely greater 0.05% and never greater than 0.1%.

BOULDER LAKE NORTH

A total of 12 core holes are available in the Boulder Lake North area (Fig. 20); also referred to as the Grid IV area by Phelps Dodge Corporation (1970 - 9 holes) and by ASARCO (1968 - 3 holes). The five igneous rock packages intersected in these holes are: 1) an upper Layered Oxide Gabbro; 2) a middle Oxide-bearing Augite Troctolite Unit; 3) a lower package of heterogeneous troctolitic rocks; 4) an isolated block (inclusion?) of anorthositic rocks; and 5) late pods of OUI. All of these igneous packages are illustrated in a hung section in Plate V. The section is constructed by hanging the drill holes on both the top and bottom contact of the middle, Oxide-bearing Augite Troctolite Unit. Drill holes that intersect the anorthositic rocks are arbitrarily hung on the section. The geology illustrated in Figure 20 is based on the rock type intersected in the collars of the drill holes and the distribution of coincident magnetic signatures (especially magnetic highs) on the Boulder Lake Reservoir aeromagnetic quadrangle (acquired from the Minnesota Geological Survey). Cross-sectional relationships for two of the igneous units at the north end of the Boulder Lake area are illustrated in Figure 21. Correlation of igneous units in Figure 21 suggests that the rocks dip about 10E east. No footwall rocks are encountered in any of the drill holes at Boulder Lake North. A description of the igneous units follows.

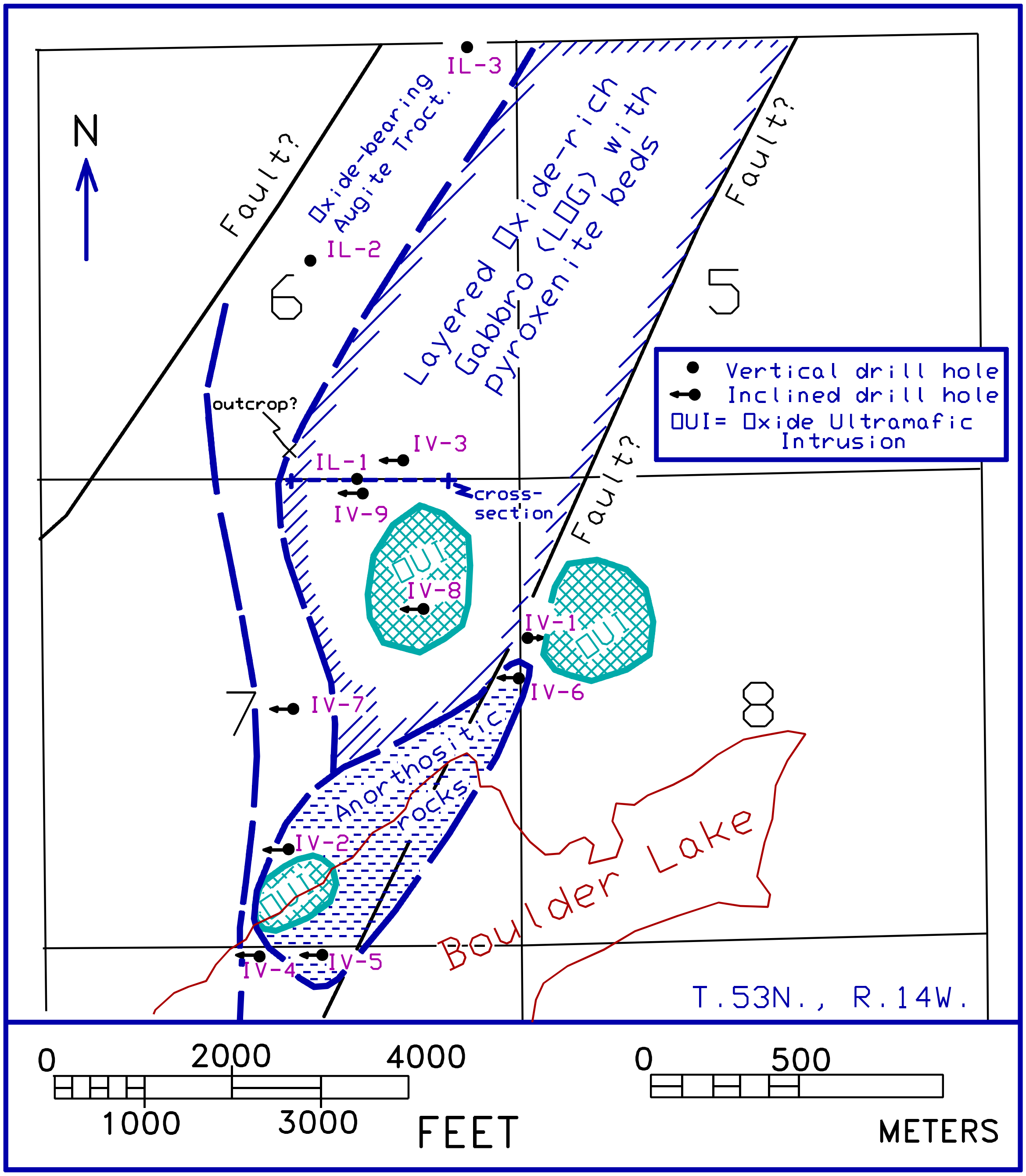


Figure 20. Drill hole location map and general geology of the Boulder Lake North area. Cross-section is show 21.

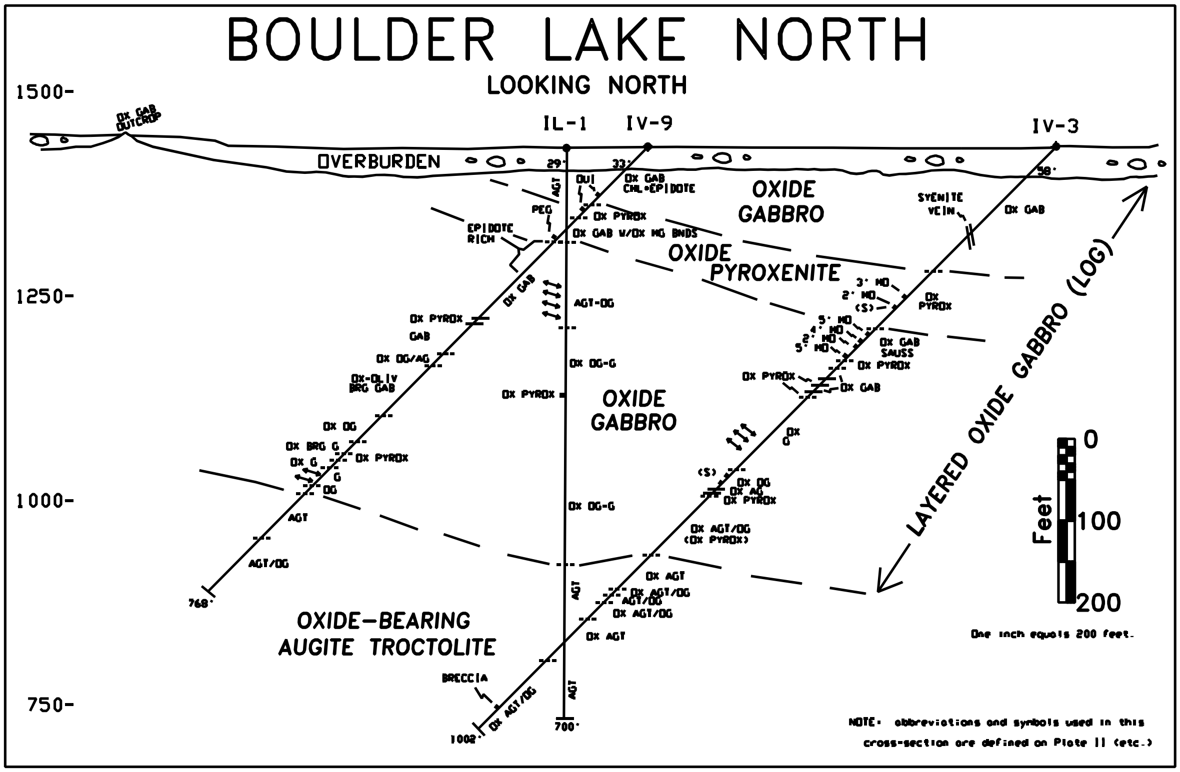


Figure 21. Cross-sectional relationships of rock units in the northern portion of the Boulder Lake North area (
location of cross-section).

Oxide-Bearing Ultramafic Intrusion (OUI)

Late pods and lenses of OUI are present in 7 of the 12 holes at Boulder Lake North. The OUIs vary from single thick intervals (or thick pods) to abundant thin intervals (or apophyses, lenses, and patches). Because there are so many OUI intervals, it would be time consuming to try and discuss them all, and therefore, only the occurrence in three holes will be discussed in detail.

These holes are IV-1 and IV-8, with thick OUI intervals, and IV-2, with abundant thin OUI intervals.

The OUI in drill hole IV-1 (inclined at -45E) is collared at the bedrock surface and is present in the top 225 feet of drill core. Three major zones of varying rock type are present in this hole. The top 92 feet of core consists of coarse-grained to pegmatitic, oxide-bearing (10-20%) augite troctolite and olivine gabbro, with 1%-2% sulfides. The middle 50 feet of the OUI consists of coarse-grained, oxide-bearing (15%-35%) peridotite, with thin intervals of pyroxenite; both rock types contain 1%-2% sulfides, and apatite is common in the pyroxenite. Rocks in the bottom 83 feet consist of semi-massive and massive oxide zones (50%-90% oxides), with decreased sulfide content (<0.5%). Magnetite is dominant (>80%) with ilmenite occurring as composite patches and very-fine to coarse oxy-exsolution lamellae. Only three analyses for TiO_2 exist, and these range from 11.16% to 27.40% TiO_2. The entire drill hole also has been previously analyzed for Cu and Ni. The OUI in this hole contains the highest values - 0.06%-0.32% Cu and 0.008%-0.40% Ni.

A large body of OUI is present in drill hole IV-8 (inclined at -45E). The OUI is collared at the bedrock surface and is present in the top 155 feet of the drill hole. It is similar to the OUI in IV-1 in that IV-8 has oxide gabbroic rocks in the upper portion of the OUI with up to 40% oxides. The bottom portion of the OUI consists of oxide picrite and oxide pyroxenite (at the very bottom) with 20%-35% oxides and trace to 2% sulfides. Two intervals of semi-massive to massive oxide (8 feet and 19 feet thick) are present in the bottom portion. TiO_2 content is 13%-16% (only two composite sample analyses); Cu content is <0.2%.

Numerous thin intervals of OUI are present within anorthositic rocks of drill hole IV-2. These intervals range from 2 inches to 10 feet thick and locally up to twenty feet. Rock type consists of coarse-grained peridotite, with lesser amounts of feldspathic peridotite and picrite. Contacts with the host anorthositic rocks are abrupt, with highly irregular and undulating boundaries that exhibit interpenetrating crystals that cross the contacts. These contact features suggest that the OUI lenses were emplaced while the anorthositic rocks were not completely crystallized. The OUI contains 10%-25% oxides. Ilmenite, rather than magnetite, is dominant in the OUI of IV-2. Also common to the OUI in IV-2 are needles of apatite, present in amounts of a few percent - Ripley (1994) refers to the thin OUIs with apatite as "nelsonites." Within drill hole IV-2, only the OUIs contain sulfides (1%-5%; locally up to 10%); whereas, the host anorthositic rocks are barren. Analyses for Cu, Ni, and TiO_2 (if analyzed) for drill hole IV-2 are not available in the open files at the MDNR.

In addition to the above OUI descriptions, several smaller OUIs are intersected in the following holes, and are shown on the hung section of Plate V: drill hole IV-4 contains many thin OUI intervals with a maximum thickness of 77 feet; drill hole IV-6 intersects a 43 foot thick OUI; drill hole IV-7 contains several thin OUIs and a 17 foot thick OUI; and drill hole IV-9 contains abundant thin (<1 foot thick) irregular patches and lenses of OUI. In most cases, the dominant rock types are oxide peridotite and oxide picrite. In drill hole IV-9, the thin OUIs are dominantly oxide pyroxenite that look like coarser-grained equivalents (recrystallized zones) of the host layered oxide gabbros and pyroxenites (LOG Unit - see below).

Troctolitic Rocks

Layered Oxide Gabbro (LOG)

An upper package of igneous rocks is the Layered Oxide Gabbro (LOG) that has common oxide pyroxenite beds and local massive oxides and is intersected in at least five inclined drill holes (Plate V). Both the oxide gabbro and oxide pyroxenite are medium-grained (locally coarse-grained) and contain 10%-20% oxides and 20%-30% oxides, respectively (magnetite>>ilmenite). Contacts between rock types vary from gradational to sharp. In some zones, the rocks are modally bedded (faint to well-defined) due to subtle to drastic changes in the modal percentages of cumulus pyroxene, plagioclase, and oxides. The modal bedding is 1-10 feet thick and subhorizontal (at steep angles to the core axis). Also present are local zones with subhorizontal primary igneous foliation defined by aligned plagioclase laths. Massive oxides are common in drill hole IV-3, where they range from 1 inch to 5 feet thick (>80% magnetite). All rock types contain trace to 15%, euhedral rods of apatite within oxide, plagioclase, and pyroxene. Late veins of granitic rock and veins of faint, pink-colored heulandite are common to all rock types of this unit. Late-stage potassium metasomatism and epidote alteration is common. This alteration occurs as zones adjacent to the granitic veins, pervasively altered zones up to tens of feet thick, and as irregular patches and blobs containing epidote, potassium feldspar, sericite, chlorite, amphibole, and calcite. Trace amounts of sulfide mineralization, consisting of chalcopyrite and pyrrhotite partially replaced by pyrite, are commonly associated with, or adjacent to, the late granitic veins. Near the bottom of this unit, the oxide gabbroic rocks grade into, and are layered with, oxide olivine gabbro and oxide augite troctolite. In turn, these rocks grade into the underlying Oxide-bearing Augite Troctolite (Plate V), due to an increase in olivine content and decrease in pyroxene and oxide content with depth.

The Layered Oxide Gabbro Unit (LOG) at Boulder Lake North bears many similarities to descriptions pertaining to Unit G of Nathan's Layered Series on the Gunflint Trail of Minnesota. Nathan (1969, p. 68) describes Unit G as "... coarse-grained olivine-plagioclase and augite-plagioclase rocks with strongly foliate plagioclase and abundant tironals [titanomagnetite and ilmenite] ... density-graded layering is prominent. Tironals-rich layers one centimeter to one meter thick are very characteristic." He also describes the upper portion of Unit G as being apatitic (Nathan, 1969, p. 72). Because Unit G, also referred to as the North Range in Grout (1950), contains several beds and zones of massive oxide, it received some exploration attention for Fe-Ti ores. Nathan (1969) also describes in Unit G several late oxide-rich plugs that are probably OUIs.

Overall, Unit G of Nathan's Layered Series sounds very similar to the LOG Unit, which also contains plug-like bodies of OUI. Unfortunately, outside of their megascopic similarities, there is no other way to compare them at this time. Geochemistry is available for the LOG Unit (this investigation), but no analyses are available for Unit G. Nathan's Layered Series (and Unit G) is related to an early period of magmatic activity associated with the Keweenawan Midcontinent Rift System and is reversely polarized, and the magnetic polarization of the LOG Unit is also unknown.

Oxide-Bearing Augite Troctolite

Below the LOG Unit of Boulder Lake North is an Oxide-bearing Augite Troctolite Unit (Plate V). The dominant rock types are medium-grained augite troctolite and olivine gabbro; both contain 3%-15% oxides (ilmenite dominant) and trace amounts of apatite. Locally present are thin intervals of gabbro and picrite. A subhorizontal primary plagioclase foliation is locally common in some drill holes.

Heterogeneous Troctolitic Rocks

The lower unit at Boulder Lake North is the Heterogeneous Troctolitic Rock unit. Rock type and grain size are extremely variable and consist dominantly of troctolite and anorthositic troctolite; both are texturally-homogeneous and texturally-heterogeneous over variable intervals in drill hole. Also common to this unit are anorthositic gabbro, augite troctolite, picrite, anorthosite, and thin OUI intervals. Only the OUIs contain sulfide mineralization.

Anorthositic Rocks

Three drill holes intersect thick sequences of anorthositic rocks that are arbitrarily correlated as an isolated block in Plate V. Rock type consists of near equal amounts of medium- to coarse-grained anorthosite and troctolitic anorthosite. Abundant thin OUI lenses, dominantly oxide pyroxenite, are common in drill hole IV-2. The relationship of the anorthositic rocks to the other troctolitic rocks in the Boulder Lake area is unknown due to their absence in all but three holes. Limited drill hole data suggests that the anorthositic rocks are an inclusion.

CENTRAL BOULDER LAKE

Near the southwestern portion of the Boulder Lake Reservoir, Phelps Dodge Corp. drilled 10 core holes (Fig. 22) in what they referred to as Grids VI and VII. Within Central Boulder Lake there are no correlative igneous units. Rather, each hole intersects a completely different package of rocks that bear no similarities to nearby drill hole rock types. A compressed cross-section is shown for diagrammatic purposes on Plate VI (**Note:** There are no geologic correlations). The cross-sectional relationships for an area with close-spaced drill holes are shown in Figure 23 (**Note:** There are some crude geologic correlations). Footwall rocks are intersected in the bottom of only one drill hole (VII-7). Data are too limited to estimate the attitude of the basal contact in this area.

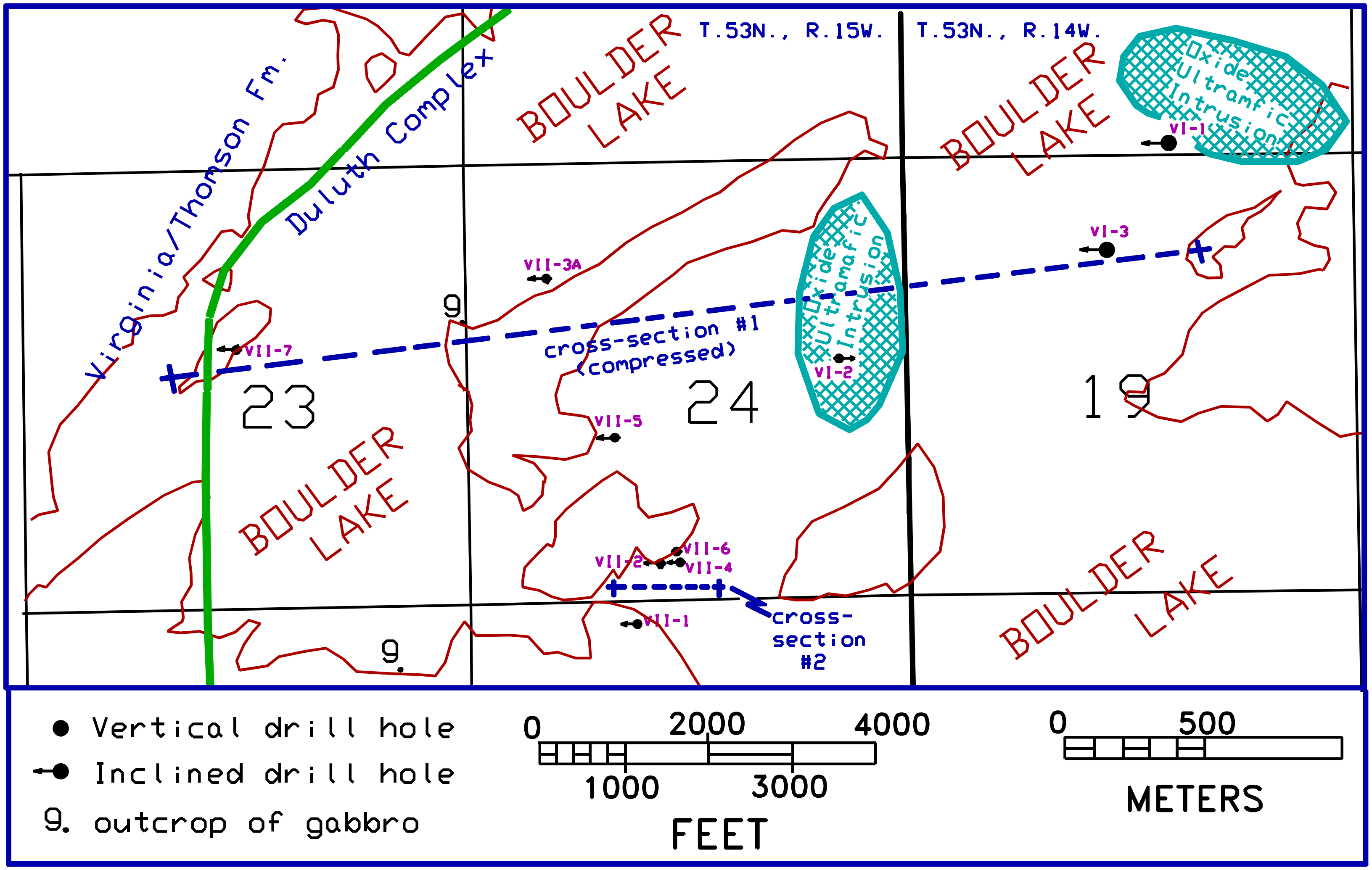


Figure 22. Drill hole location map and general geology of the Central Boulder Lake area (or Grid VI and VII area). Cross-sections #1 and #2 are sho and Figure 23, respectively.

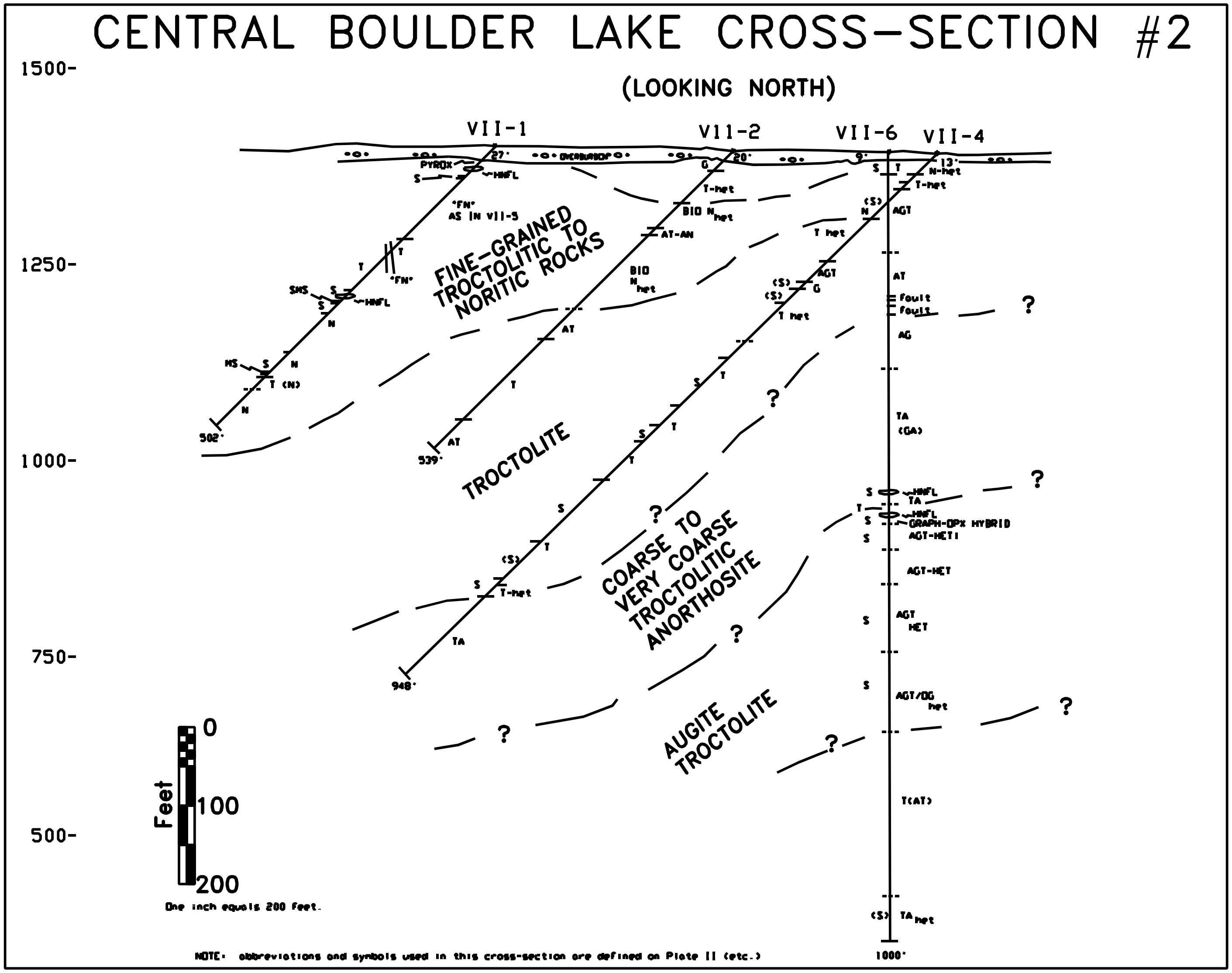


Figure 23. Cross-sectional relationship of rock units in a portion of the Central Boulder Lake area (see Fig. 22 for location of cross-section).

Oxide-Bearing Ultramafic Intrusion (OUI)

Several thin OUI intervals are present in two drill holes in the Central Boulder Lake area and may represent apophyses off of a much larger body. The maximum thickness of OUI in the holes are: 65 feet in VI-1 (skeletonized hole!) and 47 feet in VI-2. Rock type is dominantly oxide peridotite with 5%-15% oxides (magnetite dominant?). Sulfides are common in both OUI bodies (0.5%-2.0%). Net-textured sulfides with semi-massive sulfides (pyrrhotite dominant) are present in VI-2 at 266-281 feet. Analyses for Cu, Ni, and TiO_2 (if conducted) are not available for the OUI in this area. OUI bodies on Figure 23 are drawn using drill hole and aeromagnetic data.

Troctolitic Rocks

A multitude of troctolitic, gabbroic, noritic (with hornfels inclusions), and anorthositic rocks are present in the drill holes of Central Boulder Lake. Few of these rock types can be correlated between any two drill holes, except in the area of Figure 23, and even there the correlations are "forced". Overall, sulfide mineralization is the strongest in the area of Figure 23, especially in drill holes VII-1, VII-4, and VII-6. Sulfides vary from disseminated (trace to 7%) to net-textured sulfide (10%-30% sulfide) to local semi-massive sulfide zones (50%-80% sulfides). The semi-massive sulfides (<2 feet thick) are usually associated with hybrid zones (<5 feet thick) that consist of dominantly pyrrhotite, with lesser amounts of orthopyroxene, plagioclase, biotite, and local graphite. Private company data indicate that the Cu content of analyzed drill holes in Central Boulder Lake rarely exceeds 0.3% Cu. Thin section inspection indicates that pyrrhotite is by far the dominant sulfide, with lesser amounts of chalcopyrite, cubanite, pentlandite, and sphalerite.

FN Unit

Thin intervals of fine-grained rocks, similar to the FN Unit described elsewhere, are present in a few drill holes at Central Boulder Lake. These rocks are commonly associated with, or contain, inclusions of hornfelsed sedimentary rocks, and thus probably represent earlier chilled material of the Duluth Complex.

Footwall Rocks - Thomson Formation

Only specimen samples remain for the footwall rocks intersected in the bottom of drill hole VII-7 (skeletonized drill hole). These core samples consist of the RXTAL unit and massive-bedded argillite. They are presumably correlative with the Early Proterozoic Thomson Formation (Virginia Formation equivalent), which outcrops to the south in the vicinity of Duluth, Minnesota.

BOULDER LAKE SOUTH

Three core holes (Fig. 24) were drilled by the Phelps Dodge Corporation in what they referred to as Grid V. These holes intersect an OUI that intrudes both troctolitic-gabbroic rocks and an inclusion of basalt. A geologic correlation of all three drill holes is shown in Plate V (left corner). The cross-sectional relationships of two close-spaced drill holes are shown in Figure 25.

Oxide-Bearing Ultramafic Intrusion (OUI)

All three holes intersect intervals of OUI, with a range in thickness of 0.5-242 feet. The OUI intrudes both troctolitic rocks and a large basalt inclusion. Rock types of the OUI consist of medium- to very coarse-grained (locally pegmatitic) oxide peridotite and oxide pyroxenite, with 10%-15% oxides (>90% ilmenite). The OUI is the only rock type that contains sulfides

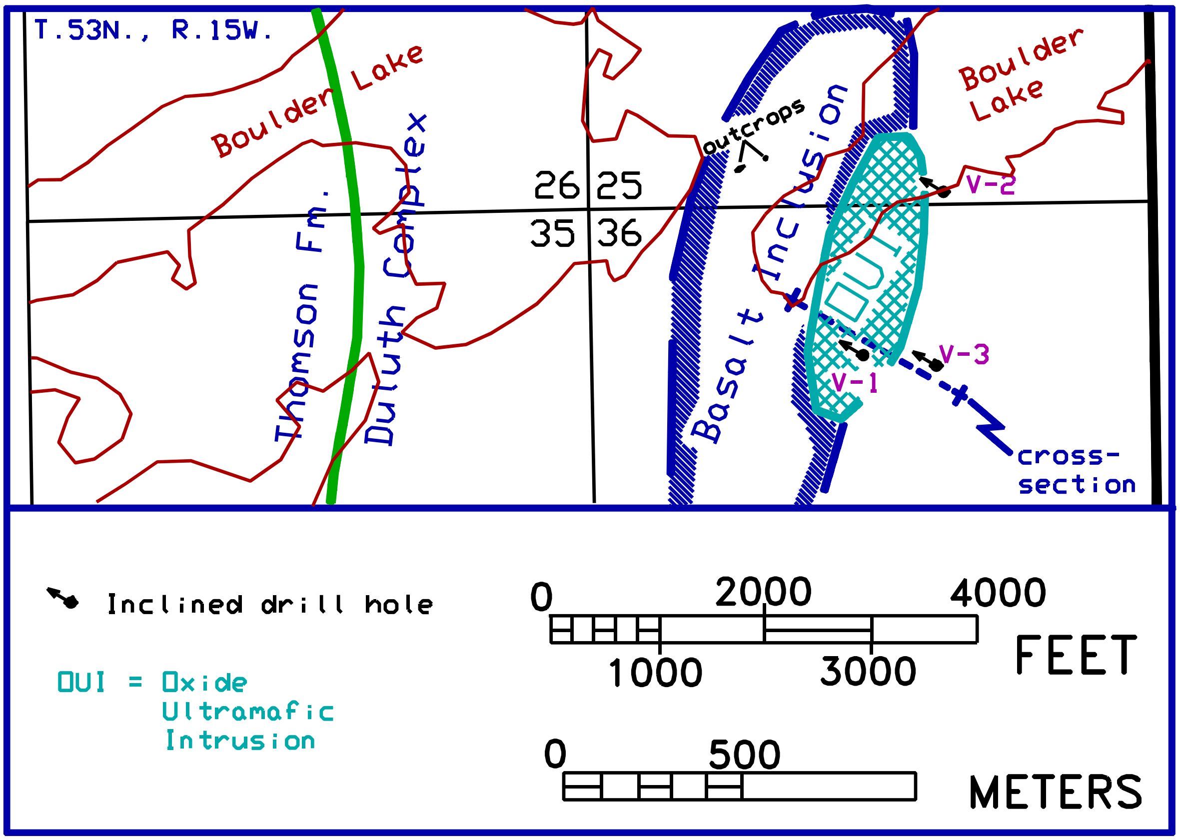


Figure 24. Drill hole location map and general geology of the Boulder Lake South area. Cross-section shown on I
outline drawn using aeromagnetic data from the Boulder Lake Reservoir quadrangle and drill hole data.

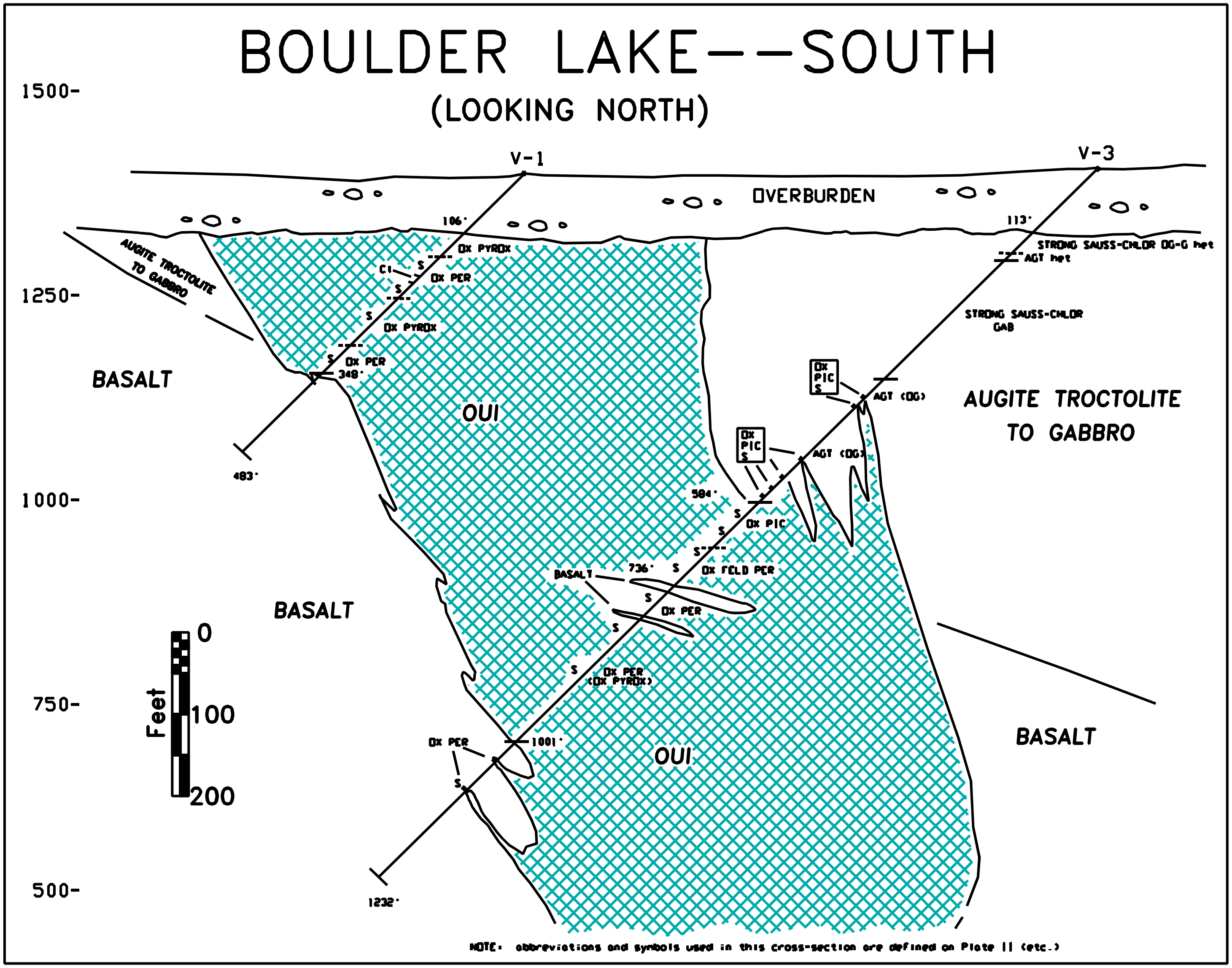


Figure 25. Cross-sectional relationship of rock units in the Boulder Lake South area (see Fig. 24 for location of cross-section).

in the Boulder Lake South area. Sulfide content is generally 0.5%-3.0%, with local net-textured sulfide (5%-7% sulfide); pyrrhotite is dominant. The Cu content of these rocks is never over 0.2%. Only two analyses for titanium are available (see SOCOTIO.WK1), and these indicate a TiO_2 content of about 16%. Bonnichsen (1972, p. 372-374) briefly describes the OUI in drill hole V-3 at Boulder Lake South. He mentions that ilmenite is the only oxide, apatite is moderately abundant in the lower part of the hole, and minor sulfides and graphite are associated with the OUI.

Although apatite is common to the OUI at Boulder Lake South, it is not readily evident in drill core. In one thin section taken from drill hole V-1 at 185 feet (this investigation), the rock consists of 30% oxide and 50% coarse apatite and could be called a nelsonite. It is not known how representative this nelsonite sample is, relative to other OUI intervals, until more sampling is completed. Geochemistry for the nelsonite sample, taken from drill hole V-1 at 181-186 feet, contains high values for P_2O_5 and F (as expected considering the high apatite content).

Troctolitic Rocks

The OUI are in sharp contact with host troctolitic rocks in only two of the drill holes (Plate V). In these holes, the rocks are characterized by an assortment of texturally-heterogeneous gabbro, olivine gabbro, augite troctolite, and troctolite. Sulfide is present only locally, and even then in only rare quantities.

Basalt Inclusion

All three of the holes in this area are terminated in a fine-grained, equigranular rock that locally contains vesicular features (round plagioclase-filled spots). In drill core, this rock is only slightly different than the FN Unit encountered elsewhere. In this investigation, the fine-grained rocks at Boulder Lake South are believed to be a basalt inclusion. Bonnichsen (1972) also refers to these rocks as a volcanic hornfels. One major difference is that basalt does not contain any sedimentary hornfels inclusions, as is common to the FN Unit in other areas. Also in thin section, the basalt exhibits a slightly different texture of granular plagioclase (with three point junctions) and clinopyroxene, with lesser amounts of granular to oikocrystic olivine and orthopyroxene (inverted pigeonite). In addition, the basalt exhibits a different geochemical signature than the FN Unit (to be discussed later).

THOMPSON LAKE

Only one drill hole (Plate I) was drilled by Phelps Dodge Corporation in an area they termed Grid X. The hole was drilled to test a sinuous, north-trending magnetic anomaly. Rocks encountered in the hole consist of troctolitic rocks with a thick dunite layer. Igneous units present in this hole are illustrated in Plate V (upper left corner). No footwall rock types are present in the inclined (-45E) 613 foot deep hole.

Troctolitic Rocks

All that remains of drill hole X-1 are 2-3 inch long specimen samples collected every 10-20 feet. Based on these core pieces, the troctolitic rocks consist of medium-grained troctolite and anorthositic troctolite, with a common subhorizontal, primary igneous foliation defined by aligned plagioclase laths. A very strongly serpentinized, fine- to medium-grained dunite is present at about 270-355 feet. No sulfide mineralization is apparent in the specimen core samples. Dr. Penelope Morton (UMD; pers. comm., 1993) has optically identified disseminated chromite grains (1.0%) in one sample collected from the dunite layer.

FISH LAKE

The Minnesota Department of Natural Resources drilled two holes in Fredenberg Township (north of Duluth, MN) on the basis of geophysical interpretations (Sellner et al., 1985; Dahlberg et al., 1987). Even though the holes were drilled on the shore of Island Lake, they have been referred to as the Fish Lake holes - the Fish Lake term is retained in this report. One of the criterion for drilling the Fish Lake holes is their location at the end of an aeromagnetic linear feature (Dahlberg et al., 1987). Actually, this linear feature is probably an early Keweenawan dike with reverse-polarity. Both holes intersect rocks of the Duluth Complex and footwall rocks of the Thomson Formation. The cross-sectional relationships of the rocks intersected in the drill holes are shown in Figure 26. The data suggest that the basal contact dips about 25E to the east in this area. Both of the Fish Lake drill holes are located south of the area of this investigation, and are most likely situated in the basal zone of the Duluth Layered Series of Miller et al. (1993). However, the holes were relogged in this investigation for comparison to rocks in the South Complex area. A detailed petrochemical discussion can be found in Sassani (1992).

Troctolitic Rocks

A wide variety of fine- to medium-grained troctolitic rocks and noritic rocks with sedimentary hornfels inclusions are present in both FHL-1 and FHL-2. Also present in FHL-2 is a subhorizontal ultramafic layer, at 252-319 feet, consisting of picrite, with zones/beds of olivine-rich troctolite, troctolite, and feldspathic peridotite. All of these igneous units are correlated in Figure 26. Sassani (1992) describes the rock types in both holes in more detail, and subdivides them into nine zones (see Fig. 26). [Note: Sassani has tentatively correlated these zones with Units I through IV of the Partridge River Troctolite Series (PRTS) that are

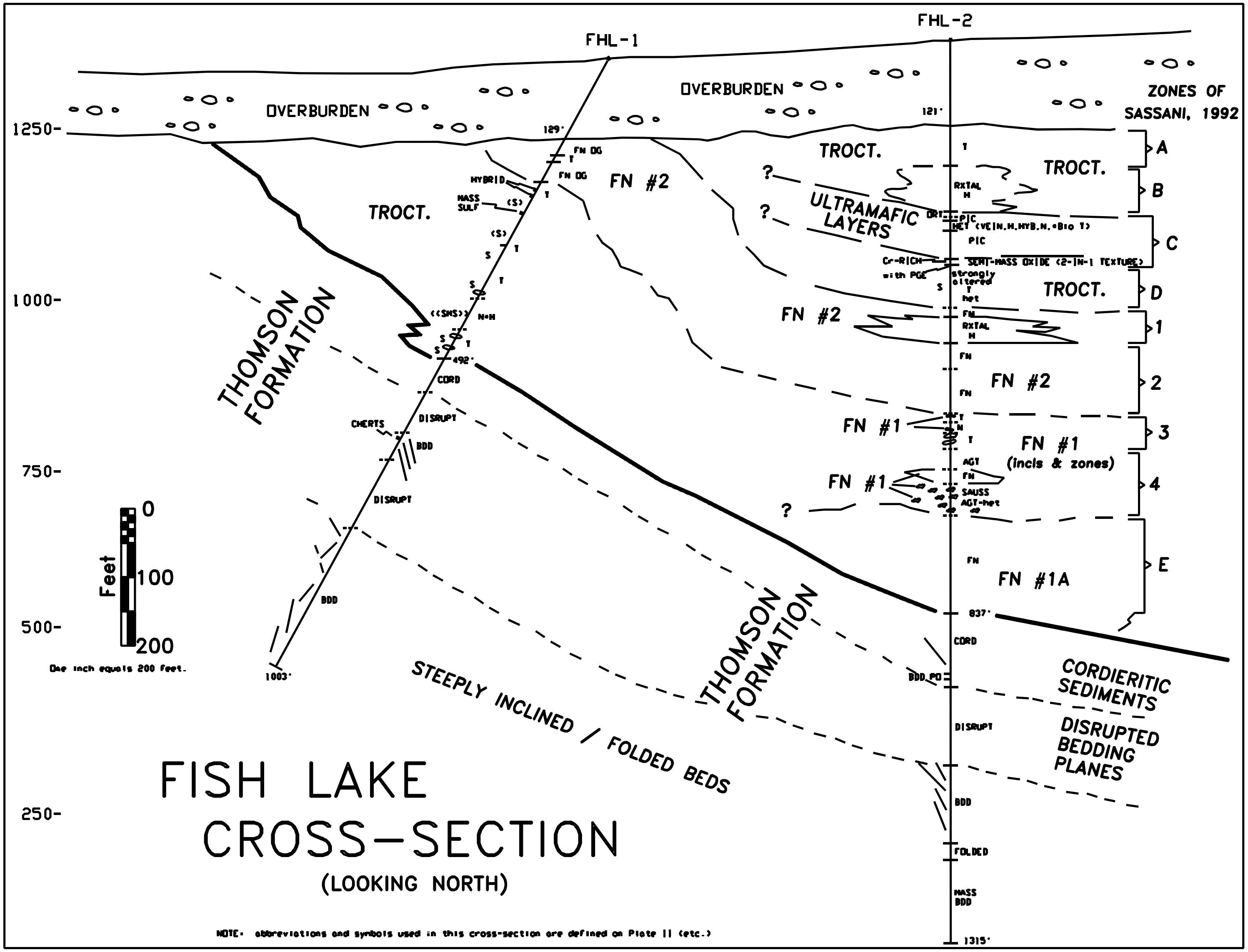


Figure 26. Cross-sectional relationship of rock units in the Fish Lake area (see Plate I for drill hole locations).

defined by Severson and Hauck (1990); however, a review of the drill holes for this investigation indicates that none of Sassani's zones are similar to any of the units of the PRTS]. Sulfide mineralization is the strongest in drill hole FHL-1 which contains up to 5% sulfides (dominantly pyrrhotite). Intervals with net-textured sulfides and semi-massive sulfides are also present in FHL-1.

At the base of the ultramafic layer is a 6 foot thick zone (319.4-325.5 feet in FHL-2) of semi-massive oxide (50%-60% oxides) that exhibits a "2-in-1" texture, consisting of fine-grained titanomagnetite that is poikilitically enclosed in medium- to coarse-grained plagioclase. As mentioned earlier (see description for drill hole SL-19A at Water Hen) this texture is usually accompanied by high Cr and PGE values. In drill hole FHL-2, the semi-massive oxide zone does have high values for Cr (27,000-48,000 ppm), but PGE values are <60 ppb (Dahlberg et al., 1987). However, mildly anomalous PGE values **are** present in highly altered troctolitic rocks that are immediately below the oxide horizon at 325.4-327 feet (120-202 ppb Pt and 370-410 ppb Pd - Dahlberg et al., 1987 and Sassani, 1992). Sassani (1992) feels that the oxide horizon may have acted as an impermeable layer to the upward migration of magmatic hydrothermal fluids.

FN Unit

Fine-grained rocks with vesicle-like features are intersected in both FHL-1 and FHL-2 (Fig. 26). Because the FN Unit at Fish Lake contains abundant sedimentary hornfels inclusions and is even present immediately beneath thick sedimentary hornfels inclusions (Fig. 26 - drill hole FHL-2), it is interpreted to be chilled, early-intruded material of the Duluth Complex rather than a volcanic hornfels. The FN Unit is characterized by fine-grained rocks, with a faint purple sheen, that consist of troctolite, augite troctolite, olivine gabbro, and norite. These rocks commonly grade into similar-looking medium-grained rocks. Thin section inspection of the FN Unit indicates it can be commonly described as either a microgranular augite troctolite or olivine gabbro; also present are gradations into norite, gabbro, and troctolite. In portions of drill hole FHL-1, the FN Unit occurs as small inclusions within troctolitic rocks.

Even though all FN Unit intervals look similar in drill core, at least three varieties of the FN Unit are portrayed in Figure 26 (FN#1A, FN#1, and FN#2). These FN varieties are based on geochemical differences that will be discussed later. The FN#1A and FN#1 varieties exhibit similar whole rock geochemistry, but vary slightly in their respective spider diagram profiles. In drill core, the sampled FN#1 material consists of variable small inclusions within a coarse-grained augite troctolite (both exhibit similar spider diagram profiles, and thus they are difficult to distinguish geochemically). The FN#1A material, at depth in the same hole, is a thick homogenous unit and contains more biotite (5%-10%) than the FN#1. The FN#2 variety differs in all geochemical aspects from the FN#1 and FN#1A varieties. The FN units are all geochemically different than other sampled volcanic hornfels (see discussions in Geochemistry section).

Footwall Rocks - Thomson Formation

Both drill holes are terminated in sedimentary rocks of the Early Proterozoic Thomson Formation. In drill hole, there is a progressive change, with depth away from the basal contact, in the preserved, primary sedimentary features of the Thomson Formation. Near the basal contact, the Thomson Formation is characterized by a zone of massive cordieritic sediments (Fig. 26), characterized by a cordierite-feldspar-orthopyroxene-biotite±graphite rock, with rarely preserved bedding planes. Pink granitic patches (partial melt zones) and pyrite-pyrrhotite coated fractures are common. Below the cordieritic sediment zone is the DISRUPTED unit (Fig. 26), characterized by chaotic/disrupted bedding planes with common bifurcating lenses, veins, and wisps of pink to white partial melts. Furthest from the basal contact, the Thomson Formation consists of regularly-bedded argillite. However, the angle of bedding is quite steep to the core axis, and local zones of tight folding are present ("steeply inclined beds and folded beds" in Fig. 26). The changes in the Thomson Formation record a progressive increase in deformation and recrystallization toward the basal contact of the Duluth Complex.

DRILL HOLES INTO THE ANIMIKIE BASIN ADJACENT TO THE COMPLEX

Several drill holes within the study area are collared in the footwall rocks of the Virginia Formation/Thomson Formation to the west of the contact with the Complex. These holes are also relogged for this investigation to document the stratigraphy of the Virginia/Thomson Formation in portions of the Animikie Basin. The sedimentary rock types present in the holes are diagrammatically shown in Plate VIII, with increasing stratigraphic height above the Biwabik Iron-formation. In all of these holes, the Virginia/Thomson Formation consists dominantly of well-bedded argillite and well-bedded to massive-bedded graywacke (Bouma B and/or D with minor C). Both the argillite and graywacke are interbedded at various scales, ranging from less than 1 inch thick beds to beds that are over tens of feet thick (this is especially true for the argillite-dominated sequences). In some areas, the argillite is a dark gray or black color, probably due to a higher organic content. In close proximity to the Complex, these carbonaceous argillites are characterized by graphite-bearing and/or sulfide-bearing argillite or the BDD PO unit. Also present within the argillite-graywacke sequences are thin interbeds of calc-silicate, chert, and quartzite. All of these sedimentary rock types are shown in Plate VIII. Bedding planes of these sedimentary rocks generally dip at shallow angles (5E-20E), except in close proximity to the Complex. Drill holes nearest to the contact the Virginia/Thomson Formation exhibit: steep bedding planes; structurally deformed bedding planes (DISRUPTED unit); and totally recrystallized zones devoid of bedding planes (RXTAL unit).

Regionally, the sedimentary rocks of the Animikie Basin, particularly the Virginia and Thomson Formations, display shallow dips in the northern half of the basin and steep dips in the southern half of the basin. In order to document where the change in bedding dips actually occurs within the basin, several additional drill holes were looked at in regard to bedding orientations. The results of this study are shown in Figure 27, which shows bedding plane dips for individual drill holes and a rough east-west trending line that separates the northern shallow-dipping rocks from the southern steeply-dipping and folded rocks. Note that in Figure 27 the actual strike of bedding can not be determined from drill core, and is **assumed** to be parallel to the axis of the Animikie Basin. The line in Figure 27 closely corresponds to a similar line of Southwick et al. (1988) that defines the "approximate northern limit of folding and cleavage development." Deformation of the Virginia and Thomson Formations, in a systematically increasing north to south direction, is inferred to have taken place during the Penokean Orogeny between 1900-1760 Ma (Southwick et al., 1988).

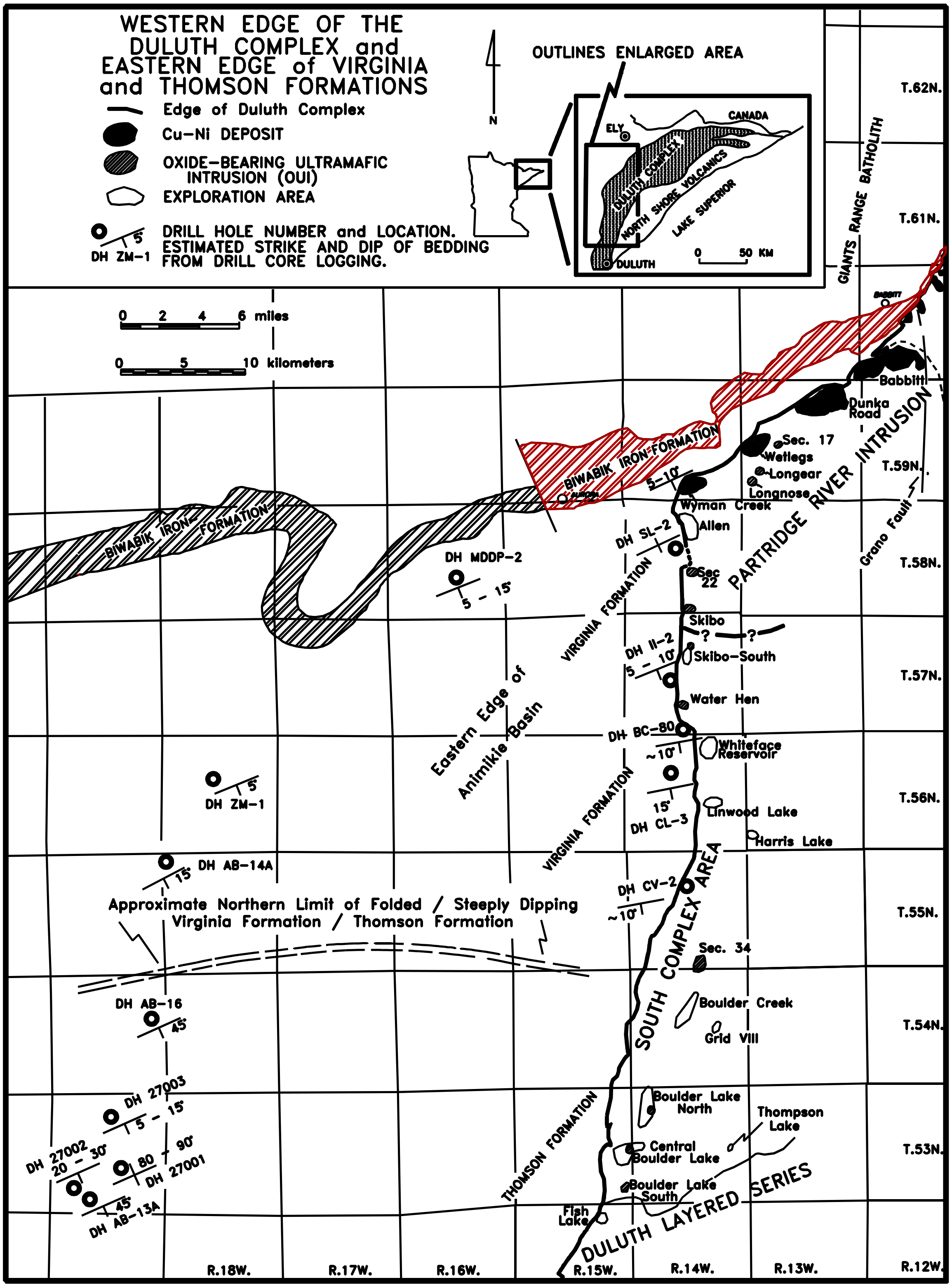


Figure 27. Inferred bedding plane dips of the Virginia Formation and northern limit of folded beds as determined in scattered drill holes.

RECONNAISSANCE GEOLOGIC MAPPING

INTRODUCTION

Twenty-three days were spent conducting reconnaissance geology mapping in the South Complex area. This task was accomplished by confirming the outcrops of Bonnichsen (1971) and searching for additional bedrock outcroppings along roads, logging roads, rivers (St. Louis and Cloquet rivers), and conducting off-road traverses. The outcrops were located on the following 1:24,000 quadrangle maps: Barrs Lake (NE 1/4 only), Bird, Boulder Lake Reservoir, Boulder Lake Reservoir NE, Comstock Lake, Harris Lake, Pequaywan Lake, and Thompson Lake. Individual outcrop locations, including drill hole locations and inferred contacts and faults, are shown on Plate I (at 1 inch = 1 mile or 1:63,360). Also on Plate I are additional geologic data for areas that are peripheral to the South Complex study area. Sources of these additional data include: Chandler, 1990; Severson and Hauck, 1990 (reconnaissance mapping); Miller, Green et al., 1993; and Miller, pers. comm., 1995. Aeromagnetic maps, at 1:24,000 quadrangle scale, are also used to aid in establishing the contacts and faults between some geologic units. Aeromagnetic maps are available from the Minnesota Geological Survey.

CONTACTS

The contacts shown on Plate I are largely inferred due to limited geologic control between widely scattered bedrock outcrops and drill holes. The contacts are drawn according to the distribution of a particular aeromagnetic signature (high or low) that is associated with a known rock type. For example, the OUI bodies are commonly expressed as small circular magnetic highs. On Plate I, wherever OUI rock types associated with a magnetic high are confirmed by drill hole data, a crude circular contact is drawn around the OUI body. In some areas, additional small circular anomalies are clustered around a known OUI body, e.g., the Section 34 area on Plate I. In these instances, small circular magnetic highs with potential OUI rock types, that have yet to be confirmed by drilling, are shown on Plate I as circular bodies with a "OUI?" designation. The same principle applies to other units shown on Plate I. Wherever a particular geologic unit is confirmed by either outcrop or drill hole data, the contacts bordering that data point are "traced outward" from the data point according to trends of coincident aeromagnetic lows and highs. It is important to note that the South Complex area contains numerous aeromagnetic highs and lows associated with unconfirmed rock types (no rock outcrops or drill holes). Many of these aeromagnetic features are not shown on Plate I, as their nature, or possible rock type, is too speculative and beyond the scope of this investigation. In essence, the geology shown in Plate I is highly simplified. More detailed geophysical modelling is necessary before additional rock types and contacts can be included. Chandler (1990) has conducted such a study, however more regional in nature, over a large portion of the Complex that includes the northern half of the South Complex area. Chandler (1990) used gravity and magnetic data to outline multiple intrusive bodies within the Duluth Complex. Contacts between these internal Duluth Complex bodies within the South Complex area, as delineated by Chandler (1990), are incorporated on Plate I.

The location of the contact of the Duluth Complex with the Virginia-Thomson Formations (Plate I) is slightly modified from the previous geologic map of Bonnichsen (1971). The contact is largely inferred on the basis of scattered drill holes, outcrops, and a coincident aeromagnetic signature. On aeromagnetic quadrangle maps in the South Complex area, rocks of the Duluth Complex are characterized by high magnetic signatures (with extreme local variations) relative to sedimentary rocks of the Virginia Formation, which are characterized by much lower magnetic signatures. The change in the aeromagnetic patterns for these two different rock types across the contact is dramatic and is utilized to geophysically trace the contact in the absence of outcrops and drill holes. Tracing the contact in this manner is generally in good agreement with areas with better geologic control.

However, in the area between Wyman Creek and Water Hen, this method of geophysically tracing the contact does not work. There, a very broad north-south-trending magnetic high spans across the actual trace of the contact (the contact is defined by detailed drilling in this area). The magnetic high reflects a strong, natural remanent magnetization overprint in the Biwabik Iron-formation (at depth near the contact) that is associated with heating by the Duluth Complex (Bath, 1962; Chandler, 1990). The individual OUI bodies at the same location, and their presumed magnetic high signature, are masked by this broad magnetic high.

FAULTS

The faults shown in Plate I are located similarly as described previously. In this instance, linear magnetic lows that offset, or truncate, sinuous magnetic highs (associated with a particular unit) are inferred to represent fault zones. In some instances, the linear distribution of magnetic highs associated with OUI bodies also suggest that they are associated with a fault zone. Two inferred fault zones with linear-distributed OUIs are present within the South Complex area. They are referred to as a Northern OUI Group (N-OUI), which includes OUIs at Wyman Creek, Skibo, Skibo South, and Water Hen; and a Southern OUI Group (S-OUI), which includes OUIs at Section 34, Boulder Creek, Boulder Lake North, and Boulder Lake South. Other OUI bodies located elsewhere within the Duluth Complex, e.g., the Longnose-Longear-Section 17 trend, are also linearly distributed along fault zones (Severson and Hauck, 1990; Severson, 1991; Severson, 1994). There are probably more faults in the South Complex area than are shown on Plate I. However, a detailed lineament study of aeromagnetic and topographical data is necessary to accurately portray the faults. Such a study is beyond the scope of this investigation.

OUTCROP AREAS

Most of the rock outcroppings of Duluth Complex found in this investigation consist of texturally-homogeneous troctolite or anorthositic troctolite. These rocks cannot be assigned to any particular igneous unit and are referred to as "troctolite undivided" (or the TU Unit) on Plate I. However, rocks other than troctolite and anorthositic troctolite are also found within the South Complex area. In the Skibo area are numerous outcrops of augite troctolite and olivine gabbro. Gabbroic rocks are common to the Boulder Lake outcrops (oxide-bearing) and to outcrops at Skibo Vista and along County Highway 16 (see Plate I). Sulfide-bearing rocks are only found in one location - in a small zone near the top of a large set of outcrops in section 1, T.53N., R.14W. In thin section, this rock contains about 2% chalcopyrite, with common patches of bornite, covellite, chalcocite and digenite; no Cu-Ni analyses were conducted. In addition to these outcrops, abundant outcrops of unique rocks are present in three areas and deserve special mention. A detailed description of these three areas follow.

Bear Lake Inclusion

Numerous outcrops are present to the west of Bear Lake in the southeastern corner of T.55N., R.13W. (Fig. 28). This area is associated with a 2,500 gamma aeromagnetic anomaly that was drilled by the MDNR in 1984 (drill hole BL-1, Sellner et al., 1985). At least two major rock types are present that include: 1) an inclusion of magnetic basalt (mb in Fig. 28) that overlies and is in sharp contact with, 2) a package of oxide-bearing gabbroic rocks. Outcrop data suggest that both the inclusion and the gabbroic rocks dip about 10E-20E toward the southeast. Drill hole BL-1 gives a minimum thickness for the inclusion of 563 feet (the hole was collared and terminated in magnetic basalt).

The inclusion of magnetic basalt is characterized by outcrops of dark-gray to black colored, fine-grained, equigranular, strongly magnetic rock with an oxide gabbro composition. These rocks have been previously referred to as "undifferentiated hornfels" (Bonnichsen, 1971) and "microgabbro" (Sellner et al., 1985). Although no foliation is seen at the outcrop scale, due to the fine-grained and granular nature of the rock, all the outcrops are characterized by steep-sloped west sides and shallow-sloped east sides with dips of about 10E-20E. All the outcrops are massive and void of any vesicle-like features; some local zones contain 5%-15% very coarse plagioclase phenocrysts. Drill hole BL-1 intersects 563 feet of similar material that is void of phenocrysts and vesicles.

Even though the rocks lack obvious volcanic features, the unit is believed to be an inclusion of magnetic basalt derived from the Keweenawan hanging-wall material. Sharp contacts, of 15E to the east, with the underlying gabbroic rocks are observed in two close-spaced outcrop areas (Fig. 28). Similar material, also referred to as magnetic basalt, is present elsewhere in the Duluth Complex: 1) within portions of the Colvin Creek Inclusion (see north end of Plate I) described by Patelke (1996); 2) associated with an anorthositic inclusion within the South Kawishiwi intrusion where it is referred to as the "INCL" unit (Severson, 1994); and 3) in a drill hole (IS-1; Sellner et al., 1985) near Isabella, Minnesota (J. Miller, pers. comm., 1994).

In thin section, the magnetic basalt is characterized by: 1) 50%-65% round to lath-shaped plagioclase with common triple point junctions; 2) 15%-35% round to tabular and/or subophitic to ophitic grains of augite; 3) 10%-25% round, weakly-embayed oxide grains consisting of magnetite-ilmenite composite grains (magnetite is slightly greater than ilmenite); and 4) minor

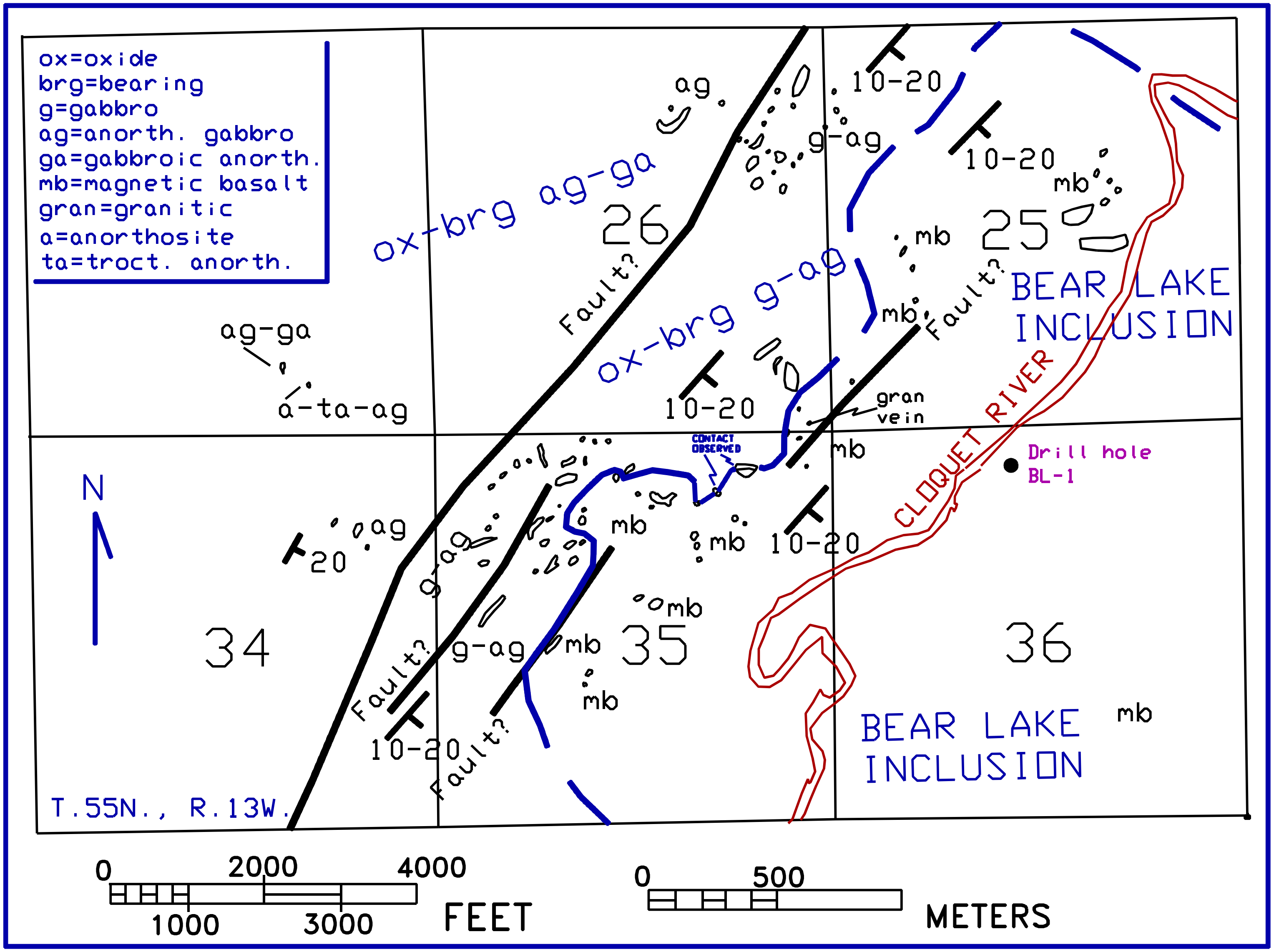


Figure 28. Outcrop and drill hole location map, with general geology, of the Bear Lake Inclusion area.

amounts of oikocrystic olivine and orthopyroxene. Twinning in both plagioclase laths and round plagioclase grains is coplanar in all thin sections. This fabric accounts for the eastward dipping outcrop morphology. Trace to 1% chalcopyrite, with common bornite patches, is present in some thin section samples. One thin section contains three minute flecks of native copper.

Underlying the magnetic basalt inclusion are fine- to medium-grained, oxide-bearing (5%-10%) gabbroic rocks. Gabbro and anorthositic gabbro are common beneath, or immediately west of, the inclusion and grade with depth (toward the west) into anorthositic gabbro and gabbroic anorthosite that have local anorthosite zones (Fig. 28). All of the outcrops are massive with no obvious primary igneous foliation, but exhibit the same outcrop morphology as the basalt outcrops. Modal bedding, with evidence of plastic deformation (slumped?), is observed near the exposed contact with the inclusion - in the top 10-15 feet of the gabbroic rocks.

Modally Layered Rocks Along the Cloquet River

Abundant large outcrops of both massive and modally layered troctolitic rocks, with rare picrite layers, are present on both sides of the Cloquet River in sections 10 and 15, T.54N., R.13W. The layering is defined by alternating plagioclase-rich and olivine-rich layers that vary from 1 inch to several feet thick. A primary igneous foliation defined by aligned plagioclase laths is also present and is parallel to the layering. Dips are generally 5E-18E to the north in section 10, and 5E-10E to the east in section 15. On Plate I, the distribution of this rock unit away from the outcrop area is based on the trend of an aeromagnetic low associated with the outcrops. Outcrops in the area are plentiful and probably more exist than what are shown on Plate I.

Modally Layered Rocks Near Lieuna Lake

Another sequence of modally layered troctolitic rocks is present in abundant, large outcrops to the east of Lieuna Lake in sections 3, 9, 10, and 16, T.53N., R.13W. (Plate I). The modal layers are defined by alternating layers of anorthositic troctolite, troctolite, and olivine-rich troctolite (with 40%-50% olivine). The layering generally dips 5E-10E to the southeast, but also locally present are dips up to 15E and north-oriented dips of 5E-10E. Some of the outcrop ridges in section 3 have steep relief of 60-80 feet. In these ridges, the overall modal percentages of plagioclase and olivine gradually increase in the rocks at the top and bottom of the ridge, respectively. Anorthositic troctolite is dominant at the top of the ridge; whereas olivine-rich troctolite, and locally thin picrite beds, are more dominant at the bottom. The distribution of this unit shown on Plate I is based on trends of an aeromagnetic high associated with these rocks. These rocks may be correlative with modally layered troctolitic rocks in the Basal Contact Zone of the Duluth Layered Series (Unit BC of Miller et al., 1993) exposed to the southwest near Duluth, Minnesota.

GEOCHEMISTRY

INTRODUCTION

Drill core samples were collected from some of the lithologic igneous units of the South Complex for whole rock, trace element, rare-earth element (REE), base metal, and precious metal analyses. A total of 19 drill core samples were analyzed and included: 10 OUI samples (includes 3 massive oxide zones) from the Section 34, Boulder Creek, Boulder Lake North, and Boulder Lake South areas; 3 samples of oxide gabbroic rocks (includes 1 massive oxide sample) from the LOG Unit at Boulder Lake North; 4 samples of sulfide-bearing troctolitic rocks from the Whiteface Reservoir area; 1 sample from a subhorizontal peridotite layer at Harris Lake; and 1 sample of a semi-massive oxide zone with "2-in-1" texture from the Water Hen area. Results are listed in the SCOMCHEM.WK1 data file in the back pocket of this report. In addition, PGE scans were conducted on all the samples; results are shown in Table 4 and are also included in the SCOMCHEM.WK1 data file. The samples were sent to X-Ray Assay Laboratories (XRAL) in Don Mills, Ontario, Canada, for whole rock analyses; and to Dr. Sarah-Jane Barnes, Geology Department, University of Quebec, Chicoutimi, Quebec, Canada, for the PGE scans. Analytical methods and detection limits for all the analyses are listed in the SCOMCHEM.WK1 data file. One blind sample of an international geochemical standard, SARM-5, was submitted to XRAL as a precision check and analytical results are listed in the data file. Internal XRAL precision checks are also listed in the file. Dr. Barnes ran internal checks using the Ax90 standard; analyzed versus accepted values are listed in the file.

Also, the geochemical results of previously sampled drill core intervals from holes in the South Complex are compiled and included in the SOCOCHEM.WK1 data file (back pocket). These data are assembled from: Bonnichsen, 1972; Sellner et al., 1985; Dahlberg, 1987;

Table 4. PGE scans conducted at the University of Quebec, Chicoutimi, Quebec, Canada.

Drill Hole	Interval (feet)	Area	Rock Type	Pt ppb	Pd ppb	Os ppb	Ir ppb	Ru ppb	Rh ppb	Au ppb	Re ppb
SL-19A	446-446.7	Water Hen	"2-in-1"	737.20	63.52	16.69	28.03	173.17	37.61	8.83	0.66
26009	186-191.5	Whiteface	Troctolite	5.63	10.68	0.68	0.37	0.60	0.60	7.82	8.44
26009	670-675	Whiteface	Troctolite	8.83	13.83	0.61	0.35	2.10	0.67	12.27	0.72
26009	770-776	Whiteface	Troctolite	14.74	14.63	<0.88	0.49	2.74	0.90	8.28	2.85
26009	1052-1057	Whiteface	Troctolite	3.22	14.45	<0.70	0.34	2.87	0.64	4.22	1.94
26006	552-558	Harris Lake	Peridotite	3.63	8.36	<1.1	0.21	1.74	0.22	1.31	0.21
26002	290-299	Sec.34	OUI	5.99	9.89	<0.81	0.21	<3.7	0.47	3.03	0.10
26002	365-372	"	"	<4.1	3.05	<0.56	0.07	2.65	0.24	0.40	0.17
26002	587-593	"	"	<3.6	1.90	<0.50	0.05	<1.7	0.25	1.70	0.13
26002	619-623	"	"	<4.3	2.73	<1.0	0.10	<3.8	0.33	2.84	0.12
26002	653-658	"	"	14.13	20.34	<0.58	0.62	1.73	0.99	8.43	0.11
26001	278-285	"	"	4.93	2.82	<1.2	0.02	<2.9	0.13	21.48	0.14
I-4	502-507	Boulder Creek	"	12.68	23.21	<0.98	0.38	<2.9	0.66	10.92	1.35
IV-1	146-151	Boulder Lake No.	"	3.89	4.00	<0.45	0.15	<2.2	0.18	2.15	0.29
IV-1	198-203.5	"	"	2.29	5.58	<0.50	0.13	2.62	0.18	1.20	0.24

IV-3	135-140	"	Log-Gabbro	2.73	4.84	0.44	0.05	2.32	0.17	0.36	0.50
IV-3	245-252	"	Log-Pyrox.	<3.8	1.49	<0.41	0.07	3.05	<0.13	1.91	0.12
IV-3	324-328	"	Log-Mass. Ox.	7.21	<2.6	<0.67	0.02	3.19	0.15	0.81	0.09
V-1	181-186	Boulder Lake So.	OUI	5.29	6.51	<0.54	0.32	2.74	0.9	4.27	2.27

Dahlberg et al., 1987, 1989; Severson and Hauck, 1990; Strommer et al., 1990; Mogessie and Stumpfl, 1992; Seitz, unfinished MS thesis (results on file at NRRI); and from private corporate data on file at the NRRI.

Analytical results from both the SCOMCHEM.WK1 (this investigation) and SOCOCHEM.WK1 (previous investigations) are combined in the SCSORT.WK1 data file. The SCSORT file was used to construct the X-Y plots and spider diagrams of this report. Because the geochemical data are from more than 10 different sources and each utilizing a different laboratory, it is difficult to evaluate the analytical precision and accuracy of the individual data sets relative to each other. Thus some of the variations in the spider plots, constructed with the SCSORT file, may be related to analytical error; however, these errors are assumed, for the most part, to be negligible. Several samples are removed from the SCSORT file (relative to the SOCOCHEM file) because the: 1) sampled intervals were collected across contacts - resulting in contrasting rock types being geochemically mixed; 2) samples had poor whole rock totals (<98% or >102%); and 3) samples were of semi-massive to massive sulfide. Whenever possible, the samples in SCSORT.WK1 are grouped according to rock type and/or geographic location, e.g., OUI and FN rock types, or AGTLL for augite troctolite at Linwood Lake.

Notable high values within the analyses include: 1) high Cr values for semi-massive oxides with "2-in-1" texture collected from Fish Lake, an OUI at Water Hen, and drill hole SL-19A at Water Hen; 2) high PGE values for the Cr-rich zone in SL-19A, and anomalous PGE values below the oxide zone at Fish Lake; 3) high P_2O_5, F, As, and Sb values for a nelsonite sample from the Boulder Lake South OUI body; and 4) high values for TiO_2 associated with the various OUI bodies.

AFM DIAGRAM

The AFM diagram shown in Figure 29 is constructed using the IGPET II program (Carr, 1987) from data in the SCSORT.WK1 file. All rock types within the South Complex plot within the tholeiitic field. Igneous units that show a clustering of points within distinct fields on the AFM diagram include the OUI, FN Units (three of them - one at Linwood Lake, and two at Fish Lake), and the Augite Troctolite at Linwood Lake.

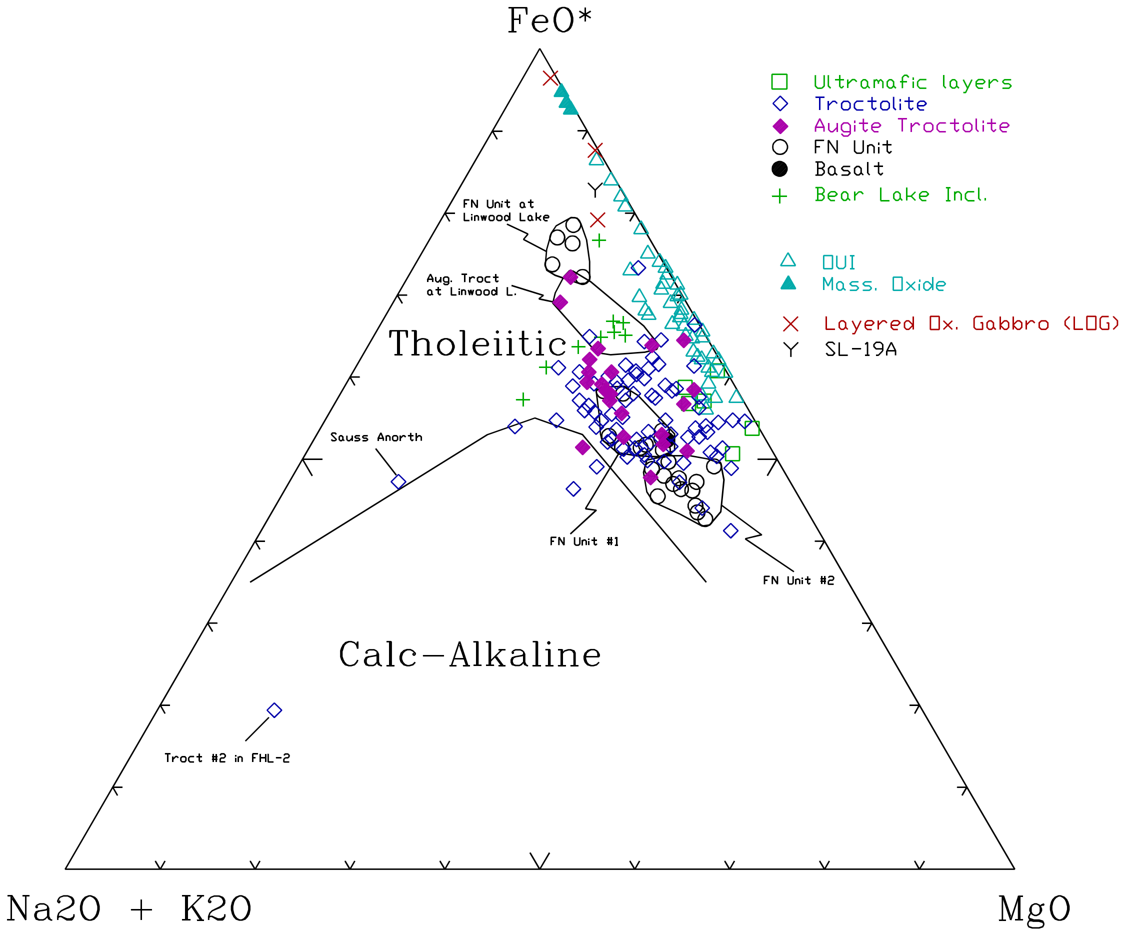


Figure 29. AFM diagram of rocks units in the South Complex area.

SPIDER DIAGRAMS

Plots of chondrite normalized incompatible elements for each of the sampled igneous units are illustrated on the spider diagrams (Figs. 30 to 68). The spider diagrams and chondrite values used in the normalization are constructed using the IGPET II program (Carr, 1987), which utilizes the technique outlined by Thompson (1982). A few of the spider diagrams are constructed using NewPet (Clark, 1994).

Individually, the spider diagram profiles generally show good internal agreement for all samples collected from a particular igneous unit, e.g., all OUI samples from the Water Hen area. Collectively, some of the spider diagram profiles are different for a particular igneous unit at a specific location, e.g., OUI at Water Hen versus OUI at Skibo. In some cases, these differences are expressed as subtle variations in the profiles. Tables 5 and 6 list comparisons for similar and dissimilar spider diagrams that were made by overlaying the spider diagram profiles and making visual comparisons. A brief discussion of the spider diagram profiles for igneous units in the South Complex follows.

Oxide-Bearing Ultramafic Intrusions (OUI)

The various OUI bodies can be divided into two groups based on geographic location, and, as will be seen in the following discussions, these same two groups differ from each other geochemically as well. These two OUI groups are: the Northern OUI Group (N-OUI) that collectively consist of OUI bodies at Section 22, Skibo, Skibo-South, Water Hen, and Whiteface Reservoir; and a Southern OUI Group (S-OUI) consisting of OUI bodies at Section 34, Boulder Creek, Boulder Lake North, Central Boulder Lake, and Boulder Lake South. Comparison of spider diagrams (Figs. 30 to 40) indicates that all of the OUIs exhibit similar spider patterns, with subtle differences in the plotted amounts of specific elements, e.g., one OUI may show "enriched" or "depleted" values for one or more elements when compared to another OUI. A brief description of each individual OUI spider diagram is presented below.

<u>Section 22 OUI</u> - All of the spider profiles from the Section 22 OUI are the same in Figure 30.

Minor differences in the plotted amounts of Zr and Ti appear to define a zonation trend (based on downhole footage) in the central core of the OUI versus the outer margins of the OUI (Fig. 30).

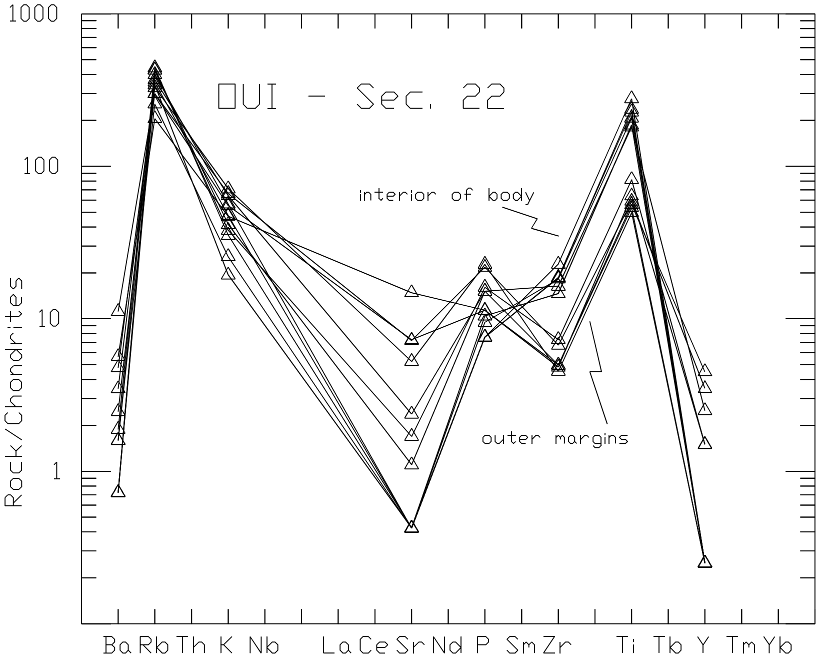


Figure 30. Spider diagram of the Section 22 OUI (N-OUI).

Skibo OUI - All of the spider profiles from Skibo are the same in Figure 31. The samples collected from the top and bottom of the OUI body are slightly different than interior OUI samples.

Skibo-South OUI - Only one sample of OUI material from the Skibo-South area is plotted in Figure 32. The spider diagram profile is similar to the Section 22 and Water Hen profiles.

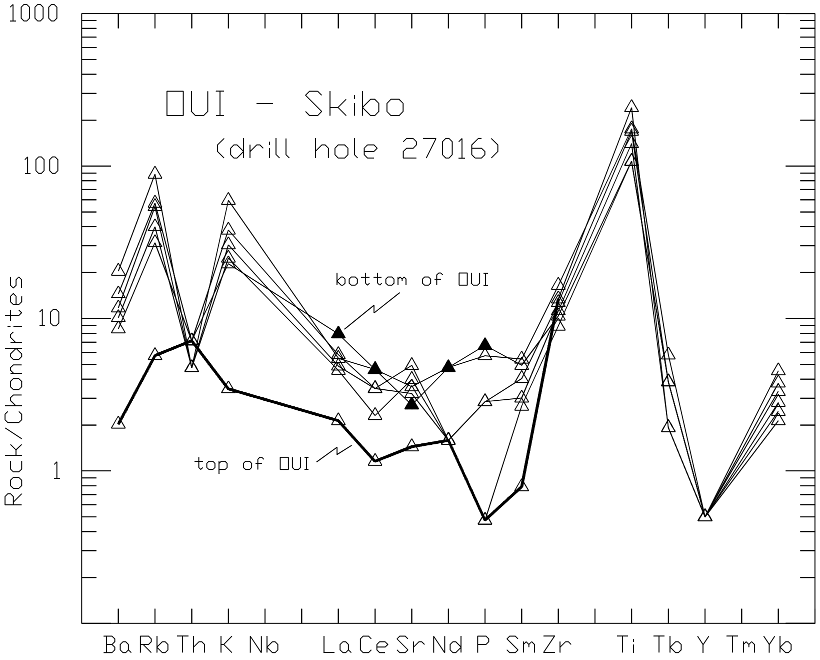


Figure 31. Spider diagram of the Skibo OUI (N-OUI).

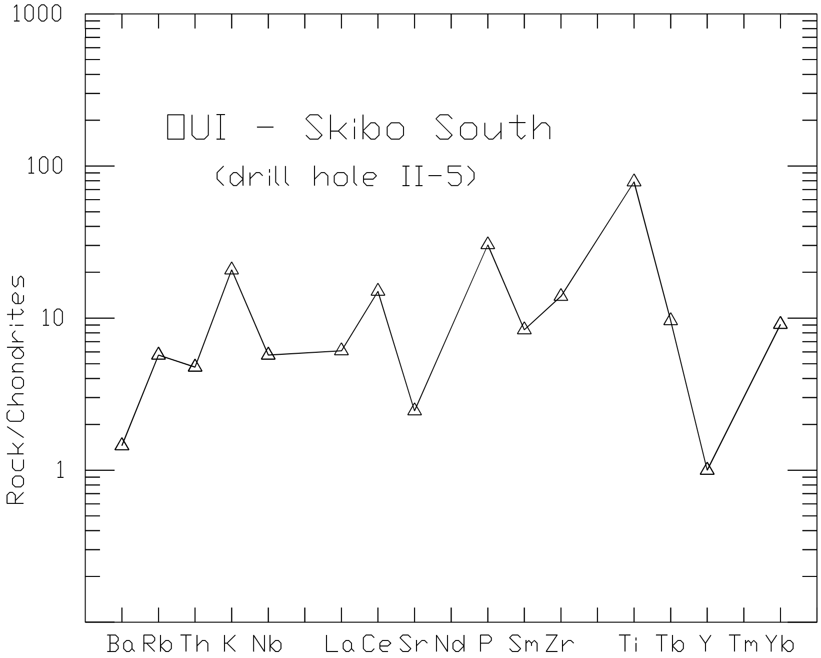


Figure 32. Spider diagram of the Skibo-South OUI (N-OUI).

Water Hen OUI - Figures 33 and 34 display the spider diagram profiles for ultramafic rocks and troctolitic rocks associated with the Water Hen OUI, respectively. In Figure 33, all of the ultramafic rocks (pyroxenite and peridotite) exhibit the same profiles; one sample of orthopyroxenite from near the base of the OUI body is also very similar. Also included in Figure 33 are four samples collected by Strommer et al. (1990) from a unit they referred to as the "cyclically layered series" (or the TL unit). The profiles for these four samples (the only ones with plotted values for Nb, La, and Ce in Fig. 33) are exact matches to the other OUI profiles. This similarity suggests that many ultramafic portions of the TL unit of Strommer et al. (1990) may actually be thin OUI apophyses that exhibit cyclic layering. Figure 34 displays spider diagram profiles for four samples of anorthositic troctolite also collected from the TL unit by Strommer et al. (1990). The profiles in Figure 34 are more similar to the OUI profiles of Figure 33 than they are to profiles of troctolitic rocks taken from the other troctolitic rocks in nearby areas (Figs. 41 to 49). This case also suggests that some of the troctolitic upper portions of cyclic layers in the TL unit are actually cyclically layered top portions of OUI apophyses.

Whiteface Reservoir OUI - Only one sample of a stratabound(?) OUI from the Whiteface Reservoir area is shown in Figure 35. The spider diagram profile is similar to profiles of OUI material in the Skibo area.

Section 34 OUI - Figures 36 and 37 display spider diagram profiles for material collected from the Section 34 OUI body. All of the profiles are similar, but have subtle differences between pyroxenite, peridotite, and massive oxide material.

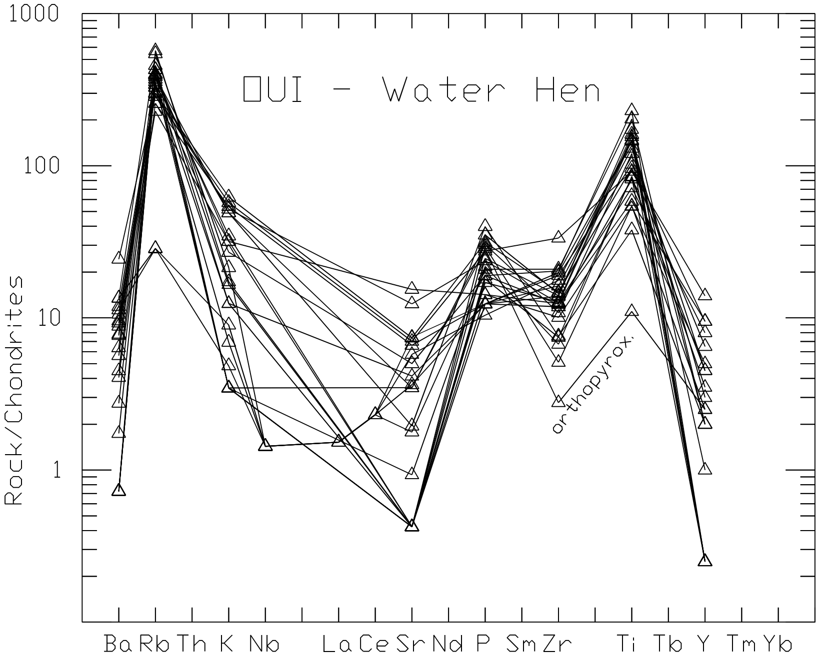


Figure 33. Spider diagram of the Water Hen OUI (N-OUI).

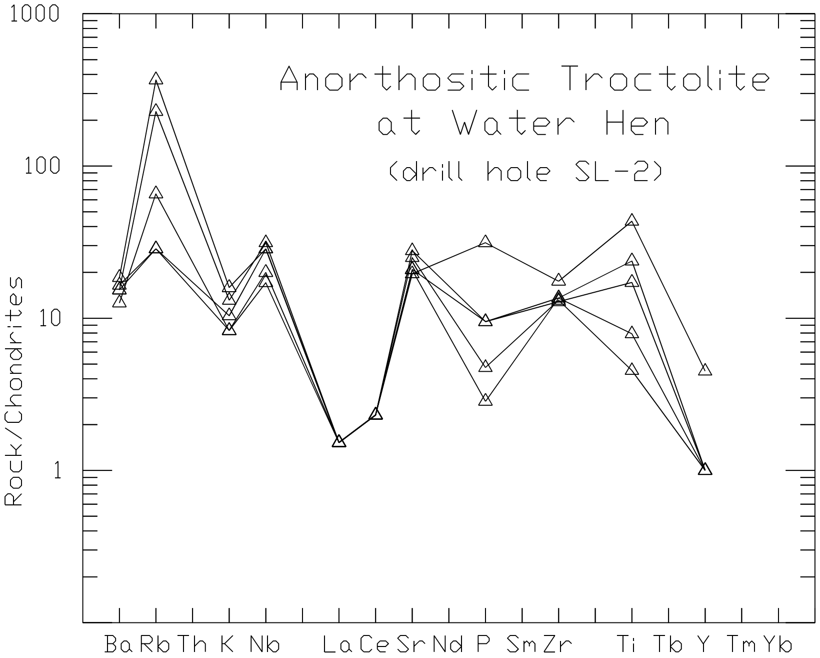


Figure 34. Spider diagram of anorthositic troctolite associated with (cyclically layered?) thin OUI apophyses at Water Hen (N-OUI).

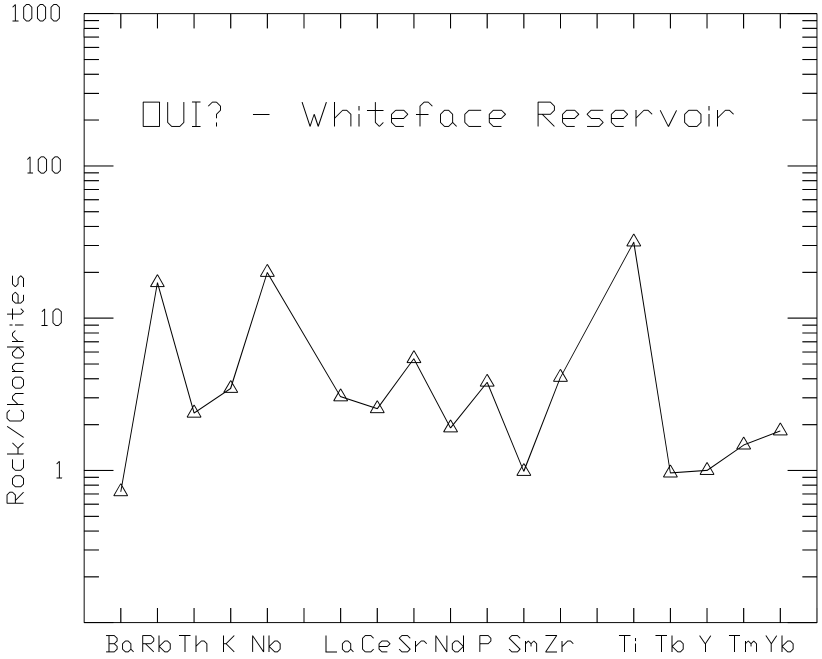


Figure 35. Spider diagram of a thin stratabound OUI(?) unit at the Whiteface Reservoir area (N-OUI).

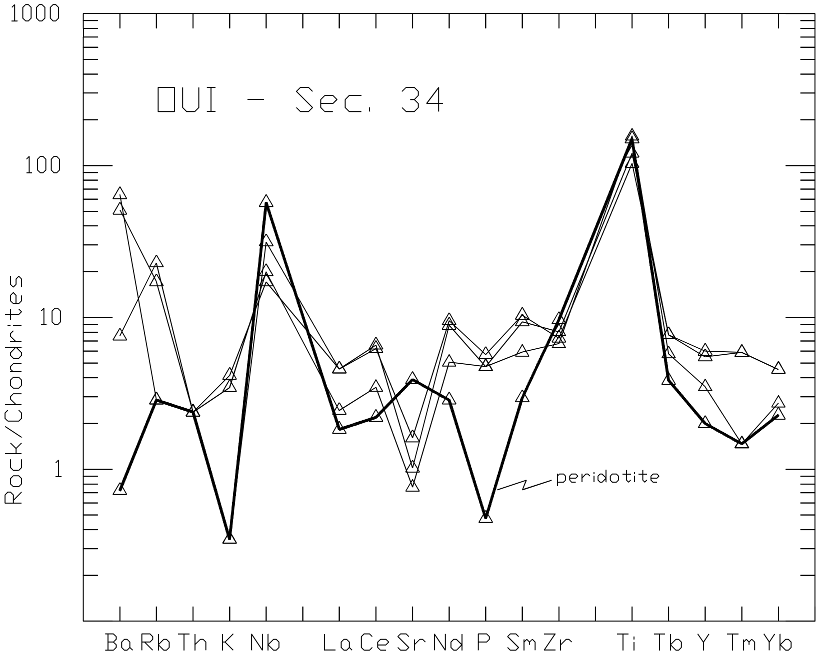


Figure 36. Spider diagram of pyroxenite and peridotite rock types within the Section 34 OUI (S-OUI).

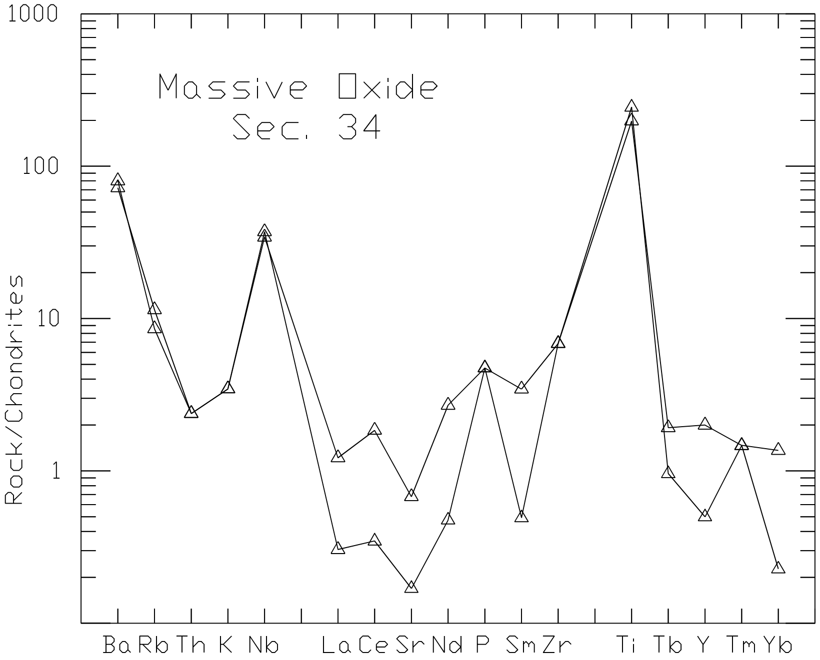


Figure 37. Spider diagram of massive oxide zones within the Section 34 OUI (S-OUI).

Boulder Creek OUI - Only one sample of the stratabound OUI at Boulder Creek is plotted in Figure 38. Its profile is similar to other OUI profiles from Section 34 and Boulder Lake North.

Boulder Lake North OUI - Both samples of OUI from Boulder Lake North exhibit similar spider diagram profiles (Fig. 39), with some subtle differences.

Boulder Lake South OUI - Only one sample taken from an apatite-rich zone (nelsonite) is shown in the spider diagram of Figure 40. The profile for this material differs somewhat from the profiles of all the other Southern OUI group. Note the relative enrichment in most plotted elements, especially P. It is unknown how representative the nelsonite sample is relative to the rest of the OUI material at Boulder Lake South.

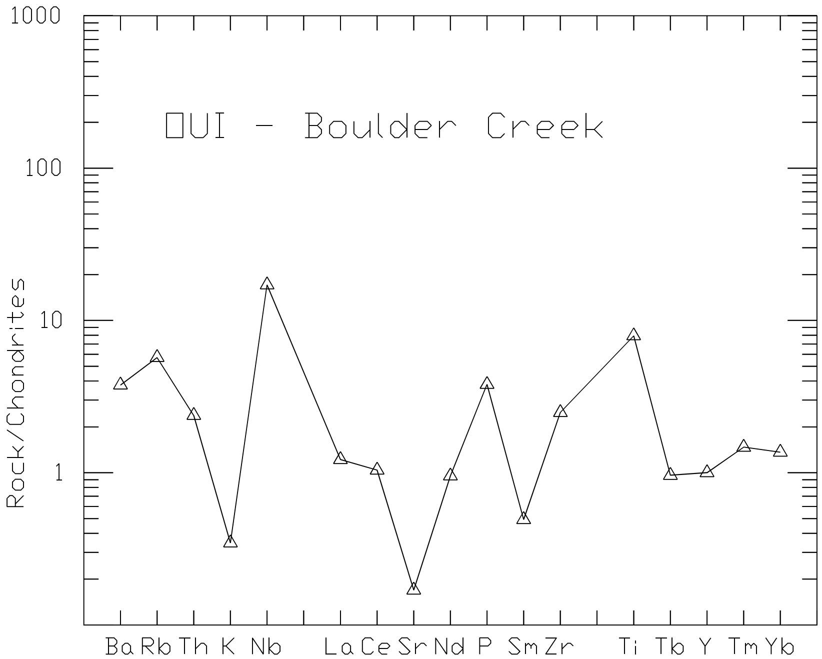


Figure 38. Spider diagram of the stratabound(?) OUI from the Boulder Creek area (S-OUI).

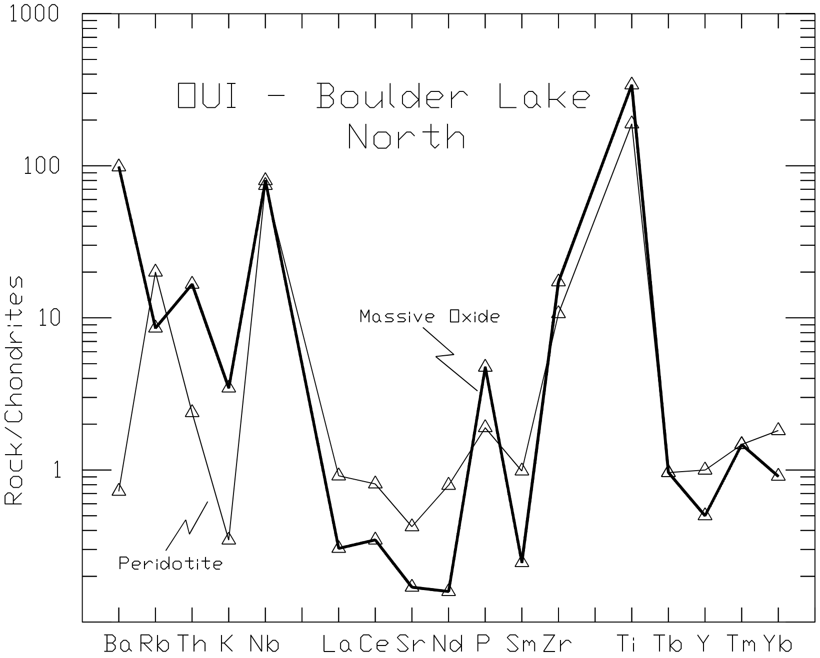


Figure 39. Spider diagram of the Boulder Lake North OUI (S-OUI).

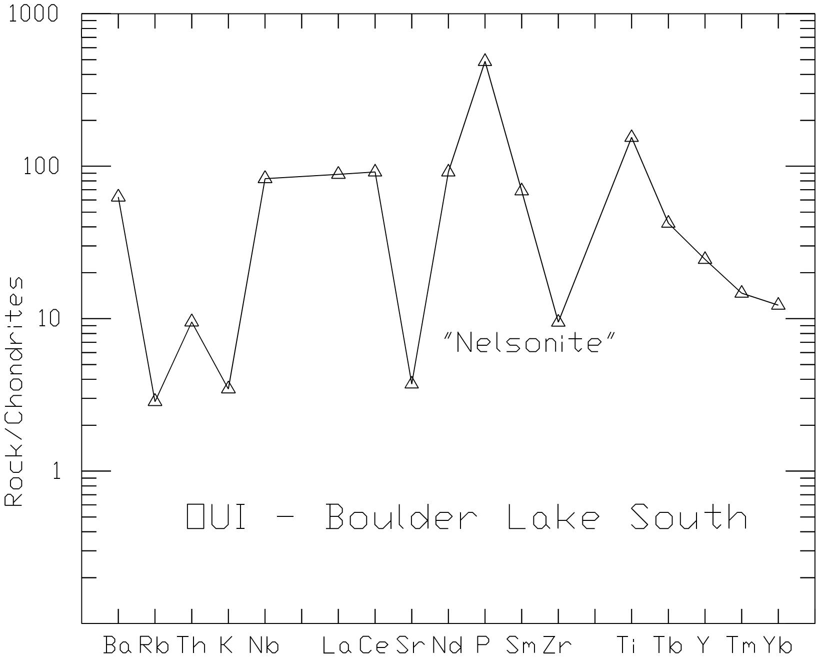


Figure 40. Spider diagram of a nelsonite within a portion of the Boulder Lake South OUI (S-OUI).

As mentioned previously, all of the OUIs exhibit similar spider diagram profiles, but with subtle differences. However, comparison of the overall spider patterns indicates that the N-OUI group and S-OUI group are markedly different (Figs. 30 to 35 versus Figs. 36 to 40). Furthermore, the N-OUI group can be divided into two additional subgroups based on spider patterns. Within the N-OUI group, the Section 22, Skibo-South, and Water Hen OUIs are similar, but differ from the Skibo and Whiteface Reservoir OUIs. Table 5 lists the division of OUIs based on similar spider diagram patterns. The reason for the two OUI groups (N-OUI versus S-OUI) may be related to the origin of the OUIs at one geographical location relative to another geographical location. The N-OUI are all associated with a broad aeromagnetic high that is related to a magnetization overprint in the Biwabik Iron-formation. These OUIs may be related to intrusion and assimilation of the iron-formation at depth, as proposed for the Longear-Longnose-Section 17 OUI of the Partridge River intrusion by Severson and Hauck (1990). An iron-formation intrusion and assimilation seems unlikely for the S-OUI because the iron-formation is inferred to be located many thousands-of-feet below the OUI bodies. Some of the S-OUI occur within, or near to, stratigraphic layers of gabbroic to troctolitic rocks with high oxide contents. These stratigraphic layers may be intimately linked to OUI development. Possible models of origin for the N-OUI and S-OUI will be discussed in more detail in the Summary section of this report.

Table 5. Potential groupings of the OUI in the South Complex area (based on similarities in spider diagram profiles).

Northern OUI (N-OUI)		Southern OUI (S-OUI)
Section 22	Skibo	Section 34
Skibo-South	Whiteface Res.	Boulder Creek
Water Hen		Boulder Lake North

The two subgroups within the N-OUI are not easily explained. This situation is complicated by the fact that these OUI alternate geographically with respect to similarities in spider diagram profiles. For example, the Section 22 and Water Hen OUI profiles are similar, but they are different than the profile for the Skibo OUI that occurs geographically between them. This "leap-frog" change in spider profiles may be related to the origin and/or timing of OUI emplacement along a common fault zone (note that all the N-OUI are linearly-distributed along an inferred fault zone - Plate I).

Troctolitic Rocks

Figures 41 to 59 display spider diagram profiles for troctolitic rocks. Rocks in each of the spider diagrams are grouped according to the rock type present in drill holes for a specific area, e.g., samples of troctolite at Linwood Lake (TRLL) are grouped in one diagram, and samples of augite troctolite at Linwood Lake (AGTLL) are grouped in another diagram. Within each rock type group, all of the profiles are generally the same, e.g., all profiles of TRLL are the same. However, profiles for two different rock types at the same area are often dissimilar, e.g., profiles of TRLL are different from profiles of AGTLL. Likewise, similar rock types (augite troctolite) from two different areas (Linwood Lake versus Section 22) may be the same, similar, or different. Salient features of each of the spider diagram profiles are described below.

<ins>Troctolite - Group #1 (at Section 22 and Skibo)</ins> - The spider diagram profiles in Figure 41a are similar. These profiles are troctolitic rock samples from stratigraphically lower portions of drill holes in the Section 22 and Skibo areas. The Group #1 profiles are markedly different than profiles of other troctolitic rocks collected from stratigraphically higher portions of the same drill holes (Troctolite - Group #2 discussion below). This difference in chemistry with stratigraphic height in the same drill hole was unknown until the spider diagrams were constructed, and two groupings became apparent. Checks of sampled intervals for the two

groupings indicate that the difference in profiles is related to the height of the sample relative to the basal contact. The profiles shown in Figure 41a correspond the "TR-PR#1 geochemical entity" unit on Plate II. Comparison with spider diagram profiles for the lower half of Unit I of the Partridge River intrusion (Severson and Hauck, 1990) indicates a similarity between Unit I and Group #1 (see Fig. 41b for comparison of Unit I to Group #1). This chemical similarity suggests that lower units of the Partridge River intrusion (specifically Unit I) are present as far south as the Skibo area.

<u>Troctolite - Group #2 (at Section 22, Skibo, and Water Hen)</u> - Spider diagram profiles (Fig. 42a) for stratigraphically higher troctolite rock samples at Section 22 and Skibo, and all the troctolite rock samples at Water Hen, regardless of stratigraphic height, are similar to each other. These profiles are markedly different than the Group #1 profiles (compare Figs. 41a and 42a) and thus, because of these differences, the upper troctolite unit is referred to as Group #2. On Plate II, Group #2 corresponds to the "TR-PR#2 geochemical entity" unit. In Figure 42b, the profiles for Group #2 are compared to spider diagram profiles for Unit V of the adjacent Partridge River intrusion (Severson and Hauck, 1990). Both Group #2 and Unit V profiles compare fairly well. This chemical similarity suggests that Unit V of the Partridge River intrusion is present in the upper halves of drill holes at Section 22 and Skibo, and is also present in the entire length of drill holes at Water Hen. Overall, troctolitic rocks from the upper units of the Partridge River intrusion appear to be present as far south as the Water Hen area.

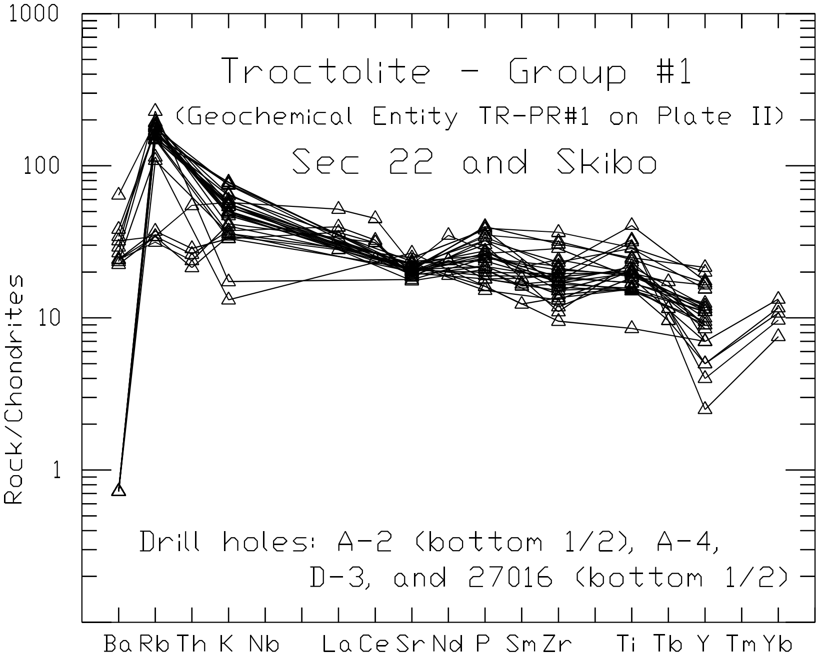


Figure 41a. Spider diagram of the Group #1 troctolite in the Section 22 and Skibo areas. The Group #1 rocks occur below the Group #2 rocks of the same area.

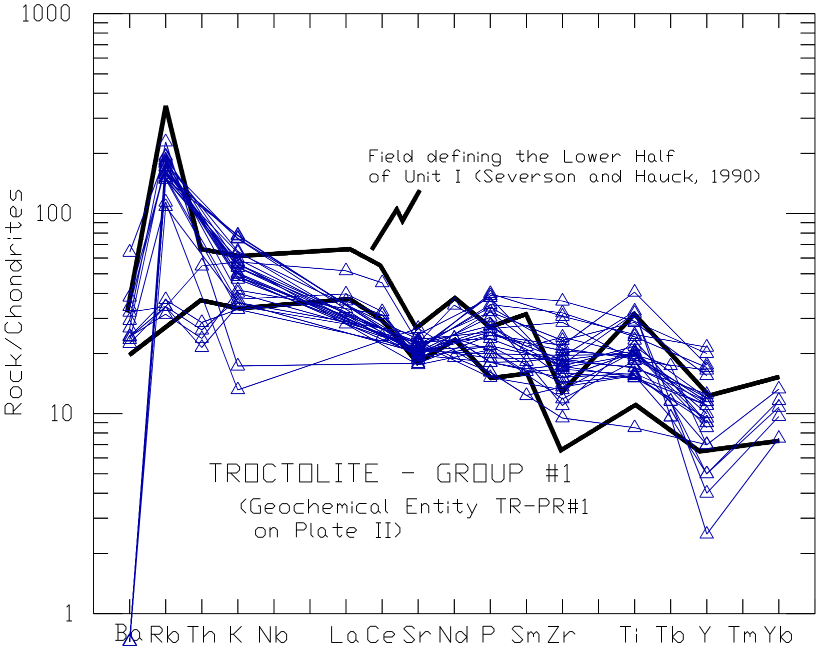


Figure 41b. Comparison of spider diagrams for the Group #1 troctolite (at Section 22 and Skibo) to Unit I in the nearby Partridge River intrusion.

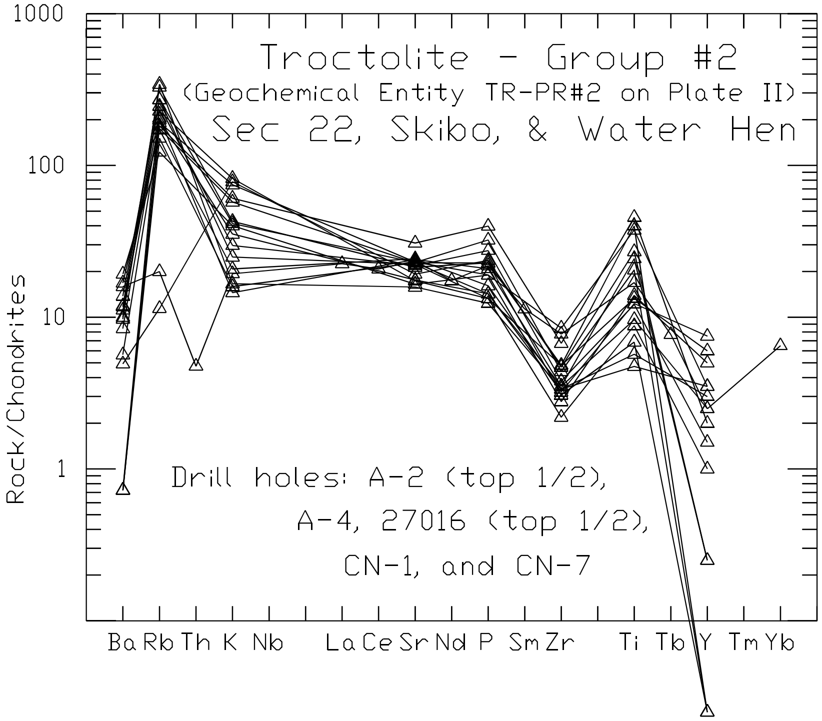


Figure 42a. Spider diagram of the Group #2 troctolite in the Section 22, Skibo, and Water Hen areas. The Group #2 rocks occur higher in the stratigraphy than the Group #1 rocks.

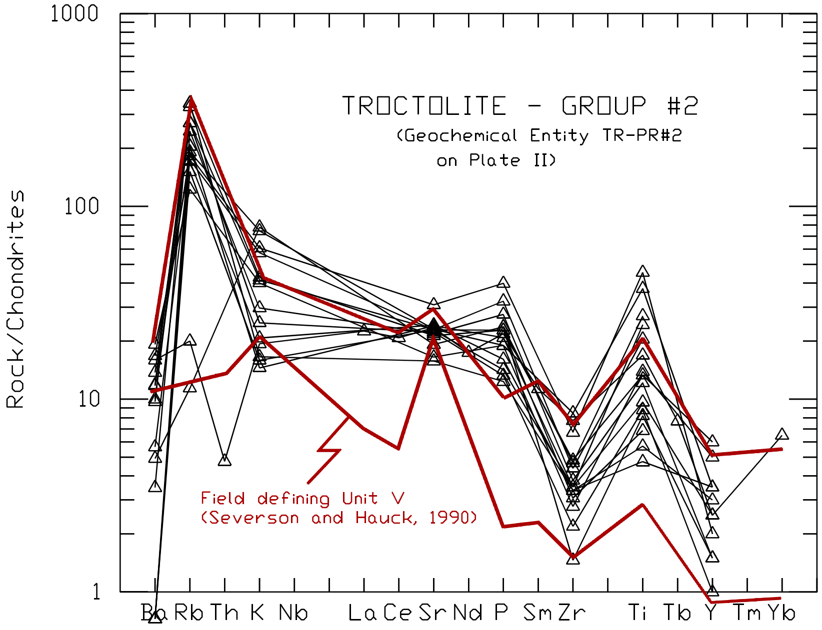


Figure 42b. Comparison of spider diagrams for the Group #2 troctolite (at Section 22, Skibo, and Water Hen) to Unit V in the nearby Partridge River intrusion.

Troctolite - Group #2B (at Section 22, Skibo, and Water Hen) - Profiles with subtle differences relative to the Group #2 profiles are shown in Figure 43 where they are referred to as Troctolite - Group #2B. The Group #2B samples are scattered randomly with the Group #2 samples in drill hole, and therefore, probably represent minor variations in geochemical signature related to local deuteric alteration. Overall, the profiles for both the #2 and #2B groups (compare Figs. 42a and 43) are very similar to each other.

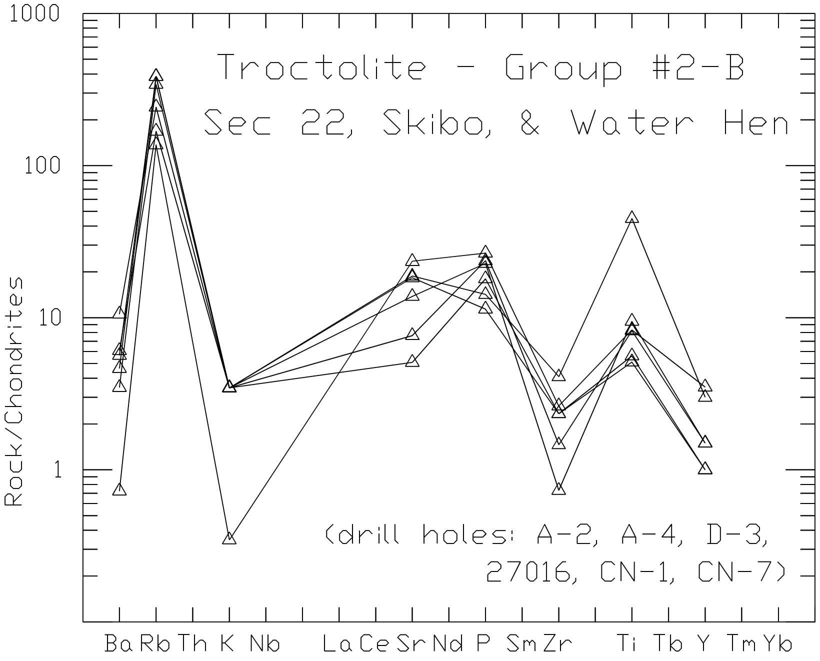


Figure 43. Spider diagram for the Group #2-B troctolite in the Section 22, Skibo, and Water Hen areas. The Group #2-B occurs as a random subset within Group #2.

Augite Troctolite at Section 22 and Skibo - Only six rock samples of augite troctolite are plotted in the spider diagrams for the Section 22 and Skibo areas, Figures 44 and 45 respectively. The profiles in both figures are very similar.

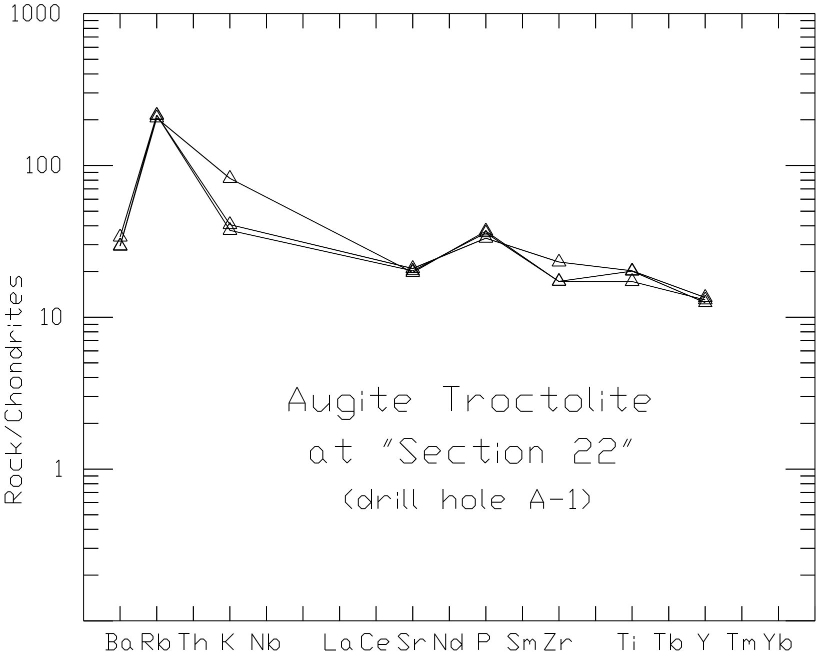


Figure 44. Spider diagram for augite troctolite at the Section 22 area (AGT22).

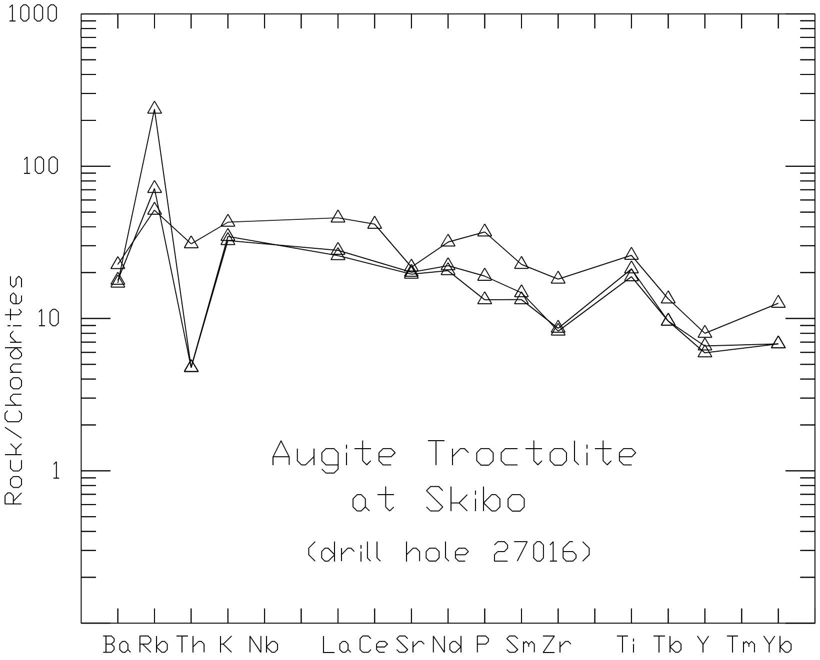


Figure 45. Spider diagram for augite troctolite at the Skibo area (AGTSKIBO).

Troctolitic Rocks at Water Hen - The profiles in Figure 46 for an augite troctolite sample and an anorthositic troctolite sample are similar. They are also similar, with minor variations, to profiles of augite troctolite from the Section 22 and Skibo areas. Note that the profile of the anorthositic troctolite sample in Figure 46 is markedly different from profiles of anorthositic troctolite (Fig. 34) collected from cyclically layered OUI at Water Hen (**Note:** Figs. 46 and 34 contain different amounts of plotted elements that may also account for the markedly different profiles).

Troctolite at Skibo-South - Only one profile of a troctolite collected from the Skibo-South area is plotted in the spider diagram of Figure 47. This profile is **not** similar to the profiles of any of the troctolitic rocks in the South Complex area and may thus represent a hybrid zone.

Troctolite at Whiteface Reservoir - Figure 48 displays the profiles for four samples of sulfide-bearing troctolite and anorthositic troctolite at the Whiteface Reservoir area. All of the profiles are similar regardless of rock type. The profiles at Whiteface do not compare with profiles of any other of the troctolitic rocks in the entire South Complex area. However, they are crudely similar to profiles of two rock types present in the Fish Lake area (TRFL2 and FN2FL, Figs. 54 and 57 respectively).

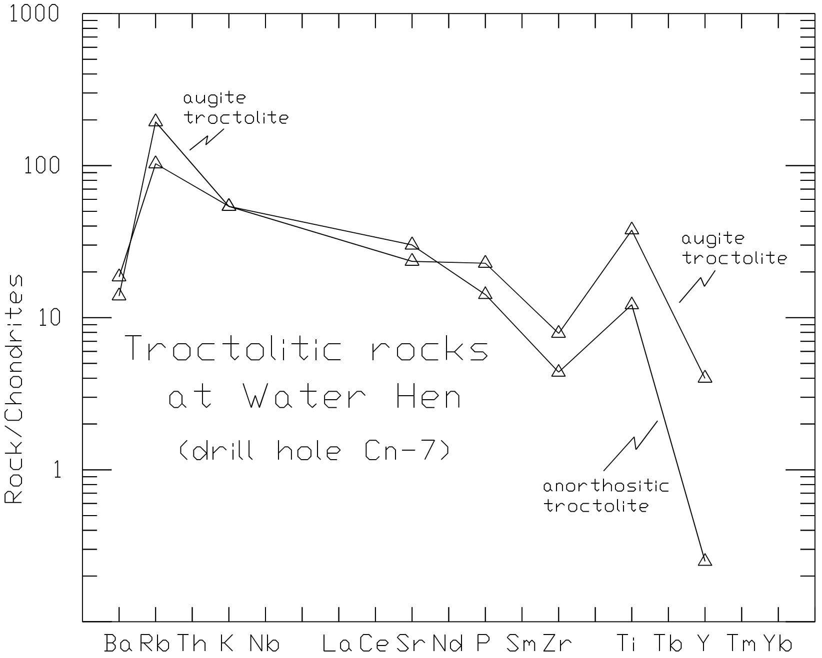


Figure 46. Spider diagram of troctolitic rocks in drill hole CN-7 at the Water Hen area (CN-7).

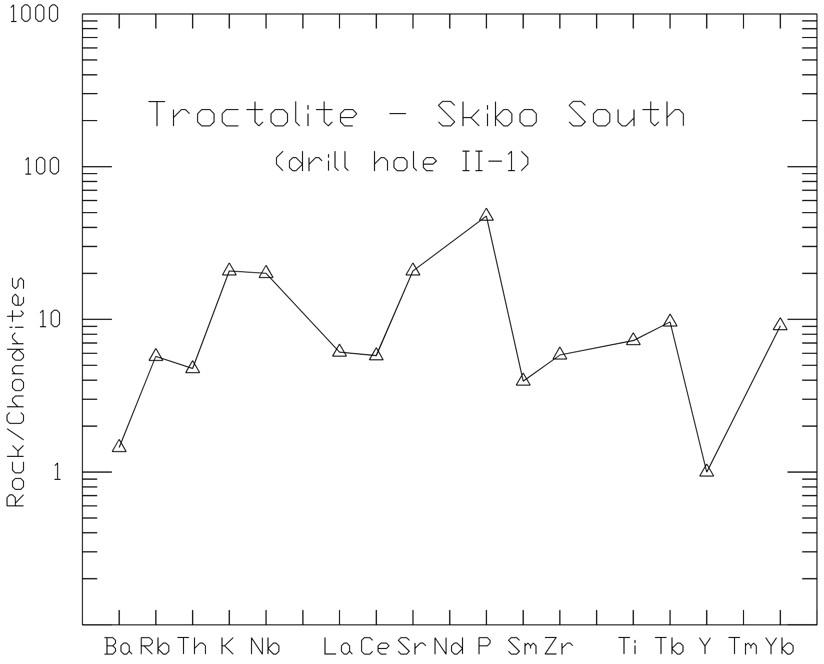


Figure 47. Spider diagram for a troctolite sample from the Skibo South area (TRSKSO).

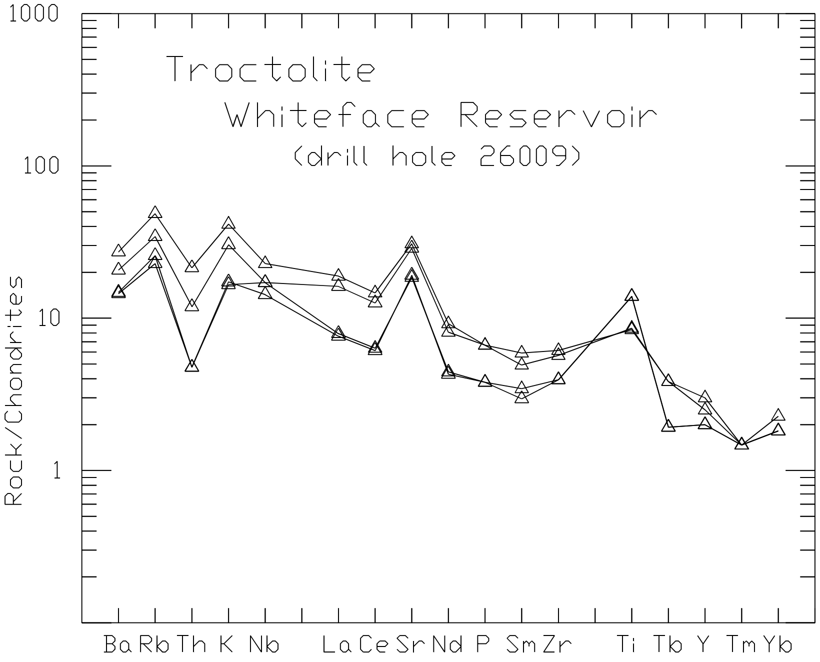


Figure 48. Spider diagram for sulfide-bearing troctolitic rocks at the Whiteface Reservoir area (TRWFR).

Troctolite at Linwood Lake - Spider diagram profiles of troctolite from the Linwood Lake area are shown in Figure 49. The profiles are crudely similar to many other profiles of troctolitic rocks within the South Complex. However, they are not similar to profiles of augite troctolite from the same drill hole (see below).

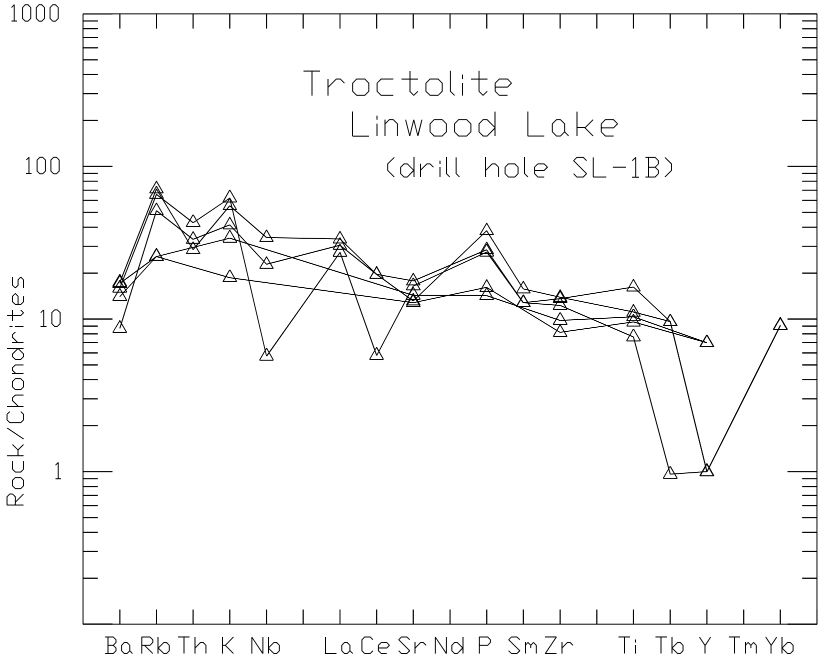


Figure 49. Spider diagram for troctolite in the Linwood Lake area (TRLL).

Augite Troctolite at Linwood Lake - Several profiles of augite troctolite from the Linwood Lake area are displayed in Figure 50. Their profiles are markedly different from profiles of troctolite within the same drill hole (see above). In fact, the profiles for the augite troctolite are unique, and they are only similar to profiles of the FN Unit at Linwood Lake.

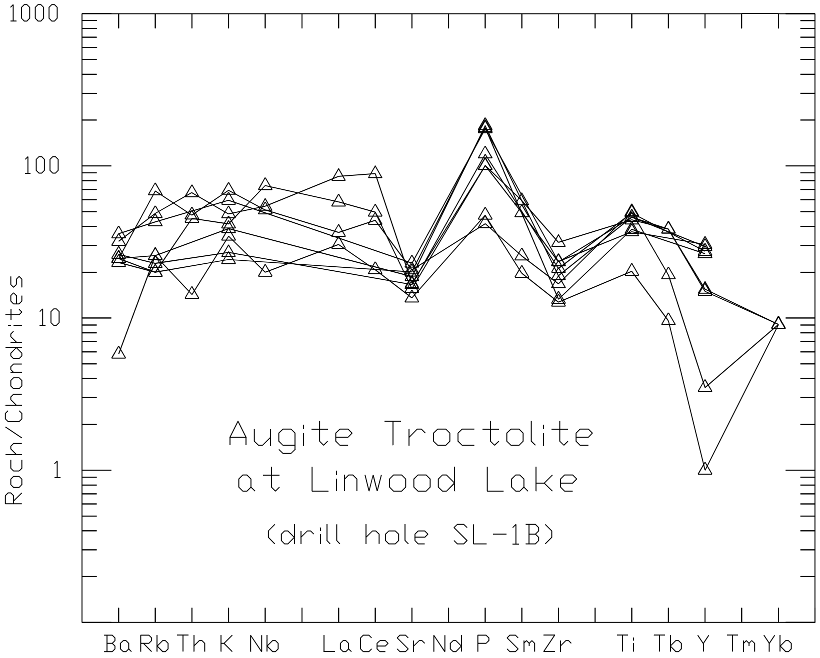


Figure 50. Spider diagram for augite troctolite at Linwood Lake (AGTLL).

<u>FN Unit at Linwood Lake</u> - Profiles of the FN Unit at Linwood Lake are discussed here because they are remarkably similar to profiles of augite troctolite from the same drill hole. This similarity indicates that the FN Unit is a fine-grained equivalent (chilled?) of the augite troctolite present in the same drill hole (see above). The profiles, shown in Figure 51, are all very similar, except for one profile of a medium-grained norite.

<u>Augite Troctolite at Fish Lake</u> - The spider diagram profiles (Fig. 52) for augite troctolite samples at Fish Lake are all the same. Their pattern is the same as profiles of almost all the other troctolite samples within the same drill hole. Profiles of the FN Unit in portions of the same hole are also similar.

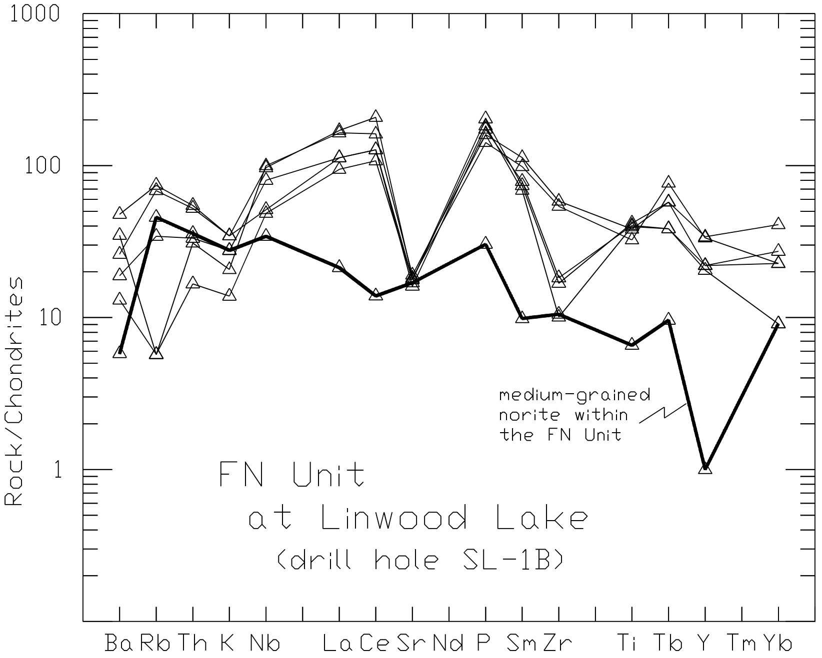


Figure 51. Spider diagram of the FN Unit at Linwood Lake (FNLL). Note that the FN Unit occurs as large inclusions(?) within the augite troctolite at Linwood Lake (Fig. 51).

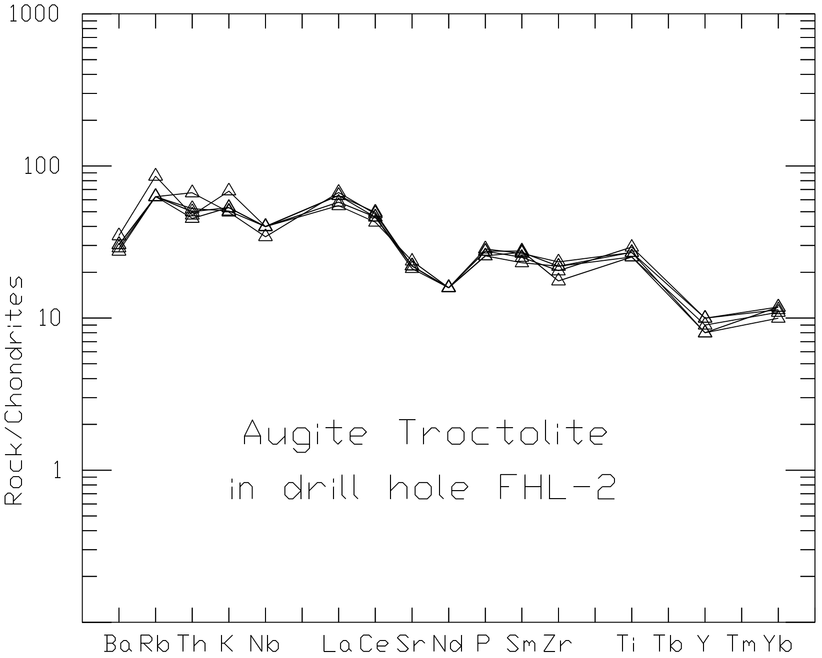


Figure 52. Spider diagram of augite troctolite at Fish Lake (AGTFL).

Troctolite (Group #1) at Fish Lake - Numerous profiles of troctolite samples at Fish Lake are shown in Figure 53. All are very similar, except for a sample of a biotite-rich troctolite. These rocks are very similar to the augite troctolite from the same hole (Fig. 52). Profiles of the FN Unit, in portions of the same hole, are also similar.

Troctolite (Group #2) at Fish Lake - The profiles for three unique troctolite samples at Fish Lake are shown in the spider diagram of Figure 54. When the spider diagrams were first constructed for this investigation, these three samples were signaled out as being markedly different from all the other profiles of troctolitic rocks in the Fish Lake area. The three samples are randomly mixed with the other troctolite samples in drill hole, and no specific distribution pattern can be discerned. Two of the profiles shown in Figure 54 are from strongly altered troctolite. The other profile is not associated with any unique characteristics seen in drill core. Interestingly, this profile pattern is not similar to any other profiles for troctolitic rocks in the South Complex area, **except** for profiles of sulfide-bearing troctolitic rock from the Whiteface Reservoir area **and** profiles for portions of the FN Unit at Fish Lake.

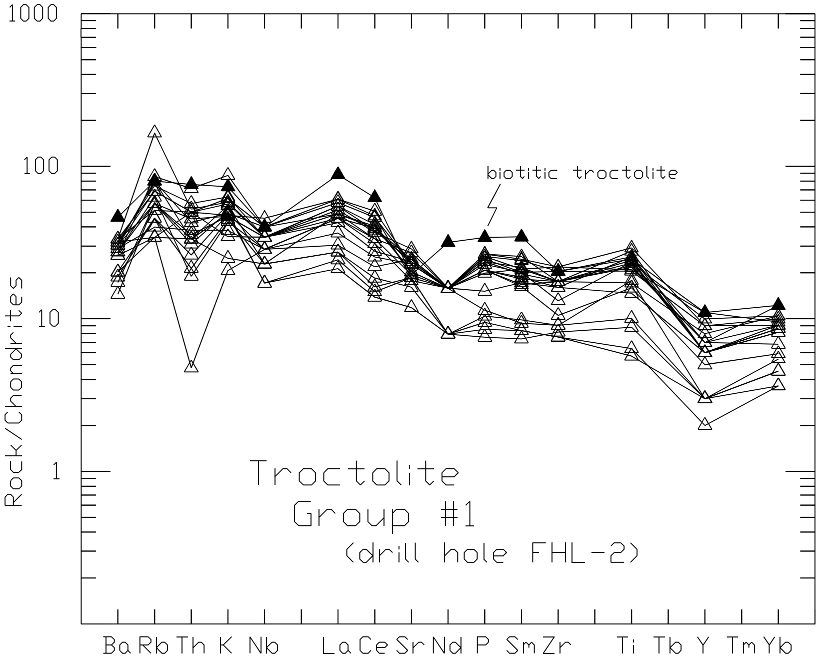


Figure 53. Spider diagram of the Group #1 troctolite at Fish Lake (TRFL1).

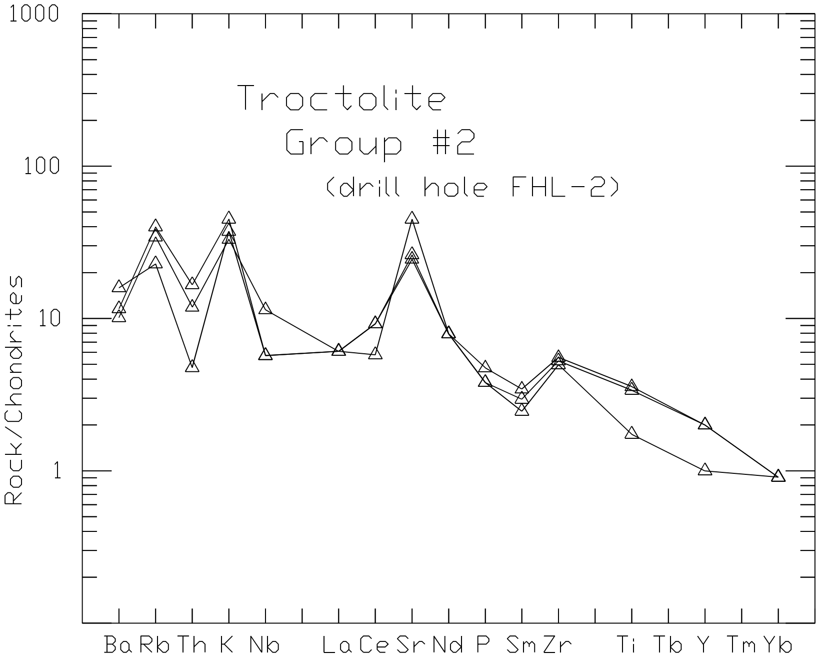


Figure 54. Spider diagram of the Group #2 troctolite at Fish Lake (TRFL2). The Group #2 rocks occur as a random subset within the Group #1 rocks at Fish Lake.

FN Unit at Fish Lake - The FN Unit is present at several different intervals within both drill holes at Fish Lake. All of these intervals look remarkably the same in drill core; however they have at least three different spider diagram profiles (Figs. 55 to 57). For this reason, the FN Unit shown in the cross-section at Fish Lake (Fig. 26) is broken-down into three categories: FN#1, FN#1A, and FN#2. Both FN#1 and FN#1A exhibit very similar spider diagram profiles, except that FN#1A profiles have strong peaks for K and P (compare Figs. 55 and 56). In drill core, both of these units occur near the basal contact, but FN#1A is present as a thick sequence with 5%-10% biotite, whereas FN#1 is present as smaller, biotite-poor inclusions within augite troctolite. Since both the FN#1 and FN#1A profiles are similar, and they plot within the same field on X-Y scatter diagrams (to be discussed below), they will hereafter be lumped together as the FN#1 Unit. The FN#1 Unit (including FN#1A) exhibits the same spider profiles as medium-grained troctolitic rocks in the same drill hole. This situation indicates that the lower FN Units at Fish Lake are fine-grained equivalents (chilled?) of the troctolitic rocks.

The FN#2 Unit exhibits markedly different profiles (Fig. 57) than the FN#1 Unit. Though both the FN#1 and FN#2 units look the same in drill core, the FN#2 is present as inclusions higher up in the igneous stratigraphy (near the top of FHL-2). The FN#2 Unit, interestingly enough, displays the same spider profile as the three unique troctolite samples of the Troctolite (Group #2) at Fish Lake (Fig. 54).

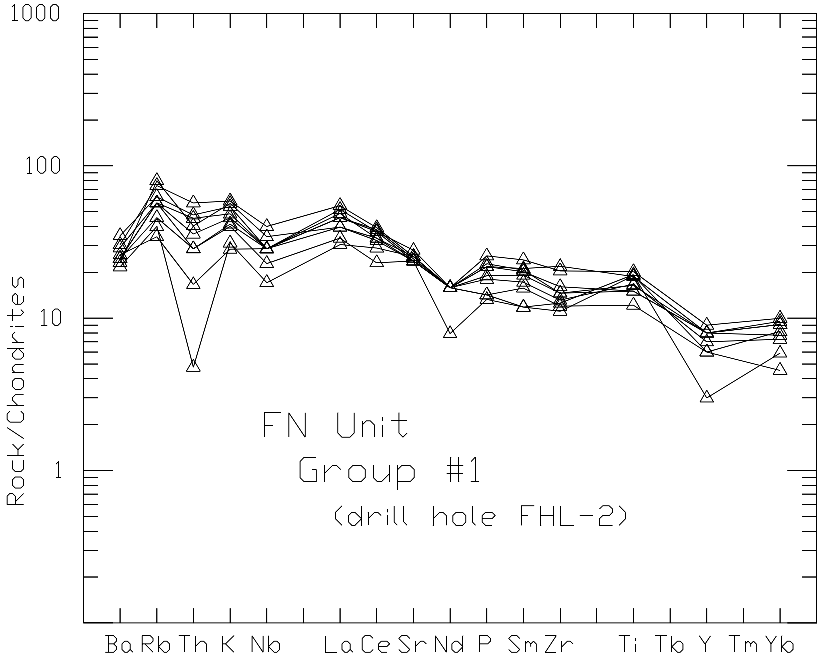


Figure 55. Spider diagram of the FN#1 Unit at Fish Lake (FN1FL). Both FN#1 and FN#1A (next figure) exhibit similar chemistry except for K and P; both also occur near the bottom of drill hole FHL-2.

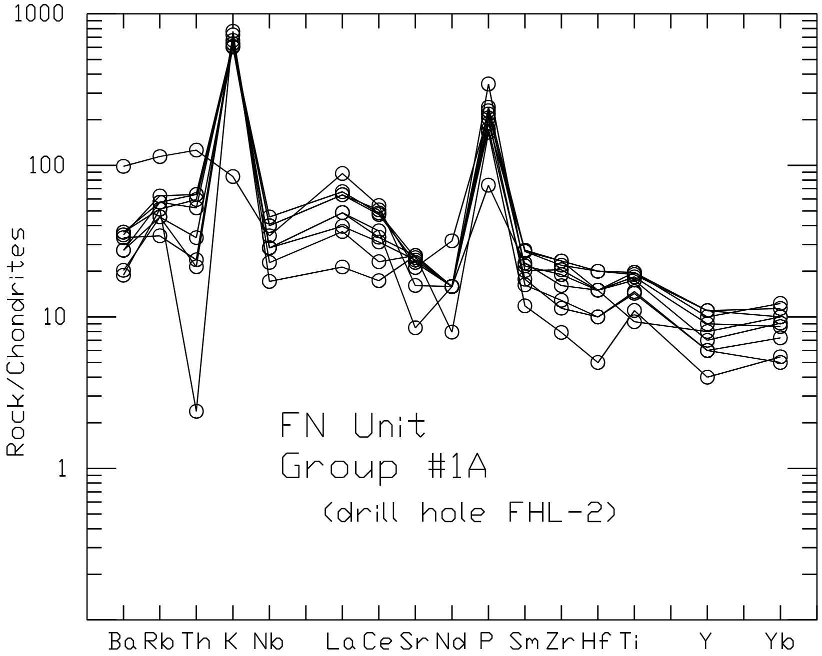


Figure 56. Spider diagram of the FN#1A Unit at Fish Lake. This unit is very similar to FN#1 shown in Fig. 54; hereafter, both FN#1 and FN#1A are lumped together as FN#1.

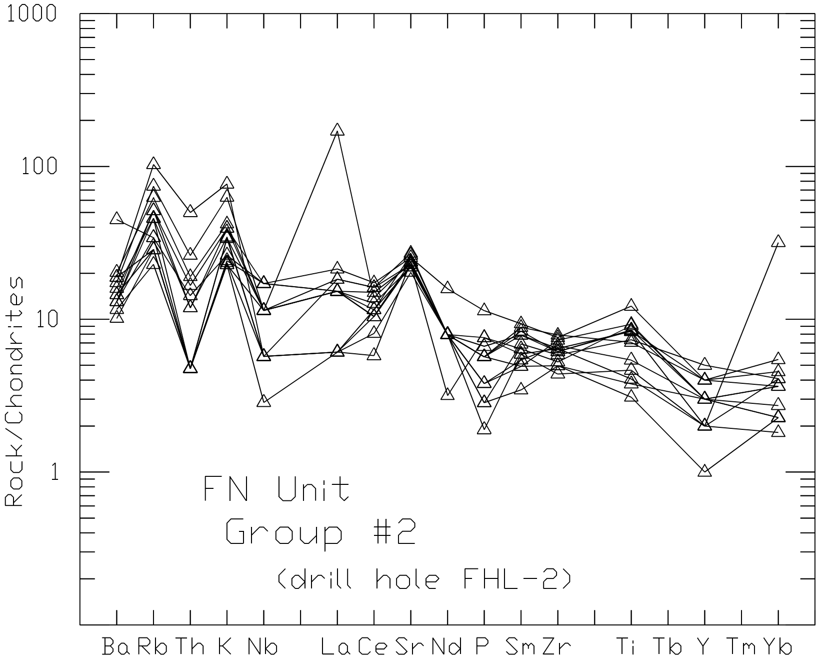


Figure 57. Spider diagram of the FN#2 Unit at Fish Lake (FN2FL). The FN#2 Unit occurs higher in drill hole FHL-2 than the FN#1 Unit.

<u>Layered Oxide Gabbro (LOG) Unit at Boulder Lake North</u> - Figure 58 displays the spider diagram profiles for three samples collected from the Layered Oxide Gabbro (LOG) Unit at Boulder Lake North. The profiles for all three different rock types are somewhat similar, with major differences in the amounts of Sr and P. The profiles for the LOG are not similar to any other troctolitic profiles in the South Complex area. The LOG may be similar to Unit G of Nathan's Layered Series along the Gunflint Trail, but no geochemical comparisons can be made at this time.

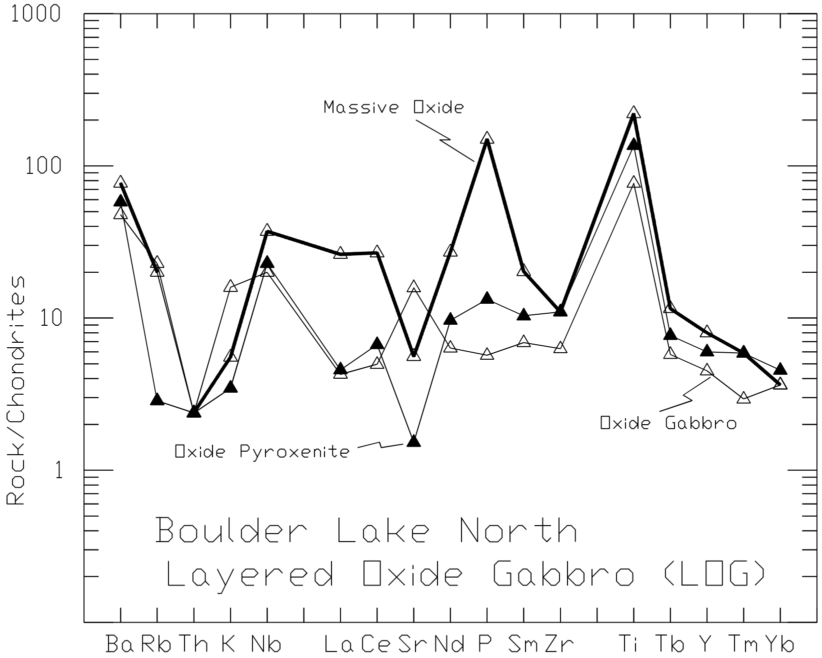


Figure 58. Spider diagram of three rock types within the Layered Oxide Gabbro (LOG) Unit at Boulder Lake North.

As mentioned previously, the spider diagram profiles for some of the troctolitic units are similar, and some profiles are different. Instead of verbally describing the comparisons between individual profiles, the comparisons are illustrated in Table 6. While it would be time consuming to go over each comparison, a few general observations pertaining to "what rock type compares to what rock type," and their implications, follow:

1. Almost all troctolite profiles are similar regardless of geographic location. Within this group, troctolite units at the northern end of the study area are geochemically similar to troctolite units within the adjacent Partridge River intrusion. This comparison includes the lowest troctolite unit at Section 22 and Skibo (Troctolite - Group #1) that is very similar to the Lower Half of Unit I of the PRTS, and the upper troctolite unit at Section 22, Skibo, and Water Hen (Troctolite - Group #2) that is similar to Unit V of the PRTS.

2. Geochemistry of augite troctolite rock types is similar regardless of geographic location. Profiles for Augite Troctolite at Linwood Lake (AGTLL in Table 6) are unique because their profiles are not similar to any other augite troctolite profiles, except for a vague similarity to Augite Troctolite at Fish Lake (AGTFL in Table 6).

Table 6. Spider diagram comparisons for troctolitic rocks of the South Complex area.

	TRPR1	TRPR2	TRPR2B	AGT22	AGTSKIBO	TRSKSO	CN-7	TRWFR	TRLL	AGTLL	FNLL	AGTFL	TRFL1	TRFL2	FN1FL	FN2FL
TRPR1		-	X	=	=	X	=	X	=	X	X	-	=	X	=	X
TRPR2	-		-	-	=	X	=	X	-	X	X	X	-	X	-	X
TRPR2B	X	-		X	X	X	-	X	X	X	X	X	X	X	X	X
AGT22	=	-	X		-	X	-	X	-	X	X	=	-	X	-	X
AGTSKIBO	=	=	X	-		X	=	X	-	X	X	-	-	X	=	X
TRSKSO	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
CN-7	=	=	-	-	=	X		X	-	X	X	X	-	X	-	X
TRWFR	X	X	X	X	X	X	X		X	X	X	X	X	-	X	-
TRLL	=	-	X	-	-	X	-	X		X	X	X	-	X	-	X
AGTLL	X	X	X	X	X	X	X	X	X		=	-	X	X	X	X
FNLL	X	X	X	X	X	X	X	X	X	=		X	X	X	X	X
AGTFL	-	X	X	=	-	X	X	X	X	-	X		=	X	=	X
TRFL1	=	-	X	-	-	X	-	X	-	X	X	=		X	=	X
TRFL2	X	X	X	X	X	X	X	-	X	X	X	X	X		X	-
FN1FL	=	-	X	-	=	X	-	X	-	X	X	=	=	X		X
FN2FL	X	X	X	X	X	X	X	-	X	X	X	X	X	-	X	

Symbols:

= Spider patterns are the same
- " " " similar
X " " " not similar

Rock Unit Abbrev. (by geographic locations):

TRPR1 - Troctolite (Group #1) at Sec. 22, and Skibo (presumably correlative with Unit I of the PRTS)
TRPR2 - Troctolite (Group #2) at Sec. 22, Skibo, and Water Hen areas (presumably correlative with Unit V of the PRTS)
TRPR2B - Troctolite Subgroup within TRPR2 Group
AGT22 - Augite Troctolite at Sec. 22
AGTSKIBO - Augite Troctolite at Skibo
TRSKSO - Troctolite at Skibo-South
CN-7 - Troctolitic rocks in drill hole CN-7 (Water Hen)
TRWFR - Troctolite at Whiteface Reservoir
TRLL - Troctolite at Linwood Lake
AGTLL - Augite Troctolite at Linwood Lake
FNLL - FN Unit at Linwood Lake
AGTFL - Augite Troctolite at Fish Lake
TRFL1 - Troctolite (Group #1) at Fish Lake
TRFL2 - Troctolite (Group #2) at Fish Lake
FN1FL - FN Unit (Group #1) at Fish Lake
FN2FL - FN Unit (Group #2) at Fish Lake

3. The only rock units that do not compare with any other rock units, or with very few other rock units, are: Troctolite - Group #2B (TRPR2B); Troctolite at Skibo-South (TRSKSO); Troctolite at Whiteface Reservoir (TRWFR); Augite Troctolite at Linwood Lake

(AGTLL); and Troctolite (Group #2) at Fish Lake (TRFL2). The TRPR2B and TRFL2 represent minor and random variations present at a local scale that are related to deuteric alteration (in both cases they represent random samples scattered within a larger unit). The TRSKSO and TRWFR profiles may also be related to local deuteric alteration; however, this is difficult to access based on one sample from each respective area. The AGTLL is the most unique, and it is defined by many samples collected over a continuous interval in a single drill hole. These profiles are not a random set within a larger group (as the other units that can be explained by local changes due to deuteric alteration).

4. The Layered Oxide Gabbro (LOG) Unit at Boulder Lake North exhibits a profile that does not compare to any other profiles within the South Complex area (**Note:** The LOG Unit is not listed in Table 6). It may be similar in origin with Unit G of Nathan's Layered Series.

FN Unit

The FN Unit at Linwood Lake and Fish Lake (three different FN Units) have been described previously (Figs. 51, 55-57, respectively). Comparison of different FN Units to each other, and to other troctolitic rocks, is also listed in Table 6. The FN Units do not compare to each other. However, the FN Units do have similar geochemistry when compared to medium- to coarse-grained troctolitic rocks with which they are associated. This comparison indicates that the FN Units are not basalt inclusions, as they seem to be when first observed in drill core, but rather, are fine-grained and chilled(?) equivalents of intrusive troctolitic rocks.

Layered Ultramafic Rocks

Complete geochemical analyses are available for only six samples of picrite and peridotite layers within the South Complex area. These samples are from: Harris Lake (one sample); Linwood Lake (two samples); and Fish Lake (three samples). Geochemically, they can be grouped into two sets (Figs. 59 and 60). However, the groupings cannot be resolved geographically. For example, out of the three picrite layers in drill hole FHL-2, two layers have similar profiles (Fig. 60), and one profile is dissimilar (Fig. 59). Similarly, the FHL-2 profile (Fig. 59) is similar to two picrite layers at Linwood Lake. Lastly, the peridotite layer at Harris Lake is somewhat similar to both groups (Figs. 59 and 60). When compared to the troctolitic rocks of the South Complex, the ultramafic layers are much flatter and show an overall depletion.

SL-19A

The spider diagram for the chromium-bearing semi-massive oxide horizon in drill hole SL-19A at Water Hen is shown in Figure 61. This profile does not compare with profiles for any other rock type within the South Complex area.

Thomson Formation

The spider diagram for the Thomson Formation samples in the Fish Lake area is shown in Figure 62a. Material sampled at Fish Lake includes: cordieritic argillite close to the basal contact; the DISRUPTED unit, with some zones of the RXTAL unit; and highly folded argillite sequences. Most of the profiles are similar, regardless of the type of sampled material (Fig. 62a). The anomalous profiles are probably related to small unique interbeds present within the sampled interval. For example, note the different profile associated with a sampled interval that contains a 3 inch thick calc-silicate bed.

Figure 62b compares Thomson Formation at Fish Lake to Virginia Formation in proximity to the Partridge River intrusion (from Severson and Hauck, 1990 - the sampled Virginia Formation also includes cordieritic, RXTAL, and DISRUPTED varieties). The Thomson and Virginia Formations patterns are almost identical (**Note:** The Nb concentration is not known for profiles of the Virginia Formation).

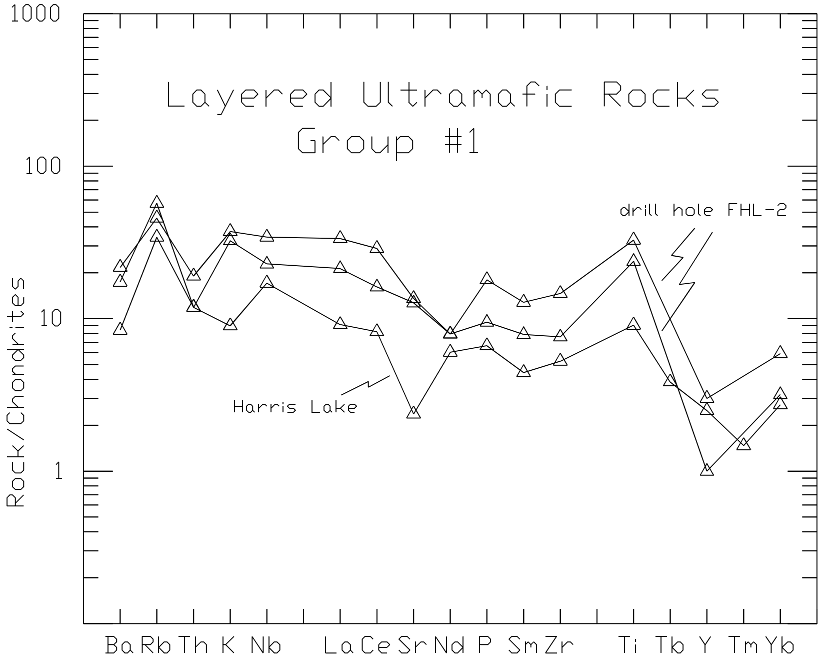


Figure 59. Spider diagram of the Group #1 ultramafic rock layers (picrite and peridotite) within the South Complex area.

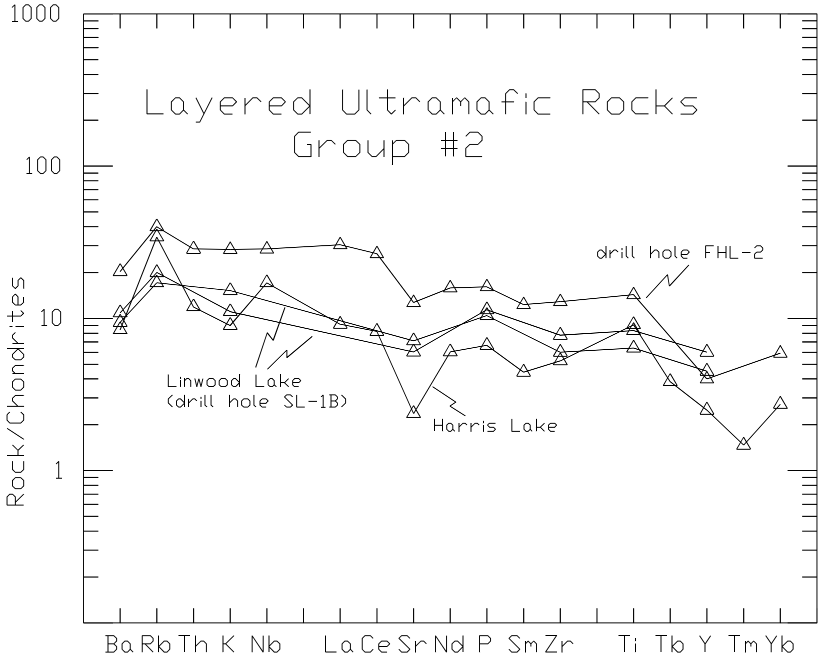


Figure 60. Spider diagram of the Group #2 ultramafic rock layers (picrite and peridotite) within the South Complex area.

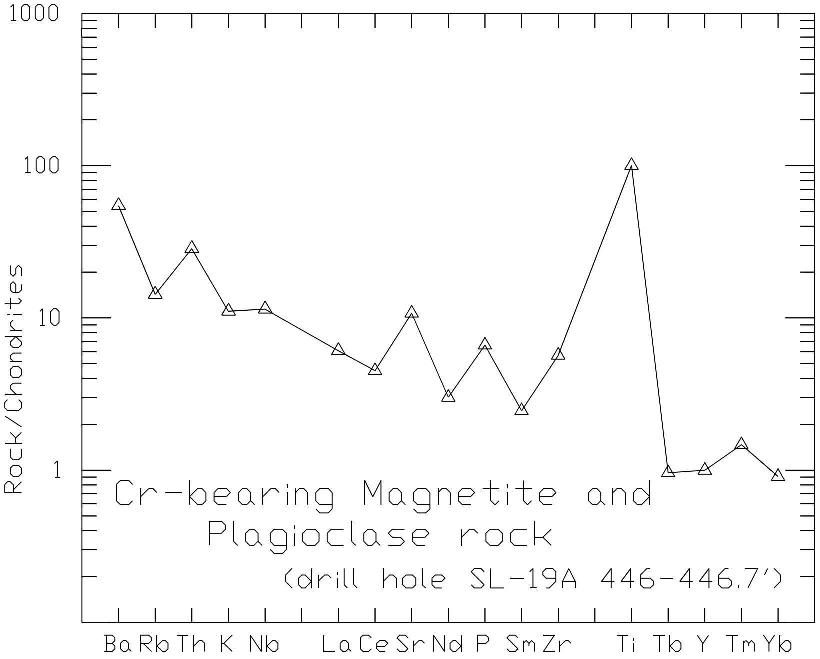


Figure 61. Spider diagram of a semi-massive oxide zone, with "2-in-1" texture, in drill hole SL-19A at Water Hen.

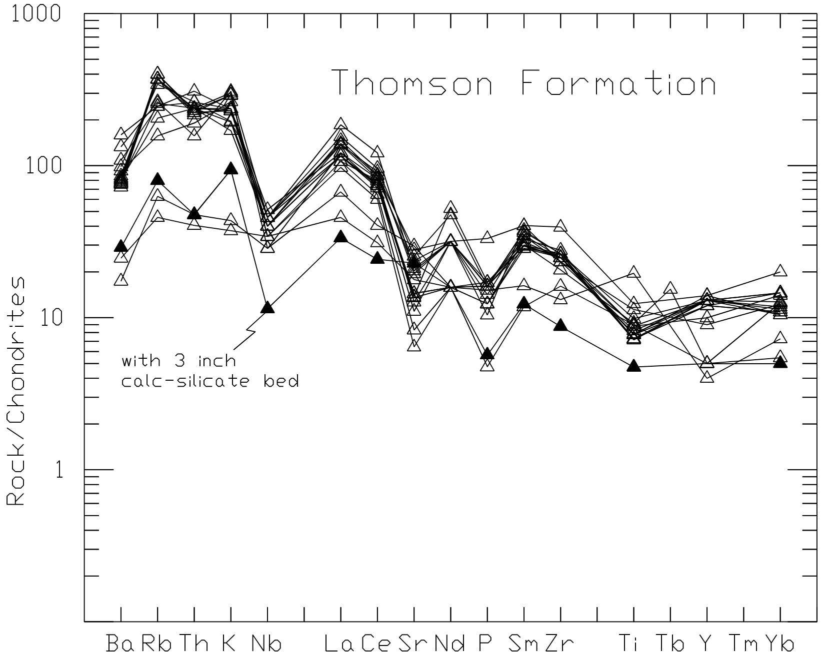


Figure 62a. Spider diagram of the Thomson Formation in the Fish Lake area.

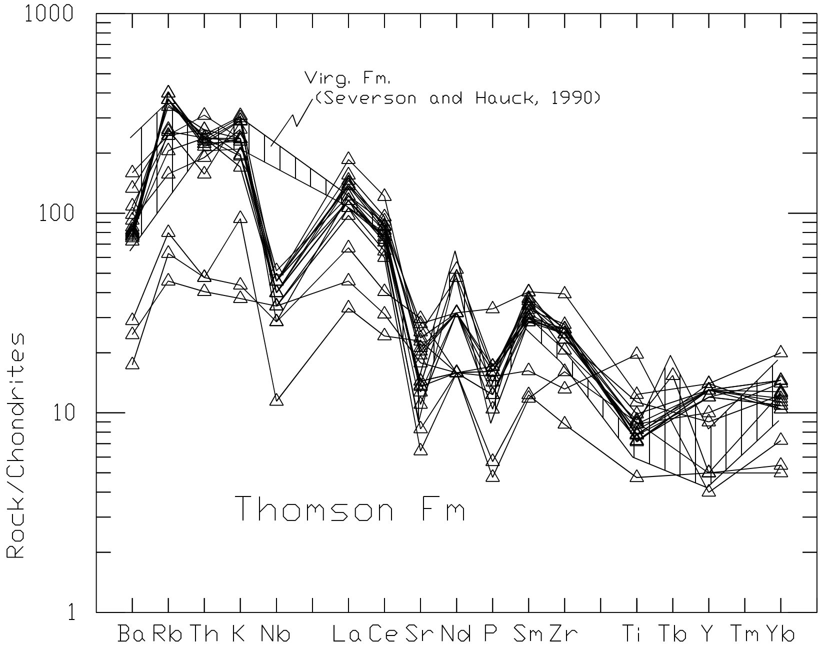


Figure 62b. Comparison of spider diagram profiles of the Thomson Formation to the Virginia Formation.

Bear Lake Inclusion

The magnetic basalt patterns from the Bear Lake Inclusion (drill hole BL-1; Fig. 63a) are essentially the same, but with minor K and Rb differences. Outcrop and drill core samples from Bear Lake Inclusion are similar to outcrops of the Colvin Creek Inclusion and to drill core of the "INCL" unit within the South Kawishiwi intrusion (Severson, 1994). All three are compared to each other in Figures 63b and 63c.

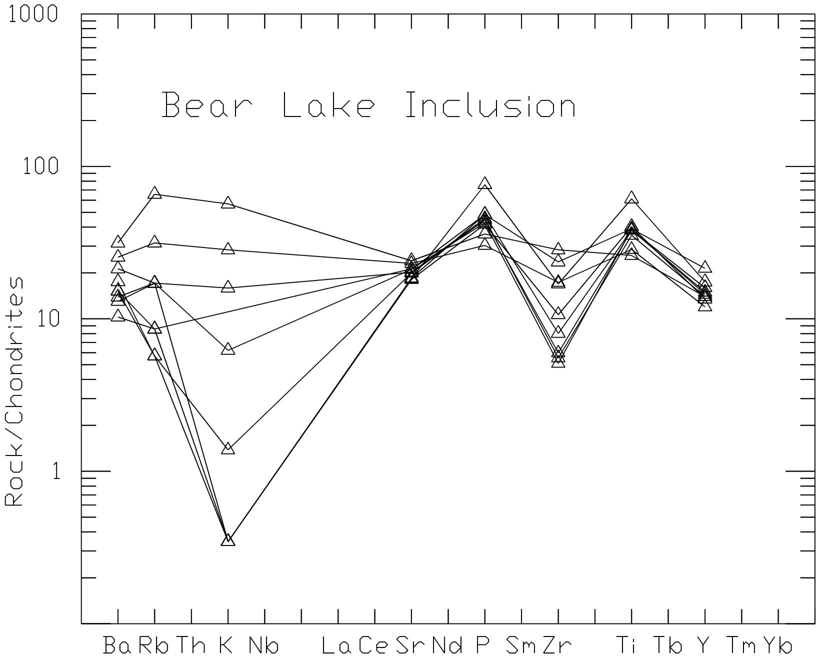


Figure 63a. Spider diagram of magnetic basalt of the Bear Lake Inclusion.

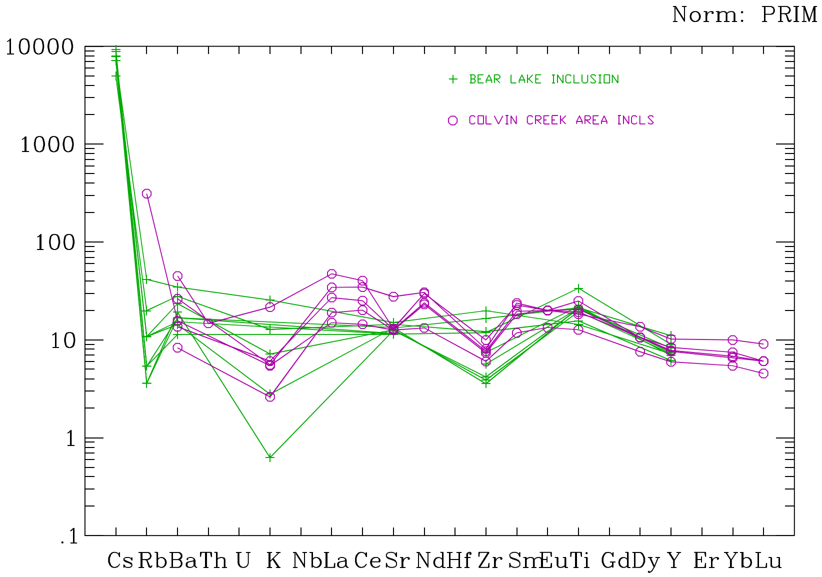


Figure 63b. Comparison of spider diagram profiles for magnetic basalt in the Bear Lake and Colvin Creek Inclusions (diagram made with NewPet).

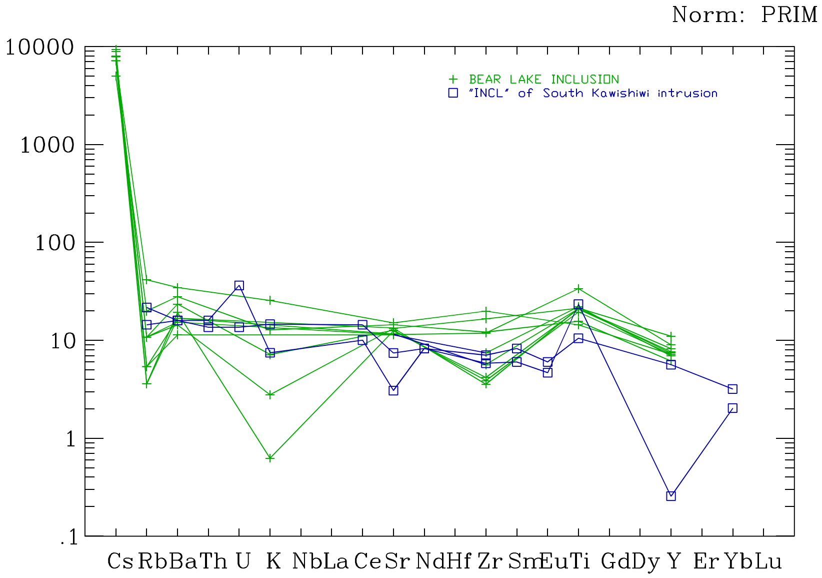


Figure 63c. Comparison of spider diagram profiles for magnetic basalt in the Bear Lake Inclusion versus the "INCL" Unit of the Highway 1 Inclusion of the South Kawishiwi intrusion (Severson, 1994).

X-Y SCATTER PLOTS

X-Y scatter plots for some of the major rock units of the South Complex area are presented in Figures 64 to 72. A plot of MG Number versus Al_2O_3 is shown for all rock types in Figure 64. Plots of MgO versus various whole rock values are presented in odd-numbered figures for the OUIs, and the even-numbered figures for the other troctolitic rock units. These diagrams illustrate that the OUIs are clearly geochemically different than the troctolitic rocks. Because the Layered Oxide Gabbro (LOG) Unit at Boulder Lake North and the semi-massive oxide rocks in SL-19A (Water Hen) are also oxide rich, they are included with the oxide-rich OUIs, rather than with the troctolitic rocks. All of the plots are constructed using IGPET II (Carr, 1987), which normalizes the major oxides to 100% on a water free basis; trace element values are not normalized. Geochemical data used to construct these plots are included in the SCSORT.WK1 data file (back pocket of this report).

In each of the OUI X-Y scatter plots, the various rock types within the OUI plot as distinct fields, e.g., peridotite versus pyroxenite. Not only can the OUIs be distinguished, but in some cases the **same** rock type for two geographically different OUI bodies plots in **two** different portions of the field that defines that rock type. Examples of these include picrite at Water Hen versus picrite at Section 22, and pyroxenite at Water Hen versus pyroxenite at Section 34. (These are discussed in more detail later.)

Several groupings of specific troctolitic rock types are also present on Figures 66, 68, 70, and 72. The FN Unit generally clusters in three different and distinct fields that correspond to the geographic area where they occur (Linwood Lake versus Fish Lake) and to stratigraphic position within a single drill hole (Fish Lake - FN#1 versus Fn#2). Even though the FN Units exhibit features similar to basalt inclusions in drill core, none of the FN Unit fields shows any overlap with the basalt inclusion from the Boulder Lake South area (geochemistry from Bonnichsen, 1972). Similarly, the magnetic basalt of the Bear Lake Inclusion has a distinct field from both the FN Units and the basalt inclusion. A brief description of the salient features in each of the X-Y scatter plots is presented below.

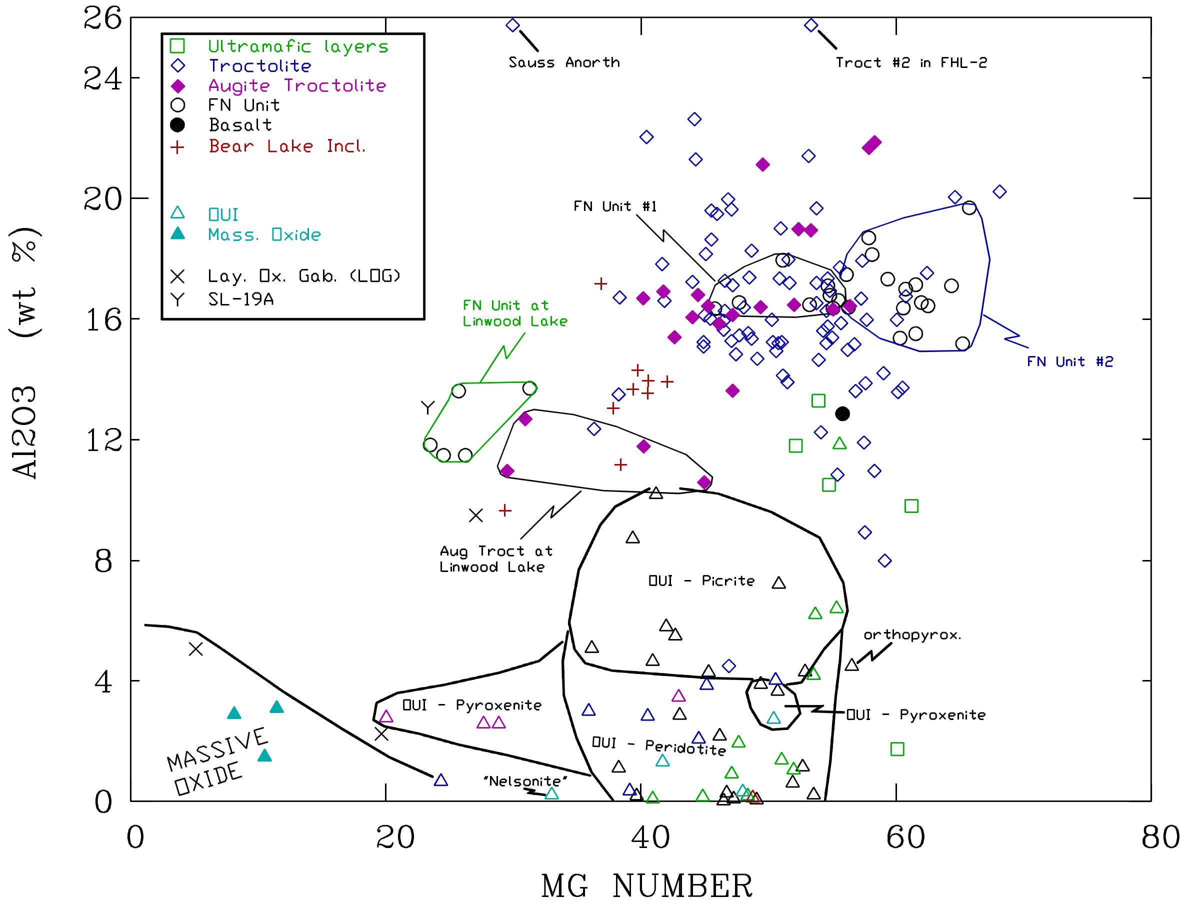


Figure 64. MG Number versus Al_2O_3.

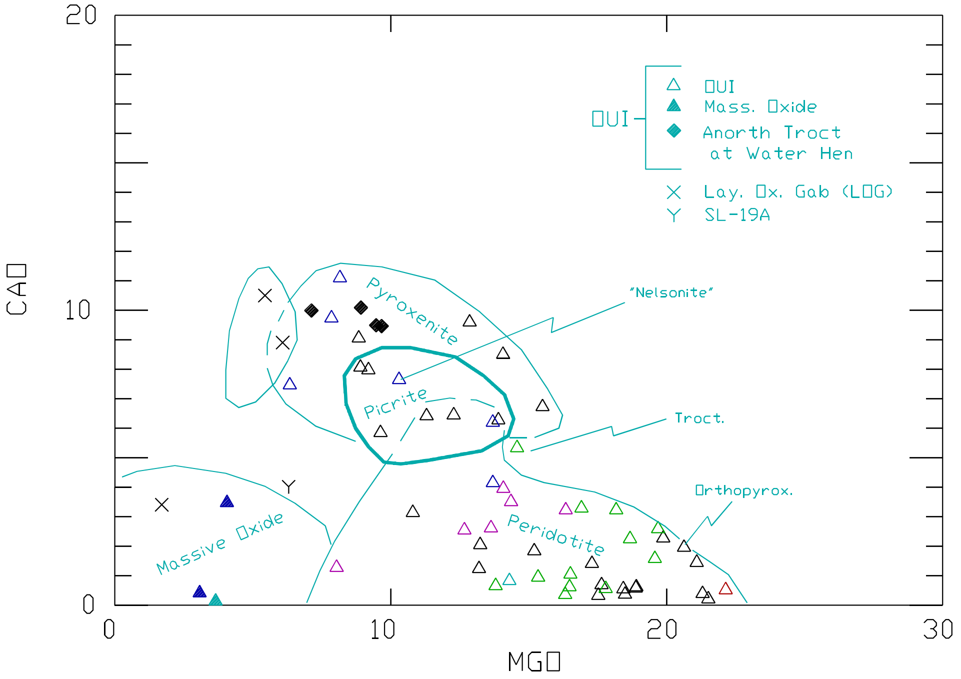


Figure 65. MgO versus CaO for the OUI of the South Complex area.

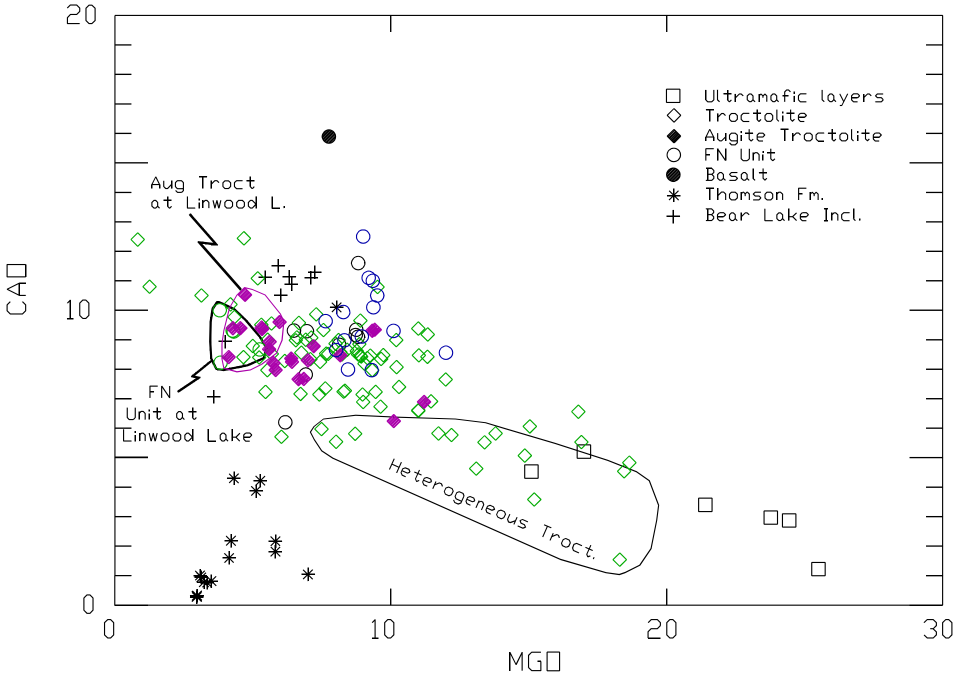


Figure 66. MgO versus CaO for troctolitic rocks of the South Complex area.

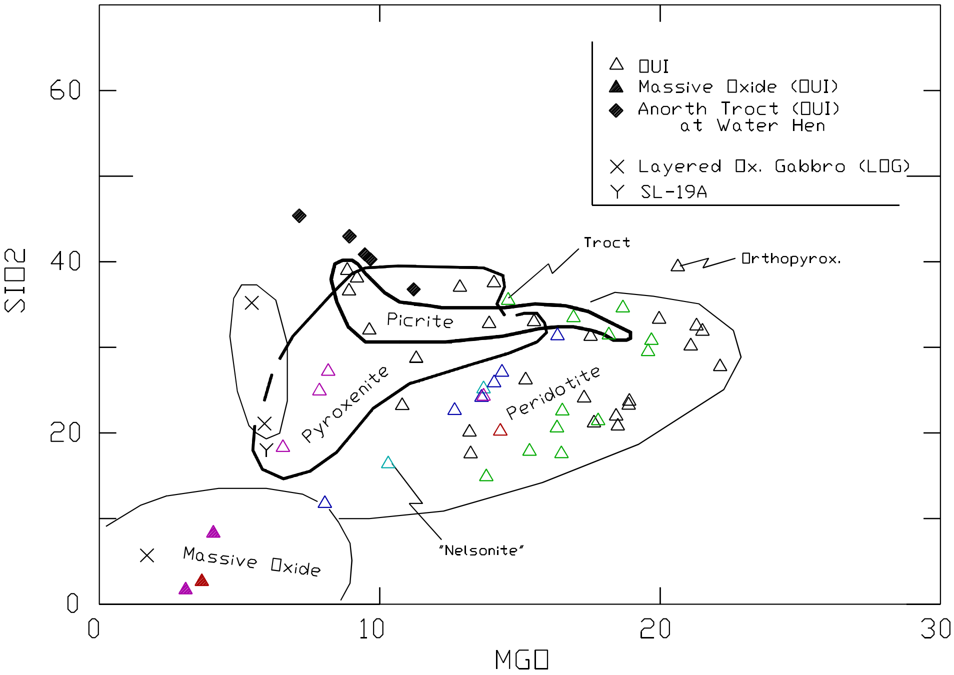


Figure 67. MgO versus SiO_2 for OUI in the South Complex area.

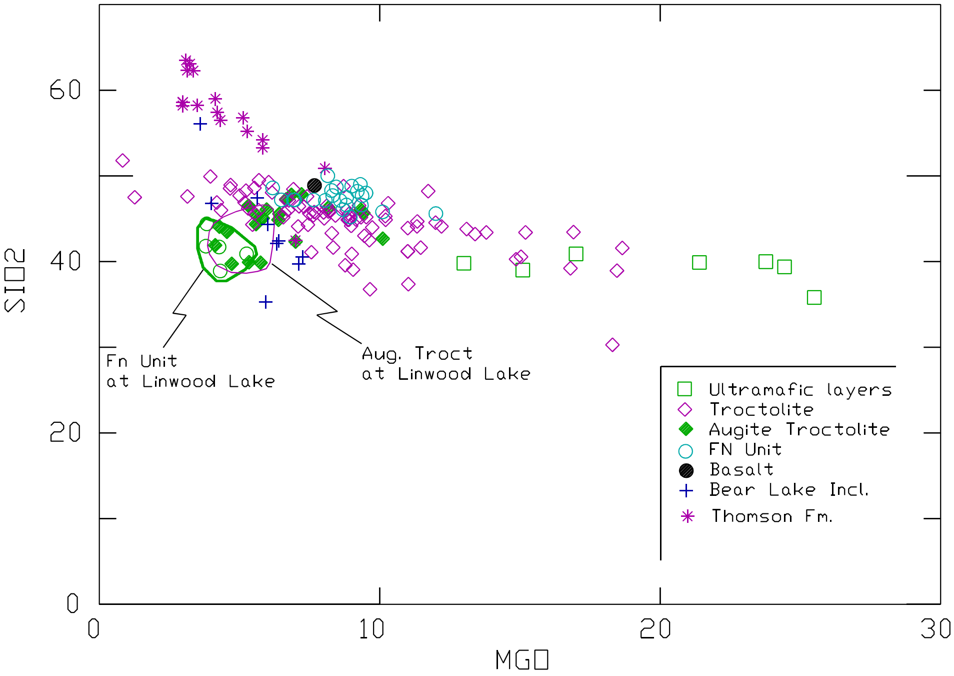


Figure 68. MgO versus SiO_2 for troctolitic rocks in the South Complex area.

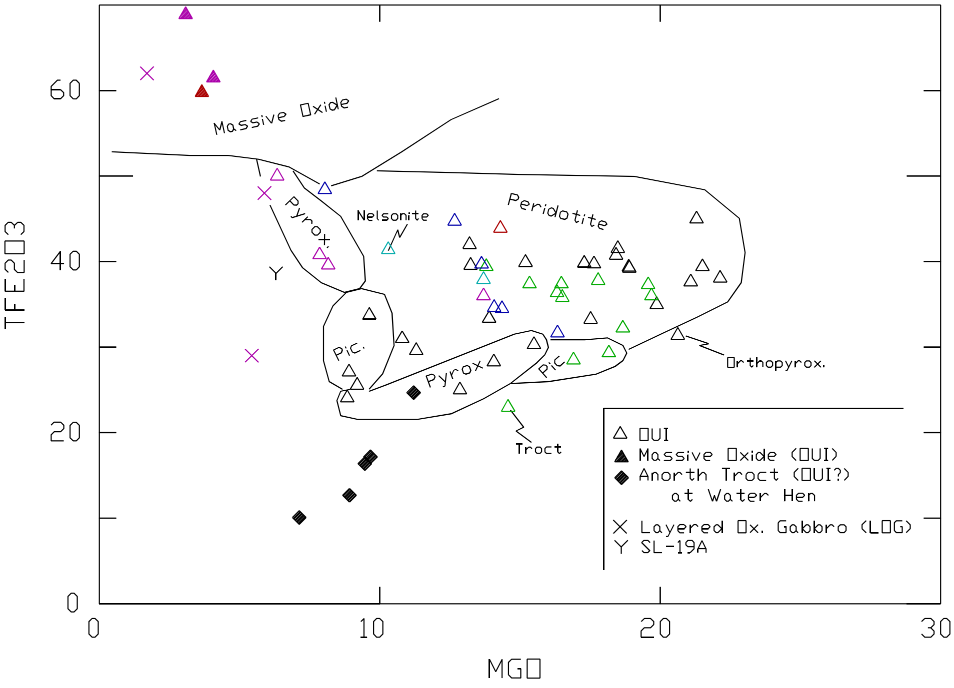


Figure 69. MgO versus total iron (as Fe_2O_3) for OUIs in the South Complex area.

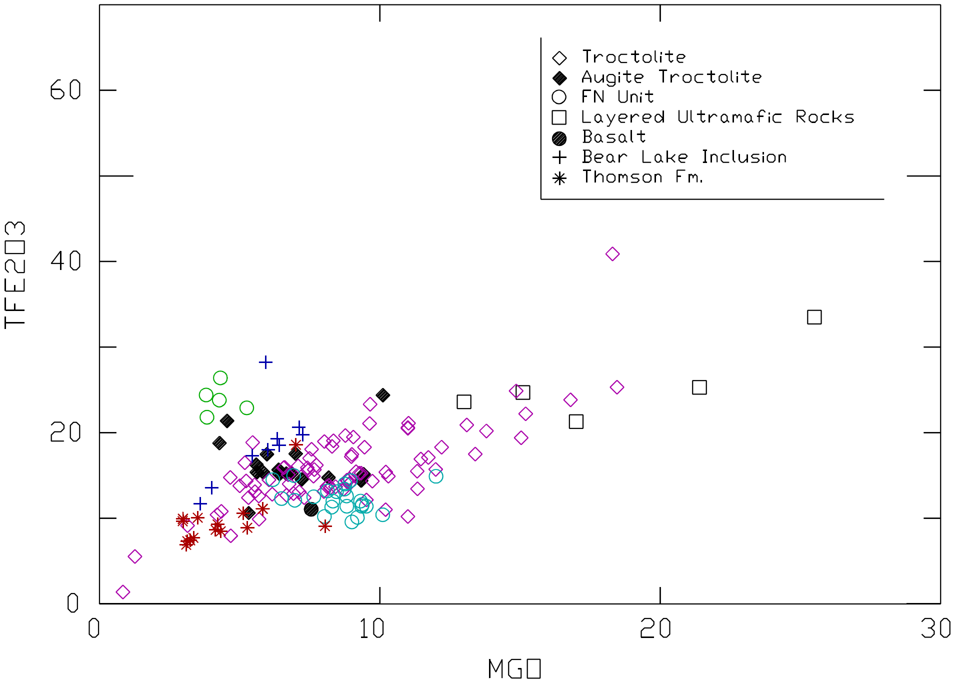


Figure 70. MgO versus total iron (as Fe_2O_3) for troctolitic rocks in the South Complex area.

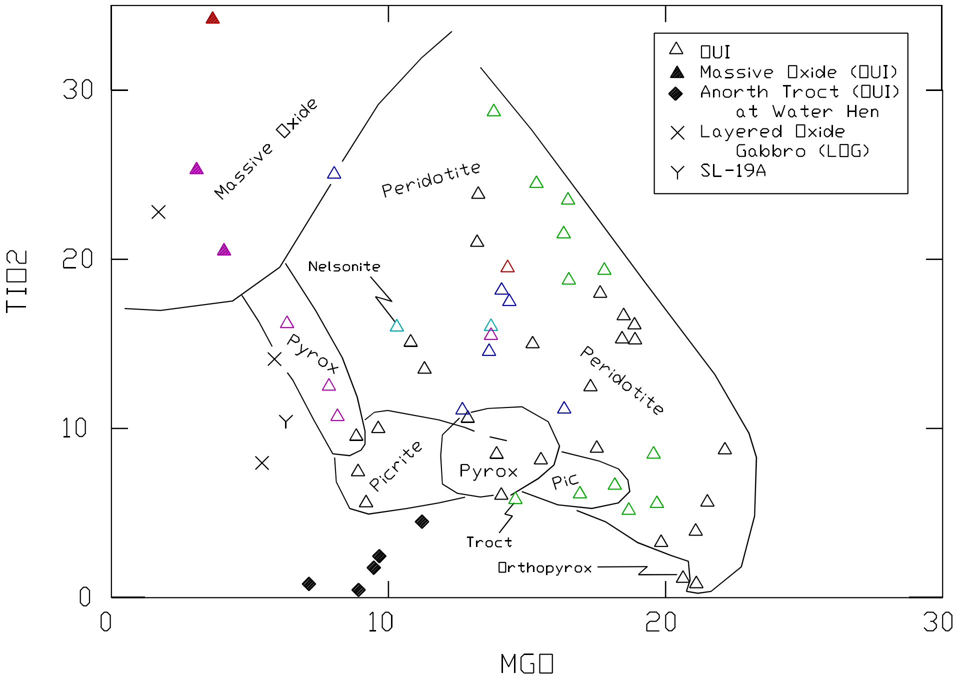


Figure 71. MgO versus TiO_2 for OUI in the South Complex area.

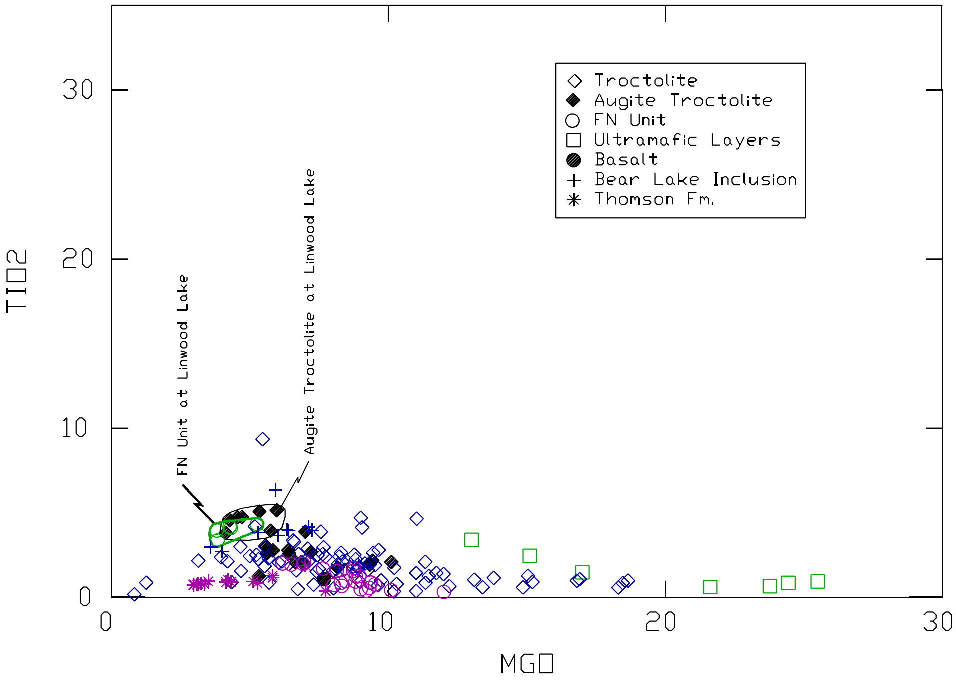


Figure 72. MgO versus TiO_2 for troctolitic rocks in the South Complex area.

MG Number Plot (Fig. 64)

Both the OUIs and troctolitic rock types occur as two distinct groups. The troctolitic rocks have a wide scatter, and within this scatter, the following units cluster in tighter groups: FN Unit at Linwood Lake; Augite Troctolite at Linwood Lake; FN#1 Unit (at Fish Lake - includes the FN#1 and FN#1A Units); FN#2 Unit (at Fish Lake); the ultramafic rock layers (squares); and the Bear Lake Inclusion (crosses). It is interesting to note that neither the FN Units, nor the Bear Lake Inclusion, plot near the sample of a basalt inclusion from Boulder Lake South. Also, each of the FN Units plot in distinct fields that are isolated from each other. Note that the FN Unit at Linwood Lake plots near the field for the Augite Troctolite at Linwood Lake. The FN Unit may represent the chilled(?) equivalent of the augite troctolite.

MgO Versus CaO (Figs. 65-66)

Within the OUIs, there is a crude grouping of rock types, with overlapping fields (Fig. 65). Rock types also group according to geographical location. For example, within the picrite field the right side of the field (higher MgO contents) corresponds to picrite samples from the Section 22 OUI body, and the left side of the picrite field corresponds the Water Hen OUI samples. Likewise for the pyroxenite field, the upper portion of the field corresponds to Water Hen samples, and the lower portion corresponds to Section 34 samples. (**Note:** In this figure and in other OUI figures, the following abbreviations are used: Orthopyrox = orthopyroxenite zone near the base of the main OUI body at Water Hen; Troct. = gradational very coarse-grained troctolitic zone within the OUI at Section 22; and "Nelsonite" = oxide-apatite rich zone from the OUI at Boulder Lake South.)

Non-OUI rock types are displayed in Figure 71. Most troctolitic rock types cluster in a tight field and cannot be distinguished from each other (including the FN Units at Fish Lake). Texturally-heterogeneous troctolitic rocks tend to cluster within a separate field in this plot (only in this plot!).

Both the FN Unit and the Augite Troctolite at Linwood Lake exhibit low MgO contents; both units show considerable overlap indicative of similar parentage. Bear Lake Inclusion samples (7) occur in a separate group that is distinctly different from the basalt sample.

MgO Versus SiO_2 (Figs. 67 and 68)

As has been described above, the various OUI rock types have separate fields and show a geographic clustering within these fields (Fig. 67), e.g., Water Hen versus Section 22. Figure 68 shows all troctolitic rocks plotting along a linear trend. Individual troctolitic rock types are difficult to distinguish within this trend. Both the FN#1 and FN#2 cluster together. Linwood Lake rocks (FN Unit and Augite Troctolite) plot within overlapping, weakly isolated fields. The ultramafic layers (picrite and peridotite) plot at the more primitive end of the troctolitic field.

MgO Versus Total Fe_2O_3 (Figs. 69 and 70)

The various OUI rock types plot in separate fields on Figure 69. The plots for the troctolitic rocks (Fig. 70) are not particularly instructive.

MgO Versus TiO_2 (Figs. 71 and 72)

Again, the various OUI rock types plot in separate fields (Fig. 71). The various troctolitic rocks show a tight linear trend (Fig. 72). The only units that cluster within slightly separate fields are the ultramafic rocks, which have higher MgO contents, and the two units at Linwood Lake (FN Unit and Augite Troctolite), which are low in MgO.

X-Y SCATTER PLOTS OF TIO_2 DATA FOR THE VARIOUS OUI BODIES

Several additional X-Y scatter plots (Figures 73 through 75) are specifically constructed for only the OUI rock types that were analyzed for their TiO_2 content. All OUI drill hole intervals with TiO_2 analyses are listed in the SOCOTI.WK1 data file (Appendix II, back pocket). Also, all available Cu, Ni, Cr, V, Pt, and Pd analyses for these same intervals are listed in the data file. These data are from corporate files that are either open-filed at the MDNR or are supplied from private corporate files (USX, American Shield, and BHP Minerals). Individual OUI bodies and the number of TiO_2 analyses available for each of the bodies are presented in Table 8. Note that Table 7 has four individual OUI bodies that are not within the South Complex area. These four OUI are located within the Partridge River intrusion (see Fig. 1 and Plate I for locations of these OUIs). These OUIs are very similar to the OUIs described in this report, and are discussed in Severson and Hauck (1990), Linscheid (1991), Miner (1995), and Miner and Pasteris (1994). Caution is advised when reviewing the values presented in Table 7 because many of the OUIs are grossly undersampled for TiO_2 analyses (virtually no samples), while other OUIs have been heavily sampled (both "lean ore" and massive oxide zones), and still other OUIs were only selectively sampled (massive oxides only). Thus, the average TiO_2 content of each OUI in Table 7 should be used with caution.

In Table 7, the OUIs are divided into two major groups, i.e., a Northern OUI Group (N-OUI) and a Southern OUI Group (S-OUI). This division is supported by similar and dissimilar profiles in the spider diagrams for each of these groups (see previous discussion). Further support for this division is apparent in the values of Cr and V - the N-OUI generally have higher contents in Cr, while the S-OUI have higher V contents. The TiO_2 contents show a wide variation in the specific OUI bodies, with no general trends in the N-OUI versus the S-OUI. However, petrographic studies indicate that ilmenite is subordinate to titanomagnetite in only the S-OUI Group (with the exception of the OUI at Boulder Lake South).

Table 7. Listing of TiO_2 values (along with V, Cr, Cu, Ni, Pt, Pd) for the various OUI bodies of the Partridge River intrusion and South Complex area. OUIs are listed geographically from top to bottom (N to S).

OUI Group	OUI Body	Intrusion/ Area	# TiO_2 Analyses	Avg TiO_2 Wt. %	Max TiO_2 Wt. %	Avg V (ppm)	Max V (ppm)	Avg Cr (ppm)	Max Cr (ppm)	Max Cu Wt. %	Max Ni Wt. %	Max Pt (ppb)	Max Pd (ppb)
N-OUI	Sec 17	Partridge River	33	10.92	14.66	790	950	490	820	0.15	0.10	25	30
	Longear	"	1,045	12.49	30.70	1,325	4,400	?	341	0.33	0.06	?	?
	Longnose	"	1,149	18.06	50.50	580	3,590	?	1,843	0.39	0.10	?	?
	Wyman Creek	"	10	17.63	28.65	?	540	1,500	3,285	0.16	0.08	50	25
	Sec 22	Partridge River/So. Complex	62	10.74	28.72	1,130	2,790	1,200	7,000	0.25	0.12	139	445
	Skibo	"	18	14.33	25.28	165	220	134	185	0.34	0.31	230	300
	Skibo-So.	"	3!	?	12.60	1,100	1,346	1,340	1,700	0.24	0.16	?	?
	Water Hen	"	608	11.15	29.30	1,065*	2,285*	863*	1,750*	1.97	0.64	127	205
S-OUI	Sec 34	So. Complex	204	15.66	26.74	2,610	4,035	250	370	0.16	0.03	14	20
	Boulder Creek	"	8	14.80	19.09	4,630	8,125	440	791	0.40	0.07	360	320
	Boulder Lake-No.	"	6	20.58	35.20	4,045	6,835	925	2,000	0.22	0.07	?	?
	Boulder Lake-Central	"	None	?	?	?	?	?	?	?	?	?	?
	Boulder Lake-So.	"	2!	?	16.03	?	787	?	260	0.18	0.02	?	?

* Excludes the unique Cr-V-rich zone in drill hole CN-7.
Note the extreme variability in sampling density (for TiO_2) within each of the various OUI bodies.

Figures 73 to 75 illustrate the differences between the various OUI bodies, even within the N-OUI and S-OUI groups. On many of these figures, a line has been drawn to illustrate trends in the plotted values for some of the OUI bodies. These lines are only visual approximations of the apparent trends - they are **not** determined in any statistical manner. A brief description of each of these figures is presented below.

TiO_2 Versus V (Figs. 73a to -c)

All available samples from all of the individual OUI bodies are plotted on Figure 73a. Because this plot is too cluttered, portions of the same data are replotted on Figures 73b and -c. Most of the OUIs exhibit increasing V content with increasing TiO_2 content, with the exception of the OUI at Skibo. In Figure 73a, the OUI with the highest V/TiO_2 ratios (defined by steep lines) are associated with the S-OUI Group, specifically with the OUIs at Boulder Creek and Section 34 (**Note:** The trend for the Boulder Creek OUI is question-marked due to limited data). Within the N-OUI Group, the Section 22 and Water Hen OUI bodies have similar V/TiO_2 trends; they also exhibit very similar spider diagram profiles (see above spider diagram discussion). In Figure 73c, the Longear OUI also has a steep V/TiO_2 trend (**Note:** High V values (>2,000 ppm) are present in only one out of three drill holes (LE-1) that were drilled into the Longear OUI body and may only reflect a small internal V-enriched zone). Figure 73c, also shows two apparent trends in the Longnose OUI. These trends are probably related to V-enrichment with depth (several drill holes exhibit increased V values at depth).

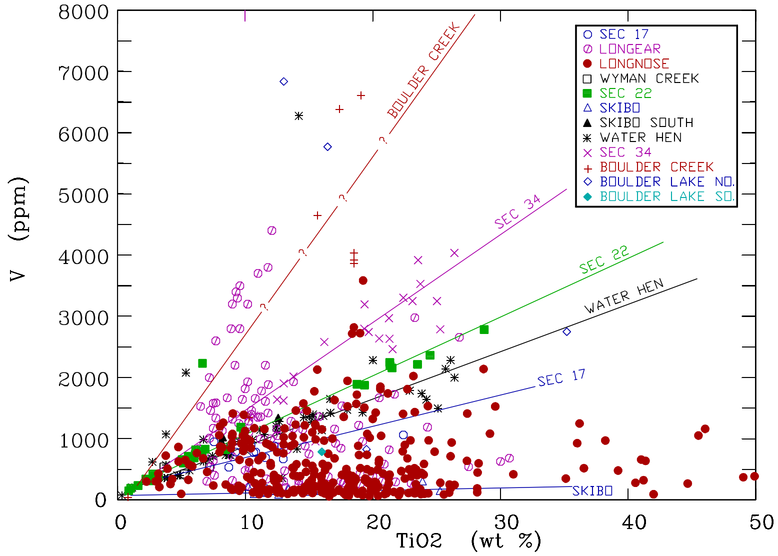


Figure 73a. TiO_2 versus V for all OUIs in the South Complex area and Partridge River intrusion.

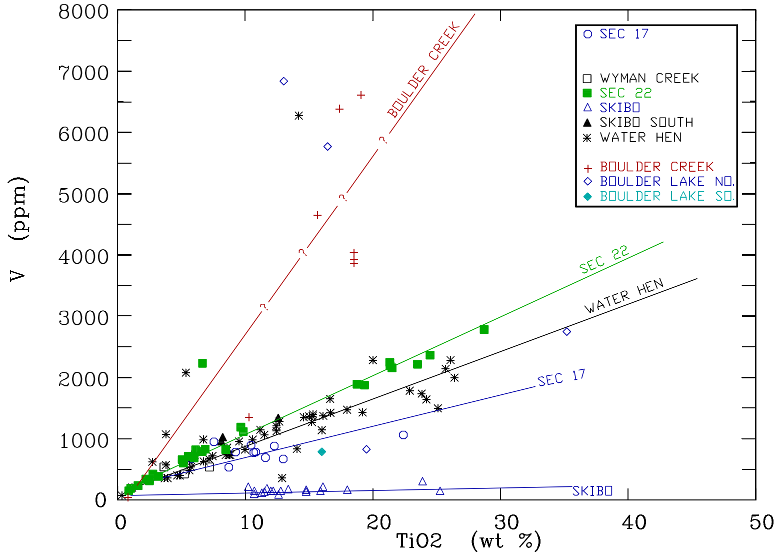


Figure 73b. TiO_2 versus V for OUIs without thick massive oxide zones (excludes the OUI at Longnose, Longear, and Section 34).

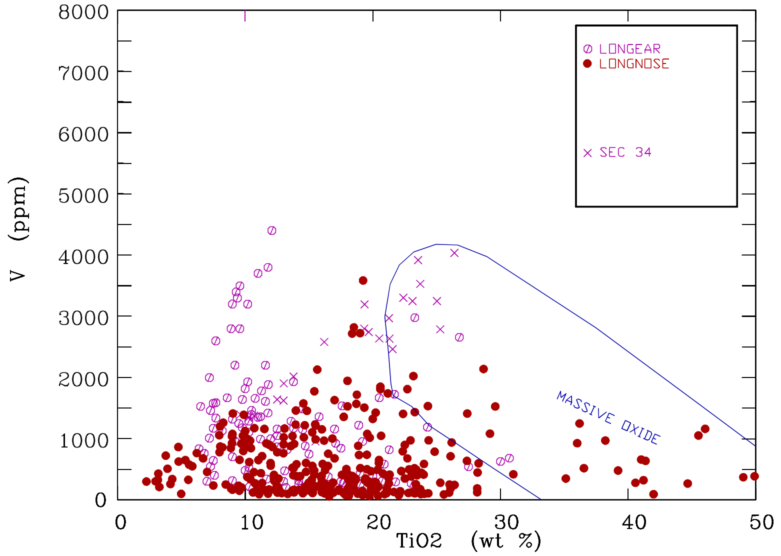


Figure 73c. TiO_2 versus V for OUIs with thick massive oxide zones (excludes the OUI data in Fig. 73b).

TiO_2 Versus Cr (Fig. 74)

Linear Cr/TiO_2 trends are apparent in Figure 74 for the OUI bodies at Water Hen, Section 22, Section 34, and Skibo. Both the Water Hen and Section 22 OUI exhibit very similar trends (as in Fig. 73). OUIs with the highest amounts of Cr (>500 ppm) are associated almost explicitly with the N-OUI Group, the only exception is the Skibo OUI.

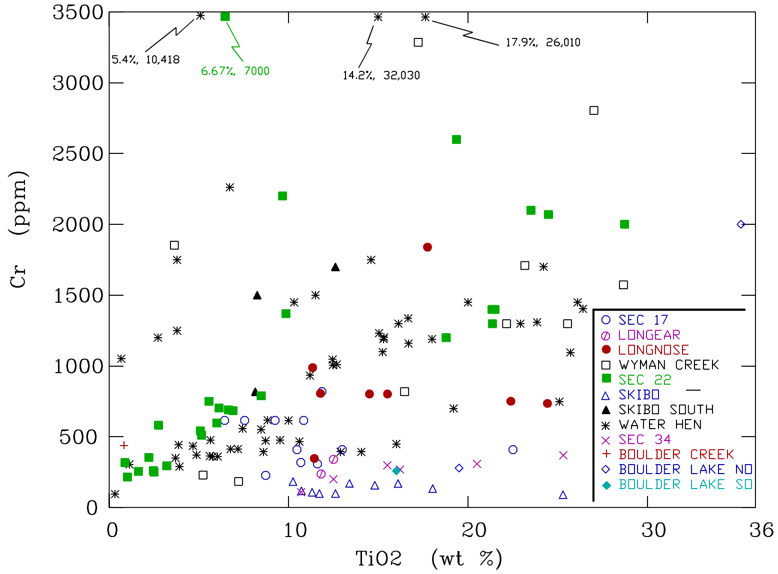


Figure 74. TiO_2 versus Cr for OUIs in the South Complex area and Partridge River intrusion.

TiO_2 Versus TFe_2O_3 (Fig. 75)

There are no apparent trends for each individual OUI body in Figure 75. Rather, specific rock types generally plot within distinct fields. However, there are some differences for the same rock type from different OUI bodies. For example, peridotite rock samples from Water Hen plot in the top half of the peridotite field; whereas, peridotite rock samples from Section 22 plot in the bottom of the field. Likewise, peridotites from the Boulder Creek OUI plot in an isolated iron-rich field (it plots high in the center of Fig. 75). Because all three of these OUIs contain roughly the same amount of oxides in drill core, the differences in total iron content may reflect different iron contents of the silicate minerals. The extreme iron-enrichment of the Boulder Creek OUI samples may also indicate that either the Fe analyses are suspect or olivines at Boulder Creek are more fayalitic than olivine in the other OUIs.

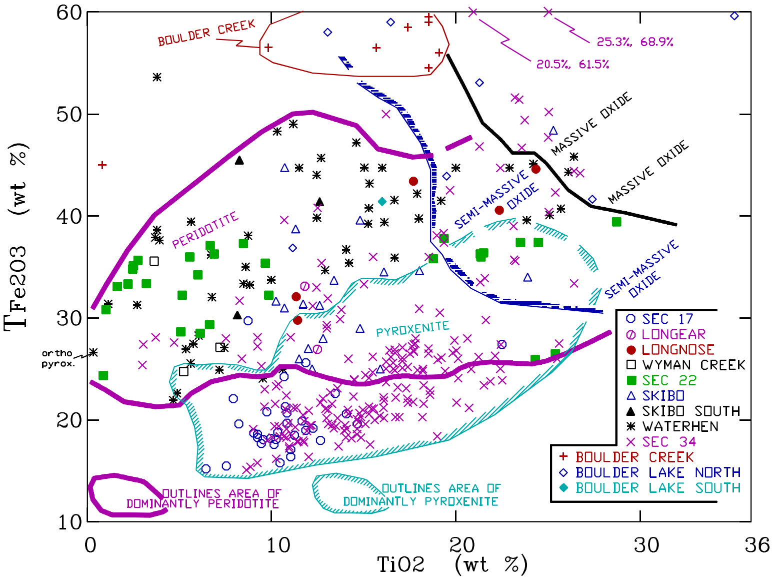


Figure 75. TiO_2 versus TFe_2O_3 in OUIs within the South Complex area and Partridge River intrusion.

PGE SCANS

Nineteen samples were submitted for PGE scans (Pt, Pd, Ir, Rh, Re, and Au) to Dr. Sarah-Jane Barnes at the University of Quebec, Chicoutimi (Table 5). The pulps were prepared by XRAL. PGE analytical procedures are outlined in Barnes and Giovenazzo (1990). Out of this data set only one sample, from drill hole SL-19A at Water Hen, contained anomalous amounts of PGE associated with a semi-massive oxide zone with "2-in-1" texture. This sample is also unique in that Pt is present in much greater quantities than Pd. In other PGE-mineralized zones of the Duluth Complex, Pd is generally much greater than Pt, and only rarely are Pt:Pd ratios greater than 1:1.

Figures 76 and 77 are plots of samples within the South Complex area with complete PGE scans. Data used to construct these figures are summarized in the SCPGE.WK1 data file (back pocket) and are from: 1) Sellner et al., 1985; 2) Morton and Hauck, 1987; 3) Strommer et al., 1991; 4) Sassani, 1992; and 5) this investigation. The fields shown in Figures 76 and 77 were originally developed by Dr. Sarah-Jane Barnes as possible exploration tools to define intrusions with potential for a PGE deposit (Barnes, 1990; Barnes et al., 1990).

The Cu/Pd versus Pd diagram (Fig. 76) was developed 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 (6×10^3 for Cu/Pd) to determine if a layered intrusion has potential for hosting a PGE reef deposit. Figure 76 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 for Cu-Ni deposits (Sudbury, Duluth Complex, etc.) plot within the depleted field (Barnes et al., 1990). Most of the samples from the South Complex plot within the depleted field, except for four samples that plot within the neutral or mantle field. These samples may have some potential for hosting a PGE reef deposit. The four anomalous samples are from: 1) a semi-massive oxide zone with "2-in-1" texture in drill hole SL-19A at Water Hen; 2) a picrite layer above a similar semi-massive oxide zone in drill hole FHL-2 at Fish Lake; 3) a strongly altered troctolite below the same semi-massive oxide zone at Fish Lake; and 4) a pegmatite zone within the FN Unit at Water Hen (drill hole SL-4). The first three samples are the most interesting in that they are associated with, or in close proximity to, a chromium-rich, semi-massive oxide zone with "2-in-1" texture. Their position within the neutral field suggests that they did not undergo previous sulfide segregation prior to emplacement, and/or little or no Cu was added to the magma through contamination of the magma by assimilation of footwall rocks. In essence, the Cu/Pd ratios of these chromium-bearing oxide-rich zones suggests that they contain primary, or magmatic, PGE mineralization. However, Sassani (1992) feels that the PGE-enrichment at Fish

Lake, immediately below the oxide-rich horizon, may be related to secondary, or hydrothermal, enrichment below an impermeable horizon. In contrast, the same type of oxide-rich zone at Water Hen contains no strongly altered rocks beneath it, and the PGE values are several magnitudes higher than Fish Lake. In comparing and contrasting these two similar oxide-rich zones, it seems that both the SL-19A and Fish Lake occurrences originally contained magmatic PGE, but the Fish Lake zone reflects very localized redistribution by later hydrothermal fluids.

On Figure 77, if a sample plots below the dashed line that defines extrusive rocks, it suggests a potential for forming a PGE deposit. The two samples that plot below this line are both related to chromium-bearing, semi-massive oxide horizons. The sample from drill hole SL-19A is from an oxide-rich horizon, and the sample from drill hole FHL-2 is from directly below the oxide-rich horizon. A sample of an orthopyroxenite dike, within the FN Unit at Water Hen, plots near the Cu-rich sulfide vein field. Anomalous PGE and high Cu values are associated with this dike (Morton and Hauck, 1987). The dike can be crudely compared to high-grade Cu-PGE veins that have been described in the footwall below the Sudbury Igneous Complex (Naldrett et al., 1992).

In summary, chromium-bearing semi-massive oxide horizons, in particular at Water Hen and Fish Lake, have potential to form a PGE deposit; however, hydrothermal fluids can also locally redistribute the PGE, e.g., as at Fish Lake. In addition, Figure 77 suggests some sulfide-rich vein-like PGE potential for the orthopyroxenite dike at Water Hen.

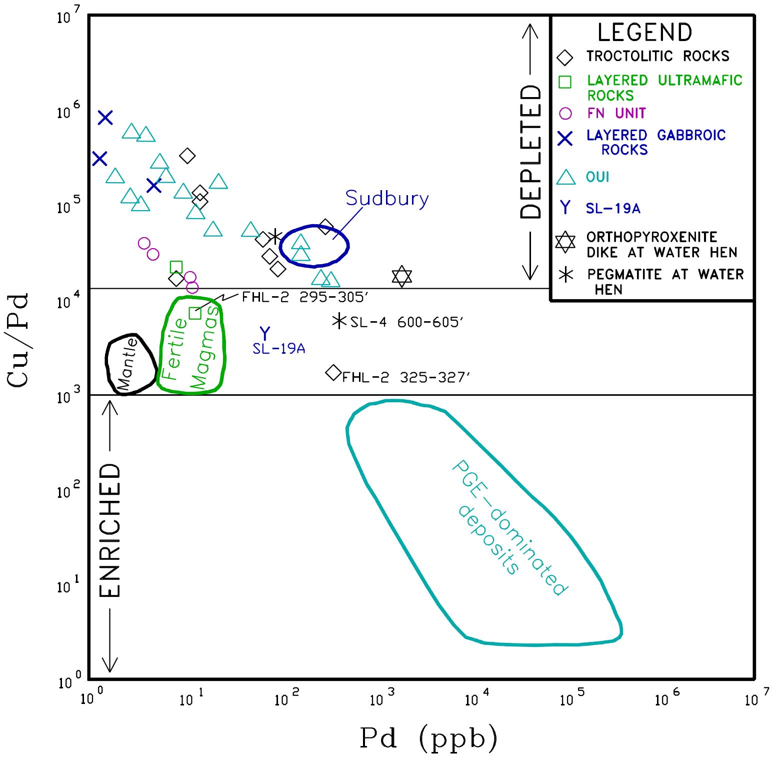


Figure 76. Plot of Cu/Pd versus Pd.

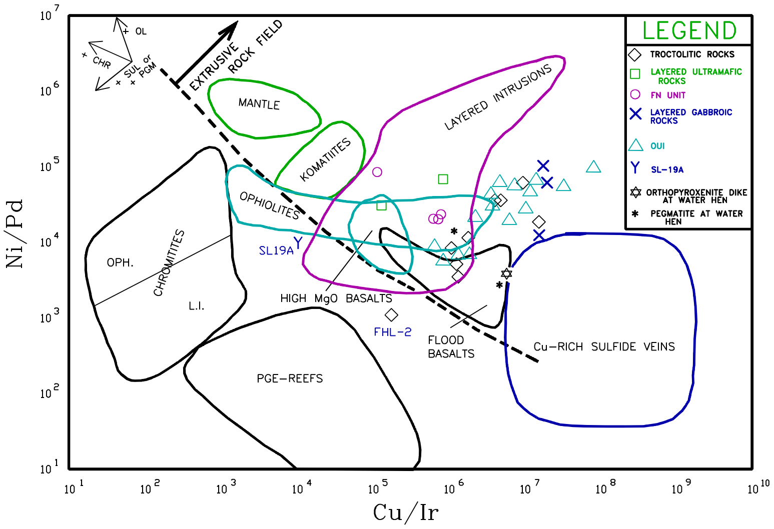


Figure 77. Plot of Cu/Ir versus Ni/Pd.

SUMMARY

BASAL CONTACT

The location of the western edge, or basal contact, of the Duluth Complex has been slightly modified in this investigation through use of drill hole and aeromagnetic data. In many areas of the South Complex, the contact appears to be very steeply inclined, or "cliff-like", and has very steep dips of 60E-90E (Allen, Water Hen, and Linwood Lake areas) to shallower dips of 35E-40E (Section 22 and Skibo areas). On the basis of gravity data, Chandler and Ferderer (1989) have estimated that the basal contact dips at 49E-60E south of the Linwood Lake area. Overall, the dips in the South Complex are much steeper than dips of the basal contact beneath the Partridge River and South Kawishiwi intrusions (15E-30E - Severson, 1988; Chandler and Ferderer, 1989; Severson, 1994). The contrasting attitudes of the basal contact suggest that the contact may be fault-related in the South Complex area (Chandler and Ferderer, 1989).

In the Water Hen area, the basal contact is very steep at the surface, but appears to flatten out with depth toward the interior of the Complex. This "steep-to-shallow" configuration is similar to a "step and riser" configuration for the geometry of the basal contact according to the half-graben model proposed by Weiblen and Morey (1975, 1980). According to the model, the "step and riser" configuration is related to steeply-dipping normal faults that were formed during an extensional tectonic event of the Keweenawan.

Structural evidence in the footwall rocks in the Linwood Lake area suggest that the Virginia Formation is strongly deformed in very close proximity to the Complex. A progressive change from shallow south-dipping to steeply east-dipping sedimentary rocks toward (and beneath) the Complex are documented in outcrops of this area. Furthermore, the outcrops exhibit a progressive change, toward the Complex, from well-bedded, to highly deformed sedimentary rocks with abundant partial melt zones (DISRUPTED unit), to completely recrystallized sedimentary rocks devoid of any bedding structures (RXTAL unit). Drill hole data, coupled with the outcrop data, suggest that the basal contact is very steep within this area and is probably fault-related. The fault was either formed during emplacement of the Complex, or the fault was pre-Complex and was reactivated during emplacement.

TROCTOLITIC ROCKS

Relogging of drill holes has defined several igneous stratigraphic sequences present in each of the drilled areas within the South Complex. Overall, the igneous stratigraphy of one area is often completely different than the stratigraphy present in a nearby area. These differences indicate that there is no "intrusion-wide" igneous stratigraphy present throughout the South Complex area. The lack of a consistent stratigraphy may be related to: 1) detailed drilling is not sufficient for regional correlation of igneous units (as a result, each drilled area represents only a small portion of a larger "stacked" stratigraphic sequence); 2) the South Complex area constitutes an area that actually includes several smaller intrusive bodies, each with a different igneous stratigraphy; 3) most of the drill holes are located near the western margin of the Complex, and correlation of regional igneous units is hampered by the effects of contamination to the magma from intruded and assimilated footwall rocks, thus rock types become more heterogenous closer to the basal contact; or 4) combinations of the above. Notwithstanding, several stratigraphic units are present within the study area and are summarized below.

Geochemistry indicates that many of the troctolitic rock units are similar to each other. However, troctolitic units at the north end of the study area (north of the Water Hen area) are geochemically most similar to Units I and V of the Partridge River Troctolite Series (PRTS) of Severson and Hauck (1990). These similarities suggest that Unit I of the PRTS extends as far south as the Skibo area, and Unit V extends southward beyond the Skibo area and into the Water Hen area (Fig. 78). The inferred southern extent of both Units I and V of the PRTS are shown on Plate I. Both of these limits correspond to contacts of Chandler (1990) within the Duluth Complex inferred on the basis of regional geophysical data. A generalized cross-section of this relationship is depicted in Figure 78.

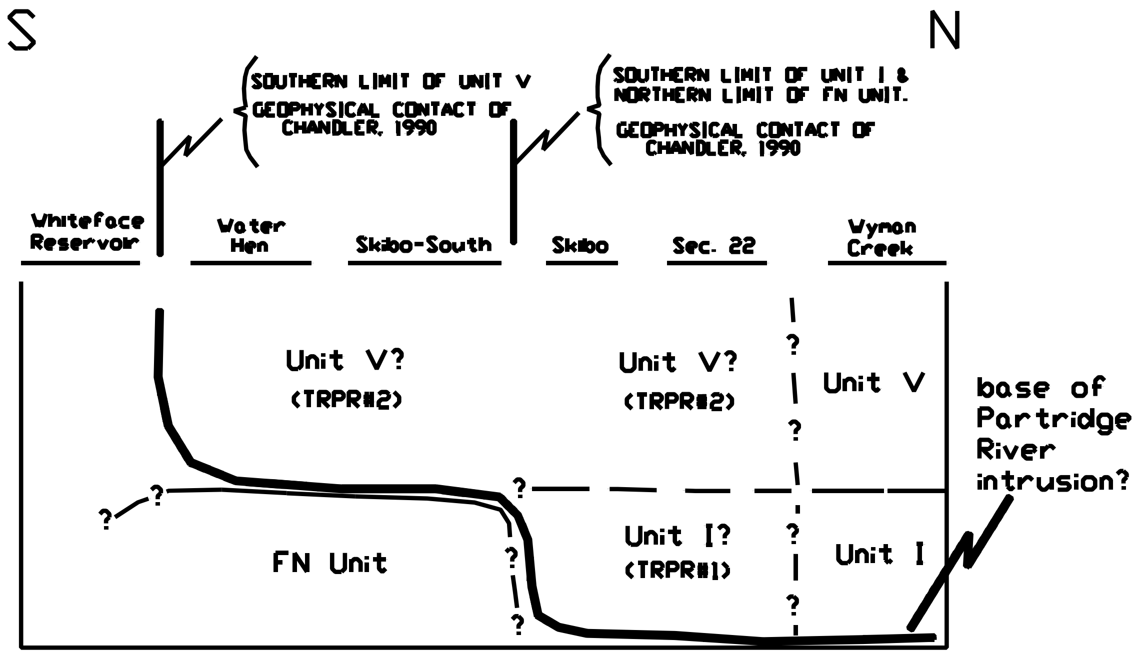


Figure 78. Schematic cross-section illustrating the spatial relations of Units I and V of the PRTS and the FN Unit in the northern portion of the South Complex area.

Sulfide-bearing zones are uncommon in the troctolitic rocks of the South Complex area. When present, they constitute highly localized zones with limited spatial extent. The best sulfide-mineralized troctolitic rocks are at the north end of the study area in the Allen, Skibo, Water Hen, and Whiteface Reservoir areas (**Note:** The first three areas are probably situated within the Partridge River intrusion). Copper values in excess of 0.4% are common to troctolitic rocks with disseminated sulfides in some holes in the Allen area. At Skibo, high grade Cu-Ni veins (with PGEs?) are present in two drill holes. Massive sulfide is present at Water Hen, but is dominantly pyrrhotite-rich. Overall, the copper content of the troctolitic rocks generally decreases to the south.

South of Whiteface Reservoir, the troctolitic rocks are only very weakly mineralized (at best). The lack of sulfide mineralization in the South Complex area relative to the Partridge River and South Kawishiwi intrusions is perplexing. Chandler and Ferderer (1989) have proposed that the lack of mineralization in the South Complex is due to the fault-related basal contact that "... provided only brief interaction between magmas and [footwall rocks], compared with the longer interaction along the [footwall] contact to the north" (p. 1695). To the north, the basal contact is coplanar with the bedding in the footwall rocks; whereas, in the South Complex the basal contact is at a steep angle relative to the bedding trends. Types of sulfides present in the troctolitic rocks, for each subarea of the South Complex, are listed in Table 8.

Table 1. Types of sulfides present in the troctolitic rocks at the various subareas in the South Complex (excludes the OUI rock types).

AREA	SULFIDES (in addition to po-cp-cb-pn)	COMMENTS	REFERENCE
Section 22			
Skibo	sphalerite; clausthalite (in footwall)	scatt. sulf-rich veins	this study
Skibo-South	safflorite, cobaltite-gerdorffite (both in OUI hybrid)		Mogessie et al., 1991
Water Hen	maucherite, bn, mack, and late pyrite maucherite, bn, nickeline, parkerite, and tetradymite in orthopyroxenite dike.	disseminated to net-textured to massive sulfides	Morton and Hauck, 1987
SL-19A (Water Hen)	mackinawite and late pyrite		this study
Whiteface Res.	mackinawite, sphalerite, and late pyrite		this study
Linwood Lake	rare sulfides		this study
Harris Lake	rare sulfides		this study
Section 34	rare sulfides		this study
Boulder Cr.	rare sulfides		this study
Grid VIII	rare sulfides		this study
Boulder Lake-North	rare sulfides		this study
Boulder Lake-Central	sphalerite and graphite	disseminated to net-textured to massive sulfides	this study
Boulder Lake-South	rare sulfides		this study
outcrop 1-53N-14W	bornite, covellite, chalcocite, digenite		this study
Fish Lake	niccolite, mauch, marcasite, gersdorffite, cobaltite, molybdenite	disseminated to net-textured to massive sulfides	Sassani, 1992
Bear Lake Inclusion	rare sulfides with bornite, native copper		this study

Ultramafic rocks (picrite, peridotite, etc.) are present as subhorizontal units in only a few areas, e.g., Water Hen (drill hole SL-19A), Linwood Lake (drill hole SL-1B), Harris Lake (thick sequence present in five drill holes), Section 34 (several layers present in only one drill hole - 26008), Thompson Lake, and Fish Lake (drill hole FHL-2). Spider diagram plots, on a very limited sample set, are not very instructive as the ultramafic rock types exhibit both contrasting and similar profiles relative to both stratigraphic height and geographic location. Interestingly, semi-massive oxide horizons (with "2-in-1" texture, high Cr values, and ± high PGE values) are associated with ultramafic horizons at both the Water Hen and Fish Lake areas.

Oxide-rich gabbroic to troctolitic rocks are present within the igneous stratigraphy in the southern half of the study area at the Grid VIII and Boulder Lake North areas. At Boulder Lake North, the oxide-rich rocks consist of layered gabbro and pyroxenite (LOG Unit), with local thin massive oxide zones. The LOG Unit may be similar to Unit G of Nathan's Layered Series; however, beside their megascopic similarities, they cannot be compared in any other manner at this time. Chemistry is available for the LOG, but not for Unit G. Unit G is part of a 1,107 Ma package of reversely-polarized rocks, but no age dates are available for the LOG. Both the LOG Unit and Unit G have common pod-like bodies of OUIs.

Modally layered rocks, present in large outcrops at Lieuna Lake, may be correlative with rocks of the Basal Contact Zone exposed further to the south in Duluth, MN (Unit BC of the Duluth Layered Series - Miller et al., 1993). Similar outcrops of modally layered rocks, but not correlative with Unit BC, are also found to the north of Lieuna Lake along the Cloquet River.

FN UNIT

The FN Unit is present as inclusions, and as a border phase along the basal contact, in several areas of the South Complex, e.g., Skibo-South, Water Hen, Linwood Lake, Boulder Creek, and Fish

Lake. In drill core, the FN Unit resembles a hornfelsed basalt inclusion due to its fine-grained, granoblastic texture with vesicle-like features (plagioclase-filled spots and wisps). However, several features of the FN Unit argue against a basalt protolith. First, common to the FN Unit (at most of the localities) are cordierite-bearing hornfelsed inclusions of the footwall Virginia Formation (up to 60 feet thick at Water Hen). Second, in some areas the FN Unit is present as a rind, or border phase, adjacent to both a steeply-dipping and flat-lying basal contact, e.g., Water Hen. The presence of the FN Unit, with footwall inclusions, that abuts against a "cliff-like" basal contact is difficult to reconcile if it represents Keweenawan basalt flows. Third, the FN Unit commonly grades into medium-grained troctolitic-gabbroic-noritic rocks with the same mineralogy as the adjacent fine-grained rocks; the medium-grained rocks also contain inclusions of the sedimentary footwall rocks. Fourth, limited geochemistry for the FN Unit suggests that they are not similar to the basalt inclusion at Boulder Lake South; however, they are chemically similar to medium-grained troctolitic rocks present in the same drill hole. These chemical similarities are present for the FN Unit at Linwood Lake and Fish Lake. Geochemistry is not available for the FN Unit at Skibo-South, Water Hen, and Boulder Creek. The FN Unit is interpreted to represent an early, and presumably chilled, intrusive phase of the Duluth Complex that was intruded into and contaminated by footwall sedimentary rocks and was subsequently hornfelsed by later magmatic pulses. This situation would explain the common presence of footwall inclusions and the apparent rind-like configuration of the FN Unit relative to the basal contact. The vesicle-like features could be related to degassing of the footwall rocks.

Geochemistry plots show differences in the FN Unit from area to area, e.g., Linwood Lake versus Fish Lake, and even within the same drill hole, e.g., Fish Lake units FN#1 versus FN#2. These differences may be related to amount of contamination associated with assimilated footwall rocks. For example, the FN#1 Unit at Fish Lake is situated closer to the basal contact; whereas, the chemically different FN#2 Unit is positioned further above the basal contact.

Spatially, the FN Unit is restricted to an area that extends from Skibo-South to Fish Lake. The northern extent of the FN Unit also corresponds to the southern limit of Unit I of the PRTS (see Fig. 78 and Plate I). The collective distribution of the FN Unit and Units I and V shown in Figure 78 suggests the FN Unit may have been emplaced before Unit I in the Skibo-South and Water Hen areas.

OXIDE BEARING ULTRAMAFIC INTRUSIONS (OUI)

Several Oxide-bearing Ultramafic Intrusions (OUIs) are intersected in drill holes throughout the South Complex area. Rock types consist of olivine-rich rocks (picrite, peridotite, etc.) and clinopyroxene-rich rocks (pyroxenite and melagabbro). Some of the OUIs exhibit a crude rock type zonation from an olivine-rich core to an outer pyroxenite margin; whereas, other OUIs consist of one dominant rock type. Oxide content is variable and ranges from 15%-20% disseminated oxides in all the OUIs to localized massive oxide zones in some of the OUIs. Sulfides are ubiquitous to all the OUIs and range from disseminated sulfides in all of the OUIs to net-textured sulfides with massive sulfide zones in some of the OUIs. In some cases, drilling is detailed enough to define a central core of OUI that is surrounded by a mixed zone of OUI apophyses and irregular OUI patches within the host troctolitic rocks. There are two major groups of OUIs within the South Complex area and adjacent Partridge River intrusion, that can be categorized on the basis of differences in geochemistry, geologic setting (and geographic location), and possibly, differences in origin. These two groups are referred to as the Northern and Southern OUI groups. Major differences and similarities for each of the various OUI are listed in Table 9 (compare with Tables 7 and 9).

Table 2. Summary of major features relative to the OUIs within the South Complex and Partridge River intrusion.

	OUI	ILM	MT	Cr-TiMT	GRAPH	SULFIDES (in addition to po-cp-cb-pn)	APATITE	DOMINANT ROCK TYPE	HOST ROCK
	Section 17	ILM>MT			none	bn	no	pyrox	Units VI & VII
	Longear	ILM>MT			none	bn, py	no	pyrox	Units VI & VII
	Longnose	ILM≥MT			none	bn	no	dunite-core pyrox-rind	Units VI & VII
N-OUI GROUP	Wyman Cr.	Ilmenite dominant with minor composite magnetite	rare - composite & product of serpent.	✓	none	?	no	perid & pyrox	Unit I
	Section 22			✓	none	mauch, park	no	perid	Unit V
	Skibo			✓	✓		no	perid	Unit V?
	Skibo-South			✓	✓*	mauch, sl, safflorite* cobaltite*	no	perid & pyrox	Unit V?
	Water Hen			✓	abundant	mauch, mk, sl, bn, py	no	pyrox-upper 1/2 perid-lower 1/2	Unit V?
S-OUI GROUP	Section 34	exsol lam and composite grains	dominant		none	bn, sl, py	no	perid & pyrox	anorth
	Boulder Cr.				common	bn, sl	no	perid	troct & FN Unit
	Boulder Lake-North				none		common	perid & pyrox	LOG Unit, troct & anorth
	Boulder Lake-South	dom	rare		yes		common	perid & pyrox	troct & basalt

MISCELLANEOUS

1. Skibo-South = local hybrid OUI (*)
2. Water Hen = local Cr-enriched zones, massive sulfide, and net-textured sulfide.
3. Boulder Creek = Stratabound OUI, graph and sulf only in "feeder zone"
4. Boulder Lake-South = local massive sulfide and "nelsonite"

The Northern OUI Group (N-OUI) consists of OUI bodies at Wyman Creek (at depth), Section 22, Skibo, Skibo-South (at depth), and Water Hen. All of these OUIs intrude troctolitic rocks that are correlative with Units I and V of the PRTS. Collectively, the OUI bodies are situated along a linear zone, probably a north-trending fault zone, that parallels the steeply-dipping basal contact. Footwall rocks of the Virginia Formation are present within 1,500 feet beneath all of these OUIs. The N-OUI are associated with a north-trending magnetic high interpreted to reflect a strong magnetic overprint caused by heating of the Biwabik Iron-formation during emplacement of the Duluth Complex (Bath, 1962; Chandler and Ferderer, 1989; Chandler, 1990). The position of these OUIs relative to the magnetic high suggests a possible genetic link. Their juxtaposition suggests that the N-OUI may have originated via a mechanism of intrusion and assimilation of the iron-formation at depth followed by upward injection of oxide-rich magmas along a fault zone to produce the OUI. A similar relationship is present for the OUIs in the Longnose-Longear-Section 17 area of the Partridge River intrusion, where the OUIs are situated over a basement window of Biwabik Iron-formation (Severson and Hauck, 1990).

The Southern OUI Group (S-OUI) consists of OUI at Section 34, Boulder Creek (stratabound), Boulder Lake North, Central Boulder Lake, and Boulder Lake South. Host rocks for these OUIs are very diverse and include anorthosite, troctolite, oxide-bearing gabbro and pyroxenite, basalt, and the FN Unit. The OUI bodies are located along a linear zone inferred to be a northeast-trending fault. The depth to footwall rocks, presumably sedimentary rocks of the Virginia/Thomson Formations (not the Biwabik Iron-formation), is unknown, but is probably on the order of thousands of feet. The origin of the S-OUI may be related to layered oxide-rich rocks (such as the LOG Unit at Boulder Lake North and oxide-rich rocks at Grid VIII) that are present above or at the same stratigraphic level as most of the OUI. The OUIs may have formed via differentiation of an iron-rich residual melt that formed at the top of a crystallizing cumulate pile (the LOG Unit?) that drained down into pile along a fault zone to produce the various S-OUI. A similar origin of downward percolating iron-rich residual melts has been presented for iron-rich ultramafic pegmatites in the Bushveld Complex of South Africa (Scoon and Mitchell, 1994). In the South Complex, the LOG Unit is a likely candidate to have produced an iron-rich residual melt. Both the LOG and many of the S-OUI are apatite-rich. Titanomagnetite is dominant over ilmenite in both the LOG and S-OUI (except the OUI at Boulder Lake South).

There are major geochemical differences between the N-OUI and S-OUI. The N-OUI have increased chromium relative to the S-OUI; whereas the S-OUI have higher vanadium. Titanomagnetite is greater than ilmenite in almost all of the S-OUI, with the exception of the OUI at Boulder Lake South; whereas, only rare titanomagnetite is present in the N-OUI and ilmenite is dominant. The S-OUI are all geochemically similar to each other, and the S-OUI are geochemically different than the N-OUI. Spider diagrams for the N-OUI show similar profiles for alternating OUI bodies, in a "leap frog" manner, relative to geographic location. For example, the Section 22 and Water Hen OUI have nearly identical spider diagram profiles, while the Skibo OUI, which occurs spatially between them, has a different geochemical signature. While apatite is common to all of the OUIs, it is especially common to the OUI at Boulder Lake North and Boulder Lake South (**Note:** Apatite is also very common to the LOG Unit at Boulder Lake North). Internal zones of nelsonite are present within the OUI at Boulder Lake South.

These differences suggest that the N-OUI and S-OUI originated by somewhat different mechanisms, perhaps related to geologic setting. Intrusion of the Complex into the Biwabik Iron-formation, at depth, may have produced an iron-rich residual melt that was intruded upward along fault zones to produce the N-OUI. Further to the south, the iron-formation is probably situated well below the basal contact relative to the S-OUI and probably played no part in their genesis. However, many of the S-OUI are situated at, or slightly below layered oxide-bearing rocks. These oxide bearing rocks may have produced a differentiated iron-rich melt at the top of the crystallizing cumulate pile that subsequently drained downward into the pile along fault zones to produce the OUIs.

Metasomatic replacement of pre-existing intrusive rocks has been proposed for the origin iron-rich plugs in the Bushveld Complex (Schiffries, 1982; Viljoen and Scoon, 1985; Scoon and Mitchell, 1994). Within the South Complex, a metasomatic replacement origin seems plausible on only a local scale, specifically toward the outer margins of some of the individual OUI bodies. In these instances, the outer margins are characterized by mixed zones that contain both lenses (apophyses) and irregular patches of OUI. In drill core, the irregular patches of OUI give a crude impression of being interconnected in a networked fashion - the patches often trail off into the host troctolitic rocks. The contacts between the patches and host troctolite are highly irregular with interpenetrating crystals that cross the contact. Adjacent to some of the coarse-grained peridotitic OUI patches, the host troctolite also contains coarse-grained olivine that becomes finer-grained with distance away from the OUI patch. These features suggest that either the host troctolite was progressively replaced by the OUI, or the host troctolite was only partly solidified when the OUI was intruded, or a mixture of the two. Overall, evidence for even localized metasomatic replacement to produce the OUI is difficult to recognize in drill core.

On a much larger scale, a metasomatic replacement mechanism cannot be considered as a possible origin for the S-OUI group. This is because the S-OUI are all similar, both megascopically and geochemically regardless of the rock type that the OUI intrudes. Each of the OUIs are hosted by a wide variety of rock that include: Section 34 - anorthosite host rocks, Boulder Creek - FN Unit and troctolitic host rocks, Boulder Lake North - LOG Unit and anorthositic host rocks, and Boulder Lake South - hangingwall basalt inclusion and troctolitic host rocks. If the S-OUI originated via metasomatic replacement of pre-existing rock, there should be profound differences between the OUIs in each of these respective areas. The data suggests this is not the case. Within the N-OUI a metasomatic replacement model cannot be evaluated with the available data. A magmatic origin with extremely localized metasomatic replacement is proposed for the genesis of the Longnose OUI (Miner and Pasteris, 1994; Miner, 1995; Miner and Pasteris, 1995).

BEAR LAKE INCLUSION

Within the Bear Lake area are numerous outcrops of fine-grained magnetic basalt that overlies fine- to medium-grained, oxide-bearing gabbroic rocks. The magnetic basalt is characterized by a dark-colored, fine-grained, granular, strongly magnetic rock with an oxide gabbro composition. The inclusion is present as a southeast dipping sheet over 500 feet thick; one drill hole (BL-1) was collared and terminated within the inclusion. The bottom contact of the inclusion, located in the field, is subhorizontal and sharp against oxide-bearing gabbroic rocks. No vesicle-like features are found in any of the outcrops, or drill hole; however, the Bear Lake Inclusion is similar to other magnetic basalts, with vesicle-like features, reported elsewhere within the Duluth Complex. Geochemistry of the Bear Lake Inclusion is similar to some rocks in the Colvin Creek Inclusion and the "INCL" unit of the South Kawishiwi intrusion.

PGE POTENTIAL OF THE SOUTH COMPLEX AREA

Within the South Complex, there are at least three areas that have potential for hosting either PGE-enriched Cu-Ni ore or a PGE deposit. Potential for PGE-enriched ore is present at depth in the Skibo and Water Hen areas and could be compared to the high-grade PGE- and Cu-enriched veins at the Strathcona mine of the Sudbury Igneous Complex. There, the veins are envisioned to have been enriched as a result of fractional crystallization of an immiscible sulfide melt as it moved down through rocks that are footwall to the intrusion (Naldrett et al., 1992). Potential for a PGE deposit is associated with a chromium-bearing oxide zone in drill hole SL-19A from the Water Hen area. Each of these three areas have been previously described and are summarized below.

Skibo Area

Two holes drilled into the Skibo area encountered thin intervals of strongly mineralized troctolite and/or massive sulfide veins; both mineralization types contain extremely high Cu and Ni values (Table 1). The high values for both Cu and Ni may be related to fractional crystallization of a sulfide melt in a vein-like setting, i.e., the Strathcona model. These mineralized zones may also be PGE-enriched, according to the model, but no drill core or coarse reject material remains for PGE analyses.

Water Hen Area

Within the FN Unit at Water Hen are common thin dikes and dikelets of orthopyroxenite that range in thickness from <3 inches to 8 feet. Most of the dikes are sulfide-enriched; chalcopyrite is the dominant sulfide. Only one of these dikes has been sampled for PGEs and contains >3 ppm combined Pt-Pd-Au (Morton and Hauck, 1987). On Figure 77, this dike plots near the field that defines Cu-rich sulfide veins. The orthopyroxenite dikes at Water Hen can also be crudely compared to the high-grade footwall veins at the Strathcona mine.

Drill Hole SL-19A

Within drill hole SL-19A, north of the Water Hen area, an 8 inch thick, semi-massive oxide horizon is intersected within a layered ultramafic package (picrite, peridotite, etc). Geochemical analyses of this horizon give values of 737-786 ppb Pt, 63-106 ppb Pd, 46,000 ppm Cr, and elevated Os, Ir, Ru and Rh concentrations (Table 4). The oxide-rich horizon in SL-19A is similar to other PGE-enriched oxide horizons located elsewhere within the Complex - at the Birch Lake deposit in drill holes Du-15 and Du-9 (recently described in detail by Severson, 1994), and the Fish Lake area in drill hole FHL-2 (Sassani, 1992; this investigation). Similarities of all these oxide-rich horizons include: 1) the oxide-rich zones often display a "2-in-1" texture; 2) the oxide-rich horizons are often associated with high Cr contents; 3) the oxide-rich horizons are associated with, or are present immediately beneath, ultramafic layers; 4) high PGE values are found in close association with, if not coincident to, the oxide-rich zones; and 5) mineral chemistry for the spinels in each of these different areas is very similar (Fig. 11). Differences between these oxide-rich horizons include: 1) strongly altered rocks (with anomalous PGE) are present immediately beneath the oxide-rich zone at Fish Lake; 2) strongly altered rocks are present in some portions of the Birch Lake deposit - high PGE values are not directly associated with these zones; 3) strongly altered rocks are not associated with the oxide-rich zone in SL-19A; 4) the majority of the massive oxide zones at Birch Lake are associated with intruded and assimilated Biwabik Iron-formation (U3 Unit of Severson, 1994) - however, in light of the occurrence of similar material at SL-19A and Fish Lake, some of the oxide zones at Birch Lake may be magmatic (Hauck et al., 1995; Hauck et al., in prep.; 5) the oxide-rich horizons at Fish Lake and SL-19A are not associated with iron-formation and are magmatic; 6) the Pt:Pd ratio for SL-19A is much higher than the ratio at Birch Lake (7:1 versus 3:1 to 1:1, respectively); and 7) additional spinels are present at Birch Lake (Fig. 11). Severson (1994) states the PGEs at the Birch Lake deposit were concentrated by upward moving Cl-rich hydrothermal solutions that deposited the PGEs at a stratigraphic trap (U3 Unit). Sassani (1992) and Pasteris et al. (1995) believe the PGEs at Fish Lake were also concentrated by hot, highly saline hydrothermal fluids beneath a stratigraphic trap (oxide-rich horizon). However, there is a total lack of any strong alteration associated with the SL-19A occurrence, and the PGEs associated with the oxide-rich Cr-bearing horizon appear to be magmatic rather than hydrothermal. In comparing all the PGE-enriched oxide horizons to SL-19A, it appears that while hydrothermal redistribution of PGE is probably operational within the Complex, e.g., Birch Lake and Fish Lake, it may only redistribute the PGE (originally present as magmatic PGE) on a very LOCAL basis. The plotted position of the SL-19A sample on Figures 76 and 77 indicates that it has near-mantle ratios (magmatic) and has some potential of forming a PGE deposit.

The PGE-enriched oxide horizon in SL-19A is particularly intriguing when compared to all the other PGE/oxide occurrences. First, the horizon in SL-19A is intersected close to the surface (within 320 feet); whereas, the PGE-enriched zone at Birch Lake is much deeper below the surface (approximately 2,400 feet). Second, the Pt:Pd ratios are much higher in SL-19A than at Birch Lake. However, additional drilling is necessary in the vicinity of SL-19A in order to confirm the lateral continuity of the oxide-rich horizon (or pod?) and whether significantly higher PGE grades are associated with (and above or below) this zone.

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APPENDIX 1

DRILL HOLE LOCATIONS AND MAJOR LITHOLOGIC BREAKS IN DRILL HOLES OF THE SOUTH COMPLEX AREA

This listing includes all locations and major lithologic unit breaks for drill holes within the study area. These data are also included in the SOCOMP.WK1 data file in the back pocket of this report. Abbreviations used in this listing are defined on the last page of Appendix 1.

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over- burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
FHL-1	Fish Lake	10-52-15	558360	5205070	1352	1003	61/263	0-129	129-492	492-1003		DNR	MJS
FHL-2	Fish Lake	10-52-15	558480	5205070	1400	1315	90	0-121	121-837	837-1315		DNR	MJS
TS-1	Fish Lake	31-52-15				241	90	0-99	-----	99-241		DNR	
TS-2	Fish Lake	31-52-15			1350	779	65/180	0-140	-----	140-779		DNR	
MPL-1		25-52-15				399	90	0-145	145-399			DNR	
V-1	Boulder Lake South	36-53-15	561840	5209230	1400	483	45/300	0-106	106-348		348-483 basalt	DNR	MJS
V-2	Boulder Lake South	25-53-15	562050	5209200	1395	983	45/300	0-79	79-944		944-983 basalt (?)	ASC	SPEC
V-3	Boulder Lake South	36-53-15	562070	5209700	1405	1232	45/300	0-113	113-1001		1001-1232 basalt	DNR	MJS
VII-1	Central Boulder Lake	25-53-15	561640	5211180	1400	502	45/270	0-27	27-502			DNR	MJS
VII-2	Central Boulder Lake	24-53-15	561725	5211400	1395	539	43/270	0-20	20-539			DNR	MJS
VII-3A	Central Boulder Lake	24-53-15	561310	5212440	1375	693	60/279	0-48	48-693			DNR	MJS
VII-4	Central Boulder Lake	24-53-15	561795	5211405	1390	948	45/270	0-13	13-948			DNR	MJS
VII-5	Central Boulder Lake	24-53-15	561560	5211860	1390	693	45/270	0-30	30-693			DNR	MJS
VII-6	Central Boulder Lake	24-53-15	561785	5211440	1390	1000	90	0-9	9-1000			ASC	MJS
VII-7	Central Boulder Lake	23-53-15	560180	5212180	1400	594	45/270	0-71	71-551	551-594		ASC	SPEC
VI-1	Central Boulder Lake	18-53-14	563575	5212935	1380	1045	45/270	0-64	64-1045			ASC	SPEC
VI-2	Central Boulder Lake	24-53-14	562375	5212150	1385	913	45/90	0-78	78-913			ASC	MJS
VI-3	Central Boulder Lake	19-53-14	563350	5212545	1380	595	45/270	0-80	80-595			ASC	SPEC
IV-1	Boulder Lake North	8-53-14	564250	5215580	1415	817	45/90	0-20	20-817		86-362 OUI	DNR	MJS
IV-2	Boulder Lake North	7-53-14	563425	5214850	1410	912	45/270	0-33	33-912		with OUIs	ASC	MJS
IV-3	Boulder Lake North	6-53-14	563820	5216195	1435	1002	45/270	0-58	58-1002			ASC	MJS
IV-4	Boulder Lake North	18-53-14	563325	5214480	1380	993	45/270	0-16	16-993			ASC	SPEC
IV-5	Boulder Lake North	18-53-14	563540	5214485	1380	600	45/270	0-27	27-600			ASC	SPEC

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
IV-6	Boulder Lake North	7-53-14	564220	5215440	1435	673	45/270	0-47	47-673		317-358 OUI	DNR	MJS
IV-7	Boulder Lake North	7-53-14	563440	5215335	1450	515	45/270	0-73	73-515			DNR	MJS
IV-8	Boulder Lake North	7-53-14	563890	5215680	1445	503	45/270	0-74	74-503		74-229 OUI	DNR	MJS
IV-9	Boulder Lake North	7-53-14	563680	5216080	1435	768	45/270	0-33	33-768			DNR	MJS
IL-1	Boulder Lake North	7-53-14	563660	5216130	1435	700	90	0-29	29-700			DNR	MJS
IL-2	Boulder Lake North	6-53-14	563500	5216885	1440	455	90	0-29	29-455			DNR	MJS
IL-3	Boulder Lake North	6-53-14	564040	5217620	1490	515	90	0-68	68-515			DNR	MJS
I-1A	Boulder Creek	10-54-14	567740	5225300	1575	344	45/298	0-72	72-344			DNR	MJS
I-2	Boulder Creek	16-54-14	566560	5223260	1560	1000	45/298	0-119	119-1000			DNR	MJS
I-3	Boulder Creek	16-54-14	566440	5223320	1565	403	45/298	0-107	107-403			DNR	MJS
I-4	Boulder Creek	16-54-14	566680	5223210	1560	1000	45/298	0-100	100-1000			DNR	MJS
I-5A	Boulder Creek	10-54-14	567910	5225220	1565	993	45/298	0-45	45-993			DNR	MJS
I-6	Boulder Creek	9-54-14	567360	5224530	1580	1203	45/298	0-116	116-1203			DNR	MJS
I-7	Boulder Creek	16-54-14	567010	5223880	1585	1283	45/298	0-107	107-1283			DNR	MJS
I-8	Boulder Creek	16-54-14	566280	5222665	1545	1432	45/298	0-101	101-1432			DNR	MJS
I-9	Boulder Creek	16-54-14	567150	5223400	1535	1002	45/298	0-68	68-1002			DNR	MJS
I-10	Boulder Creek	16-54-14	566400	5222880	1545	572	45/298	0-74	74-572			DNR	MJS
I-12	Boulder Creek	16-54-14	566620	5223490	1560	1083	45/298	0-125	125-1083			DNR	MJS
I-13	Boulder Creek	16-54-14	566520	5223155	1565	994	45/298	0-115	115-994			DNR	MJS
VIII-2	Grid VIII	23-54-14	569365	5222260	1550	802	45/270	0-141	141-802			DNR	MJS
VIII-4A	Grid VIII	14-54-14	569570	5222870	1570	962	45/270	0-52	52-962			DNR	MJS
26000	Sec 34	34-55-14	568560	5228350	1560	730	46/250	0-98	98-730		533-687 with OUIs	USX	MJS
26001	Sec 34	3-54-14	567960	5227270	1585	552	90	0-89	89-552		89-552 OUI	USX	MJS

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
26002	Sec 34	34-55-14	568120	5228110	1555	901	90	0-59	59-901		59-901 OUI w/ mass. ox.	USX	MJS
26003	Sec 34	3-54-14	567840	5227350	1590	466	90	0-111	111-466		OUIs throughout	USX	MJS
26007	Sec 34	34-55-14	568270	5228120	1560	587	90	0-98	98-587		98-587 OUI	USX	MJS
26008	Sec 34	34-55-14	568170	5227980	1560	607	90	0-85	85-607		85-540 with OUIs	USX	MJS
X-1	Thompson Lake	23-53-14	569870	5212400	1455	613	45/310	0-182	182-613		264-353 dunite (Cr)	ASC	SPEC
BL-1	Bear Lake	36-55-13	580900	5229005		563	90	0-130	130-563		Bear Lake inclusion	DNR	MJS
CV-1		29-55-14	564330	5229350	1570	874	60/295	0-145	145-750		750-874 granite (vein)	DNR	MJS
CV-2		9-55-14	566670	5234410	1560	884	60/295	0-142	142-782	782-884		DNR	MJS
26004	Harris Lake	31-56-13	572390	5238460	1560	557	90	0-114	114-557			USX	MJS
26005	Harris Lake	31-56-13	572340	5238645	1590	400	90	0-140	140-400			USX	MJS
26006	Harris Lake	31-56-13	572440	5238580	1580	697	90	0-141	141-697			USX	MJS
HL-1A	Harris Lake	31-56-13	572420	5238325	1545	1061	45/310	0-140	140-1061			DNR	MJS
HL-2	Harris Lake	31-56-13	572850	5238285	1545	703	45/310	0-119	119-703			DNR	MJS
OL-1	Otto Lake	22-56-13	577950	5240620	1665	574	90	0-207	207-574			DNR	
CL-1	Linwood Lake	22-56-14	568480	5240620	1545	704	60/270	0-91	91-704			ASC	MJS
CL-2		3-55-14	567920	5236830	1490	534	60/270	0-40	40-534			ASC	MJS
CL-3	Whiteface Res.	9-56-14	566780	5243775	1500	360	60/270	0-155	-----	155-360		ASC	MJS
SL-1B	Linwood Lake	22-56-14	568150	5240880	1493	1008	90	0-18	18-1008			DNR	MJS
26009	Whiteface Res.	2-56-14	568840	5245280	1520	1294	56/270	0-115	115-1294			USX	MJS
26012	Linwood Lake	23-56-14	569320	5240930	1495	764	50/45	0-39	39-764			USX	MJS
26070	Whiteface Res.	3-56-14	568700	5245270	1510	809	55/270	0-91	91-809			USX	MJS
26071	Whiteface Res.	2-56-14	569285	5246360	1510	1019	50/123	0-60	60-1019			USX	MJS
26072	Whiteface Res.	2-56-14	569360	5246640	1530	800	50/90	0-74	74-800			USX	MJS

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
BC-80-1	Whiteface Res.	34-57-14	567610	5246900	1555	603	47/255	0-163	----	163-603		DNR	MJS
CN-1	Water Hen	28-57-14	566855	5249040	1520	1182	90	0-70	70-1109		no core 70-170	DNR	MJS
CN-2	Water Hen	28-57-14	566630	5249050	1515	561	90	0-50	50-561			DNR	MJS
CN-3	Water Hen	28-57-14	566620	5249420	1515	461	65/270	0-74	74-320	320-461		DNR	mjs
CN-4	Water Hen	28-57-14	566720	5248800	1515	695	65/270	0-43	43-695			DNR	mjs
CN-5	Water Hen	28-57-14	566600	5248330	1535	589	60/270	0-90	90-589			DNR	
CN-6	Water Hen	28-57-14	566500	5248330	1525	745	60/270	0-55	55-674	698-745	676-698 quartzite	DNR	mjs
CN-7	Water Hen	27-57-14	567085	5249020	1530	1752	90	0-76	76-1752			DNR	MJS
CN-8	Water Hen	28-57-14	566665	5249670	1515	434	60/270	0-63	63-434			DNR	
CN-9	Water Hen	28-57-14	566760	5248315	1540	745	60/225	0-73	73-745			DNR	
CN-10	Water Hen	28-57-14	567030	5248290	1540	1875	90	0-65	65-1745	1745-1875		DNR	MJS
CN-11	Water Hen	27-57-14	567505	5248860	1550	2975	90	0-93	93-2863	2863-2975		DNR	MJS
SL-1	Water Hen	28-57-14	566870	5248910	1525	722	45/270	0-80	80-722			ASC	MJS
SL-2	Water Hen	28-57-14	566755	5248680	1525	944	60/270	0-67	67-944			ASC	MJS
SL-3	Water Hen	28-57-14	566700	5249170	1515	502	45/270	0-80	80-502			ASC	MJS
SL-4	Water Hen	28-57-14	566680	5248440	1535	673	60/270	0-60	60-673			ASC	mjs
SL-5	Water Hen	28-57-14	566640	5248560	1520	670	50/270	0-101	101-670			ASC	mjs
SL-6	Water Hen	28-57-14	566690	5248680	1520	607	45/270	0-130	130-607			ASC	MJS
SL-7	Water Hen	28-57-14	566770	5248920	1520	562	45/270	0-108	108-562			ASC	MJS
SL-8	Water Hen	28-57-14	566620	5249300	1515	562	45/270	0-83	83-562			ASC	mjs
SL-9	Water Hen	28-57-14	566610	5249540	1515	742	60/270	0-66	66-742			ASC	mjs
SL-10	Water Hen	28-57-14	566830	5248910	1525	993	90	0-69	69-993			ASC	mjs
SL-11	Water Hen	28-57-14	566820	5249160	1515	1192	45/270	0-71	71-1192			ASC	MJS

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over- burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
SL-13	Water Hen	28-57-14	566865	5249280	1515	1183	45/270	0-50	50-1183			ASC	mjs
SL-14	Water Hen	28-57-14	566980	5248900	1535	457	45/270	0-92	92-457			ASC	MJS
SL-15	Water Hen	28-57-14	566750	5249415	1515	721	45/270	0-70	70-721			ASC	mjs
SL-16	Water Hen	28-57-14	566480	5249185	1515	869	50/90	0-29	29-869			ASC	MJS
SL-17	Water Hen	28-57-14	566580	5248685	1515	774	45/270	0-55	55-774			ASC	MJS
SL-19A	Water Hen	22-57-14	567285	5250110	1515	603	45/270	0-63	63-603			ASC	mjs
SL-20	Water Hen	21-57-14	566460	5250415	1518	213	45/270	0-49	49-213			ASC	MJS
SL-21	Water Hen	28-57-14	566870	5249020	1522	606	90	0-50	50-606			ASC	mjs
SL-22	Water Hen	28-57-14	566820	5248795	1525	124	90	0-53	53-124			ASC	MJS
SL-23	Water Hen	28-57-14	566665	5248800	1515	131	90	0-46	46-131			ASC	MJS
SL-24	Water Hen	28-57-14	566760	5249040	1515	262	90	0-24	24-262			ASC	mjs
SL-25	Water Hen	28-57-14	566960	5249020	1522	429	90	0-83	83-429			ASC	mjs
SL-26	Water Hen	28-57-14	566920	5249150	1520	987	90	0-54	54-951	951-987?	951-987 hnfl incl ?	ASC	MJS
SL-27	Water Hen	28-57-14	566975	5249140	?	277	90	0-50?	50?-277			nc	Ross, 1985
SL-28	Water Hen	28-57-14	566945	5249140	?	251	inclined	0-70?	70?-251			nc	Ross, 1985
II-1	Skibo South	16-57-14	566560	5252330	1535	493	45/285	0-100	100-493			DNR	MJS
II-2	Skibo South	16-57-14	565760	5251900	1540	1702	45/285	0-20	-----	20-1702		DNR	MJS
II-3	Skibo South	16-57-14	566730	5252790	1530	510	45/285	0-70	70-510			DNR	MJS
II-4	Skibo South	16-57-14	566560	5252590	1530	623	45/285	0-105	105-623			DNR	MJS
II-5	Skibo South	16-57-14	566500	5252100	1525	593	45/285	0-65	65-593		380-593 FN Unit	DNR	MJS
II-6	Skibo South	16-57-14	566770	5252290	1535	1323	45/285	0-88	88-1323		975-1323 FN Unit	DNR	MJS
SR-1	Skibo South	9-57-14	566900	5253550	1505	754	60/W	0-85	85-754			ASC	MJS
27016	SKIBO	34-58-14	567470	5256685	1510	1605	90	0-94	94-1580	1580-1605	121-583 with OUIs	USX*	MJS

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
11547	SKIBO	34-58-14	567340	5256640	1510	485	60/270	0-72	72-349	349-485 incl?		nc	--
11549	SKIBO	34-58-14	567670	5256630	1510	955	60/270	0-89	89-955			nc	--
13603	SKIBO	34-58-14	566830	5256680	1490	375	90	0-32	-----	32-375		nc	--
13605	SKIBO	34-58-14	567115	5256640	1510	953	90	0-23	23-794	794-953		nc	--
13608	SKIBO	34-58-14	567115	5256640	1510	744	45/270	0-36	36-660	660-744		nc	--
13610	SKIBO	34-58-14	567230	5256650	1510	535	55/270	0-28	28-535			nc	--
13612	SKIBO	34-58-14	567150	5256570	1510	1054	90	0-49	49-888	888-1054		nc	--
13615	SKIBO	34-58-14	567330	5256510	1510	1450	90	0-63	63-1237	1237-1450		nc	--
13616	SKIBO	34-58-14	567400	5256760	1510	447	90	0-114	114-447			nc	--
13617	SKIBO	34-58-14	567760	5256750	1510	787	90	0-67	67-787			nc	--
13618	SKIBO	3-57-14	567230	5256280	1510	1585	90	0-57	57-1530	1530-1585		nc	--
13619	SKIBO	34-58-14	567260	5257000	1520	1209	90	0-16	16-1084	1084-1209		nc	--
13621	SKIBO	34-58-14	567270	5257340	1520	1185	90	0-19	19-1125	1125-1185		nc	--
13624	SKIBO	34-58-14	567640	5257950	1500	389	90	0-15	15-389			nc	--
13625	SKIBO	27-58-14	567710	5258690	1490	2295	90	0-33	33-2236	2236-2295		nc	--
34898	SKIBO	34-58-14	567380	5256640	1510	1475	90	0-78	79-1415	1415-1475		nc	--
40901	SKIBO	34-58-14	567720	5256725	1510	1141	80/270	0-68	68-1141			nc	--
40902	SKIBO	3-57-14	567530	5256315	1510	925	80/270	0-35	35-925			nc	--
40904	SKIBO	3-57-14	567530	5256375	1510	707	80/270	0-73	73-707			nc	--
DDH-3	SKIBO	34-58-14	567710	5257680	1540	1200	90	0-40	40-1090	1090-1200	SKELETONIZED HOLE!	DNR	MJS
A-1	Sec 22	21-58-14	566800	5260060	1510	563	60/?	0-32	32-429	429-563		DNR	MJS
A-2	Sec 22	22-58-14	567290	5260060	1511	1611	60/?	0-47	47-1559	1559-1611		DNR	MJS
A-3	Sec 22	22-58-14	567395	5260720	1530	405	90	0-76	(108-110)	76-405		DNR	MJS

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
A-4	Sec 22	22-58-14	567520	5259840	1525	829	90	0-57	57-829			DNR	MJS
A-5	Sec 22	22-58-14	567870	5260420	1530	509	90	0-67	67-509			DNR	MJS
A-6	Sec 22	22-58-14	567520	5259940	1525	692	45/288	0-79	79-692			ASC	MJS
SL-2	Allen	16-58-14	566820	5262120	1520	895	90	0-63	-----	63-895		DNR	MJS
A2-1	Allen	9-58-14	566785	5263620	1470	232	63/250	0-20	-----	20-232		DNR	MJS
A2-2	Allen	9-58-14	566395	5264110	1470	304	90	0-29	29-36	36-304		DNR	MJS
A2-3	Allen	9-58-14	566725	5264410	1470	1535	90	0-12	12-1535			DNR	MJS
A2-4	Allen	9-58-14	566520	5264250	1488	593	60/250	0-27	27-520	520-593		DNR	
A2-5	Allen	9-58-14	566625	5263470	1480	324	60/250	0-20	20-192	192-324		DNR	MJS
A2-6	Allen	4-58-14	566540	5264640	1460	2570	45/297	0-38	38-2508	2508-2570		DNR	
A2-7	Allen	9-58-14	566180	5264380	1448	1224	45/355	0-32	990-1224	32-990		DNR	MJS
A3-1	Allen	4-58-14	565870	5264580	1440	300	60/W	0-35	-----	35-300		DNR	MJS
A3-2	Allen	4-58-14	565730	5264660	1440	345	60/W	0-38	-----	38-345		DNR	MJS
W-4	Wyman Cr.	4-58-14	566600	5265060	1470	3114	90	0-53	53-3114			DNR	MJS
W-5	Wyman Cr.	3-58-14	566700	5265560	1480	1634	90	0-9	9-862	862-1574	BIF 1574-1634	DNR	MJS
W-15	Wyman Cr.	3-58-14	567800	5265540	1495	2545	90	0-19	19-2545			DNR	MJS

ABBREVIATIONS:

MJS = logged by Mark J. Severson

mjs = checked by Mark J. Severson

SPEC = drill core preserved as 2 inch specimen samples taken every 10 feet

DNR = drill core stored at Minnesota Department of Natural Resources, Hibbing, MN

USX = drill core stored at USX Corp. facilities at Coleraine, MN, on the premises of the NRRI Coleraine Minerals Research Laboratory

USX* = drill core stored at USS/MINNTAC facilities at Mt. Iron, MN

Drill Hole	Deposit/Area	Location (S-T-R)	UTM Easting	UTM Northing	Collar Elev. (ft.)	Total Depth (ft.)	Incl./ Azimuth	Over-burden	Complex	Virg. Fm.	Misc.	Core at:	Logged
ASC = drill core stored at American Shield Corp. facilities at Duluth, MN													
nc = no drill core preserved													
OUI = Oxide-bearing Ultramafic Intrusion													
BIF = Biwabik Iron-formation													
bslt = basalt													

APPENDIX 2

DATA FILE INFORMATION

The following files are given in Appendix 2 on the floppy diskette (1.2 Mb) in the back pocket of this report:

SOCOMP.WK1 - Drill Hole Locations (32,098k, 04-28-95, 12:03p)
Drill hole locations and major lithologic unit breaks for all drill holes within the South Complex study area.

SOCOCHEM.WK1 - South Complex Geochemistry (350,957k, 04-10-95, 2:35p)
Whole rock geochemical data (previous analyses) for drill core samples from the South Complex area. Results are grouped according to drill hole and deposit/area. Corresponding rock type and rock unit are also listed.

SCOMCHEM.WK1 - South Complex Geochemistry (41,840k, 04-04-95, 1:42p)
Whole rock geochemical data (this investigation) for drill core samples from the South Complex. Results are grouped according to deposit/area.

SCSORT.WK1 - South Complex Geochemistry (231,202k, 04-20-95, 3:02p)
The SOCOCHEM.WK1 and SCOMCHEM.WK1 data files are combined in this data file. These data are used to make the geochemical plots of this report. Note that this file does not contain all of the sampled intervals that are listed in the SOCOCHEM.WK1 data file. Sampled intervals ("improper" or bad samples) that cross contacts, or with poor whole rock totals (<98% and >102%) have been eliminated from the SOCOCHEM.WK1 file and are not included in this data file. Sampled intervals of massive sulfide are also eliminated from this data file.

SOCOTI.WK1 - OUI TiO_2 Geochemistry (171,498k, 04-06095, 2:34p)
Listing of all available TiO_2 analyses for only the Oxide-bearing Ultramafic Intrusions (OUI) within the South Complex area and within the Partridge River intrusion. Analyses for Cu, Ni, S, Cr, V, Fe_2O_3, FeO, Total Fe, Pt, and Pd are also listed for intervals with the TiO_2 analyses. The values are grouped according to drill holes within each deposit/area.

SCPGE.WK1 - South Complex PGE Scans (10,129k, 04-28-95, 11:58a)
Listing of all samples within the South Complex area with complete PGE scans (intervals analyzed for only Pt and Pd are not included).