GEOLOGY, MINERALIZATION, AND GEOSTATISTICS OF THE MINNAMAX/BABBITT CU-NI DEPOSIT (LOCAL BOY AREA), MINNESOTA

PART I: GEOLOGY

By

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ABSTRACT

The Minnamax Cu-Ni deposit (also called the Babbitt deposit) is situated within what has been informally referred to as the Partridge River intrusion (or Partridge River Troctolite) of the Duluth Complex (1.1 Ga), northeastern Minnesota. The deposit has been subdivided into five contiguous ore zones; the Local Boy area and Bathtub area are two ore zones described in this report. Within the deposit are a wide variety of troctolitic, ultramafic, and footwall rock types, and hornfelsed inclusions (both footwall and hanging wall). Many specific rock types are correlative between drill holes and can be grossly categorized into seven sub-horizontal troctolitic units, three types of hornfelsed inclusions, and a late cross-cutting pegmatitic phase. Also present are correlative units within the footwall rocks. All rock units were identified by detailed relogging of 61 surface drill holes (117,605 feet of core) and are portrayed on nine cross-sections that extend through various portions of the Minnamax deposit.

Severson and Hauck (1990) described the stratigraphy of the troctolitic rocks of the Partridge River Troctolite to the west of the Minnamax deposit; the stratigraphy is referred to as the Partridge River Troctolite Series (PRTS). Most of the PRTS rock units defined at the Dunka Road Cu-Ni deposit (located to the immediate SW of Minnamax) by Severson and Hauck (1990) are present at Minnamax. However, the overall picture at Minnamax is more complicated than Dunka Road due to rock type changes that are manifested by: 1) pinch-out and reappearance of specific marker bed units; 2) down-strike gradational changes of ultramafic horizons; 3) extremely limited areal extent of some ultramafic horizons; and 4) gradational changes in the troctolitic rock types between drill holes. In some areas a particular marker horizon may "disappear" laterally and then reappear at the same stratigraphic level in another group of drill holes. In spite of these local difficulties, a gross stratigraphy of seven subhorizontal igneous units is present at Minnamax and consists of (from

bottom to top): Unit I - heterogeneous, sulfide-bearing augite troctolite and troctolite with abundant metasedimentary inclusions; Unit II - homogeneous troctolite with a basal picrite horizon (Unit II is present only in the SW portion of the Minnamax deposit); Unit III - mottled textured anorthositic troctolite to troctolite with characteristic olivine oikocrysts (Unit III is present mainly in the SW portion of Minnamax and is enveloped by Unit I to the NE); Unit IV - mixed homogeneous troctolite and augite troctolite (augite troctolite is at the top of Unit IV in localized areas) with a semi-persistent basal ultramafic horizon termed the "± picrite"; Unit V - homogeneous anorthositic troctolite that exhibits a gradational contact with Unit IV; and Units VI and VII - homogeneous troctolites with persistent basal ultramafic horizons. More abundant and thicker ultramafic horizons are present in Units VI and VII in the Bathtub area of the Minnamax deposit. Specific marker horizons utilized in drill hole correlations include: Unit III, "± picrite," "pocket picrite," top of Unit IV (augite troctolite), and the ultramafic base of Units VI and VII.

The troctolitic stratigraphy is cut by pegmatitic orthopyroxenite and peridotite bodies that are referred to as OUI - Oxide-bearing Ultramafic Intrusions. Pegmatitic hybrid hornblendite and granophyre also cut the stratigraphy and are often related to the OUI bodies. Rusty chlorine-rich drops may commonly coat the core of the ultramafic horizons and OUI bodies.

Several enigmatic hornfelsed inclusions are present in Units VI and VII at Minnamax. These are grouped in two categories that include: 1) CC-type inclusions that are similar to outcrops of the Colvin Creek hornfels; and 2) "pic"-type inclusions that are similar to nearby outcrops of basalt inclusions. Both inclusion types are similar in that they contain fine-grained plagioclase-filled ovoids or wisps that may represent vesicles, and they exhibit the same chemical signature. However, they exhibit a different mineralogy (the CC-type inclusions are oxide-rich). Their stratigraphic position in the troctolitic rocks suggests that they are probably hanging wall material

(North Shore Volcanic Group). While these two inclusion types are readily correlative between drill holes, the nature of their different mineralogy remains unknown.

Another enigmatic rock type is present within the lower portion of the Virginia Formation footwall rocks. The rock is unique in that it contains hornblende ± olivine and locally grades into serpentinized picrite with hornblende. It is generally concordant with the overall bedding of the Virginia Formation and is referred to as the sill(?) unit. Whole rock geochemistry indicates that this unit locally exhibits: high Cl contents that are similar to Cl values of ultramafic horizons in the troctolitic rocks; MG numbers that are more primitive than the ultramafic horizons; and high Cr contents that are much higher than anything sampled in the overlying troctolitic section. If the unit was a sill, it now exhibits gradational contacts with the metasedimentary rocks and is characterized by a granoblastic texture with superimposed euhedral hornblende. These data may indicate that the sill was intruded before, and hornfelsed during, emplacement of the majority of the Partridge River Troctolite Series.

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INTRODUCTION

BACKGROUND

A detailed geological-geostatistical investigation of the Minnamax/Babbitt Cu-Ni deposit was undertaken in order to assist a private mining firm in their assessment of the potential for a non-ferrous underground mine. Rhude and Fryberger, Inc. (R & F) of Hibbing, Minnesota, has leased a portion of the Minnamax deposit from the State and is currently evaluating the potential of mining only the high-grade massive sulfide portion of the deposit. This high-grade portion is referred to as the "Local Boy area" -- it is one of five subareas within the entire Minnamax deposit. The five subareas within the Minnamax deposit were subdivided by AMAX Inc. geologists and include: Local Boy area, Tiger Boy area, Bathtub area, updip area, and SW Extension area (see Figure 2).

Recent investigations (Morton and Hauck, 1987; Hauck and Barnes, 1989; Geerts et al., 1990; and Kuhns et al., 1990) have shown that "near ore grade" values of platinum group elements (PGEs) and other precious metals (gold, silver) are often associated with high-grade copper zones, and thus additional mineral value may be present within the Cu-Ni ore bodies. However, the data regarding PGE values in the associated ore zones are often quite limited in spatial extent and are not conducive to conducting overall ore reserves.

The main objective of this investigation is to assist R & F in their evaluation of establishing a non-ferrous mine within the Local Boy area. The project is funded through the Greater Minnesota Corporation (GMC), which is a state-funded agency designated to promote the state's economic advancement. The assistance given to R & F by the Natural Resources Research Institute (NRRI) is to: 1) determine geologic, stratigraphic, and structural ore controls through detailed logging of existing drill cores; 2) conduct a geochemical sampling campaign on previously analyzed, high-grade copper intervals for PGE and precious metals; 3) determine PGE and precious metal ore controls (if distinct from the Cu-Ni mineralization); 4) conduct a "state of the art" geostatistical analysis of the Cu-Ni (plus PGE) ore reserves; and 5) determine (if possible) the mineralogical modes of the PGE minerals within the Cu-Ni ore zones. The results of this investigation are presented in two parts: Part I (this report) includes descriptions pertaining to the general geology, igneous stratigraphy, igneous petrography, and whole rock chemistry; Part II (Severson and Barnes, 1991) includes descriptions pertaining to the basal massive sulfide mineralization, sulfide petrography, PGE analytical results, and geostatistical ore reserve analysis.

Because the detailed geology of the entire Minnamax deposit and the Local Boy area was totally unknown, relogging of drill core (both surface and underground drill holes) was imperative for categorizing the Cu-Ni ore and the geologic controls. Previous studies (Severson, 1988; Severson and Hauck, 1990) have shown that a stratigraphic layering pattern is present within the troctolitic rocks (Partridge River Troctolite Series). This pattern, in turn, can be used to define fault offsets that may have served as ore fluid conduits. Geerts et al. (1990) and Geerts (1991) have since utilized this same stratigraphy within the Dunka Road Cu-Ni deposit (located about two miles WSW of the Minnamax deposit), and has shown that the layering pattern can be used to help outline specific horizontal ore zones that contain anomalous Pd values (800 to >2000 ppb). Thus, knowledge of geologic controls is essential to understanding the origin and distribution of specific ore horizons within a deposit.

An attempt was made to strategically relog surface drill holes that: 1) encountered the most rock section (deepest holes along the southern margin of the deposit); 2) had been previously logged for Masters and Ph.D. theses; and 3) were put down within the general vicinity of the underground drifting (Local Boy area). Underground drill holes situated within the highest Cu-Ni zone of the Local Boy area massive sulfide ore were also relogged. Drill holes that had previously been logged for M.S. and Ph.D. theses and were relogged in this investigation include: B1-128 (Fellows, 1976);

B1-295 (Molling, 1979); B1-91 ,B1-297, B1-304, and B1-364 (Tyson, 1979); B1-132 (Ryan, 1984); B1-221 (Chalokwu, 1985), and B1-82 and B1-363 (Mills-Ervin, 1988). The concept for relogging these holes was to eventually incorporate their geology, geochemistry, and microprobe data into a regional understanding of the Partridge River Troctolite Series (PRTS) as defined in Severson and Hauck (1990), and to tie their drill holes to a common overall stratigraphy. Only the latter has been accomplished in this investigation.

GEOLOGIC SETTING

The Duluth Complex (Complex) is a multiple series of tholeiitic intrusions of Keweenawan age (1.1 b.y.) that formed with associated basaltic volcanism along a portion of the Midcontinent Rift. The Complex is sporadically exposed in an arcuate belt extending from Duluth, Minnesota, north toward Ely and from there east-northeast toward Hovland, Minnesota. Along the western edge, from Duluth to Babbitt, the base of the Complex is in sharp contact with shallow-dipping, middle Precambrian (1.7 b.y.) metasediments of the Virginia/Thompson Formations, and at some

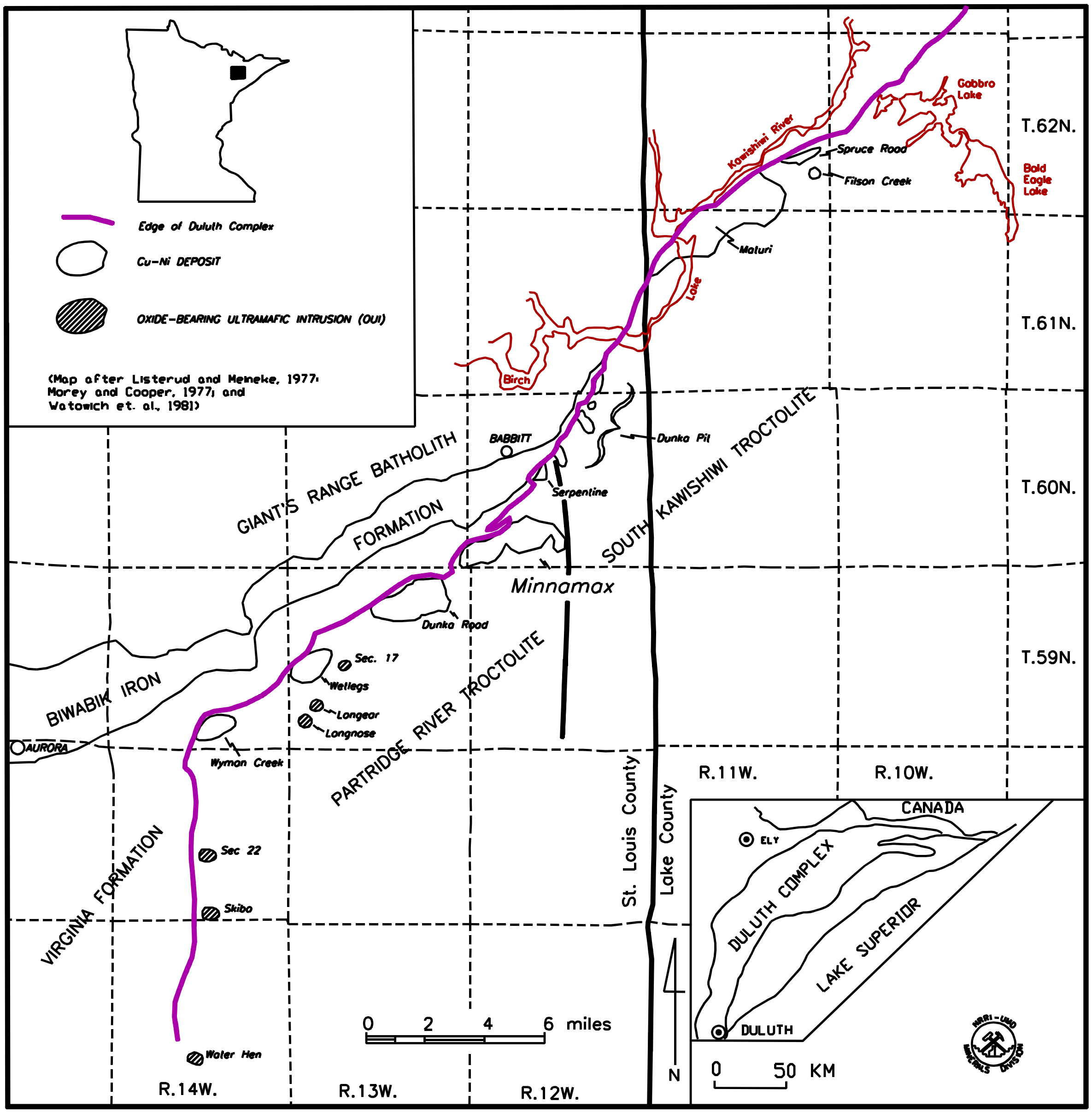

Figure 1. Location of Cu-Ni and Fe-Ti deposits within the Duluth Complex, northeastern Minnesota.

localities the underlying Biwabik Iron-Formation (Fig. 1). Northeast from Babbitt to the Gunflint Trail, the footwall rocks of the Complex consist of Archean (2.7 b.y.) granites and greenstones. At the upper contact (hanging wall) of the Duluth Complex are the mafic volcanics of the North Shore Volcanic Group; however, because gradations between the two are commonly present, the "upper contact" of the Complex is arbitrarily chosen in places (Weiblen and Morey, 1976).

Rocks of the Duluth Complex are varied, but in general can be divided into an early Anorthositic Series (Davidson, 1972) and a later Troctolitic Series (Bonnichsen, 1972). Near Babbitt, Minnesota, the Troctolitic Series has been further subdivided into at least three intrusions/areas that have been given the informal names of: South Kawishiwi Troctolite (SKT) or intrusion; Partridge River Troctolite (PRT) or intrusion; and Bald Eagle intrusion (Foose and Weiblen, 1986). Within this region, several large Cu-Ni deposits have been delineated at the base of the SKT and PRT intrusions/areas. From north to south these deposits are: Spruce Road, Maturi, Dunka Pit, Serpentine, Minnamax (also known as Babbitt), Dunka Road, Wetlegs, and Wyman Creek (Fig. 1). Oxide-bearing Ultramafic Intrusions (OUI -- Severson and Hauck, 1990) are also present within the PRT and include, from north to south: Section 17; Longear; Longnose; Section 22; Skibo; and Water Hen (Fig. 1).

Host rocks of the Cu-Ni mineralization are predominantly augite troctolite and troctolite. However, anorthositic troctolite, picrite (melatroctolite), olivine gabbro, and norite also host the mineralization. Cu-Ni mineral phases consist predominantly of disseminated interstitial sulfides (1-5% volume in the intrusive rocks) of chalcopyrite, cubanite, pyrrhotite, and pentlandite. Massive sulfide mineralization is rare, but is present within the Local Boy area of the Minnamax deposit and in scattered drill holes in the Serpentine deposit. Host rocks for the massive sulfide ore include the footwall sediments (Virginia Formation) and norite-troctolite intrusive rocks. The major sulfide minerals are essentially the same as for the disseminated ore.

Studies of the sulfides present within the disseminated ore (Boucher, 1975; Matlack, 1980; Ripley, 1981, 1986a, 1990; Rao and Ripley, 1983; Tyson and Chang, 1984; Al-Alawi, 1985; Foose and Weiblen, 1986; Ripley and Alawi, 1986; Ripley and Al-Jassar, 1987) point to the probable role of country rock contamination in sulfide generation. Sulfur isotopic studies (Mainwaring and Naldrett, 1977; Ripley, 1981; Ripley and Al-Jassar, 1987) indicate that the majority of sulfur in the deposits is of sedimentary derivation (Ripley and Taib, 1989, p. 320). However, addition of sulfur through an *in situ* process alone is considered inadequate in the massive sulfide zone of the Local Boy area. Ripley (1986a, 1986b) proposed a model of sulfur introduction prior to (within a secondary or auxiliary magma chamber at depth), or during magma emplacement to explain the Local Boy area massive sulfides.

HISTORY OF EXPLORATION - MINNAMAX

Mineralized rocks were first discovered in 1948 by local prospectors Childers and Whitesides, in an excavation dug for a newly constructed forest service road located along the Kawishiwi River near Ely, MN (Watowich et al.,1981). Subsequent exploration and drilling by several companies during the late 1950s through the middle 1970s has delineated at least eight deposits (from Ely to Hoyt Lakes) that contain a combined 4.4 billion tons of ore averaging 0.66% Cu (3:1 Cu:Ni) when a 0.5% Cu cut-off grade is assumed (Listerud and Meineke, 1977). The Minnamax/Babbitt deposit is situated about five miles south of Babbitt, MN in sections 28, 29, 30, 31, 32, 33 (T.60N., R.12W.) and section 36 (T.60N., R.13W.). The deposit was first explored by the Bear Creek Mining Company (Kennecott Corp.) and was delineated by a series of drilling programs (1958-1960 and 1967-1971). In 1974, AMAX Inc. reached an agreement with Bear Creek to evaluate the feasibility of developing the property; the project was named Minnamax at this time. AMAX proceeded to drill 228 surface holes during 1974-1978, complete an exploratory shaft in

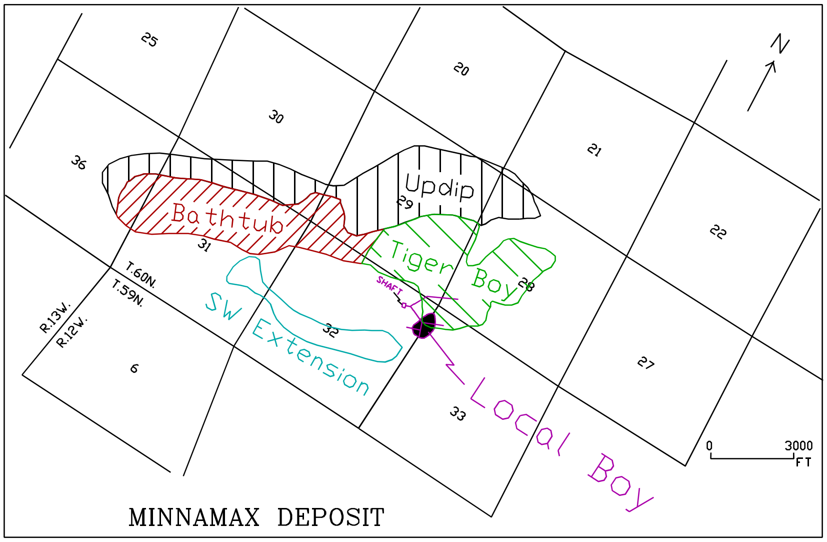

Figure 2. Ore zones of the Minnamax Deposit (as defined by AMAX).

1976, complete four drifts in 1977 (1700 foot level), and complete an underground drilling program in 1978 (Watowich et al., 1981).

To date, 432 surface drill holes, 219 underground drill holes, and 3,800 feet of underground drifting have been completed within the deposit. AMAX subdivided the deposit into five contiguous portions (Fig. 2) that they determined collectively contained 364 million tons of 0.84% Cu (using a 0.6% Cu cut-off). The Local Boy area is the most unique of all the Complex-hosted Cu-Ni deposits in that its ore is massive to semi-massive sulfide situated in both the sedimentary footwall rocks and the troctolitic rocks. The ores of the other Complex-hosted deposits are situated entirely within the troctolitic rocks and contain no massive to semi-massive ore. AMAX estimated that five million tons of 1.89% Cu ore are contained within the Local Boy area massive sulfide ores (utilizing a 0.6% Cu cut-off). Due to a decrease in copper prices and environmental conflagration, AMAX -- and subsequently Kennecott -- dropped their state and private leases within the Minnamax deposit. Recently, with increased copper prices and increasing knowledge of PGE potential, R & F has leased the state lands and is considering mining only the highest-grade portion (> 2-4% Cu cut-off) of the Local Boy area.

PRESENT INVESTIGATION

This report is a summary of activities conducted from November, 1989, to June, 1991. To date, 61 surface drill holes (117,605 feet of core) and 76 underground drill holes (19,891 feet of core) have been relogged in detail from the Minnamax deposit -- specifically in the Local Boy area. Because the drill core was in the process of being transferred to the Minnesota Department of Natural Resources Drill Core Library in Hibbing, Minnesota, and was scattered about the Iron Range, a wide variety of logging conditions were encountered.

After the majority of the holes in a specific area were logged, cross-sections were constructed and individual rock units were correlated. In this manner, a particular bias of "looking for" a specific horizon was minimized. Several cross-sections of both surface and underground holes were prepared and are included in Parts I and II.

Approximately 800 geochemical samples of previously analyzed (Cu, Ni, S) intervals were selected from the underground Local Boy area drill holes to be analyzed for Pt, Pd, Au, and Ag. These samples were selected specifically from the high-grade (>1% Cu) material that exhibited spatial continuity. Unfortunately, no lower grade material outside of >1% Cu material was sampled due to budget constraints and thus a bias was introduced in the subsequent geostatistical analysis -- essentially the weakly mineralized Cu-Ni halo was ignored. This bias was considered before the sampling campaign was initiated; however, at that time, it was decided only the high-grade Cu material could be economically mined anyway. Thus, knowledge of the value of precious metals within the adjacent halo was of lesser importance and samples were not taken (a proper statement from a mining point of view, but incorrect in the exploration sense). PGE , Au, and Ag results of 791 samples, along with 275 additional analyses obtained from a R & F sampling campaign, have been entered into a data base that was used in the geostatistical analysis (Part II - Appendix 2). This data base also includes all previously analyzed intervals (Cu, Ni, and S values) from: 1) all the underground holes; 2) all underground drift samples; and 3) pertinent surface drill holes within the Local Boy area.

Twenty-nine samples were collected from eight different rock units for whole rock, trace element, and rare earth element analyses. PGE scans were conducted on eight pulverized samples by Dr. Sarah-Jane Barnes of the University of Quebec at Chicoutimi. Six of these samples were known to contain >1.0 ppm Pd and/or Pt. Results of the whole rock analyses (Appendix A) and PGE scans (Table 5) are included in Part I.

A geostatistical analysis of the Local Boy area was conducted by Dr. Randal Barnes (University of Minnesota, Minneapolis) and is included in Part II. Data completed to date include: grade/tonnage curves, grade/tonnage figures, inter-variable correlations, variograms, and a block model interpolation of the Cu and Ni mineralization in 50 x 50 x 50 foot blocks. These blocks are collectively displayed for six different levels at the Local Boy area.

ACKNOWLEDGEMENTS

This project has been funded by Minnesota Technology, Inc. (formerly the Greater Minnesota Corporation). Thanks are extended to Dan England and R & F personnel for geochemical analytical results, and for their discussions pertaining to the Local Boy area. Drill core and corporate files pertaining to the entire Minnamax deposit area are stored at the Minnesota Department of Natural Resources (MDNR) facility in Hibbing, Minnesota. Special thanks are extended to the MDNR core library staff for their constant aid in locating drill holes, shuffling pallets of core, and sawing drill core. Copies of drill hole logs (by Bear Creek and AMAX geologists) and analytical results (Cu, Ni, S) are also on file at the NRRI. Discussions with Steven Hauck (NRRI), Dr. Penelope Morton (University of Minnesota, Duluth), and Dr. Tuomo Alapieti (University of Oulu, Finland) proved extremely valuable in deciphering the sulfide and oxide petrography and in unraveling some of the complexities inherent within the Duluth Complex.

Thanks are also extended to Linda Lindberg (NRRI) for entering all the geochemical data that was used in the geostatistical analysis, and for preparing the countless thin sections, polished thin sections, and polished sections that were used in this investigation.

The writers of both parts (Part I and II) are deeply indebted to Steven Hauck (NRRI) for his: help in coordinating this effort; endless proofreading of the manuscript; aid in handling/manipulating the data base; and criticisms, comments, and encouragements.

LITHOLOGIC DESCRIPTIONS OF TROCTOLITIC UNITS

INTRODUCTION

Detailed relogging of drill core for 61 surface holes, spread throughout the entire Minnamax deposit (Plate I), identified at least seven major sub-horizontal troctolitic rock units. These seven units are correlative with rock units identified by Severson and Hauck (1990) in the Dunka Road, Wetlegs, and Wyman Creek deposits. Thus, a fairly regular stratigraphic layering pattern has been identified within the Partridge River over a 15-mile strike-length. A generalized stratigraphy of the Partridge River Troctolite Series (PRTS) from Wyman Creek to Minnamax is portrayed in Figure 3. However, it is important to remember that the stratigraphy depicted is generalized, and it is not uncommon to find a particular hole that partially or totally deviates from the "norm" (this occurs the most readily within the Minnamax deposit area). Therefore, the stratigraphy shown in Figure 3 is only a general stratigraphic section that represents the majority of drill holes logged to date -- some variations are present locally. These local variations are shown on all the cross-sections (Plates II through X) and are readily observed only when the cross-sections are closely scrutinized (a close scrutiny of the sections is encouraged for those that may relog additional holes in the same vicinity as the holes portrayed in this report).

During relogging, rock types were classified according to the classification scheme depicted in Figure 4. The igneous rock names were based on visually estimated modal percentages of plagioclase, olivine, and pyroxene. When there was a dramatic fluctuation in the modal percentages of minerals, either an average rock name was assigned, or a range of two rock type names was assigned to the particular interval. In some cases there were such extreme variations in modal percentages that a particular interval was simply designated as "het," for

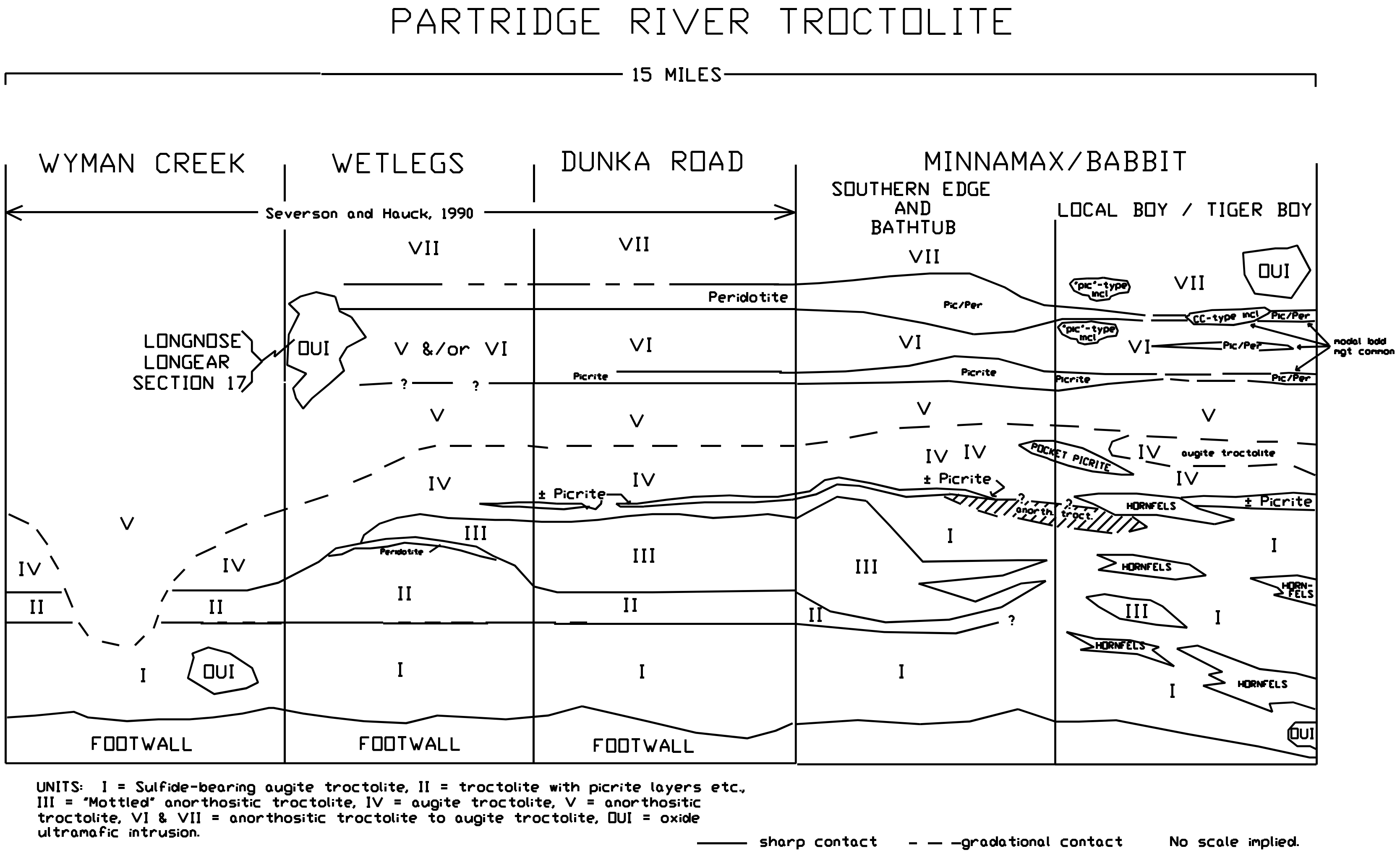

Figure 3. Generalized stratigraphy of the Partridge River Troctolite Series (after Severson and Hauck, 1990).

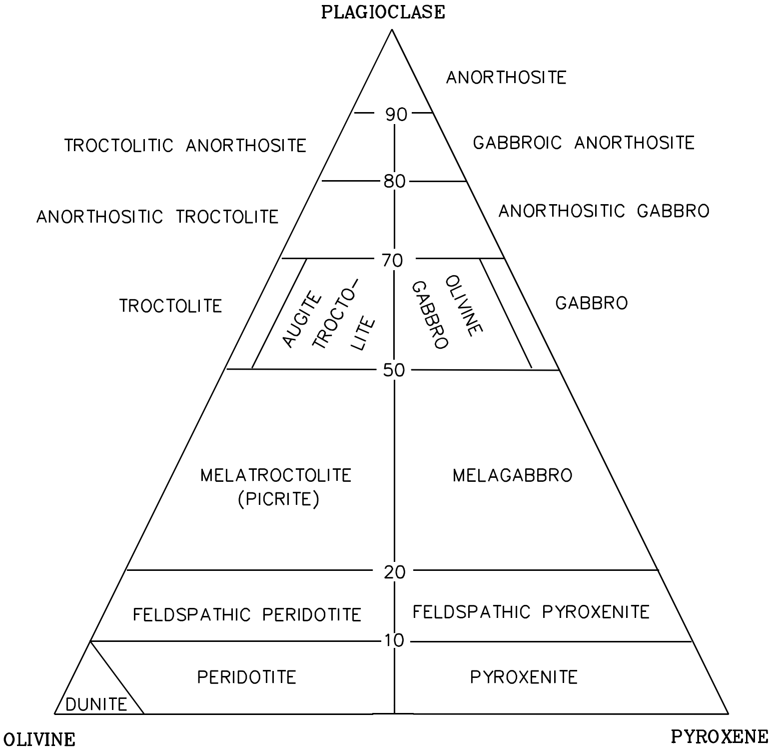

Figure 4. Rock classification (after Phinney, 1972).

heterogeneous, on the drill logs and cross-sections. The modifier "oxide-bearing" and "sulfide-bearing" refer to zones with >10% oxides and >0.5% sulfides, respectively.

The drill holes along the southern margin of the Minnamax deposit ("Stratigraphy" line on Plate I) were relogged first because they are the deepest (>2,800 feet) and therefore, intersect the most stratigraphic rock section. After all the holes in this line were logged, the data were plotted on a "hung" stratigraphic section (Plate II) and specific rock units were correlated between drill holes. These rock units are designated Units I through VII (from bottom to top) using the same numbering scheme as Severson and Hauck (1990). Plate II is actually a doubly hung section -- the western half is hung on the top of Unit III (persistent "marker bed" described in Severson and Hauck, 1990), and the eastern half is hung on the top of Unit IV (persistent augite-rich augite troctolite present in the upper half of Unit IV -- present only in the Local Boy area). When the drill holes were portrayed in this manner other significant marker horizons could be correlated between drill holes, e.g. ultramafic horizons and <u>distinctive</u> troctolitic units. The footwall rocks (Virginia Formation and Biwabik Iron-Formation) are portrayed twice in Plate II to show details of internal variations within the footwall rocks (variations are shown at the bottom of Plate II where the footwall portion of each hole has been hung on the top of the Biwabik Iron-Formation).

After the deepest holes had been relogged, a line of holes within the Bathtub area of the Minnamax deposit were relogged (Plate III), followed by relogging of several lines of drill holes in the Local Boy area of the deposit (Plates IV through X = Local Boy 0 through 6). Plate III was prepared by hanging the holes from their collar elevations and then correlating persistent rock units (note that the distance between drill holes is not to scale on Plate III). Plates IV through X were prepared by drawing true cross-sections, with projected drill hole drifts, and then making the necessary rock unit correlations.

In viewing the above cross-sections, it is readily apparent that even though a persistent layering pattern are present, there are also numerous pinch-outs, variable unit thicknesses, and lateral lithologic changes. Not all of these variations are described in detail, but they can be recognized on the accompanying cross-sections.

UNIT I - SULFIDE-BEARING TROCTOLITE AND AUGITE TROCTOLITE

The lowest troctolitic unit of the PRTS in the Minnamax deposit consists dominantly of intermixed troctolite and augite-rich (>15% augite) augite troctolite that grades to olivine gabbro (due to increased augite content); most are sulfide-bearing. Grain size is variable, from fine (<1 mm) to pegmatitic (>10 mm), but overall, the troctolitic rocks are medium- (1-5 mm) to coarse-grained (5-10 mm). Unique to Unit I are extreme variations in modal mineral percentage and average grain size; both change rapidly over zones from a few feet to tens of feet. These changes are manifested by alternating heterogenous-textured zones and homogeneous-textured zones (in both the troctolite and augite troctolite rock types) that are <u>not</u> correlative between drill holes. An attempt to correlate specific alternating augite troctolite horizons and troctolite horizons between drill holes met with limited success. In most cases these horizons showed some crude correlation as interfingering (± bifurcating) zones; but overall, they exhibit a low predictability toward always occurring at the same stratigraphic level or having the same spatial configuration. Thus individual augite troctolite and troctolite zones within Unit I have not been specifically delineated on the accompanying cross-sections. In general, augite troctolite is more common in the lower half of Unit I. The heterogenous nature of Unit I is probably related to repeated injection of magma, accompanied by country rock contamination, along bedding planes of the Virginia Formation.

The thickness of Unit I is also highly variable. Along the southern periphery of the deposit (Plate II) Unit I ranges from 150 to 600 feet thick; whereas, elsewhere in the deposit it ranges from 600 to 1,000 feet thick. The latter range occurs where overlying Units II and III are not present. In some instances, Unit III is "enveloped" by Unit I and occurs as a lense approximately in the center of Unit I.

The position of the top contact of Unit I is generally based on four criteria, of which, all or only one are present in a particular drill hole. These criteria include: 1) decrease in sulfide content upwards into sulfide-free rocks; 2) presence of a semi-persistent coarse- to very coarse-grained (locally medium-grained or pegmatitic) anorthositic troctolite (denoted by the "at" subunit on the accompanying cross-sections); 3) presence of a semi-persistent large hornfels inclusion of Virginia Formation (present only in the Local Boy area); and 4) appearance of a semi-persistent ultramafic horizon (base of Unit II or base of Unit IV). However, in some instances the top of Unit I is not as apparent and the contact "pick" is based on where the known top is in surrounding drill holes.

Minor ultramafic horizons are scattered throughout the entire section of Unit I. They are characterized by olivine-rich (>40%) troctolite (ort), picrite (pic), feldspathic peridotite (fp), and peridotite (p). Vertical gradations between the above rock types are present within a single drill hole, and lateral gradations between the rock types are present between correlative drill holes. The ultramafic horizons are laterally discontinuous and can only be correlated with certainty in 2-4 closely spaced drill holes.

Inclusions of Virginia Formation are the most common in Unit I and vary from one inch to 210 feet thick. Rock types are the same as the sediments present at the basal contact. Several large shallow-dipping hornfels inclusions (raft-like in shape and up to 2,400 x 3,200 feet across) occur stacked above each other within the Local Boy area. The configuration of these inclusions suggests that Unit I was intruded along the bedding planes of the Virginia Formation in repeated pulses; coupled with the subsequent assimilation of the footwall rocks. The exact sequencing and timing of each individual intrusive that collectively make up Unit I is unknown. Dips of bedding planes within the inclusions vary from 20-50E, with local highly contorted zones, indicating that only minor rotation of these sedimentary rafts occurred during the continuous emplacement of Unit I.

Near the basal contact and surrounding the hornfels inclusions, the intrusive rocks have undergone sufficient contamination, and norite is the dominant igneous rock type. Norite describes generally fine-grained rocks that contain more hypersthene relative to olivine or augite. The thickness of norite intervals within Unit I is extremely variable (less than one foot to tens of feet) and can not always be correlated between drill holes. Even though norite is commonly present adjacent to hornfelsed sedimentary footwall rocks, there are several cases where troctolitic rocks and the footwall rocks are in direct contact. When present, the norite generally exhibits a gradational contact with the troctolitic rocks and a gradational to sharp contact with the metasedimentary rocks. The latter contact is difficult to pinpoint in some drill holes due to the fine-grained nature and similar mineralogy of both norite and metasedimentary rocks.

Sulfide-bearing zones are the most common within Unit I. On the accompanying cross-sections sulfide zones are designated on the left side of the drill hole by an "s" or "(s)" for >1.0% sulfides and 0.5-1.0% sulfides, respectively. In some drill holes, almost the entire section of Unit I is sulfide-bearing, whereas a spotty distribution is present in other drill holes. Spotty sulfide zones located in the upper portion of Unit I were referred to as "cloud zones" by AMAX geologists.

However, an isolated cloud zone of one drill hole often merges into continuous sulfide mineralization in surrounding drill holes. Overall, sulfide distribution and corresponding high Cu-Ni values are sporadic and complex and can not be projected from hole to hole with any degree of certainty.

The majority of sulfides present include pyrrhotite, chalcopyrite, cubanite, and pentlandite, which occur as interstitial grains within a plagioclase-augite-olivine framework. Other ore minerals include talnakhite, sphalerite, mackinawite, bornite, maucherite, chalcocite, covellite, godlevskite, galena, parkerite, native silver, and native copper. A detailed description of sulfides is included in Part II. Grain size is variable, ranging from <1 mm to 1.5 cm across. The sulfides also occur as coarse-grained aggregates associated with biotite, ilmenite, uralite, and/or coarse-grained apatite needles. Biotite is the most common and occurs as partial rims around the sulfides. Sulfide content generally averages 1-3%, but internal zones with 3-5% sulfides and zones with only trace-0.5% sulfides also occur. Zones with up to 10% sulfides are present locally. Pyrrhotite content generally increases, at the expense of other sulfides, toward the basal contact and/or hornfels inclusions.

Massive sulfide mineralization is only present at the basal contact within the Local Boy area. The host rocks are dominantly hornfelsed footwall rocks, but massive sulfides are also present within the adjacent norite and troctolitic rocks. The massive sulfide mineralization will be discussed in more detail in Part II.

UNIT II - TROCTOLITE

To date, Unit II has been found only in the deep holes in the southwestern portion of the Minnamax deposit area. It is characterized by a homogeneous-textured, medium-grained troctolite that locally grades to augite troctolite and anorthositic troctolite. Minor hornfels inclusions and sulfide-bearing zones are present in some of the drill holes that intersected Unit II. Unit II varies from 70 to 220 feet thick when present.

Toward its base, Unit II grades into a persistent 2-8 foot thick ultramafic horizon characterized by picrite and/or olivine-rich (>40%) troctolite. At its base, the picrite horizon is in sharp contact with the underlying Unit I. The top of Unit II generally exhibits a sharp contact with the overlying Unit III.

UNIT III - MOTTLED-TEXTURED ANORTHOSITIC TROCTOLITE TO TROCTOLITE

Unit III is the major "marker bed" of the PRTS in the Wetlegs, Dunka Road, and southwestern Minnamax deposit areas. This unit is fine-grained (1-2 mm) and characterized by troctolite to anorthositic troctolite that consistently grades into irregular patches that are plagioclase-rich and olivine-rich and gives the rock its mottled-texture. Locally augite troctolite or troctolitic anorthosite may be dominant, but the mottled-texture is retained. This mottled appearance is due to the highly irregular distribution of olivine oikocrysts that are the main characteristic feature of Unit III. Olivine oikocrysts are found exclusively in Unit III and in thin intervals within Unit VII at Minnamax. Their formation may be linked to a lack of initial nucleation points during crystallization of the magma, as has been suggested by Miller (1986) for similar olivine oikocrysts in mapped units of the Snowbank Lake Quadrangle. Because the distribution of olivine in Unit III is so erratic, the core has to be "looked at from a distance" in order to visually estimate the modal mineral percentages and assign an overall rock name. Plagioclase is generally lath-shaped (1-2 mm) and arranged in a decussate texture. Overall, Unit III is the finest-grained rock in the troctolitic section. Locally, pyroxene and ilmenite also occur as oikocrysts.

The thickness of Unit III is highly variable and ranges from 300 feet thick to over 850 feet thick at the extreme western edge of the Minnamax deposit. However, Unit III pinches out to the east and is only locally present (1-50 feet thick) in the holes logged in the Local Boy and Bathtub areas of the Minnamax deposit. In some cases, Unit III bifurcates and grades into typical-looking heterogeneous Unit I troctolites that lack olivine oikocrysts, or Unit III occurs as thin lenses totally "enclosed" in Unit I. Overall, Unit III is rarely present in the Local Boy area. However, Unit III is again present to the north of the Local Boy area, and has been noted in drill holes B1-65 and B1-430 (note that these holes are not portrayed on any of the accompanying cross-sections of this report).

Either Unit I or Unit II is present at the bottom contact of Unit III, which in most cases is sharp, but locally may be gradational. The top contact is generally sharp with either the overlying Unit IV or overlapping Unit I. Hornfelsed sedimentary inclusions are fairly common in Unit III and range up to 300 feet thick in drill hole B1-199. Only minor sulfide-bearing zones are present within Unit III.

UNIT IV - TROCTOLITE AND AUGITE TROCTOLITE

Unit IV is characterized by thick intervals of homogeneous troctolite and augite troctolite. Augite troctolite is common in the top half of Unit IV within the Local Boy area and grades downward into troctolite. This upper augite troctolite was utilized as a major "marker bed" in the Local Boy area. Note that the western drill holes of the stratigraphic section (Plate II) have been hung on the top of this augite troctolite ("agt"). In this area, there is a gradational increase in augite content in the interior of the "agt" and olivine gabbro is locally present. To the north of the Local Boy area this "agt" zone grades into troctolite; however, another augite troctolite zone is present in the bottom half of Unit IV (Plate VIII). Also at the Local Boy area, the "agt" zone is locally present throughout the entire section of Unit IV, e.g., Plate VIII. Augite troctolite is also the dominant rock type of Unit IV in the Bathtub area (Plate III). Both the troctolite and augite troctolite are homogeneous-textured and medium- to coarse-grained.

Sulfide-bearing zones are locally scattered throughout Unit IV in an inconsistent pattern. Minor sedimentary hornfels inclusions are also widely scattered throughout Unit IV.

An ultramafic horizon is present at the base of Unit IV in over one half of the relogged drill holes. Due to its semi-persistent occurrence, this horizon has been informally termed the "± picrite." When present, the "± picrite" ranges from 1 to 120 feet thick but is commonly about 5-15 feet thick -- the high thickness range is for intervals with several stacked ultramafic horizons interbedded with troctolites and thus represents a collection of several cyclic zones. Rock type is generally picrite, but olivine-rich troctolite (ort), feldspathic peridotite, and peridotite may be locally present as the dominant rock type. Both vertical and lateral gradations between all ultramafic rock types are present. Internal vertical contacts between these rock types, including troctolitic interbeds, generally exhibit a gradational increase in olivine with depth to a peridotitic base that, in turn, exhibits a sharp base (cyclic). Overall, the "± picrite" is characterized by a gradational top and a sharp base, but exceptions are also present. The rock is variably serpentinized, which has imparted a foliation (± slickensides) to the drill core.

Near the top of Unit IV is another semi-persistent ultramafic horizon that has been informally termed the "pocket picrite." It is confined to an east-west trending lense (open to the east) and is present in drill holes B1- 121, 138, 142, 144, 147, and 228. The "pocket picrite" varies from a few feet to 25 feet thick and consists of alternating beds of picrite, peridotite, dunite, olivine-rich troctolite, and troctolite; fine-scale modal bedding is locally present. Internal gradational tops and sharp bottoms are present in well developed cyclic units. All olivine-rich rocks are variably serpentinized.

The top contact of Unit IV is generally highly gradational (over tens of feet) into Unit V in most of the relogged drill holes. In some locales, the "pocket picrite" is present at the contact, the top of which exhibits either sharp or gradational contacts with Unit V. The contact between Units

IV and V is difficult to determine to the north of the Local Boy area and the division shown on Plate VIII (Local Boy 4) has been arbitrarily chosen.

UNIT V - TROCTOLITE/ANORTHOSITIC TROCTOLITE

Unit V is characterized by a homogeneous-textured, medium- to coarse-grained plagioclase-rich (65-70% plag.) troctolite that commonly grades into anorthositic troctolite; however, troctolite with <65% plagioclase is dominant in some areas. Locally, the rock also grades into troctolitic anorthosite or minor olivine gabbro. Sulfide-bearing zones, sedimentary hornfels, and ultramafic horizons are extremely rare within Unit V. Highly heterogeneous zones (variable grain size and/or modal percentages) and zones with primary igneous foliation (defined by aligned plagioclase laths) are locally present but cannot be correlated between drill holes. Thin zones of mottled-textured troctolite (inclusions?) occur in Unit V but are volumetrically unimportant. Minor inclusions of hanging wall rocks(?) first appear in Unit V and will be described later. The bottom contact of Unit V is gradational into Unit IV due to an increased percentage of olivine and augite with depth. The top contact of Unit V is sharp against an ultramafic horizon (base of Unit VI).

UNITS VI AND VII - TROCTOLITE TO ANORTHOSITIC TROCTOLITE

The two uppermost troctolitic units at Minnamax are remarkably similar, and thus they are both described in this section. Both are characterized by homogeneous-textured, medium- to coarse-grained troctolite and/or anorthositic troctolite (gradational) with minor augite troctolite and troctolitic anorthosite. Both contain: 1) a basal ultramafic horizon(s); 2) minor laterally discontinuous internal ultramafic horizons; 3) modally bedded adcumulus magnetite horizons; 4) heterogeneous zones that cannot be correlated between drill holes; 5) zones with primary igneous foliation (defined by aligned plagioclase laths) that <u>cannot</u> be correlated between drill holes; 6) rare sulfide-bearing zones; and 7) inclusions of both footwall (rare) and hanging wall rocks (designated as CC and "pic" on the accompanying cross-sections). Due to these similarities, actual unit assignment to either Unit VI or VII is difficult unless the drill hole has penetrated a lower marker bed, e.g., top of Unit IV, and the hole has been hung and correlated accordingly.

The ultramafic horizons at the base of Units VI and VII are characterized by an alternating assemblage of either/or: picrite, feldspathic peridotite, peridotite, dunite, olivine-rich (>40%) troctolite, picrite with troctolite beds, and troctolite with thin picrite interbeds. One or more of these rock types may be stacked above the other in no particular order within an individual drill hole. Lateral gradations between drill holes are common and are exhibited by changes along strike from peridotite to picrite to troctolite with olivine-rich bands, e.g., B1-141 in Plate V. During the initial drill hole relogging, olivine-rich modal bands/zones within troctolite were not originally thought to represent a particular ultramafic horizon. However, when all the cross-sections in the Local Boy area were collectively correlated (three dimensional correlation), these zones were found to occur at the same stratigraphic level as the major picrite and peridotite horizons. These overall lateral changes in ultramafic rock type may indicate local variations in the magma chamber controlled by floor topography or magmatic density currents. Overall, the ultramafic horizons exhibit a gradational top and sharp base. When present, internal cyclic zones also exhibit gradational tops and sharp bases.

The thickness of the basal ultramafics are highly variable depending on how many individual ultramafic horizons are stacked upon each other and on how much intervening troctolitic material is present between beds. In some cases, the ultramafic horizon appears to bifurcate into two distinct ultramafic horizons that can be correlated between drill holes over a small area. Generally, the ultramafic horizons are 5 to 30 feet thick, but thicknesses up to 150 feet thick occur locally (especially in the Bathtub area where abundant cyclic units are present in Units VI and VII). Serpentinization is variable in the ultramafic horizons and imparts a foliation (± slickensides) to the drill core. Generally, rocks with higher olivine content exhibit more intense serpentinization and foliation development.

Modally bedded magnetite horizons occur in three specific horizons within Units VI and VIII:

1) At the base of VII, associated with CC-type inclusions (to be described later). Modally bedded oxides occur in troctolitic rocks located either at the top of or near the base of these inclusions. Present in drill holes: B1-116 (46-59', 84-85'), B1-117 (141-142'), B1-134 (270-271.5'), B1-139 (136-143',186-187'), B1-140 (423-434',485-488'), B1-161 (46-59',84-85'), and B1-214 (29-42',69-70',80-81' - correlated as being in the top of Unit V ?).

2) In the middle of Unit VI within modally bedded troctolites and picrites. Present in B1-150 (208-213',229-230') and B1-295 (525-530').

3) At the base of Unit VI within modally bedded troctolite in B1-135 (359-390.5').

The magnetite beds vary from 1.0 to 40.0 mm thick (average 2-4 mm) and are parallel and planar in drill core. Bedding plane dips are about 15-25E from horizontal. In some zones, the beds are mildly contorted suggesting that some slumpage occurred soon after deposition. Magnetite content varies from 50-100% in the beds. The magnetite is fine- to medium-grained.

Both Units VI and VII contain a fair amount of fine-grained inclusions that exhibit sharp contacts with the troctolitic rocks. The inclusions may be hanging wall material and can be broken into two types designated as: 1) "pic"-type inclusions -- fine-grained equigranular olivine gabbro to melagabbro; and 2) CC-type inclusions -- fine-grained equigranular oxide gabbro to oxide norite (both will be discussed later). In some areas, the CC-type inclusions are present at the base of Unit VII instead of the ultramafic horizon.

Locally within Unit VII are thin zones of mottled-textured anorthositic troctolite that contain olivine oikocrysts. These zones are extremely similar to Unit III and may be inclusions(?) of Unit

III. Unit III-type zones/inclusions have also been found in Unit VII at Dunka Road (Severson and Hauck, 1990). To date, no Unit III-type zones have been found within Unit VI.

PETROGRAPHY OF THE TROCTOLITIC UNITS

INTRODUCTION

The overall petrographic characteristics of both cumulus and intercumulus minerals that comprise the troctolitic rocks of the PRTS are briefly summarized in this chapter. Cumulus is defined only as the framework, or first generation, of touching and interpenetrating crystals (plagioclase and olivine) that accumulated from a magma and does not imply crystal settling (Irvine, 1982). Intercumulus, as defined by Irvine (1982), refers to "postcumulus material" of three habits: 1) intercumulus space-filling, 2) overgrowth on cumulus crystals; and 3) reaction replacement of cumulus minerals. The later group includes plagioclase, olivine, augite, hypersthene, oxides, sulfides, biotite, symplectite, and minor apatite. Overall, the igneous rocks of the PRTS are medium- to coarse-grained orthocumulates (25-50% intercumulus material) and mesocumulates (7-25% intercumulus material) with minor adcumulus ultramafic horizons.

PLAGIOCLASE

Plagioclase is the major cumulus mineral and occurs as randomly oriented, subhedral to anhedral, tabular to lath-shaped crystals of widely varying grain size. Crystal boundaries are generally curvilinear to undulating due to mutually interfering crystal growth boundaries. The most euhedral plagioclase crystals are found within clinopyroxene (Cpx) oikocrysts. Twinning in the plagioclase is characterized by albite, combined Carlsbad-albite twins, and minor pericline twinning. Commonly, a small proportion of the plagioclases are optically zoned.

The plagioclase often contain minute exsolved iron oxide needles (tentatively identified as ilmenite) that tend to be aligned along cleavage. The iron oxide needles are generally concentrated in the plagioclase core, but an uneven distribution throughout the crystal or in isolated patches within the crystal are also common. Plagioclase may show varying degrees of deuteric alteration to sericite and/or saussurite. The highest degree of alteration occurs in close proximity to fractures or in areas that have undergone uralitization.

Localized zones of primary igneous foliation, defined by aligned plagioclase laths, were identified in all the troctolitic units (most common in Units V, VI, and VII). The plagioclase laths generally exhibit dips of 10-50E (from horizontal) in the drill core over intervals ranging from ten to tens of feet thick. Attempts to correlate zones with igneous foliation between drill holes did not yield any specific pattern or consistent stratigraphic horizons.

OLIVINE

The second most abundant mineral is olivine (cumulus and intercumulus), which occurs in a variety of morphologies. The most common olivine morphology is subhedral to anhedral, granular (or equant) crystals that commonly form local chains around the edges of plagioclase crystals. These crystals suggest the simultaneous crystallization of plagioclase and olivine. Commonly these equant crystals occur in clusters that exhibit triple point junctions. The second most common olivine morphology is irregular (or amoeboid), anhedral, interstitial grains. The texture of these grains suggest that they crystallized later than the plagioclase; however, they may also be the result of post-cumulus growth. There is generally no correlation of olivine crystal habit with a specific troctolitic unit, and both olivine types can be found in the same thin section.

Lastly, olivine occurs as large (2-30 mm) optically continuous oikocrysts that occupy more than three adjacent void spaces within a fine-grained plagioclase-rich framework. These poikilitic olivines are petrographically unique to Unit III and to localized horizons within Unit VII -- both exhibit a mottled texture due to the erratic distribution of olivine oikocrysts.

Generally, all varieties of olivine are partially to completely surrounded by orthopyroxene kelyphitic rims due to the reaction of the earlier cumulus olivine with later intercumulus liquid. Portions of Cpx oikocrysts also partially rim a small amount of olivine. Present in trace quantities are olivine symplectites that occur as wormy iron oxide and orthopyroxene reaction fronts into olivine.

Olivine is commonly altered to serpentine + chlorite ± magnetite along curved internal cracks and along grain boundaries. The intensity of serpentinization commonly increases within the more olivine-enriched zones, e.g., picrite and peridotite, and in zones adjacent to faults and fractures. Spotty serpentinization of olivine is also present in the uralitized zones. Within the uralitized zones it is not uncommon to find "fresh," weakly serpentinized and strongly serpentinized olivines in alternating (1-12 inch) zones, or intermixed in a random pattern.

Within the ultramafic horizons, olivine occurs as subrounded, equant, adcumulus grains with triple point junctions. The olivine may be partially enclosed in poikilitic Cpx and/or plagioclase. Primary igneous foliation is also often encountered in the ultramafic horizons. Serpentinization varies from weak to strong within these zones, and in the more extreme cases, the entire olivine grain may be replaced by a mixture of serpentine + magnetite + chlorite ± talc. Serpentinization imparts a foliation to the drill core that is parallel to subparallel to modal bedding (if present) and generally exhibits dips of 10-30E (from horizontal).

CLINOPYROXENE (CPX)

Augite is the dominant intercumulus mineral of the troctolitic units. Augite occurs as either large oikocrysts enclosing grains of olivine and plagioclase, or as grains interstitial to the plagioclase framework. A feature of most augites is the presence of exsolved rods and plates of opaques oriented in the two dominant major planes of cleavage. The opaques have been identified by others

(Bonnichsen, 1972; Molling, 1979; Chalokwu, 1985) as ilmenite, magnetite, rutile and biotite. Both inclusion-rich and inclusion-poor Cpx-types may occur in the same thin section. Biotite is commonly associated with augite oikocrysts and occurs as isolated blocky flakes either peripheral to and/or epitaxial to augite-plagioclase boundaries. Fine exsolution lamellae of orthopyroxene, parallel to (100) or (001), may be locally present within the clinopyroxene.

ORTHOPYROXENE (OPX)

Hypersthene is present in all troctolitic rock units. It commonly occurs as partial coronas around olivine generally in amounts less than 2%. Rare to minor quantities of cumulus and intercumulus Opx may be locally present. The overall amount of Opx in the troctolitic units is generally very low, except for a gradational increase in Opx adjacent to the basal contact and adjacent to sedimentary hornfels inclusions where norite may often be the dominant rock type. Opx is also common in inclusions of the hanging wall(?) -- designated as CC and "pic" units on the accompanying cross-sections.

SYMPLECTITE

Two types of symplectite occur within the troctolitic rock units and are referred to as "plagioclase symplectite" and "olivine symplectite" as used by Miller (1986). Plagioclase symplectite occurs as a wormy intergrowth of hypersthene and plagioclase at the edges of plagioclase laths in contact with olivine. This reaction product replaces plagioclase laths from the edges inward and resembles a "front" in that its innermost boundaries are lobate and sharp. Biotite may also be present at the outermost edge of plagioclase symplectite. Plagioclase symplectite is a fairly common constituent of Unit I and is only rarely present in the other troctolitic units. Severson and Hauck (1990) noted that plagioclase symplectite is common in Units I, IV, and V to the west of Minnamax.

"Olivine symplectite" is also a late crystallization product with textures similar to plagioclase symplectite. In this case, wormy iron oxide and hypersthene replace the outermost portions of olivine. Olivine symplectite is present in all troctolitic units in trace amounts; the greatest percentage occurs in Unit I.

Chalcopyrite symplectite is present within the basal massive sulfide zone at Minnamax. It is described in a later section.

BIOTITE

Biotite is a common constituent of all rock types within the PRTS but generally composes <1%, except within the basal zone of Unit I where up to 5% is present. Biotite generally occurs as interstitial sheaths and in most cases is strongly associated with iron oxides and sulfides. Rao (1981) notes that biotite exhibits a reddish-brown color due to the high titanium content. Greenish-brown epitaxial biotite is also present at augite-plagioclase boundaries. Epitaxial biotite was found to occur in all the troctolitic units in no consistent pattern or stratigraphic height.

OXIDES

The oxides occur as either interstitial (locally oikocrystic) or adcumulus grains (only within the modally bedded magnetite zones). Interstitial ilmenite is the most common oxide mineral in the troctolitic units. Composite grains of ilmenite-magnetite are also present in lesser amounts. Within the composite grains, the magnetite (MAG-I) commonly exhibits ilmenite exsolution lamellae (Fig. 5a) parallel to (111). The MAG-I may also contain spinel (tentatively identified as ulvospinel) as an extremely fine cloth-like net parallel to (111). Pleonaste blebs (tentative identification) may occur locally within some of the ilmenite lamellae of the MAG-I (Fig. 5a). There is no correlation between a particular troctolitic unit (Units II through VII) and the amount of composite ilmenite-magnetite grains present. However, composite grains are not as common in Unit I and ilmenite is the dominant oxide. Ilmenite is the only interstitial oxide within the ultramafic horizons; however magnetite (MAG-II) is present as stringers within olivine -- it is a product of serpentinization.

Composite grains of ilmenite and Ti-chromite are also found at several stratigraphic levels within the troctolitic units. An example of an interstitial ilmenite-chromite composite grain is shown in Figure 5b. These types of composite grains have been found to date in: Unit VI (B1-330 100'), Unit IV (B1-66 1,438', B1-330 658'), and Unit I (B1-131 1,359', B1-330 910', 1,011', and 1,939'). Table 1 lists microprobe analyses for the ilmenite-chromite composite grains in three polished sections. A spinel compositional plot is presented in Part II (see Figure 14) that compares the composition of these composite grains to other oxide compositions reported in the Duluth Complex.

Adcumulus magnetite grains (MAG-III) are found exclusively within the modally bedded magnetite zones of Units VI and VII. The MAG-III grains (Figs. 6a & 6b) are equant, subround, and vary from <1 mm to over 7 mm in diameter. Other adcumulus oxides found within these zones are green pleonaste (Figs. 6a & 6b) and ilmenite (also as composite grains with magnetite). Microprobe analyses for the magnetite (MAG-III) and green pleonaste grains are listed in Table 2. A spinel compositional plot is presented in Part II (see Figure 14) that compares the composition of the MAG-III and green pleonaste grains to other oxide compositions reported in the Duluth Complex.

Figure 5a. MAG-I magnetite(MT) with exsolved ilmenite(ILM) parallel to (111) and exsolved ulvospinel(U) parallel to (111). Note pleonaste blebs in ilmenite lamellae. Sample B1-135 304'. Field of view is 0.27 mm across.

Figure 5b. Composite ilmenite(ILM)-titanium chromite(Cr) grain in troctolite. Sample B1-330 658'. Bar is 1.0 mm.

Figure 5c. Typical texture of sill(?) unit within the Virginia Formation with hornblende(H), olivine(OL), plagioclase, Opx, and biotite. Plane polarized light. Sample B1-131 1,909'. Bar is 1.0 mm.

Figure 5d. Typical granular texture of "pic"-type inclusion. Sample B1-153 454'. Bar is 1.0 mm. Transmitted light (crossed polars).

PHOTO PAGE

Table 1. Mineral compositions of coexisting ilmenite(I) and titanium chromite(C)--composite grains (all samples from drill hole B1-330)

Sample	100'I	100'C	658'I	658'I	658'C	658'C	910'I	910'C	910'C	910'C
MgO	1.09	0.32	3.41	3.24	1.77	1.66	3.53	2.23	2.20	2.28
FeO	42.75	36.85	38.49	38.41	35.37	36.23	38.62	37.59	39.11	38.50
MnO	0.42	0.20	0.30	0.43	0.24	0.18	0.63	0.24	0.29	0.33
ZnO	0.05	0.37	0.22	0.22	0.06	0.34	0.00	0.30	0.07	0.37
Al_2O_3	0.13	3.75	0.00	0.09	6.13	6.60	0.09	11.66	7.31	6.75
Cr_2O_3	0.35	6.12	0.20	0.30	11.30	11.56	0.00	20.26	18.13	17.70
Fe_2O_3	6.42	48.36	8.01	7.62	39.04	38.73	6.29	21.25	22.48	23.15
TiO_2	50.18	5.95	49.90	50.61	6.47	6.77	50.66	8.03	10.88	10.96
Total	101.39	101.92	100.53	100.92	100.38	102.07	99.82	101.56	100.47	100.04
ti	0.935	1.312	0.923	0.930	1.409	1.449	0.940	1.667	2.328	2.362
mn	0.009	0.050	0.006	0.009	0.059	0.043	0.013	0.056	0.070	0.080
fe	0.885	9.034	0.791	0.785	8.566	8.622	0.797	8.680	9.308	9.225
zn	0.001	0.080	0.004	0.004	0.013	0.071	0.000	0.061	0.015	0.078
mg	0.040	0.140	0.125	0.118	0.764	0.704	0.130	0.918	0.933	0.974
al	0.004	1.297	0.000	0.003	2.094	2.215	0.003	3.798	2.454	2.281
fe_3	0.120	10.673	0.148	0.140	8.512	8.297	0.117	4.418	4.816	4.994
cr	0.007	1.419	0.004	0.006	2.588	2.602	0.000	4.424	4.081	4.011
	2.000	24.004	2.001	1.995	24.004	24.004	2.000	24.022	24.005	24.004

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

Internally, the MAG-III grains exhibit variable amounts of: 1) coarse ilmenite exsolution lamellae parallel to (111) - the ilmenite lamellae may contain minor internal ulvospinel blebs; 2) an extremely fine, cloth-like net (Fig. 6c) of spinel (tentatively identified as ulvospinel) parallel to (100), and to a lesser extent (111); 3) extremely fine lenses of green pleonaste (Fig. 6c) parallel to (100); and 4) minor elongate dendritic blebs of ulvospinel(?). Interestingly, these

Figure 6a. Adcumulus MAG-III magnetite(MT) and green pleonaste(P) grains. Sample B1-116 177' from modally-bedded magnetite in troctolite. Reflected light, bar is 0.5 mm.

Figure 6b. As above, transmitted light (plane polarized).

Figure 6c. Close-up of MAG-III type magnetite(MT) with an extremely-fine, cloth-like net of ulvospinel(U) parallel to (100) and green pleonaste(P) lenses parallel to (100). Sample B1-116 177', reflected light. Field of view is 0.27 mm across.

Figure 6d. Typical granular texture of CC-type inclusion with magnetite, plagioclase, Cpx, and Opx. Sample B1-140 450', transmitted light (crossed polars), bar is 1.0 mm.

PHOTO PAGE

Table 2. Coexisting MAG-III magnetite (M) and green pleonaste (P)

Sample	B1-116	B1-116	B1-116	B1-116	B1-116	B1-116	B1-139	B1-139	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295	B1-295
	175' M	175' M	175' P	175' P	175' P	175' P	140' P	140' P	527' P	527' P	527' P	527' P	527' P	527' P	527' P	527' P	527'P	527' M	527' M	527' M	527' M	527' M	527' M
MgO	1.34	1.39	14.02	14.12	13.22	13.90	17.58	17.72	12.35	12.36	12.24	12.88	13.86	13.16	13.12	13.29	12.73	1.50	1.58	1.78	1.52	1.35	1.75
FeO	41.63	41.69	19.80	19.86	21.18	18.10	14.55	14.60	22.30	21.95	22.00	20.55	18.38	20.02	19.93	20.00	21.27	42.39	41.60	41.21	42.44	40.50	41.49
MnO	0.16	0.28	0.00	0.11	0.11	0.13	0.14	0.08	0.17	0.07	0.12	0.29	0.09	0.20	0.11	0.18	0.16	0.33	0.24	0.37	0.37	0.25	0.19
ZnO	0.07	0.00	0.52	0.56	0.45	0.35	1.16	1.07	0.77	0.87	0.61	0.75	0.60	0.93	0.88	0.80	0.87	0.11	0.08	0.01	0.17	0.26	0.10
Al_2O_3	3.61	3.60	59.10	61.07	59.17	55.32	62.09	63.20	61.34	59.52	59.36	59.03	56.46	58.54	58.83	59.45	59.89	3.89	3.68	3.98	4.71	2.36	4.32
Cr_2O_3	0.13	0.03	0.12	0.13	0.03	0.25	0.14	0.22	0.23	0.20	0.29	0.14	0.19	0.21	0.38	0.16	0.33	0.19	0.28	0.15	0.18	0.31	0.20
Fe_2O_3	41.75	41.04	6.61	5.14	6.81	9.39	5.83	5.11	3.63	4.96	4.87	5.39	7.88	5.86	4.76	5.01	4.13	37.19	36.92	35.91	38.67	39.58	37.50
TiO_2	12.73	13.05	0.32	0.13	0.27	0.00	0.34	0.15	0.11	0.31	0.13	0.21	0.16	0.29	0.24	0.20	0.38	14.53	14.14	14.33	13.85	13.55	13.85
Total	101.42	101.08	100.49	101.12	101.24	97.44	101.83	102.15	100.90	100.24	99.62	99.24	97.62	99.21	98.25	99.09	99.76	100.13	98.52	97.74	101.91	98.16	99.40
ti	2.790	2.867	0.051	0.021	0.043	0.000	0.052	0.023	0.018	0.050	0.021	0.034	0.026	0.047	0.039	0.032	0.061	3.208	3.175	3.231	2.997	3.080	3.070
mn	0.040	0.069	0.000	0.020	0.020	0.024	0.024	0.014	0.031	0.013	0.022	0.053	0.017	0.037	0.020	0.033	0.029	0.082	0.061	0.094	0.090	0.064	0.047
fe	10.145	10.186	3.522	3.489	3.763	3.342	2.490	2.481	3.958	3.941	3.973	3.712	3.375	3.619	3.624	3.603	3.818	10.409	10.386	10.332	10.212	10.236	10.226
zn	0.015	0.000	0.082	0.087	0.071	0.057	0.175	0.161	0.121	0.138	0.097	0.120	0.097	0.148	0.141	0.127	0.138	0.024	0.018	0.002	0.036	0.058	0.022
mg	0.582	0.605	4.444	4.421	4.186	4.573	5.360	5.365	3.906	3.955	3.938	4.146	4.535	4.239	4.251	4.266	4.072	0.656	0.703	0.795	0.652	0.608	0.769
al	1.241	1.241	14.829	15.135	14.830	14.406	14.985	15.147	15.356	15.074	15.118	15.041	14.622	14.927	15.087	15.106	15.164	1.347	1.296	1.407	1.599	0.841	1.502
fe_3	9.160	9.027	1.059	0.813	1.089	1.561	0.898	0.782	0.580	0.802	0.792	0.877	1.303	0.954	0.779	0.812	0.667	8.221	8.298	8.105	8.377	9.006	8.321
cr	0.030	0.007	0.020	0.022	0.005	0.044	0.023	0.035	0.039	0.034	0.050	0.024	0.033	0.036	0.065	0.027	0.056	0.044	0.066	0.036	0.041	0.074	0.047
Total	24.003	24.003	24.007	24.007	24.007	24.007	24.007	24.007	24.007	24.007	24.011	24.007	24.007	24.007	24.007	24.007	24.007	23.992	24.002	24.002	24.003	23.967	24.003

Note: Cation proportions normalized to 32 oxygen atoms.

features have also been noted in oxide-rich zones (with PGEs) of drill hole Duval-15 within the South Kawishiwi Troctolite (Alapieti, 1991).

Silicate mineralogy within the bedded magnetite zones (MAG-III) consists of: 1) plagioclase - tabular to equant/polyhedral grains (locally with primary igneous foliation or triple point junctions, respectively); 2) olivine - equant to oikocrystic (up to 1.5 cm), the latter are often elongated along bedding; 3) Cpx - minor, equant to oikocrystic crystals; 4) rare, brown hornblende as reaction rims around the oxides; and 5) highly variable biotite content.

APATITE

Euhedral, short prismatic crystals of apatite enclosed in plagioclase, or associated with coarse sulfide blebs, are a very minor constituent of the troctolitic units. Apatite generally occurs in rare amounts, except within the bottom portion of Unit I and in the Oxide-bearing Ultramafic Intrusions (OUI).

DEUTERIC ALTERATION

Patches of deuteric alteration, or uralitization, are present in all the troctolitic units of the PRTS. Uralitization is characterized by replacement of interstitial Cpx by fine-grained mats consisting of radiating bundles of chlorite, hornblende, actinolite, sericite, ±tremolite, ±calcite that often interpenetrate with adjacent plagioclase crystals. Also associated with this type of alteration are variably saussuritized plagioclase and moderately to strongly serpentinized olivine. The dimensions of the uralitized patches in drill core vary from about one inch to tens of feet; in many instances, both uralitized and "fresh" rock alternate within these zones on a scale ranging from less than one inch to several feet. In some cases, the uralitization is related to hairline fractures (all are parallel and regularly spaced in some instances), and the alteration exhibits a diminished intensity away from the fractures (alteration haloes down to 1 cm across have been noted in drill core). However, in many instances, large uralitized zones are not apparently related to fractures in drill core. Sulfide content does not usually show an increase in these zones.

Attempts to correlate large uralitized zones between drill holes in the Local Boy area met with limited success. The zones are sub-horizontal and appear to lense-out, bifurcate, and change stratigraphic level within an individual troctolitic unit with no apparent consistency. The zones are present locally in Units IV, V, VI, and VII in drill holes B1-105, 116, 129, 130, 132, 133, 135, 137, 139, 141, 146, 148, 159, 160, and 161.

CHLORINE DROPS

Slimy, rust-colored, fluid drops are locally present on the drill core surfaces and split core surfaces of several drill holes within the Minnamax deposit area. These drops are also reported from other holes scattered throughout the PRT and SKT areas of the Duluth Complex (Dahlberg et al., 1988; Severson and Hauck, 1990; Dahlberg and Saini-Eidukat, 1991). Dahlberg and Saini-Eidukat (1991) report that the drops appear on freshly cut drill core surfaces within four months of exposure to air; personal communication with exploration sources indicates that the drops can form within less than a month. Analysis of the drops indicates high chlorine content values up to 3,000 ppm (Dahlberg, 1987; Dahlberg et al., 1988; Dahlberg and Saini-Eidukat, 1991). The chlorine drops noted in this, and previous studies, are almost always associated with weakly to strongly serpentinized olivine grains. The drops are the most common within, or in close proximity to, some of the major ultramafic horizons of the troctolitic units, and in the Oxide-Ultramafic Intrusions (OUI). Their distribution is indicated on the cross-sections accompanying this report (Part I). Slimy drops, and more commonly dried-up encrustations, are also present on the basal massive sulfide drill core from the Local Boy area. They are described in Part II.

Interestingly, these drops form soon after the drill core is exposed to the air. It is possible that as moisture condenses on the drill core, with alternating daily cold-to-warm temperatures in the spring and early summer months, the rock zones with initial high chlorine contents are able to retain condensed moisture droplets (much as CaCl is used to absorb humidity to keep the dust down on gravel roads). Whole rock analyses of the ultramafic horizons and OUI bodies (Severson and Hauck, 1990; Severson, this report) indicate high Cl contents in the ultramafics and OUIs regardless of whether the slimy drops are present or not. Thus the presence of Cl drops on drill core can be attributed to high Cl content within the rock and the rocks ability to retain condensed moisture. However, the mechanism (post-cumulate?) that produced the initial high Cl content within the ultramafics is unknown. Dahlberg and Saini-Eidukat (1991) suggest that the rocks of the Duluth Complex were subjected to invasion by Cl-bearing solutions during or after serpentinization. These Cl-bearing solutions may have moved upwards along fault zones and then laterally along the major ultramafic horizons, which because of serpentinization were more permeable than the enclosing troctolitic rocks. The timing of this event is unknown. Because both ultramafic horizons and OUIs exhibit the slimy drops, the Cl-bearing solutions may have been channeled along fault zones at the same time as OUI formation. The OUIs are intrusive (or metasomatic replacements?) into the troctolitic rocks and are often associated with fault zones (described in the next chapter).

LITHOLOGIC DESCRIPTION OF THE FOOTWALL ROCKS, INCLUSIONS, AND MISCELLANEOUS

VIRGINIA FORMATION (HORNFELS)

The Virginia Formation (middle Precambrian) is the uppermost unit of the Animikie Group within the area of study. It is the major footwall rock at the base of the Duluth Complex in the Minnamax, Dunka Road, Wetlegs, and Wyman Creek deposits. Due to intrusion of the Complex along bedding planes, coupled with assimilation, only the bottom 10-400 feet of the Virginia Formation is present in the Minnamax deposit area. Note that the thickness estimate excludes the Virginia Formation inclusions located within the troctolitic units -- the inclusions are still relatively "in place," but do not display a continuous measurable section of the Virginia Formation. Rocks of the Virginia Formation are characterized by a sequence of well-bedded to massive bedded argillite, fine-grained graywacke, and siltstone with minor interbeds of graphitic argillite, calc-silicate, chert, and rare marble. These rocks exhibit a granoblastic texture in close proximity to the Complex. They contain variable amounts of plagioclase, orthopyroxene, cordierite, biotite, and minor quartz. Mineralogy varies due to the initial differences in bulk composition of the protolith. In general, cordierite content increases toward the contact with the Complex. Minor constituents of the hornfels include ilmenite, apatite, and graphite ± pyrrhotite beds. Bedding planes are locally present in drill core and vary from planar (15-30E) to highly contorted. It is impossible to tell how the bedded zones correlated between drill holes, but Kirstein (1979) reports that bedding could not be traced for more than 3 to 4 feet in the underground drifts. He also reported that "the bedding shows complex folding, presumably caused by intrusion of the Duluth Complex" (Kirstein, 1979, p.16). However, the folding may be very local in nature as some internal marker beds within the Virginia Formation can be traced with relative consistency.

Within the Virginia Formation are several graphitic argillite horizons that can locally be traced with certainty between drill holes. Often, they pinch-out and then "reappear" at the same stratigraphic level in a more distant drill hole or group of drill holes. Several thick graphitic argillite horizons are also present in the large hornfels inclusions in the Local Boy area. These are very continuous and exhibit excellent correlations in the third dimension (see cross-sections on Plates V through X). Interestingly, graphitic argillites are present most often on the peripheries of the large hornfels inclusions. Bedding is generally well preserved in all the graphitic argillites and more than often is highly contorted. Syngenetic(?) pyrrhotite beds and lenses (<2 mm thick) and disseminated pyrrhotite are also common within the graphitic argillites.

Calc-silicate horizons, up to 5 feet thick in drill core (average about 1 foot thick), are present within both the hornfels inclusions and footwall Virginia Formation. They are generally well-bedded, light-colored, fine- to coarse-grained, and occasionally occur as sausage-shaped segments (similar to boudins) in drill core. Kirstein (1979) reports that in the underground drifts they occur as ellipsoidal to spherical pods ranging from 4 inches to 8 feet across. The principle minerals include diopside, grossular garnet, plagioclase, sphene, wollastonite, calcite, and minor quartz (Kirstein, 1979). Disseminated sulfides (epigenetic?) are locally present within some calc-silicates. Overall, the calc-silicate pods/horizons do not correlate with any specific stratigraphic level, with two exceptions: 1) located about 5-10 feet above the base of the Virginia Formation is a semi-persistent 6 inch to 3 foot thick chert-calc-silicate horizon (designated as c-cs on Plates II through X); and 2) located about 250-350 feet above the base of the Virginia Formation is a locally persistent 2-30 foot thick calc-silicate horizon with interbeds of chert and massive diopside (Plates XII through XV accompanying Part II).

The massive to semi-massive sulfide ore of the Local Boy area is situated at/near the basal contact of the Duluth Complex. It appears that the majority of this ore type is intimately associated with the footwall rocks. Massive sulfides are present: 1) at the basal contact; 2) below the basal contact; 3) within hornfels inclusions close to the basal contact; and 4) in close proximity to, or surrounding, hornfels inclusions. The footwall ore commonly exhibits a gradational change from hornfels with scattered hairline chalcopyrite-coated veinlets to sulfide-flooded microbreccias (almost network-textured) to a chaotic assemblage of semi-massive and massive sulfide mineralization. Sulfides diminish drastically within the adjacent intrusive rocks (norite and troctolite). When massive sulfides are intersected in the intrusive rocks they are almost always associated with small hornfels inclusions. This may indicate that at some early phase the footwall rocks near the basal contact were structurally prepared and flooded by an immiscible sulfide melt (produced in an auxiliary magma chamber?). At some later period, the basal mineralized zone was re-intruded along bedding planes to produce a disjointed zone of mineralized footwall rocks, and mineralized inclusions separated from each other by the later "barren" intrusive rocks. A more detailed description of sulfide minerals is presented in Part II.

SILL(?) WITHIN THE VIRGINIA FORMATION

During relogging of both surface and underground drill holes an unusual subunit within the bottom-most 5-120 feet of the Virginia Formation was identified. This unit was first distinguished as being different from the Virginia Formation metasediments in that olivine is locally present. The rock has an unusual speckled appearance consisting of pale olive-green and light-brown spots within a medium-gray background. Olivine content locally decreases and increases along strike, and the rock is locally a serpentinized peridotite or picrite, e.g., bottom of drill holes B1-119 and B1-153. Contacts with the Virginia Formation, which was logged as "massive graywacke" with occasional beds, are in almost all cases gradational. Due to the gradational nature of the contacts, it was often difficult to visibly separate this unit from the footwall rocks, and a certain amount of "lumping" took place during logging of the drill core. Regardless of this unfortunate "lumping," the relative positions and thicknesses of this sill(?) are portrayed on the cross-sections that accompany this investigation (Part I, Plates II through X; and Part II, Plates XII through XV).

Stratigraphically, the sill(?) is generally present just above the "c-cs" unit at the base of the Virginia Formation. However, local bifurcations into two or more lenses higher up in the Virginia Formation are present. Also, the sill(?) is situated below the "c-cs" unit in some drill holes. The massive sulfide mineralization is not present within or beneath the sill(?) horizon. The top of this horizon could be used as a datum for future geostatistical ore zone investigations.

The typical texture of this rock type is granoblastic with subhedral to euhedral brown hornblende (shown in Fig. 5c). Major constituents of the sill(?), in decreasing order, are:

Hornblende - 15-70%, subhedral to euhedral equant crystals superimposed on the granoblastic texture, locally contain minute specks of oxide tentatively identified as chromite.

Plagioclase - 5-55%, fine to very fine-grained polygonal grains that locally may exhibit a preserved(?) decussate lathy texture.

Orthopyroxene - 10-35%, equant and poikiloblastic grains.

Olivine - trace to 30%, equant cumulus(?) grains (highly serpentinized) to irregular amoeboid grains.

Biotite - trace to 5%.

Clinopyroxene - locally present up to 20%, polygonal.

Ilmenite - trace amounts, very finely disseminated.

Sulfides - trace amounts, disseminated round droplets consisting of pyrrhotite with chalcopyrite.

The different mineralogy of this unit with respect to the surrounding metasedimentary rocks suggests an intrusive origin. However, it is hard to reconcile the granoblastic texture and gradational contacts unless a pre- or early Duluth Complex intrusive age is assumed. The sill(?) would have, therefore, been metamorphosed by later intrusions.

Similar-looking sills have been reported to be present within the Virginia Formation and top of the Biwabik Iron-Formation to the north of the Minnamax deposit (Morey and Cooper, 1977). They are exposed in the walls of the open pit taconite mines.

BIWABIK IRON-FORMATION

The Biwabik Iron-Formation (middle Precambrian) conformably underlies the Virginia Formation and is the oldest footwall rock present within the study area. The top 5-30 feet of the Biwabik Iron-Formation (Upper Slatey member) were intersected in most of the drill holes at Minnamax. Submembers (after Gundersen and Schwartz, 1959) present within the upper portion of the Upper Slatey member include (top to bottom): A - marble with chert interbeds; B - irregularly bedded diopside-chert taconite; and C - thinly laminated quartz taconite with ferrohypersthene, fayalite and magnetite. Generally all three submembers are present in drill hole; however subunits A and B may be locally omitted due to local unconformities. Contacts with the overlying Virginia Formation are sharp, but the presence of cherty calc-silicate horizons (± diopside beds) in the Virginia Formation suggest that some interfingering of the two formations may be present.

Within the Local Boy area an EW-trending anticline and syncline is defined by the top of the Biwabik Iron-Formation. Corresponding to this structure is an EW-trending ridge and trough at the basal contact of the Duluth Complex. Several investigators have recognized this feature and have suggested that pre-existing structural conditions in the footwall rocks strongly influenced the form of the base of the Complex as it was repeatedly intruded along bedding planes in the Virginia Formation (Mancuso and Dolence, 1970; Watowich, 1978; Holst et al., 1986; Severson, 1988). The top of the Biwabik Iron-Formation was utilized as a datum for the geostatistical analysis conducted in this investigation (Part II - Severson and Barnes, 1991).

At the extreme southeast portion of the Minnamax deposit, the Biwabik Iron-Formation is in direct contact with the Duluth Complex. The distribution of drill holes where the footwall is the Biwabik Iron-Formation is summarized in Severson (1988).

CC-TYPE INCLUSIONS

A fine-grained, granular rock of gabbroic composition with variable amounts of oxides was intersected in the top portions of several drill holes in the Local Boy area. Because the core strongly resembles rock outcrops exposed in the Colvin Creek area, described by Severson and Hauck (1990), it is designated as "CC" on the accompanying cross-sections of this report. The rock exhibits a granular or granoblastic texture (Fig. 5d) characterized by polygonal plagioclase that tend to meet at 120E triple point junctions. Variable amounts of Cpx and Opx occur as equant grains, slightly amoeboid grains, and minor oikocrysts. Cpx is generally the more dominant pyroxene, but exceptions are present. Olivine is locally present and occurs as oikocrysts. Hornblende is also locally present and occurs as reaction rims around oxides. Magnetite (MAG-III type) is the dominant oxide (10-30%) and occurs as subrounded grains that commonly exhibit an extremely fine, cloth-like net of spinel (tentatively identified as ulvospinel) parallel to the (100) and (111). Ilmenite is present in subordinate amounts and occurs as composite grains with magnetite and as exsolution lamellae parallel to (111). Rare green pleonaste is locally present as small blebs on the edge of magnetite grains. Biotite and apatite are present in trace amounts. Overall, the rock exhibits a massive appearance, but it may locally contain occasional plagioclase phenocrysts (up to 1.5 cm), ovoid plagioclase-filled wisps (vesicles?), and thin (< 1 cm) subparallel magnetite bands (beds?) displaying shallow dips of 10-30E (from horizontal).

The protolith of the CC-type inclusions is somewhat perplexing. The rock locally contains features indicating a volcanic origin (plagioclase-filled wisps = vesicles?). However, modally bedded oxide horizons with adcumulus magnetite (and green pleonaste) are also common adjacent to these inclusions and to a lesser extent within the inclusions. In some cases the bedded magnetite horizons exhibit a sharp contact with the troctolitic rocks and a gradational contact with CC inclusions. The mineralogy of both the bedded magnetite zones and CC inclusions is essentially the same, with differences only in grain size and modal percentages. Also, both rock types are exclusively characterized by unique magnetite grains (MAG-III) that exhibit an extremely-fine, cloth-like net of ulvospinel parallel to the (100) -- Figure 6c. Because of these similarities, both rock types may be interrelated and part of the same package. However, modally bedded magnetite horizons also occur lower in the troctolitic sequence where they grade into modally bedded troctolites; no CC inclusions are apparently present. The distribution of the modally bedded magnetite horizons and the CC inclusions within the troctolitic sequence (Units VI and VII) is portrayed in Figure 7. As can be seen on the diagram, most of the CC inclusions occur at or near the base of Unit VII. Modally bedded magnetite horizons occur at the same horizon (but at the top or near the base of the CC inclusions), and lower down in Unit VI where only rare CC inclusions have been located to date. Cumulus magnetite has been observed in the bedded magnetite zones that have been sampled for thin sections, but more sampling is needed to determine if all the bedded oxide zones contain cumulus magnetite.

The CC inclusions are remarkably similar to outcrops of the Colvin Creek Hornfels exposed about six miles southwest of Minnamax. The Colvin Creek rocks were first described

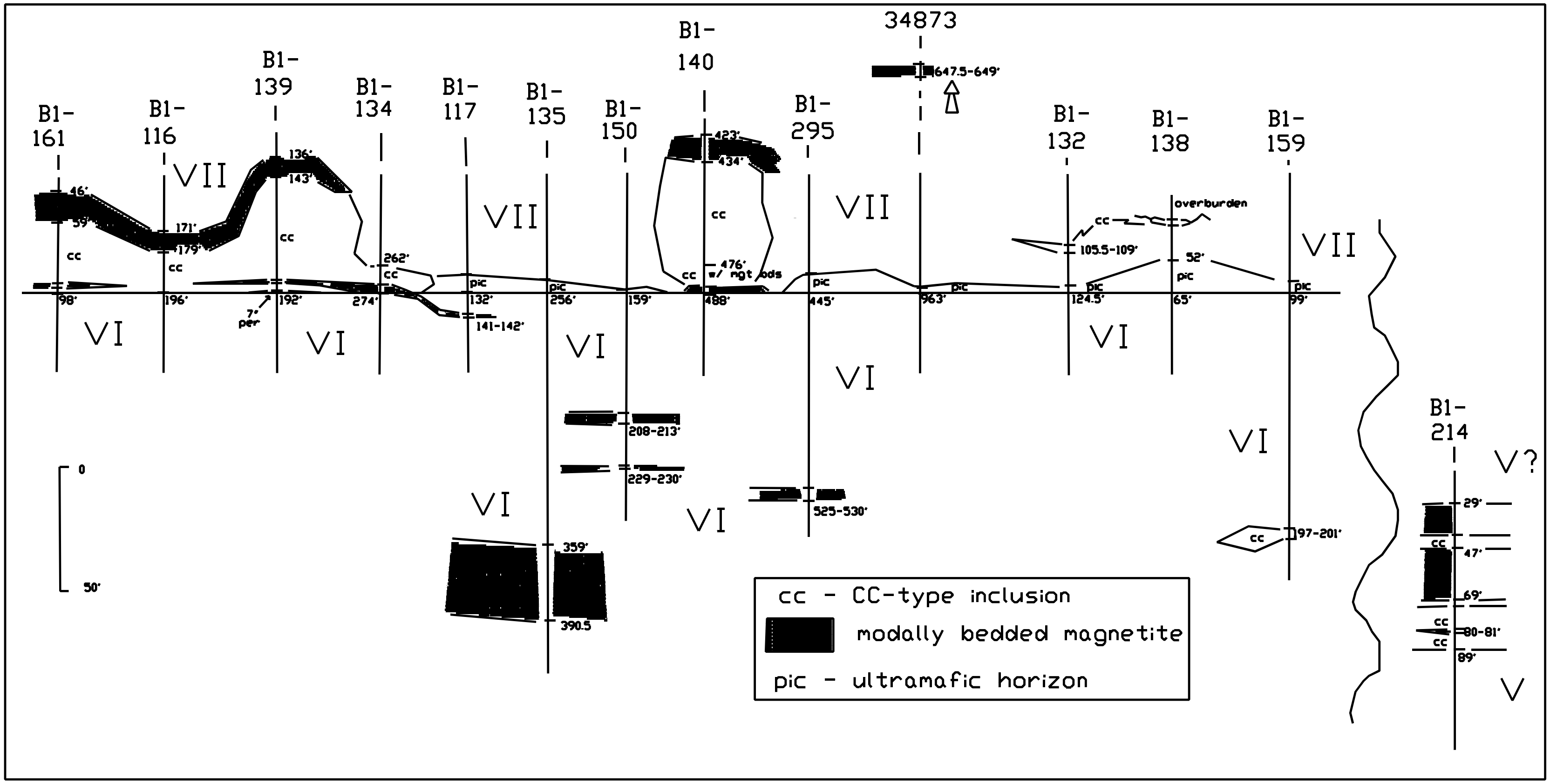

Figure 7. Distribution of CC-type inclusions in relation to bedded magnetite zones in troctolites. Drill holes have been hung on the base of Unit VII. Drill holes are <u>not</u> arranged in any systematic order.

by Bonnichsen (1972) who concluded that the inclusion was a hornfelsed basalt of the North Shore Volcanic Group. Tyson (1976) looked at the Colvin Creek material, as well as three other hornfelsed basalt inclusions, and concluded that Colvin Creek was different than "typical" basalt inclusions. He felt that Colvin Creek was an oxidized North Shore Volcanic basalt, and the difference was due to weathering of the basalt prior to metamorphism. Severson and Hauck (1990) conducted reconnaissance mapping in the area and found several mappable features that conflicted with a typical hornfelsed basalt protolith. Some of these features include: a 1,000 foot cross-bedded zone (strike-length of about 6,000 feet); coarse-grained modally bedded gabbro and troctolite near the northern edge of the inclusion; and similar mineralogy and chemistry to the nearby Powerline Gabbro. Severson and Hauck (1990) theorized that these unusual features may collectively indicate deposition of the Colvin Creek package via magmatic density currents, and tentatively classed the inclusion as the Colvin Creek "Gabbro." However, features indicative of a hornfelsed basalt origin (augite filled amygdules, pipe vesicles, and sheeted vesicles) are also present and the exact nature of the Colvin Creek inclusion is far from resolved. The area is currently being further investigated by Mr. Richard L. Patelke, an M.S. candidate at the University of Minnesota, Duluth.

The nature of the CC inclusions present in drill core at Minnamax is also still far from being resolved. The presence of modally bedded magnetic (cumulus) horizons adjacent to, at the same stratigraphic level as, and grading into the granular textured CC inclusions is perplexing. The common spacial association of the two may indicate magmatic deposition of the magnetite beds that alternate with chilled(?) granular textured rock. Another possibility is that the only some of the magnetite beds are cumulus, and the CC inclusions are hornfelsed footwall rocks with scattered magnetite band "sweatouts" rather than beds. In the latter case, the similar mineralogy and stratigraphic position of the cumulus magnetite beds and CC inclusions may be coincidental(?). Clearly, much more petrographic study is needed to resolve this enigmatic rock type and its spatial association with the adjacent cumulus magnetite horizons. An investigation of this nature is beyond the scope of this study, and the results reported in this study can only be considered preliminary.

"PIC"-TYPE INCLUSIONS

Fine-grained, granular, pale olive-green colored rocks with plagioclase-filled ovoids/wisps are locally present in the upper portions of drill holes situated at the southwestern and southern extremities of the Minnamax deposit. The field term of "picrite" or "pic" (in quotes) was used whenever these rocks were encountered in drill core. The term was used to denote dark-colored, very fine-grained rocks with an indeterminate mineralogy as opposed to the olivine ultramafic horizons, e.g., picrite - no quotes. The field term of "pic" is used on the cross-sections that accompany this report. In drill core, the rock generally exhibits a massive, relatively homogeneous texture with local internal zones that contain fine-grained plagioclase-filled ovoids (vesicles?) that average about 5-10 mm in diameter. Contacts with the surrounding troctolitic rocks vary from sharp to gradational. Occasionally, thin troctolitic intervals are present within these zones -- contacts are also sharp to gradational. Also, locally the "pic" rocks are complexly intermixed with medium-grained to pegmatitic, extremely heterogeneous troctolite zones that were logged as "het." Overall, the "pic" zones are common within troctolitic Units VI and VII, and minor "pic" zones are present in Unit V. They can locally be correlated between close-spaced drill holes, and their overall spatial distribution is as laterally discontinuous raft-like inclusions. For example, an individual "pic" zone was correlated in three dimensions in the deepest drill holes on Plates VIII, IX, and X. Because of their overall raft-like distribution, and because of the presence of plagioclase-filled ovoids (vesicles), the "pic" zones are interpreted as being inclusions of hornfelsed basalt (North Shore Volcanic Group?). They are similar in appearance to nearby railroad-cut outcrops of the Reserve Hornfels

(32-60N-12W) and Dunka Road Hornfels (33-60N-12W) that Tyson (1976) postulated are basalt inclusions of the North Shore Volcanic Group.

In thin section (Fig. 5d), these rocks are characterized by a fine-grained, equigranular texture consisting of:

Plagioclase - 40-60%, most variable grain size of all minerals, polygonal grains with straight to weakly undulose grain boundaries, triple point junctions are common at plag./plag. junctions. Local plagioclase needles.

Augite - 25-50%, homogeneous grain size, equant grains with straight to weakly undulatory grain boundaries.

Olivine - rare to 15%, occurs as equant grains, weakly ameboid grains, and oikocrysts (<1.0 cm).

Orthopyroxene - trace to 5%, equant grains, inverted pigeonite mosaic superimposed on equigranular texture in one thin section.

Minor constituents - trace to rare amounts of very finely disseminated ilmenite (no magnetite), pyrrhotite, chalcopyrite, and apatite.

The "pic"-type inclusions differ from the CC-type inclusions in that the latter contain more oxides (dominantly MAG-III type magnetite), less augite, and scattered magnetite bands/beds. Both rock types are similar in that they exhibit the same granular texture with local plagioclase ovoids/wisps. Both inclusion types occur at the same stratigraphic position within the troctolitic units (dominantly in Units VI and VII); the CC inclusions are more confined to the lower portion of this stratigraphic position. Only rare metasedimentary hornfels inclusions (footwall material) have been found stratigraphically above the stratigraphic position of the "pic" and CC inclusions. This indicates that the "pic" inclusions are probably hanging wall material (North Shore Volcanic Group). Because the CC inclusions are slightly lower in stratigraphic position than the "pic" inclusions, the CC material may have been originally present at the pre-Duluth Complex hanging wall-footwall contact.

OXIDE-BEARING ULTRAMAFIC INTRUSIONS (OUI)

Several late-stage pegmatitic ultramafic bodies (OUI) intrude the troctolitic stratigraphy at Minnamax. The acronym OUI was first used by Severson and Hauck (1990) to designate cross-cutting pegmatitic bodies of dunite, peridotite, picrite, melagabbro, and clinopyroxenite that had a high percentage of oxides. These bodies are roughly spheroidal in shape with apophyses into the troctolitic country rock. In almost all cases the OUIs exhibit sharp contacts with the troctolitic units and are clearly younger. Severson and Hauck (1990) briefly described several OUI bodies informally known as: Longnose; Longear; Section 17; Section 22; Skibo; and Wyman Creek (a OUI body is located within the Cu-Ni deposit). The Water Hen intrusion is also interpreted to be a pegmatitic OUI body that intrudes troctolitic rocks (Strommer et al., 1990). Small OUI lenses are present in the deepest drill holes at the Dunka Road deposit where they may represent apophyses of undrilled larger OUI bodies located to the south of the deposit. All the previously described OUI contain abundant oxides ranging from 10-15% disseminated oxides to massive oxide (>80%) bands up to tens of feet thick in drill core. Oxide content in OUI bodies at the Minnamax deposit area is generally very low (<1% with minor 5-15% zones), and thus the designation of OUI is somewhat of a misnomer. However, the OUIs at Minnamax exhibit the same overall textures (pegmatitic), and the same intrusive relationships to the surrounding troctolitic rocks, therefore, the OUI term has been retained. The OUIs at Minnamax also show some variation in mineralogy relative to the OUIs described by Severson and Hauck (1990).

At Minnamax, the OUI bodies are a varied assortment of orthopyroxenite, feldspathic orthopyroxenite, hornblende-bearing orthopyroxenite, and hornblendite, with minor clinopyroxenite and picrite to dunite patches. Rock types are gradational, and gradational grain size changes are present within a specific rock type (grades from medium-grained zones into pegmatitic zones). Also associated with the ultramafic rock types are granophyric patches/lenses characterized by pegmatitic quartz, bull quartz veins, and most commonly, vermicular potassium feldspar (K-spar) and quartz. In some cases, orthopyroxenite grades into hornblendite, which in turn grades into hornblendite with 20% vermicular K-spar/quartz blebs up to several inches across, e.g., top of drill hole B1-155. Also, present in some drill holes is a down-hole gradation of rock types in the OUI lenses/apophyses from orthopyroxenite to hornblendite with granophyre patches to granophyre; all of which exhibit the same intrusive contact relationships with the troctolitic rocks.

Petrographically unique to the OUIs are coarse-grained to pegmatitic pyroxenes that exhibit mutually sinuous to consertal grain boundaries. Within the olivine-rich zones are medium- to coarse-grained, subrounded, equant olivine grains that exhibit triple point junctions with other olivine grains. Hornblende is present as subhedral to euhedral coarse-grained crystals. Also petrographically unique to the ultramafic OUIs are intercumulus plagioclase (<20%) and rare calcite. Minor amounts of biotite (<5%), coarse-grained apatite (up to 10% locally), oxides (typically ilmenite), and sulfides (trace amounts) are also present within the OUIs. Sulfides occur as <1-2 mm round droplets consisting of pyrrhotite ± chalcopyrite. Minor graphite is commonly present in all types of OUIs.

Stratigraphic position of the OUIs in the troctolitic rocks is two-fold. Olivine-rich ultramafic OUIs (picrite to dunite) are present in Unit I close to the basal contact in drill holes B1-221, B1-65, B1-128, and BA-2. The latter three drill holes occur where the Biwabik Iron-Formation is in direct contact with the Duluth Complex. These OUIs commonly have a much higher oxide content (>15%) due to assimilation of the underlying Biwabik Iron-Formation. Rusty chlorine-rich drops also commonly coat the core surface of these stratigraphically lower OUI bodies. All other olivine-poor varieties of OUI (described above) are present at the top of the troctolitic stratigraphy in Units VI and VII; very small bodies are locally present in Units IV and V. These OUI bodies are situated along an EW-trending magnetic high. Their spatial distribution in drill holes (logged to date) to the magnetic high is shown in Figure 8. The magnetic high roughly corresponds to the axis of an EW-trending anticline defined by the top of the Biwabik Iron-Formation. This implies that late-Complex structure may have been important in the OUI genesis.

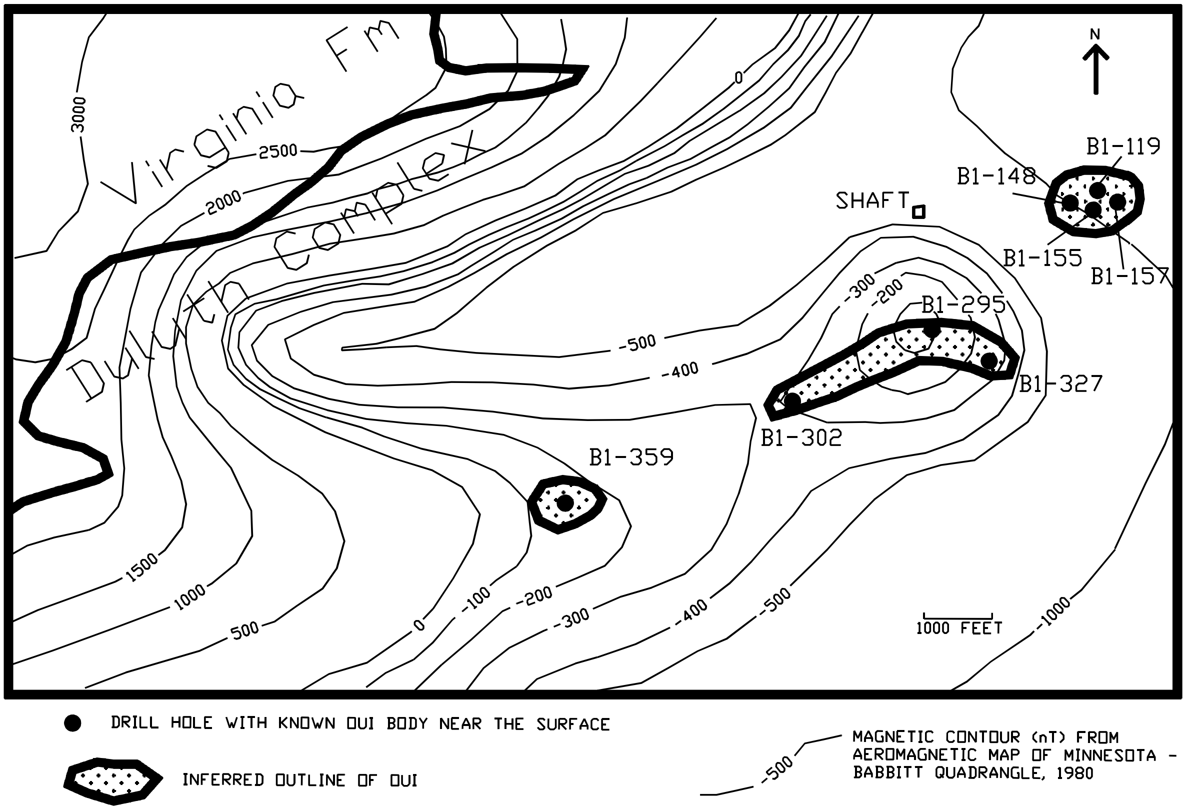

Figure 8. Distribution of near-surface OUI bodies and aeromagnetics of the Minnamax deposit.

MISCELLANEOUS

Numerous pegmatitic troctolitic zones are present in all the troctolitic units. They exhibit both sharp and gradational contacts with the surrounding troctolites. Their size is also extremely variable ranging from 1 foot thick to larger bodies measured in tens of feet. There is no obvious stratigraphic correlation for the pegmatitic zones.

Fault zones are present in most drill holes. They are characterized by a brecciated to crumbly, slickensided, chlorite+serpentine mixture ± calcite-plagioclase-quartz veins and veinlets. Fault contacts with the surrounding rocks (both troctolitic and footwall rocks) exhibit a gradational and/or sharp nature.

A fine-grained diabasic dike was intercepted in drill hole B1-60 and is portrayed on Plate III. The dike is also reported in AMAX lithologic logs for drill holes B1-298, B1-332, and B1-368, which indicates the dike is northwest-trending. In drill hole B1-60, the exterior margin of the dike is chilled and epidotized, and the adjacent troctolitic country rocks exhibit brecciation. This indicates a late to post-Complex age for the dike.

Minor granophyric lenses are present throughout the troctolitic units. They generally exhibit steeply inclined, sharp contacts. In some cases the lenses are apparently related to the OUI bodies (especially in the southeastern portion of the Minnamax deposit area); however, this inferred relationship is not clear cut in most drill holes. Granophyric lenses are not common within the footwall rocks in the drill holes logged at Minnamax. They are, however, more common in the footwall rocks at the Dunka Road deposit (Severson and Hauck, 1990).

GEOCHEMISTRY

INTRODUCTION

Several drill core samples were collected from some of the major lithologic units for whole rock, trace element, rare earth element (REE), base metal, and precious metal analyses. A total of 30 drill core samples were analyzed (Table 3) and include: 26 unmineralized rocks; 3 weakly mineralized (sulfide) rocks; and one mineralized metasedimentary hornfels inclusion (analyzed for base and precious metals only). Results pertaining to the geochemical analyses for the drill core samples are provided in Appendix A. PGE scans (Pt, Pd, Ir, Os, Ru, Rh, Re, and Au) were conducted on eight pulp samples from both disseminated sulfide mineralized horizons and massive sulfide mineralized zones. The Pt and Pd contents were known from previous analyses (five of which contained >1 ppm Pt and/or Pd).

Table 3. Grouping of geochemistry samples

Rock Unit	No. of Samples	Rock Type	Miscellaneous
I	5	Augite Troctolite	One sample from pegmatoidal zone at top of Unit I
IV	3	Augite Troctolite	Augite-rich unit at top of Unit IV
Pic-Per	6	Ultramafic Horizons	Three at bottom of IV, one in middle of V, two at bottom of VI
	4	Modal. Bdd Mgt	Within Units VI and VII (two are adjacent to CC-inclusions)
CC	2	Inclusion	Massive granular CC-inclusion
"Pic"	3	Inclusion	Basalt Inclusion?
0	3	Sill(?)	Olivine-hornblende bearing unit in Virginia Formation
OUI	3	Late Ultramafic	Two orthopyroxenites, one peridotite (w/chlorine drops)
Hnfl	1	Metased. Inclusion	Analyzed only for Cu, Ni, Co, Au, Ag, Pt, and Pd

SAMPLING

Geochemical samples were collected from previously unsampled (whole drill core) portions of surface drill holes at Minnamax. The intervals sampled range from two to six feet, with an average thickness of 4-5 feet. Geochemical sample numbers of drill core are represented by the drill hole number followed by the footage of the sampled interval. The drill core was sawn in half by MDNR personnel, and all traces of metal from the saw were later ground off at the NRRI. An attempt was made to sample only homogeneous intervals that were void of: 1) intense fracturing or jointing; 2) pegmatitic lenses with sharp contacts; 3) deuteric alteration (uralitization); and 4) strong serpentinization (this was somewhat unavoidable within the ultramafic horizons; however, the least serpentinized zones were sampled in these cases). Two of the samples exhibited rusty chlorine drops on the core surface (Appendix A). Four of the samples contained abundant magnetite beds (Appendix A).

All samples were sent to X-Ray Assay Laboratories in Don Mills, Ontario, Canada. Analytical method and detection limits are listed in Appendix A. Two standards were also submitted for analysis: SARM-5 (or NIM-P, pyroxenite) and MRG-1 (Mount Royal Gabbro). Analyzed values, accepted values, and percent difference between the analyzed and accepted values are listed in Appendix A for these standards.

Notable high values within the analytical list include: 1) high Cl values (>1,000 ppm) associated with the ultramafic horizons, olivine-rich OUIs, and an olivine-rich sill(?) within the Virginia Formation; 2) elevated Pd (230-970 ppm) values in sulfide-bearing augite troctolites and a sulfide-bearing (finely disseminated chalcopyrite) hornfels inclusion (600 ppm Pd); 3) high fluorine values associated with some Unit I samples and one OUI sample; 4) elevated REEs associated with a pegmatoidal zone at the top of Unit I; and 5) high Cr values (800-2,327 ppm) associated with the sill(?) unit within the Virginia Formation. The Cr values for the sill(?) are much higher than anything reported for the overlying troctolitic units (unmineralized samples in Severson and Hauck, 1990). Minute oxide specks (tentatively identified as chromite) are present within hornblende crystals that are the major constituent of the sill(?).

SPIDER DIAGRAMS

Plots of chondrite normalized incompatible elements for each of the sampled lithologic units are illustrated on spider diagrams (Figs. 9 to 16). The spider diagrams and chondrite values used in the normalization were constructed using the IGPET II program (Carr, 1987), which uses the technique outlined by Thompson (1982). The spider diagram profiles generally show good internal agreement for the samples within each major rock unit group. However, differences between each of the major rock unit groups are apparent. Whenever possible, the major rock unit group profiles are compared to the spider diagram profiles for the major units (unmineralized) presented in Severson and Hauck (1990).

Unit I

Five samples of augite troctolite were collected from Unit I, of which two are sulfide-bearing and one contains gradational pegmatitic zones (also sulfide-bearing). The spider diagram profiles (Fig. 9) are extremely similar, and tight, for each of the samples, regardless of whether the sample contained sulfides. The obvious anomalous profile in Figure 9 is the sample with pegmatitic zones that was taken from the top of Unit I. A review of the raw analytical data (Severson and Hauck, 1990; Severson, this report) indicates that this sample is enriched in B, Cs, Hf, Hg, La, P_20_5, Ta, Tl, Y, Zn, Zr, and REE relative to all troctolitic samples reported in the aforementioned reports. This enrichment in incompatibles is to be expected if the top of Unit I (± pegmatite material) was the last to crystallize within the Unit I system.

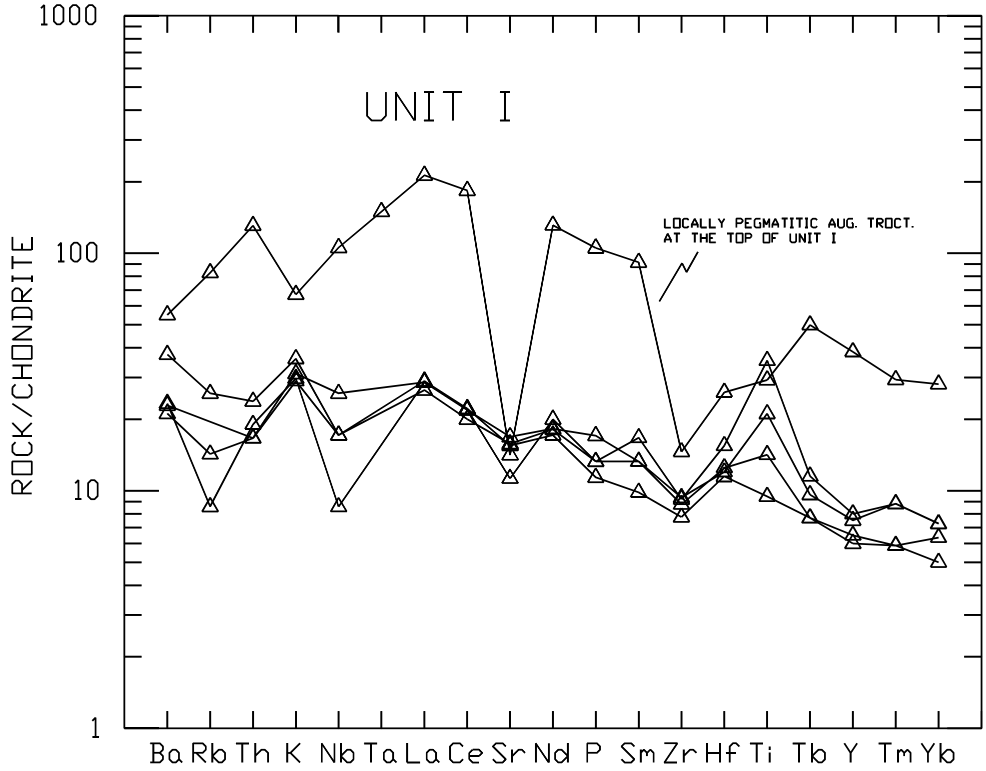

Figure 9. Spider diagram of Unit I troctolites.

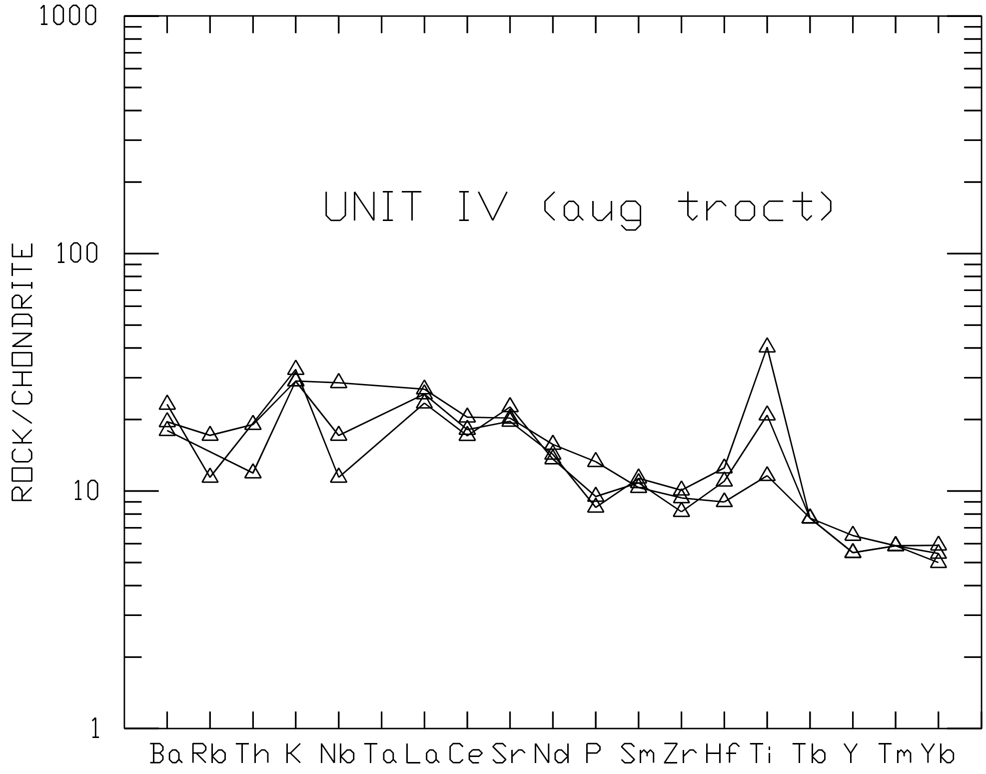

Figure 10. Spider diagram of Unit IV (top) augite troctolite.

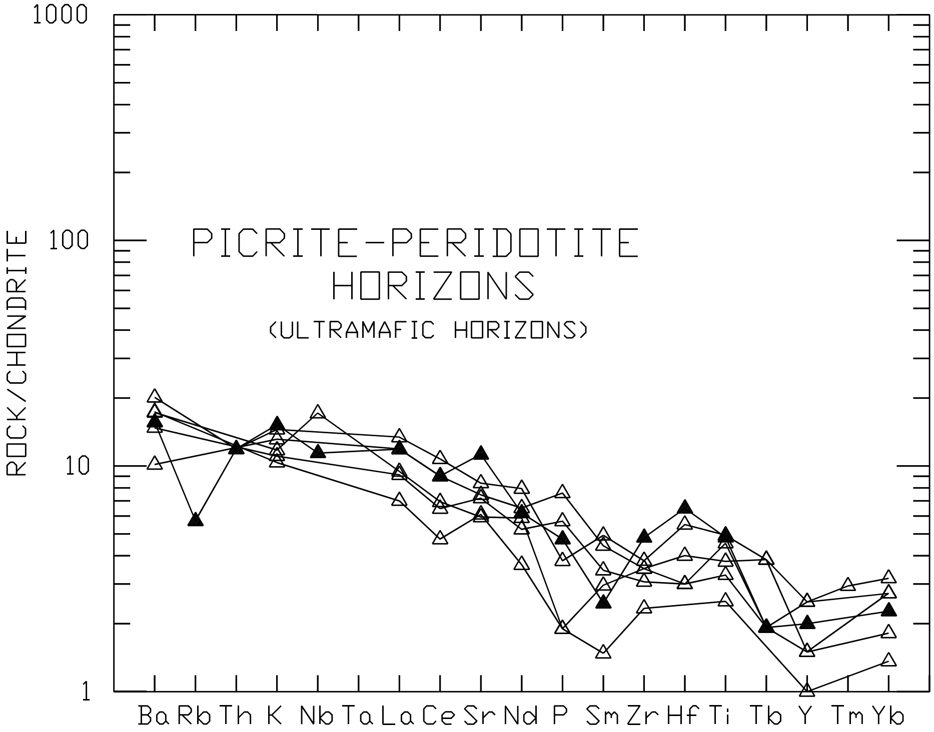

Figure 11. Spider diagram of ultramafic horizons in Units IV, V, VI, and VII.

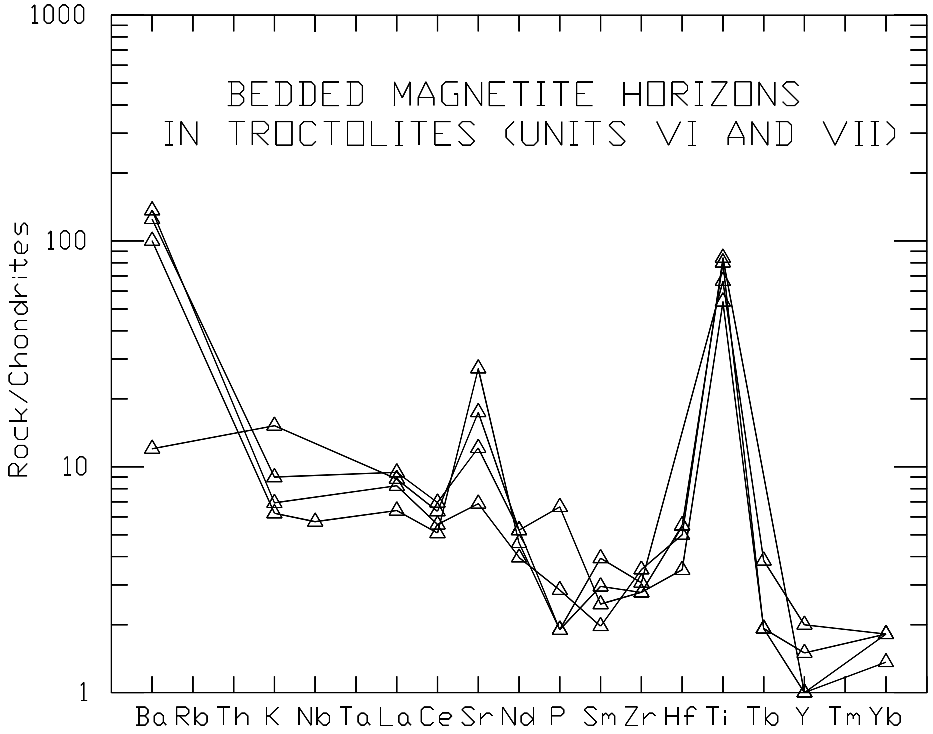

Figure 12. Spider diagram of zones where magnetite beds (cumulus) are present in troctolite (within Units VI and VII).

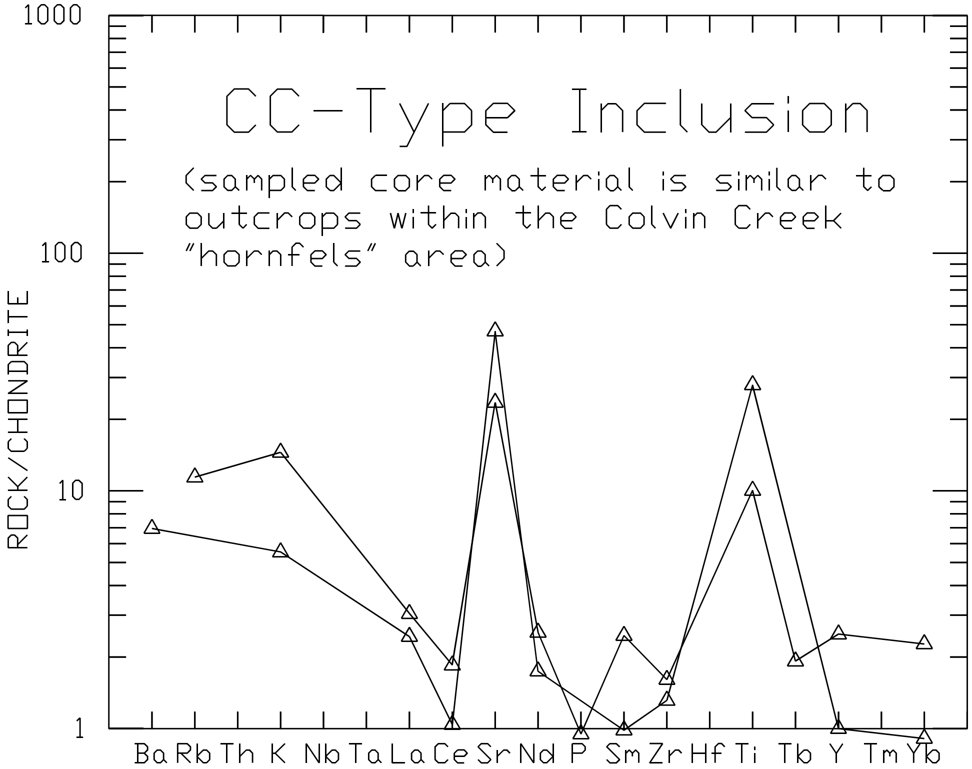

Figure 13. Spider diagram of CC-type inclusions.

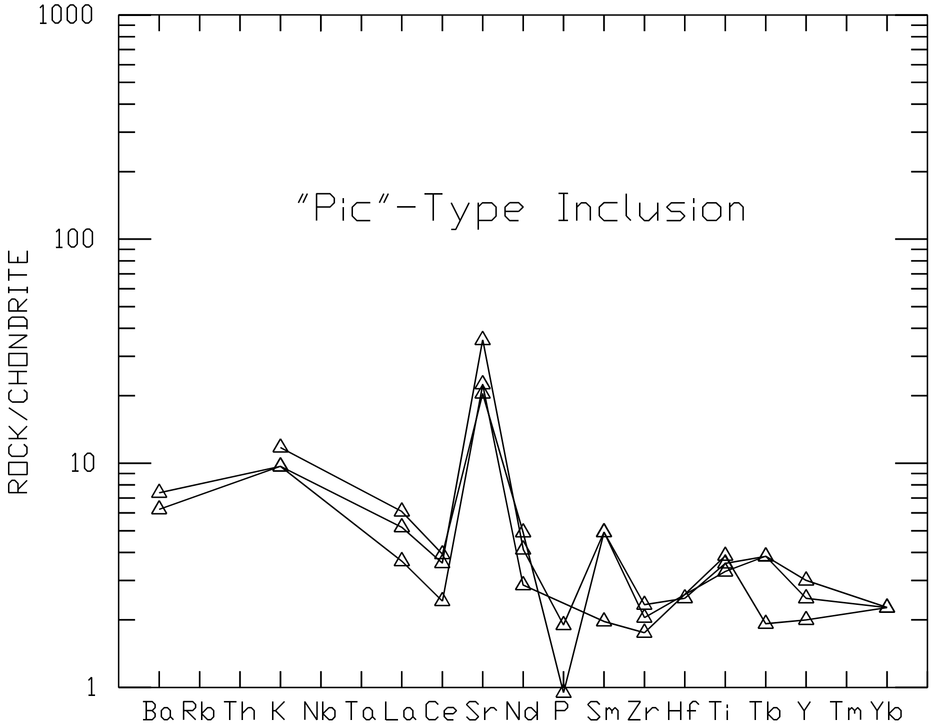

Figure 14. Spider diagram of "pic"-type inclusions.

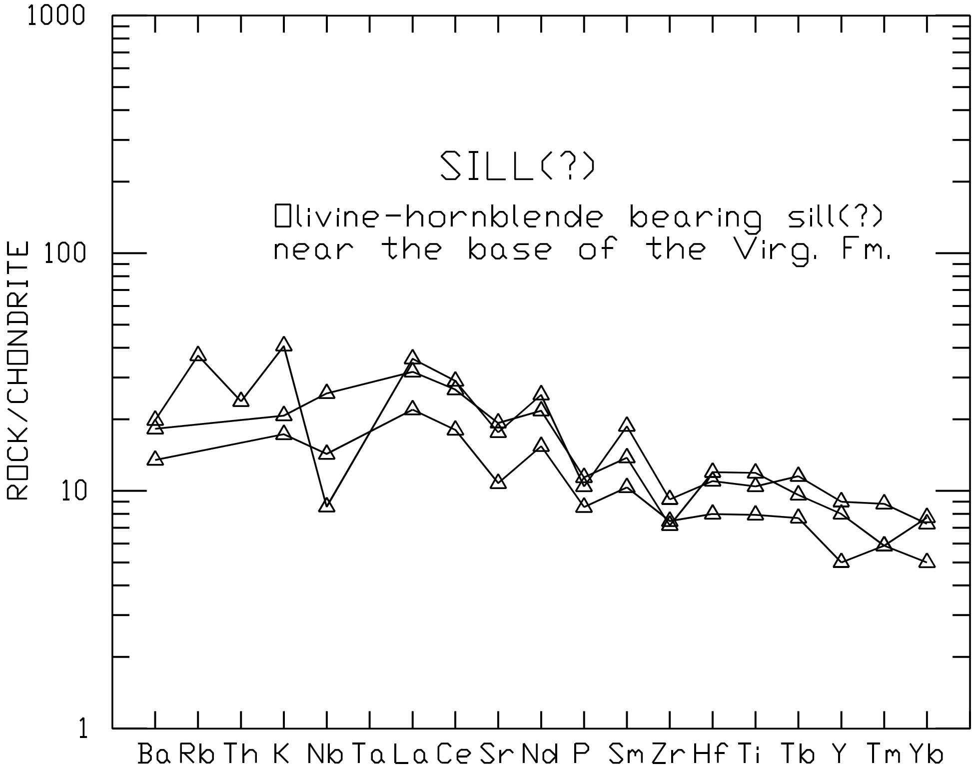

Figure 15. Spider diagram of sill(?) unit within Virginia Formation.

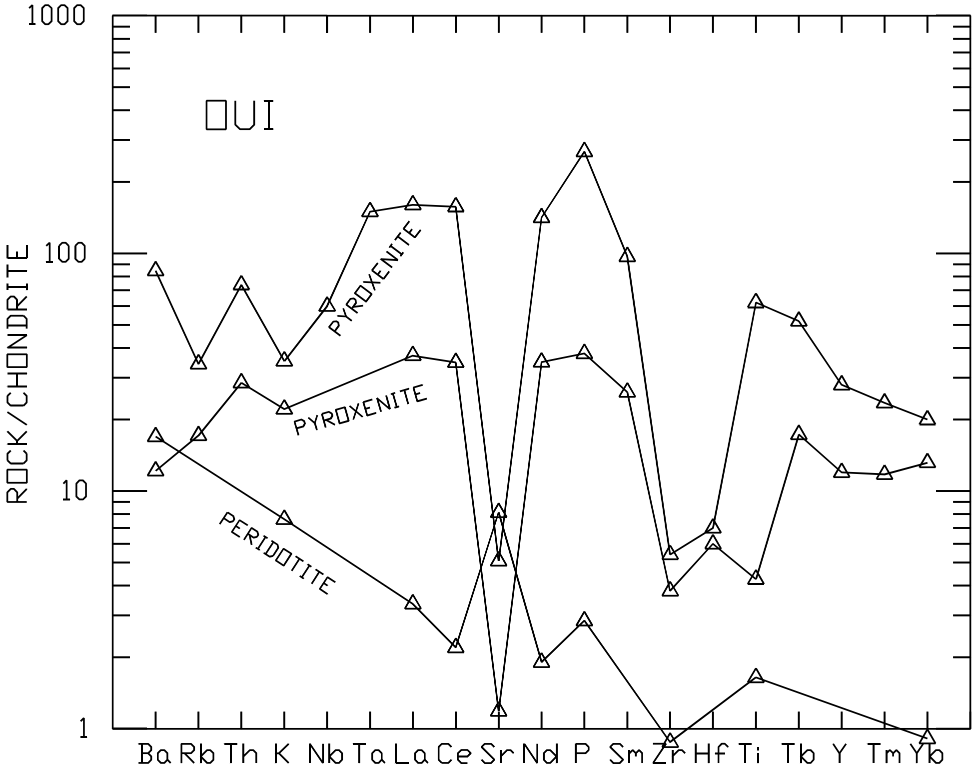

Figure 16. Spider diagram of OUI units at Minnamax.

The spider diagram signatures of the Unit I samples from the Minnamax deposit (except the pegmatitic sample) are the same as spider diagram signatures for "the Lower Half of Unit I" collected elsewhere in the PRTS (Severson and Hauck, 1990). Severson and Hauck (1990) report that the lower half of Unit I exhibits an entirely different signature that is distinctly different from all the other troctolitic units. The difference in pattern is due to higher values of Sm and Nd relative to lower values of Sr. Thus the lower half of Unit I exhibits a negative Sr signature, while a positive Sr signature is characteristic of all the other troctolitic units. Severson and Hauck (1990) also report that even though the upper and lower halves of Unit I are chemically distinct, they are texturally the same and cannot be distinguished in drill core. Samples collected at Minnamax exhibit only the "lower half of Unit I" signature throughout the entire section of Unit I. This interpretation is, however, based on an extremely limited number of samples.

Unit IV - Augite Troctolite

Three samples were collected from a persistent augite-rich augite troctolite horizon ("agt") situated at the top of Unit IV. This augite troctolite is present at the southern periphery of the Minnamax deposit but grades into troctolite to the north of the Local Boy area (see Plate VIII). Because of the augite-rich character of this unit (locally grades into olivine gabbro due to the high augite content), it was utilized as a marker bed in the Local Boy area. Spider diagram profiles for the three samples are presented in Figure 10. All three samples exhibit the same profiles in a tight pattern. They are similar to the Unit I profiles except that the Unit IV samples exhibit a weakly positive Sr signature. A positive Sr signature is characteristic of all the troctolitic units of the PRTS, except the "lower half of Unit I" (Severson and Hauck, 1990).

Ultramafic Horizons

Spider diagram profiles for six samples of ultramafic horizons (picrite to peridotite) are portrayed in Figure 11. The ultramafics were collected from several different stratigraphic levels, and include: three samples from the "± picrite" at the bottom of Unit IV (one sample had Cl drops that coated the core surface); two samples from the bottom of Unit VI; and one sample from the middle of Unit V. All samples, regardless of stratigraphic position, exhibit the same spider diagram profiles. The shape and slope of the profiles is the same as the troctolitic units (Figs. 9 and 10), except the ultramafics are depleted in all plotted elements due to their more primitive nature.

Troctolite with Magnetite Beds

Spider diagram profiles for four samples collected from troctolites that contain modally bedded magnetite are portrayed in Figure 12. Troctolite with bedded magnetite occurs in, at least, three horizons within Units VI and VII. Samples collected for this investigation include: two samples adjacent to the CC-type inclusions at the base of Unit VII; one sample from the middle(?) of Unit VI; and one sample from the bottom of Unit VI. Regardless of stratigraphic position, all four samples exhibit tight and similar spider diagram profiles (Fig. 12). The profiles are the same as profiles for the ultramafic horizons, except that the bedded magnetite horizons exhibit a relative enrichment in Ti -- due to increased oxide content, and Ba and Sr -- due to increased plagioclase content in the bedded magnetite horizons. The similar nature in spider diagram profiles for the ultramafic horizons and bedded magnetite horizons is not too surprising as both occur at the same stratigraphic levels and lateral gradations from one rock type may be present between drill holes.

Hanging Wall Rocks

Two inclusion types, that are thought to be representative of hanging wall material, are present in the top portions of drill holes in the Local Boy area. Only four samples of the two inclusion types were collected for analysis. Two samples from the CC-type and two samples from the "pic"-type; spider diagram profiles are shown in Figures 13 and 14, respectively. The spider diagram profiles are the same for the two inclusion types, except that the CC-type inclusions exhibit a relative Ti enrichment due to the increased oxide content. The similarity in spider profiles for the two inclusion types indicates a common origin; however, the profiles are different than profiles for the North Shore Volcanic Group (in Severson and Hauck, 1990). Profiles for the CC-type inclusion do not compare with profiles of Colvin Creek "hornfels" reported by Severson and Hauck (1990).

Sill(?) in the Virginia Formation

An unusual hornblende-olivine-bearing rock is present within the lower 5-120 feet of the Virginia Formation. The rock has been referred to as a sill(?) because it is concordant to the bedding trends in the Virginia Formation, but it also changes stratigraphic position within the Virginia Formation. The sill(?) is generally present just above the "c-cs" unit (chert-calc silicate) of the Virginia Formation, but locally it is present beneath the c-cs unit, or it displays bifurcations into several horizons above the c-cs unit. Contacts with the enclosing metasedimentary rocks are gradational, and the sill is inferred to have been metamorphosed, along with the metasediments during intrusion of the Duluth Complex. Three samples of the sill(?) were collected from three different scenarios, which include: 1) typical sill(?) material located above the c-cs unit; 2) serpentinized olivine-rich sill(?) material located above the c-cs unit; and 3) typical sill(?) material located below the c-cs unit.

Spider diagram profiles for the three sill(?) samples are portrayed in Figure 15. The profiles are the same, and all three samples plot in a tight pattern, regardless of the different sampled scenarios. The relatively flat slope in the spider profiles is characteristic of the sill(?) unit. The spider profiles of the sill(?) unit do not compare with the spider profiles for metasediments of the

Virginia Formation (in Severson and Hauck, 1990). However, they crudely compare to the profiles of Unit I (except for differences in Ti content).

Oxide-bearing Ultramafic Intrusions - OUI

A wide variety of OUI rock types are present at Minnamax -- the dominant rock type is orthopyroxenite with hornblendite and granophyre. Due to budget constraints, only three samples of OUI were collected. The samples include two orthopyroxenites and one feldspathic peridotite (with Cl drops on the core surface). Spider diagram profiles for the three OUI samples are presented in Figure 16. The two orthopyroxenites exhibit the same profiles. These profiles are vastly different than the olivine-rich OUI. None of the profiles of OUIs at Minnamax compare to profiles of OUIs collected elsewhere in the PRT (Severson and Hauck, 1990). However, the Minnamax OUIs are different in that: 1) they contain drastically less oxides; 2) the dominant rock type is orthopyroxenite rather than clinopyroxenite or peridotite; and 3) hornblendite and granophyre patches are present only in the OUIs at Minnamax. Interestingly, the orthopyroxenite profiles are similar to the profile of the pegmatitic zone at the top of Unit I (Fig. 9).

X-Y SCATTER PLOTS

X-Y scatter plots of MgO versus various whole rock values are presented in Figures 17 through 27. All sample points were plotted using IGPET II (Carr, 1987), which normalized the

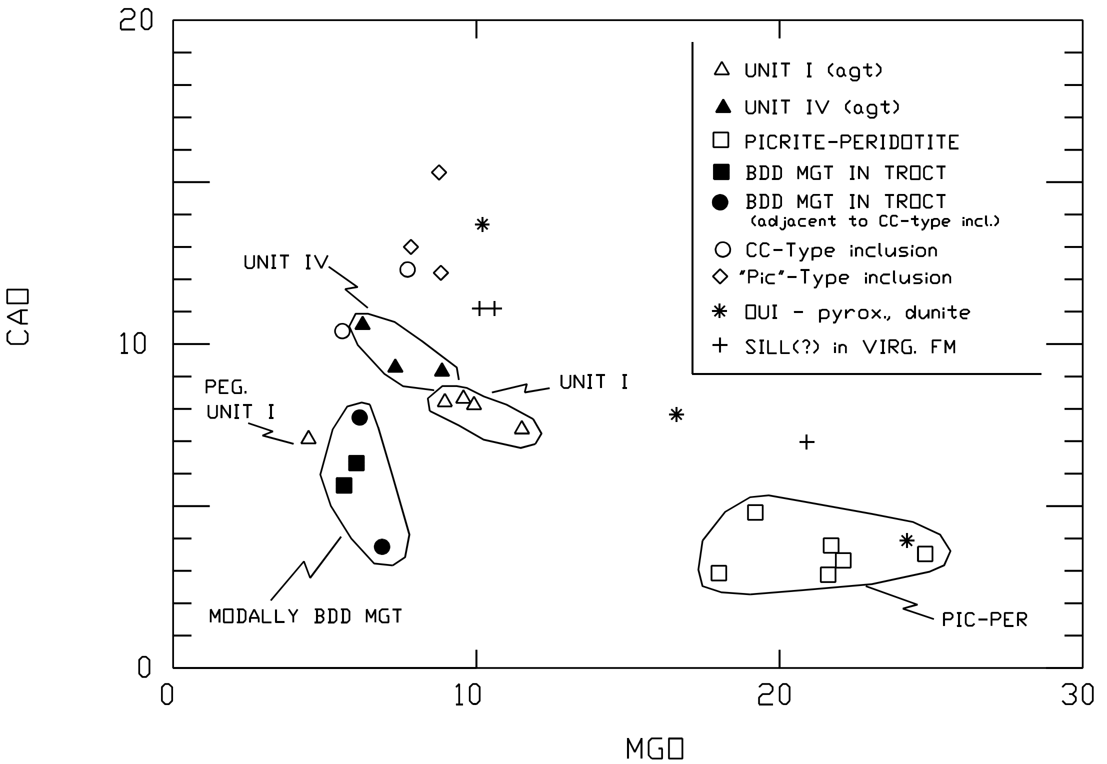

Figure 17. MgO versus CaO, Minnamax samples.

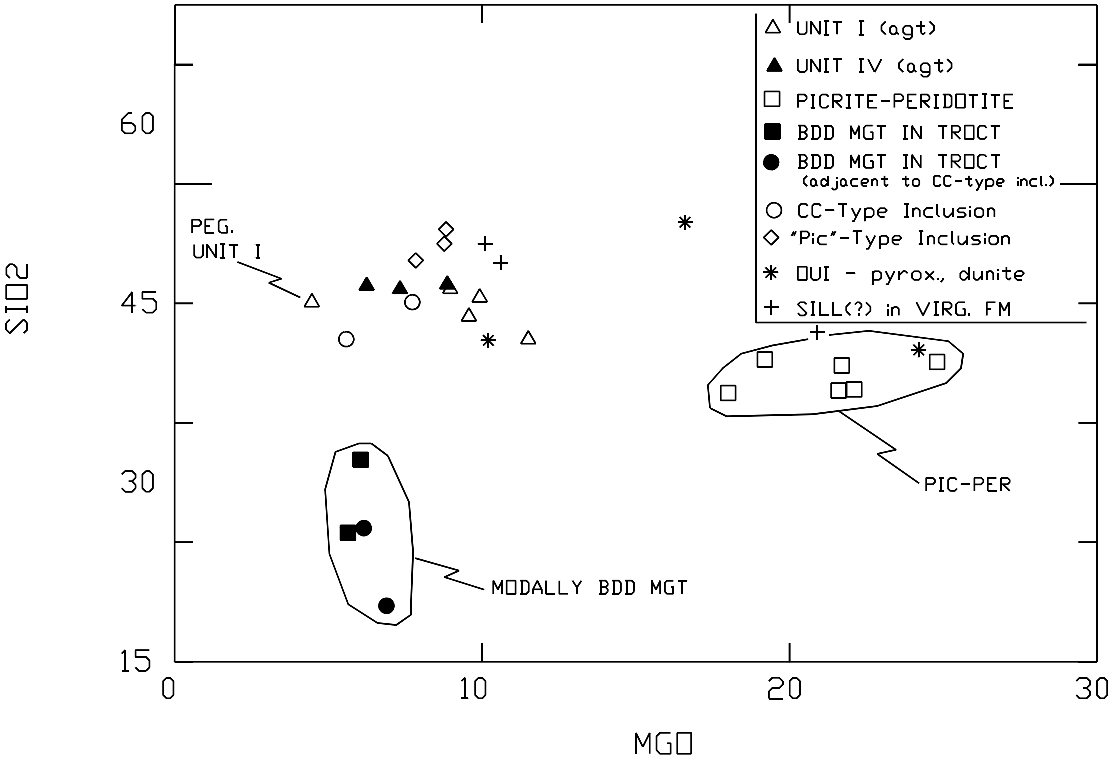

Figure 18. MgO versus SiO_2, Minnamax samples.

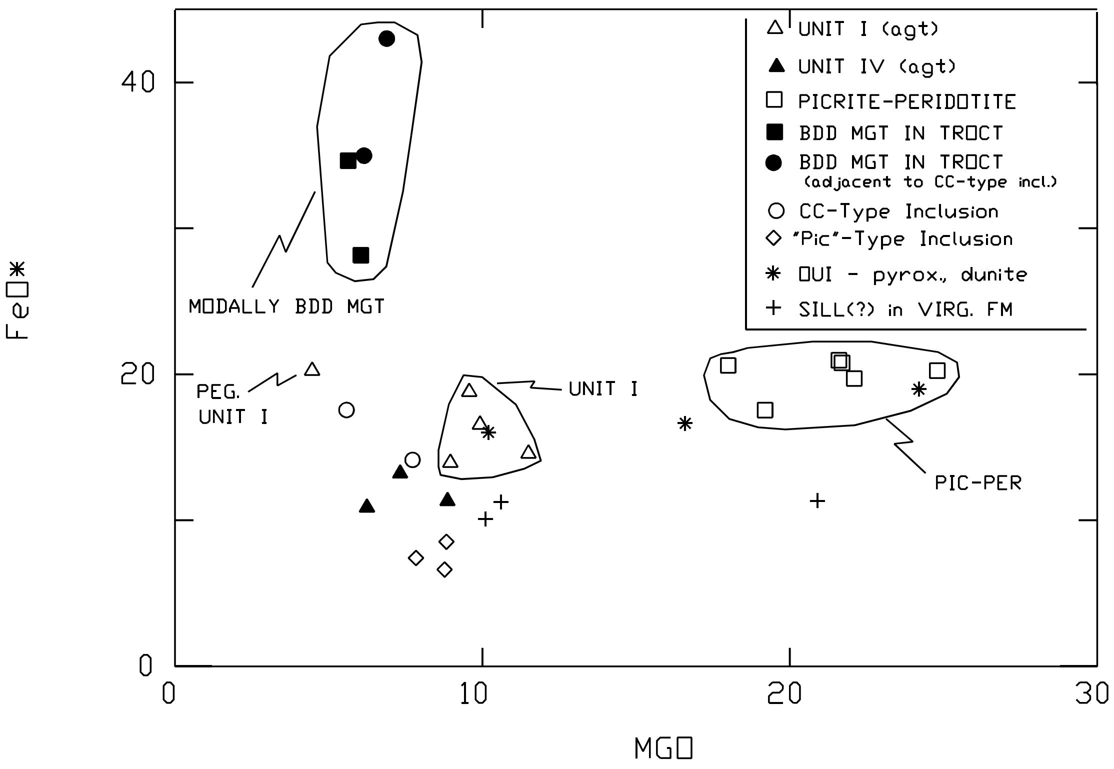

Figure 19. MgO versus FeO*, Minnamax samples. (FeO* = FeO + 0.8998 Fe_2O_3)

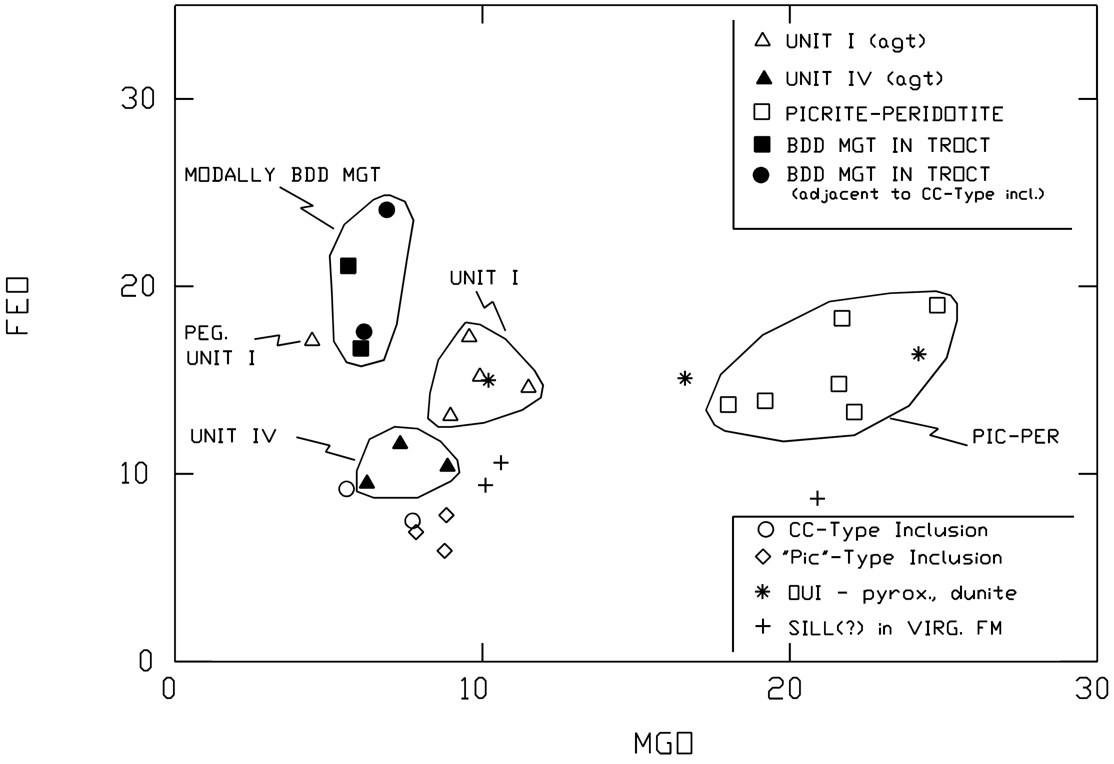

Figure 20. MgO versus FeO, Minnamax samples.

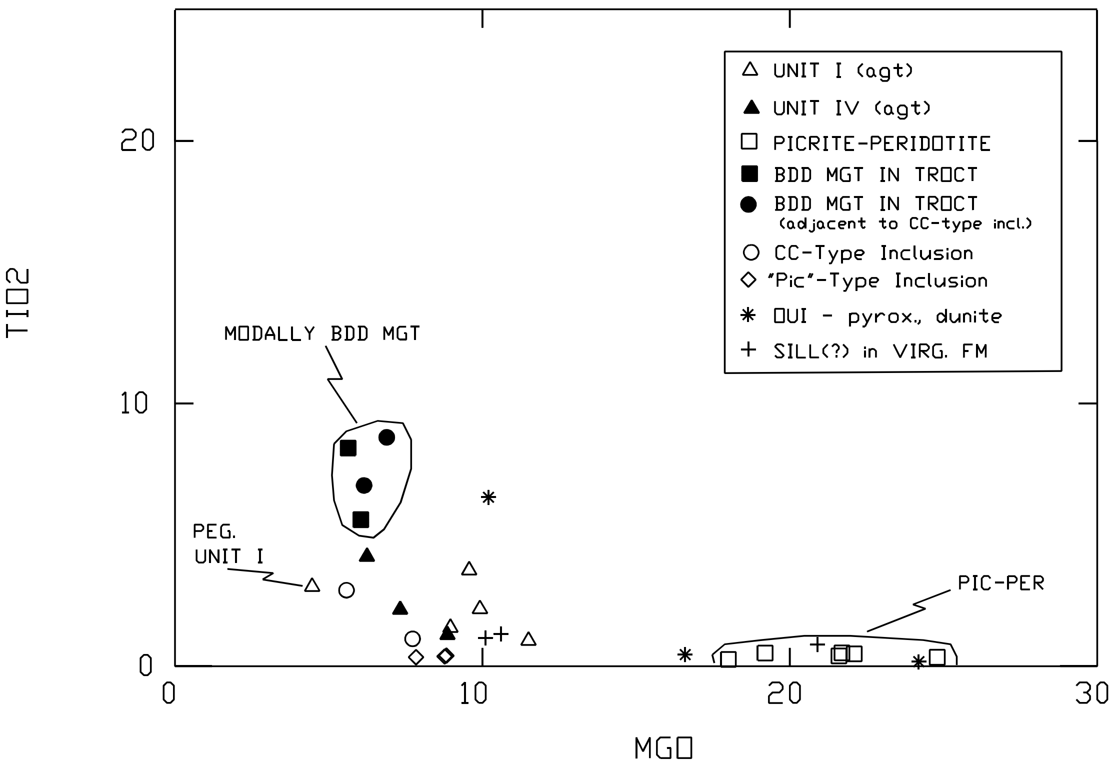

Figure 21. MgO versus TiO_2, Minnamax samples.

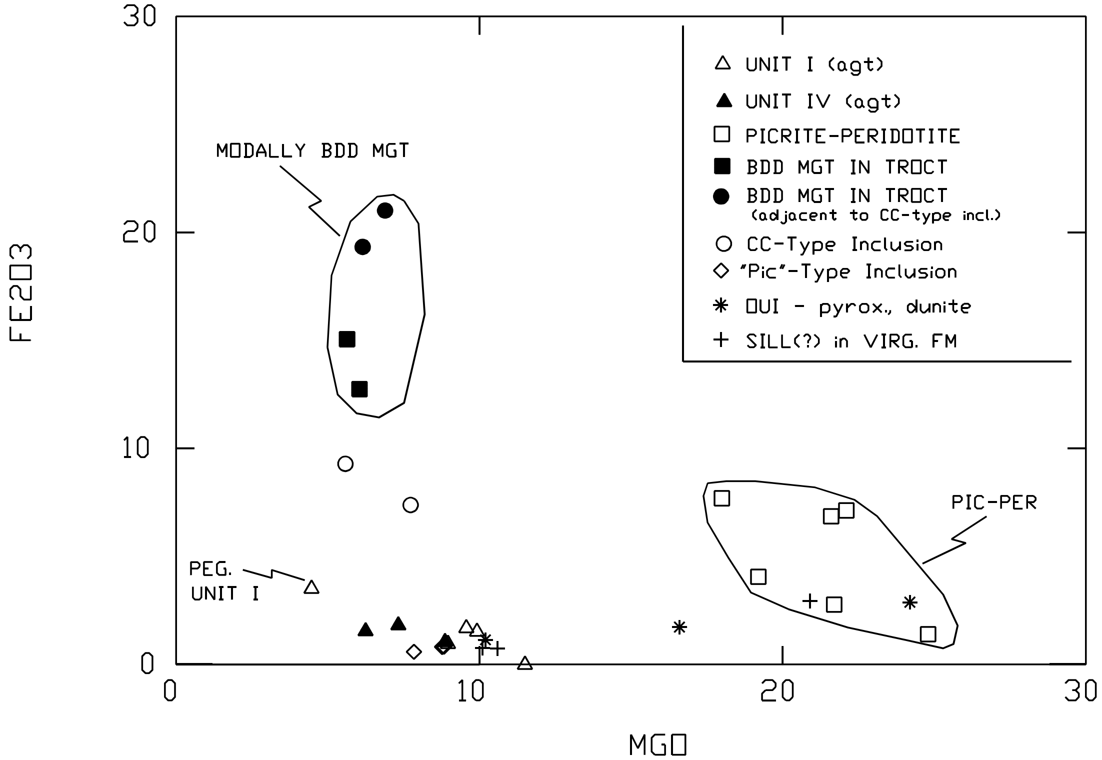

Figure 22. MgO versus Fe_2O_3, Minnamax samples.

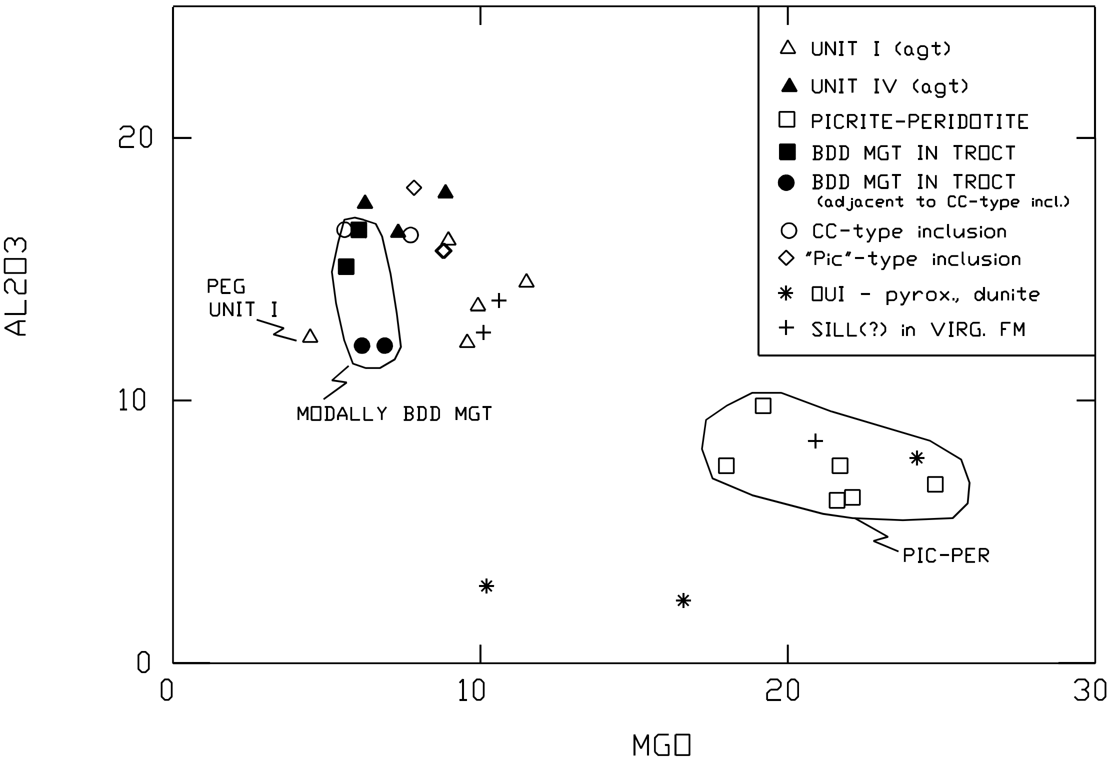

Figure 23. MgO versus Al_2O_3, Minnamax samples.

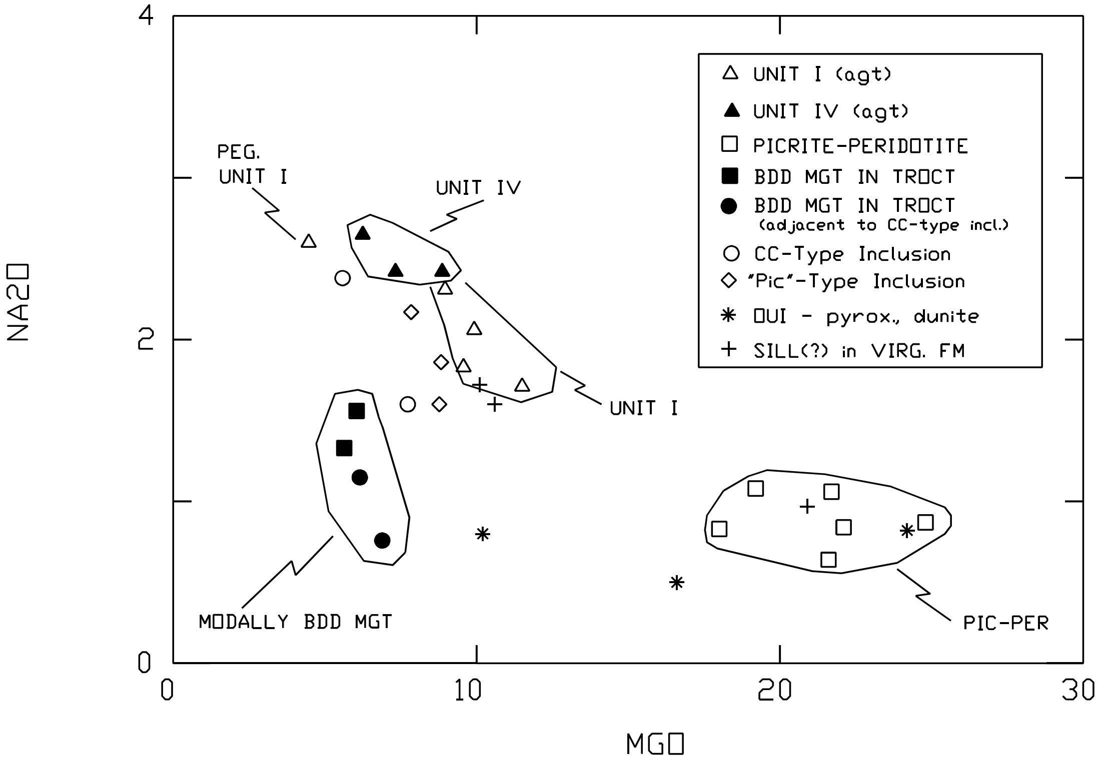

Figure 24. MgO versus Na_2O, Minnamax samples.

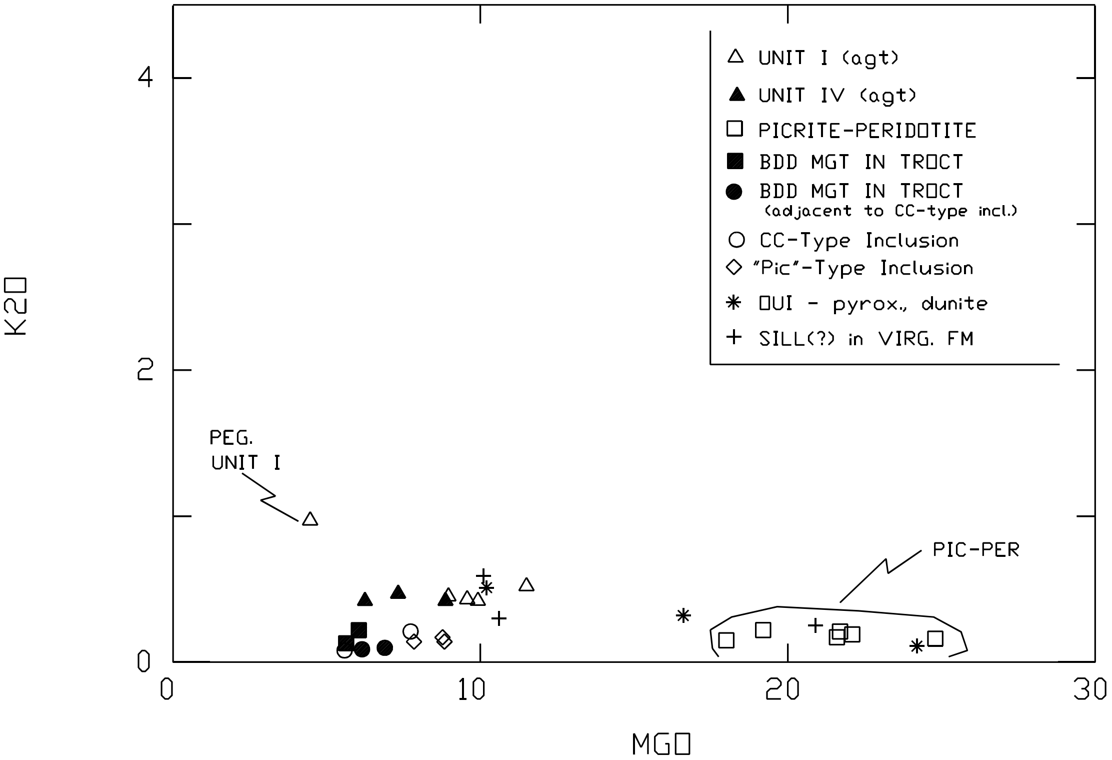

Figure 25. MgO versus K_2O, Minnamax samples.

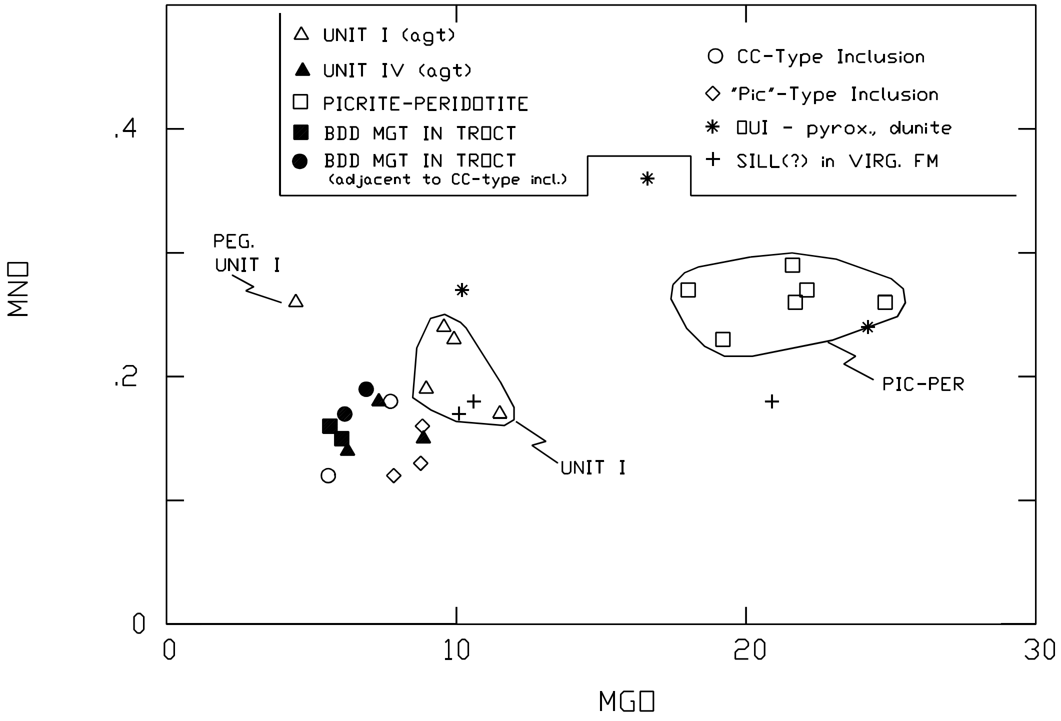

Figure 26. MgO versus MnO, Minnamax samples.

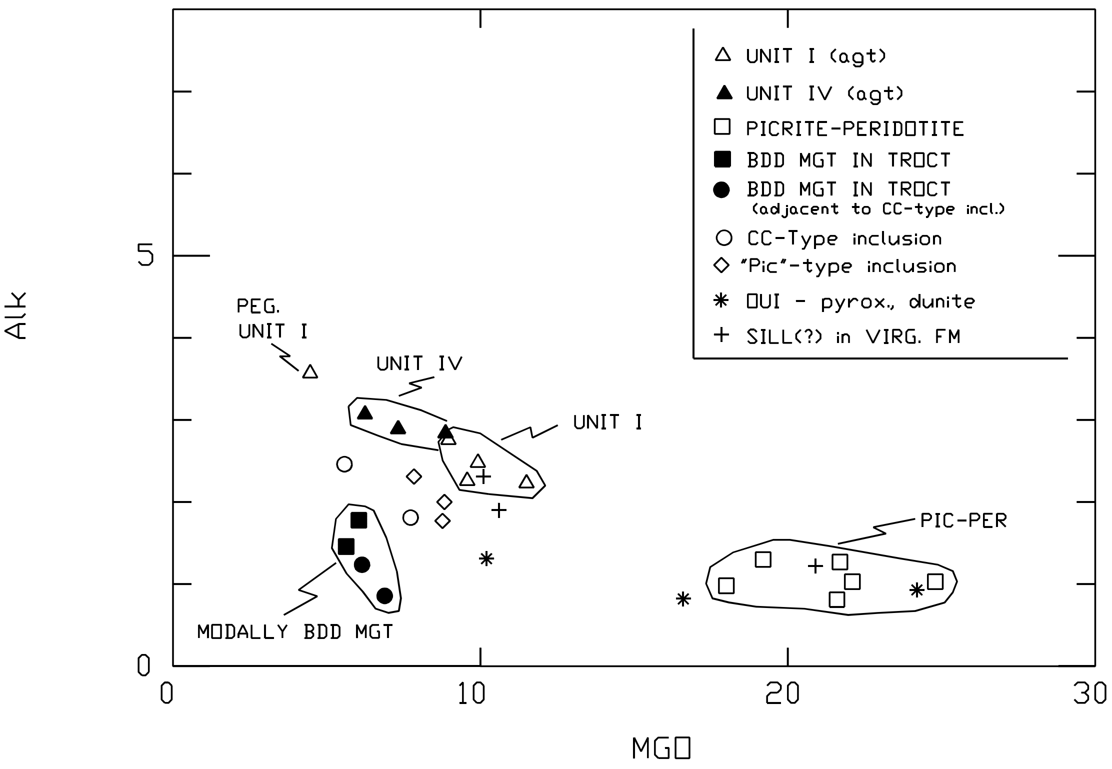

Figure 27. MgO versus alkalies, Minnamax samples. (ALK = $Na_2O + K_2O$)

major oxides to 100% on a water free basis. A plot of MG Number vs Al_2O_3 is shown in Figure 28. In most cases, distinct fields for the various rock units are apparent on the scatter plots. Whenever possible, these fields have been outlined on the accompanying figures and are briefly discussed below.

The two troctolitic units (Units I and IV) plot in separate fields that are distinct from each other. A notable anomalous sample point is the pegmatitic zone collected at the top of Unit I. The field for the Unit I samples collected at Minnamax (excluding the pegmatitic sample) is the same as the field for samples of the "lower half of Unit I" collected elsewhere in the PRTS (Severson and Hauck, 1990).

The ultramafic horizons (picrite-peridotite), collected from several stratigraphic levels at Minnamax, plot in a separate more primitive field (higher MgO content) than the troctolitic rocks.

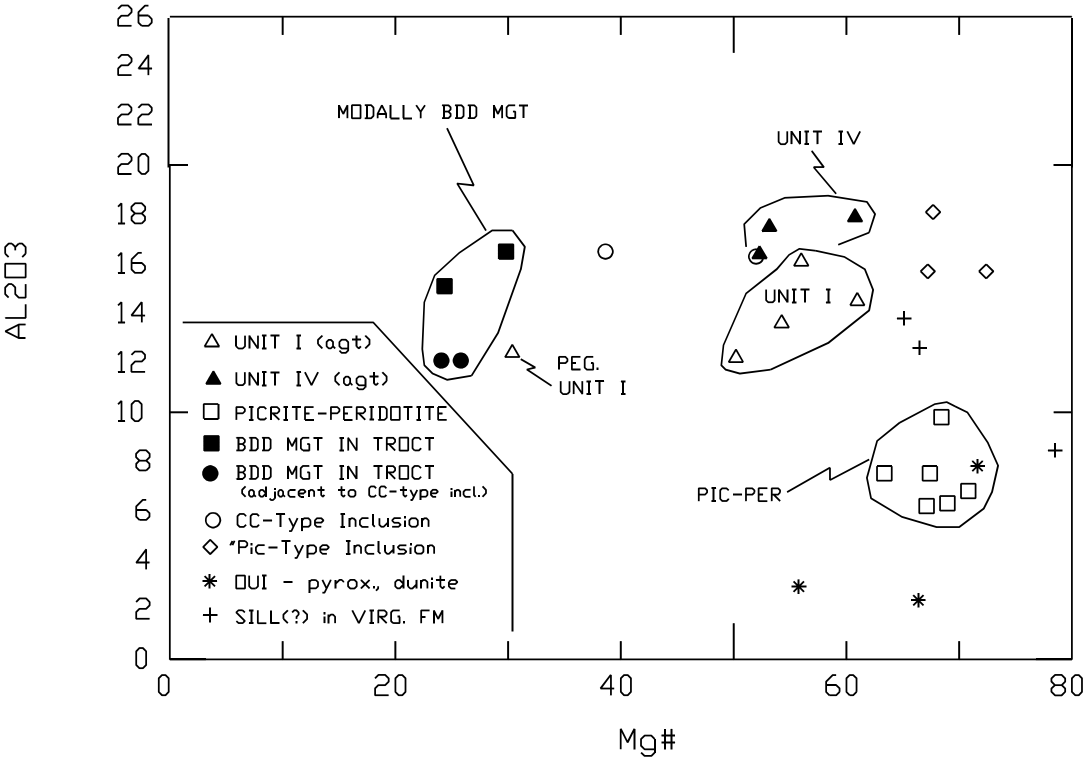

Figure 28. MG number versus Al_2O_3, Minnamax samples.

A differentiation trend is suggested by the linearity between the primitive ultramafic horizons and the more evolved troctolitic rocks. The ultramafic horizons of this investigation plot in the same field as ultramafic horizons sampled elsewhere in the PRTS (Severson and Hauck, 1990).

Bedded magnetite horizons occur at the same stratigraphic levels as several ultramafic horizons in Units VI and VII at Minnamax. Although spider diagram profiles of the two rock types are similar, their fields on the x-y scatter plots are isolated. All four of the samples collected from bedded magnetite zones, but at different stratigraphic levels, cluster in the same field on the x-y scatter plots.

Both the CC-type and "pic"-type of hanging wall inclusions plot close together in the x-y scatter plots. The position of their fields in the plots of this investigation is similar to the position of the field for the Colvin Creek outcrop samples reported by Severson and Hauck (1990). The hanging wall inclusions also plot around, but not entirely within, the field for the North Shore Volcanic Group (reported in Severson and Hauck, 1990).

On the x-y scatter plots, the sill(?) unit within the Virginia Formation, plots in two general areas: 1) in close proximity to the fields for Units I and IV; and 2) within or close to the field for the ultramafic horizons. In the latter case, a serpentinized olivine-rich portion (picritic) of the sill(?) was sampled. This sample has the highest known Cr values (2,327 ppm) for an unmineralized rock, and the highest known MG number (0.78) of all the samples collected in the PRTS (Severson and Hauck, 1990; Severson, this report) -- the primitive ultramafic horizons generally range from 0.60 to 0.75.

The OUI samples plot in two general areas on the x-y scatter plots. The orthopyroxenites (2 samples) plot as isolated points, and the olivine-rich OUI (feldspathic peridotite) plots within the field of the ultramafic horizons. The OUI rock samples of this investigation (dominantly orthopyroxenite) and OUI samples from Severson and Hauck (1990-dominantly clinopyroxenite and dunite) do not plot in the same fields.

PGE SCANS

Eight pulp samples were submitted for PGE scans to Dr. Sarah-Jane Barnes, Geology Department, University of Quebec, Chicoutimi, Quebec, Canada. The pulps had previously been analyzed by X-Ray Assay Labs (XRAL) for Pt and Pd, which indicated that five out of the eight selected samples contained >1 ppm Pt and/or Pd. The percentage of Cu, Ni, and S for each of the pulps had also been previously determined, the results of which were obtained from AMAX files stored at the MDNR. The purpose for selecting these eight samples was to confirm the XRAL Pt and Pd values, and to determine the amount of the other PGEs present in samples that contained both elevated and near background Pt and Pd concentrations. Sample numbers, analyses, and rock descriptions of the samples submitted for PGE scans are shown in Table 4. The PGE scan results are shown in Table 5. Out of the eight samples that were selected: four samples were from troctolites with 2-3% interstitial sulfides (one of which contained elevated Pt); one sample was from a mixed massive sulfide-norite-hornfels zone; and three samples were from the basal massive sulfide zone (one exhibited Cl drops on the core, one had extremely high Pt values, and one had extremely high Pd values). Samples were also selected so that Pt was elevated relative to Pd and vice versa.

Results of the PGE scans confirmed the elevated Pt and Pd values in all the samples. The samples with the highest amount of Pd (11,100 ppm/12,520 ppm) and Pt (8,300 ppm/6,934 ppm) also contained the highest amounts of Os, Ir, Ru, Rh, and Re. Overall, the PGE content of the samples generally increased with increased sulfide content. Gold results are substantially lower in the PGE scan results -- the reason for this discrepancy is under investigation.

The PGE scan results were also compared to PGE scans conducted by Dr. S-J. Barnes on samples collected from the Dunka Road deposit (Geerts, 1991). The major difference between the two deposits are higher Re values for the Minnamax samples. A preliminary interpretation of this difference suggests that the higher Re numbers at Minnamax could be: 1) since Re is a mobile element, the higher numbers may reflect redistribution by hydrothermal fluids; or 2) since Re is concentrated in the crust relative to the PGE, the higher Re numbers might be evidence of more crustal contamination (Dr. S-J. Barnes, pers. comm., 1991).

The PGE scan samples of this investigation, along with previous PGE scan samples from the Minnamax deposit (Morton and Hauck, 1987; Ripley, 1990), have been plotted on Fig. 29 (plot of Cu/Pd versus Pd). This plot was developed by Dr. S-J. Barnes as a means of evaluating when sulfide segregation occurred, and evaluating subsequent changes to the segregation during and after emplacement, by looking at metal ratios such as Cu/Pd (Barnes et al., 1990). In this

Table 4. Geochemistry and description of samples submitted for PGE scans (see Table 5)

Sample #	Drill Hole	Interval	% Cu*	% Ni*	% S*	Pd (ppb)	Pt (ppb)	Au (ppb)	Ag (ppm)	Description
H2153	B1-159	1760-1765'	1.54	0.20	2.59	540	1400	83	3.0	Dissem. sulf. in troct.
H2170	B1-159	1855-1860'	0.89	0.13	2.83	190	30	200	1.5	Dissem. sulf. in aug. troct.
H108	B1-124	1754-1759'	1.08	0.30	2.24	280	60	76	2.0	Dissem. sulf. in troct.
H115	B1-124	1789-1794'	1.57	0.18	2.75	400	40	94	3.0	Dissem. sulf. in troct.
H618	B1-135	1670-1675'	3.59	0.27	7.66	1200	30	74		Sulf. in hnfl with norite
10992	10046	9.8-13'	9.75	1.80	15.19	11100	460	270	28.0	Mass. sulf. w/chlorine drops
11319	10051	41-47'	8.50	1.57	20.67	1900	8300	270	12.5	Massive sulfide
C2196	B1-116	1665-1670'	16.40	0.50	18.41	1100	120	1400		Mass. sulf. w/chlorine drops

**Data from AMAX files*

Precious metal analyses conducted by X-Ray Assay Laboratories, Don Mills, Ontario

Table 5. PGE scan results (see Table 4 for descriptions)

PGE Scans - Dr. S. J. Barnes, University of Quebec, Chicoutimi, Quebec, Canada

Sample #	Os (ppb)	Ir (ppb)	Ru (ppb)	Rh (ppb)	Pd (ppb)	Pt (ppb)	Au[x] (ppb)	Re* (ppb)
H2153	4.9	4.63	9	8.6	572	1394	71.5	10.7
H2170	1.2	1.00	6	2.5	178	43	11.3	6.7
H108	2.9	2.03	9	5.8	208	39	85.4	12.3
H115	1.4	1.56	8	4.8	225	40	22.0	10.6
H618	1.9	2.8	11	8.8	1210	36	13.2	13.3
10992	6.6	6.3	25	20	12520	799	187.7	16.2
11319	25	5.19	30	18.3	1774	6934	129.2	13.2
C2196	<10	0.37	25	11+	640+	151	494.3	13
Ax90 (standard)	2.6	2.95	25	11	361	128	4.6	1.8
Ax90 (accepted)	2.3	2.7	18.6	12	338	120	5.1	

**Results are experimental as there is some question as to whether Re is completely collected in the Ni-sulfide bead.*

[+] *High dead time, therefore, the counting errors are large.*

[x] *Lack of agreement between XRAL Au values and these Au values are still being investigated.*

(S. J. Barnes, pers. comm., 1991)

manner, the interelement ratios (Cu/Pd) for a particular deposit can be compared to mantle ratios (6 x 10^3 for Cu/Pd) to determine if a layered intrusion has potential for hosting a PGE reef deposit. Figure 29 is broken into three fields: 1) "depleted" relative to mantle ratios; 2) "enriched" relative to mantle ratios; and 3) a field that roughly corresponds to mantle ratios (unmarked area between the "depleted" and "enriched" fields). The Cu/Pd ratios of PGE reef deposits (Merensky Reef, J-M Reef, etc.) plot within the enriched field, and the Cu/Pd ratios of Cu-Ni deposits (Sudbury, Duluth Complex, etc.) plot within the depleted field (Barnes et al., 1990). The Cu/Pd ratios of samples collected from strata bound PGE-bearing horizons at Dunka Road plot in the unmarked field -- roughly equal to mantle ratios (Geerts, 1991).

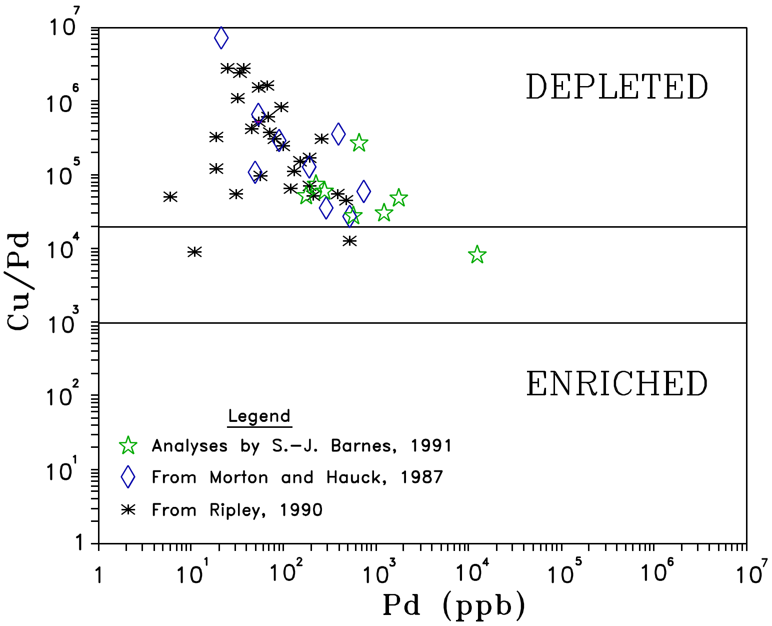

Figure 29. Plot of Cu/Pd versus Pd for sulfide-bearing Minnamax samples.

Almost all of the samples collected at the Minnamax deposit plot within the depleted field of Figure 29; three samples plot slightly below the depleted field within the unmarked field. This suggests that the Cu/Pd ratios have been altered after sulfide segregation occurred, relative to mantle ratios. The Cu/Pd ratios at Minnamax may be high (depleted) because: 1) Pd has been removed by a previous sulfide segregation; 2) Cu was added to the magma by contamination of the magma by sediments (the higher Re at Minnamax relative to Dunka Road could have been added at the same time); or 3) the ratios are high due to Cu (and possibly Re) redistribution by hydrothermal fluids (Dr. S-J. Barnes, pers. comm., 1991). Overall, the Minnamax material shows evidence of a more complex history (than the Dunka Road material) involving either contamination and/or deuteric redistribution of some elements (Dr. S-J. Barnes, pers. comm., 1991).

SUMMARY AND CONCLUSIONS

SUMMARY OF THE TROCTOLITIC UNITS

A definable stratigraphic package is recognizable in the troctolitic rocks of the Minnamax deposit area. This makes possible, for the first time, drill hole to drill hole correlations of rock units. Previous studies conducted on one to four drill holes have indicated that this is not possible, and thus definition of the overall igneous stratigraphy was unfortunately overlooked. However, when enough drill holes are relogged and specific marker beds are utilized, a relatively uniform stratigraphy can be worked out and extended on a hole-by-hole basis. After a generalized knowledge of the overall stratigraphy is developed, gross differences in the stratigraphy can be recognized and re-examined. The previous researchers were unable to pinpoint the overall stratigraphy because not enough holes were examined to completely understand what the "norm" was in the first place. Thus, the observations of individual drill hole studies became increasingly important and a veritable "sea" of uncorrelatable troctolites was the final result. Martineau (1989, p. 117) similarly explains this difficulty as "Published studies of single holes, or isolated groups of holes, have tended to cause confusion because of the extrapolation of good observation from one area to [elsewhere in the Duluth Complex]."

Detailed relogging of 61 surface holes at Minnamax has delineated at least seven major sub-horizontal troctolitic units. These same units are present to the WSW in three additional Cu-Ni deposits. Collectively, the units have been delineated in 143 drill holes (totalling 218,235 feet of core) that extend over a 15-mile strike-length within the Partridge River Troctolite (Severson and Hauck, 1990; this report). In addition, Geerts (1991) has extended the stratigraphy to all the drill holes in the Dunka Road deposit. The major key in unraveling the stratigraphy was the recognition of the uniqueness of Unit III (mottled-texture due to olivine oikocrysts) and the top of Unit IV (augite-rich augite troctolite up high in the stratigraphic section) and their utilization as marker beds. All drill holes could then be hung on the top of Unit III or Unit IV and then other significant marker horizons could be correlated between the holes. The second-most important marker beds are the ultramafic horizons (picrite, peridotite, dunite). Finally, once these horizons were correlated, the intervening troctolitic rocks were categorized as to dominant rock type and correlated with dominant rock types in adjacent holes. Major correlative troctolitic units were then numbered upwards from the footwall contact and include Units I through VII in the Minnamax area.

Most of the rock units defined at the Dunka Road, Wetlegs, and Wyman Creek deposits (Severson and Hauck, 1990) are present at the Minnamax deposit. However, the overall picture at Minnamax is somewhat more complicated than the other deposits due to rock type changes that are manifested by: 1) pinch-out and reappearance of specific marker bed units; 2) down-strike gradational changes of the ultramafic horizons; 3) extremely limited lateral extent of some ultramafic horizons; and 4) gradational changes in the dominant troctolitic rock type per stratigraphic unit between drill holes. In some areas a particular marker bed may "disappear" and be replaced by another marker horizon, which in turn, may "disappear" laterally. The major lesson learned at Minnamax is to not depend solely on any one specific marker bed as it may not persist throughout the deposit, and even if lost, the marker bed may "reappear" again at the same stratigraphic horizon elsewhere. In spite of these local difficulties, a gross stratigraphy of seven sub-horizontal igneous units have been delineated at Minnamax. The major characteristics of each unit (Units I through VII) for the drill holes logged to date are summarized in Table 6.

What emerged during this investigation and previous investigations (Severson and Hauck, 1990; Geerts et al., 1990; Geerts, 1991) is that several of the upper igneous units (Units IV

Table 6. Summary of distinguishing characteristics pertinent to the various troctolitic units at the Minnamax deposit

UNIT	MAJOR ROCK TYPE	ULTRAMAFIC LAYERS	SULFIDE-BEARING INTERVALS	UNIQUE PETROGRAPHIC FEATURES	INCLUSIONS	CONTACT RELATIONSHIPS	MISCELLANEOUS
VII	HOMOGENEOUS TROCT. TO ANORTH. TROCT.	LATERALLY DISCONT. PIC & PER LAYERS WITHIN UNIT PIC-PER BASE	VERY RARE	NONE COMPOSITE ILMENITE-MAGNETITE GRAINS	RARE METASED. INCL. "PIC" & CC INCL. (CC INCL COMMON AT BASE)	ULTRAMAFIC HORIZON OR CC INCL. SHARP	LARGE OUI BODIES LOCALLY COMMON SCATTERED INCLUSIONS(?) OF UNIT III ? LOCAL ZONES WITH MODALLY BDD MGT VERY THICK ULTRAMAF. HORIZ. AT BATHTUB
VI	HOMOGENEOUS TROCT. TO ANORTH. TROCT.	LATERALLY DISCONT. PIC & PER LAYERS WITHIN UNIT PIC-PER BASE	RARE	NONE	RARE METASED. INCL. MINOR CC INCL. "PIC" INCL. ARE COMMON	ULTRAMAFIC SHARP	OUI BODIES LOCALLY COMMON LOCAL ZONES WITH MODALLY BEDDED MAGNETITE AT MIDDLE AND BOTTOM ABUNDANT CYCLIC UNITS AT BATHTUB
V	HOMOGENEOUS TROCT. TO ANORTH. TROCT. (TROCT ANORTH LOC.)	MINOR - LATERALLY DISCONT.	MINOR	NONE	MINOR CC AND "PIC" INCL (AT TOP OF UNIT?) MINOR METASED. INCL.	GRADATIONAL	
IV	HOMOGENEOUS AUGITE TROCT. & TROCTOLITE	"POCKET PICRITE" LATERALLY DISCONT PIC & PER WITHIN UNIT " ± PICRITE"	SCATTERED ZONES	NONE	METASED INCL FAIRLY COMMON	SEMI-PERSISTENT ULTRAMAFIC SHARP	AUGITE TROCTOLITE AT TOP LOCALLY ALL AUGITE TROCT AT BATHTUB
III	MOTTLED ANORTHOSITIC TROCTOLITE TO TROCTOLITE	VERY RARE	SCATTERED ZONES	OLIVINE OIKOCRYSTS OXIDE OIKOCRYSTS LOCALLY	METASED INCL COMMON	SHARP, LOCALLY GRADATIONAL	PRESENT AT SW MINNAMAX PRESENT AS LENSES AT BATHTUB AND LOCAL BOY
II	HOMOGENEOUS TROCTOLITE	PICRITE AT BASE	SCATTERED ZONES	NONE	METASED INCL COMMON	ULTRAMAFIC HORIZON SHARP TO GRAD	PRESENT ONLY AT SW MINNAMAX
I	HETEROGENEOUS -- TROCTOLITE AND AUGITE TROCTOLITE WITH OLIVINE GABBRO, PEG, & NORITE LOCALLY	MINOR - LATERALLY DISCONT.	MAIN ORE ZONE	INCREASED BIOTITE AND CPX CONTENT INCREASED OPX CONTENT LOCALLY APATITE COMMON PLAGIOCLASE-SYMPLECTITE OLIVINE-SYMPLECTITE ILMENITE IS THE DOMINANT OXIDE WITH ONLY MINOR COMPOSITE ILM-MGT GRAINS	ABUNDANT METASED INCL ! SEVERAL LARGE RAFT-LIKE HORNFELS INCL STACKED ABOVE EACH OTHER IN THE LOCAL BOY AREA	SULFIDE-BEARING / HNFL INCL / CS-GRN ANORTH TROCT NORITE LOCALLY	OLIVINE-RICH OUIs, WITH INCREASED OXIDE CONTENT, COMMON IN AREAS WHERE THE BIWABIK IRON-FORMATION IS THE FOOTWALL ROCK.

through VII) are characterized by thick intervals of homogeneous textured "troctolite" that contain persistent basal ultramafic horizons. Each ultramafic horizon exhibits modally graded tops and sharp bases indicating crystal settling. The ultramafic base of these units indicates that: 1) each troctolitic unit was intruded sill-like as a single magmatic pulse and crystallized as a single unit; or 2) each ultramafic member represents the inception of periodic magma replenishment that then mixed with an earlier pulse.

Unit III (main marker bed) exhibits considerable textural variations relative to the upper troctolitic units and apparently was intruded as a single pulse. Unit III is only locally present in the Local Boy area and is described as pinching out. This may not be a physical pinch out, but rather the conditions that favored formation of the mottled texture of Unit III (fine-grained plagioclase and large olivine oikocrysts) may not have been met within the Local Boy area.

Unit I appears to reflect an entirely different intrusive style than all the other overlying units. Unit I is highly heterogeneous with abundant metasedimentary hornfels inclusions and abundant sulfide-bearing zones. These differences suggest that Unit I was collectively intruded as a series of repeated closely spaced magmatic pulses. The concept of continuous magma replenishment and magma blending is envisioned as an important ore-forming process (in Unit I) by several authors (Rao, 1981; Rao and Ripley, 1983; Ryan, 1984). In addition, large metasedimentary rafts are stacked above each other in the Local Boy area. The configuration of these rafts indicates that Unit I was repeatedly intruded along bedding planes within the footwall Virginia Formation.

The timing of emplacement for each of the major troctolitic units (Unit I and Units II through VII) is unknown. Several authors (Grant and Molling, 1981; Rao and Ripley, 1983) propose that the PRT was intruded sill-like and the sills young downward. This is substantiated by mineral composition investigations (Hardyman, 1969; Molling, 1979; Tyson, 1979; Grant and Molling, 1981; Chalokwu, 1985) that concluded that more primitive rocks occur at the top of the troctolitic section and become more evolved (Fe and Na enrichment) with depth. However, the exact nature of the reversed differentiation trend is disputed. Some authors (Hardyman, 1969; Tyson, 1979; Tyson and Chang, 1984) propose that the Fe-enrichment is related to contamination from the underlying Virginia Formation. Whereas, others (Grant and Molling, 1981; Chalokwu and Grant, 1987) suggest that the inverted fractionation trends are related to downward increases in intercumulus liquid followed by reequilibration of cumulus olivine. Detailed microprobe studies of the silicates in the troctolitic rocks was not conducted in this investigation.

In regards to the timing of igneous units delineated in this investigation, a sequential intrusion of magma pulses from top to bottom is not indicated. Instead, a more complex pattern of intermixed intrusions is suggested by: 1) the heterogeneous nature of Unit I; 2) the presence of mottled textured Unit III-type inclusions(?) higher up-section in Unit VII; 3) the localized nature of Unit III within the Local Boy area (Unit III is enclosed in Unit I); and 4) a down cutting relationship of Unit V into Units I and II at Wyman Creek (Severson and Hauck, 1990). In addition to the complicated timing of magmatic pulses, a difference in the style of emplacement is also indicated. Units IV through VII are characterized by a monotonous sequence of homogeneous-textured troctolites, with relatively thin ultramafic bases, that may be related to widely spaced pulses into a well-developed large magma chamber. Because these units contain progressively less metasedimentary hornfels inclusions with height, there was probably less interaction with the footwall rocks. Unit I and Unit II at Wetlegs (Severson and Hauck, 1990) exhibit a different intrusive history. These units appear to have formed by rapid magmatic pulses that were emplaced along bedding planes in the footwall rocks within an early, progressively developing magma chamber. Intrusion was accompanied by assimilation of larger volumes of footwall rock indicated by the abundant amount of inclusions within Unit I.

Martineau (1989) has suggested that there are several intrusive bodies within the Minnamax area, which he has named: Dunka River intrusion; Allen intrusion; and Babbitt intrusion. On the cross-sections that accompany his report, Martineau (1989) indicates that the Babbitt intrusion is the earliest and is cut off down dip by the Allen intrusion, which in turn, is cut off still further down dip by the Dunka River intrusion. This implies a younging age toward the interior of the Complex. However, the configuration of intrusions being cut off down dip by later intrusions is not substantiated in this study. Rather, all the units (I through VII), along with specific key marker beds, have been found within all three of Martineau's individual intrusions. Specific key marker beds include: "± picrite"; "pocket picrite"; ultramafic horizons at the base of Units VI and VII; the augite troctolite zone ("agt") at the top of Unit IV; and the large hornfels raft-like inclusions in the Local Boy area. Overall, the correlation of specific units and marker beds across Martineau's down dip cut-offs is too coincidental, and therefore, his proposed intrusions should be rejected.

Lastly, the ultramafic horizons exhibit lateral gradational rock type changes and thickness changes that are not fully understood. The ultramafic horizons were utilized as marker beds, and thus their behavior in three dimensions could be closely observed. Rock type is characterized by an alternating assemblage of either/or: picrite; feldspathic peridotite; peridotite; dunite; picrite with variable amounts of troctolitic interbeds; olivine-rich troctolite; and troctolite with thin picrite interbeds. One or more of these rock types may be stacked above the other in no particular order, and the thickness of this assortment may be highly variable between drill holes. Gradational tops and sharp bases are commonly present, in both the overall horizon and in internal cyclic layers, indicating that crystal settling may have been important. In addition to vertical gradations between rock types in a single drill hole, lateral gradations between the rock types are also present between drill holes. These lateral gradations are exhibited by changes along strike from peridotite to picrite to olivine-rich troctolite to stratigraphic levels where the ultramafic horizon is absent. All the above differences may indicate local variations in the magma chamber that were controlled by floor topography and/or magmatic density currents.

Changes in the floor topography of the magma chamber may also explain why certain ultramafic horizons are confined to limited areas. For instance, the "pocket picrite" is confined to an east-west trending lense (open to the east) that has inferred dimensions of only 700 feet wide by 2,500 feet long and up to 25 feet thick. The dimensions of the "pocket picrite" suggest that it may have been deposited in a topographic low in the floor of the magma chamber. Interestingly, the "pocket picrite" projects into the Bathtub area where extremely thick ultramafic horizons and abundant cyclic zones are encountered. Thus, the anomalously thick ultramafic horizons at Bathtub may also be confined to the same topographic low as the "pocket picrite." Unfortunately, not enough drill holes have been relogged to ascertain if there is a correlation between the "pocket picrite" and the Bathtub ultramafic horizons.

In almost all cases, the ultramafic horizons have been moderately to strongly serpentinized while the enclosing troctolitic units are relatively unaffected. This indicates that any structural readjustment that took place after the units were emplaced (and cooled?) was focused more strongly on the thin ultramafic horizons. The enclosing, more structurally competent, troctolitic rocks may have then acted as a buttress between which structural movement took place (in the ultramafic horizons). Chlorine-rich fluids may have been channeled into the ultramafic layers via vertical fault zones. This may explain the high Cl content of the ultramafic layers. The timing of this event is unknown but may be related to the period of emplacement of the OUI bodies, which also locally exhibit high Cl contents.

SUMMARY OF OUI UNITS

Several bodies of OUI are present at Minnamax and in all cases exhibit sharp intrusive contacts with the troctolitic units. The bodies are roughly spheroidal in shape with apophyses into the troctolitic country rock. Two main rock type OUI suites are present in Minnamax: 1) orthopyroxenite is most common to OUIs high up in the PRTS stratigraphic section (Units V, VI, and VII); while 2) olivine-rich OUIs (peridotite, dunite) are common to OUIs low in the PRTS stratigraphic section. The orthopyroxenite commonly exhibits gradational hornblendite and granophyre patches; all with only minor amounts of oxides. OUIs described elsewhere in the PRT are dominantly clinopyroxenite, peridotite, and dunite; all contain abundant oxides that locally may be present as massive oxides. The reason for these differences in OUI rock type for specific areas is unknown. However, in almost all instances, the OUIs are associated with a structural discontinuity, such as faults present in both the footwall and troctolitic rock units. The Longnose, Longear, and Section 17 OUI bodies are situated over a northeast trending fault that may be a true half-graben fault (as envisioned in the half-graben model of Weiblen and Morey, 1980) that was later reactivated (Severson and Hauck, 1990). At the Water Hen OUI body, an east-west trending fault is present in the interior of the OUI (Mainwaring and Naldrett, 1977; Strommer et al., 1990). The OUIs at Minnamax are aligned along an east-west trending direction that coincides with a magnetic high (Fig. 8). All these point to the local importance of structural conditions in the formation, and/or emplacement, of the OUI bodies.

Also, oxide-rich OUI bodies, of picrite to dunite composition, have been delineated low in the troctolitic section at Minnamax. These types of OUI have only been found in areas where the Biwabik Iron-Formation is the footwall and is in direct contact with the Duluth Complex. The Longnose, Longear, and Section 17 bodies may also be associated with an inferred window of Biwabik Iron-Formation present at the basal contact (Severson and Hauck, 1990). These spatial relationships suggest a genetic link of oxide-rich OUIs to areas where massive iron-formation assimilation may have occurred at the basal contact.

SUMMARY OF HANGING WALL(?) INCLUSIONS

Both CC-type and "pic"-type inclusions are present in Units VI and VII at Minnamax. Their distribution in drill holes suggests that they are present as laterally discontinuous raft-like inclusions. Because relatively rare metasedimentary hornfels inclusions occur at, or above, their stratigraphic level, these inclusions are inferred to represent hanging wall material. The occasional presence of plagioclase-filled ovoids and wisps (vesicles?) in both rock types indicates that they may be basalts that could be correlative with the North Shore Volcanic Group. The "pic"-type inclusions are similar in appearance to nearby outcrops that Tyson (1976) postulated are basalt inclusions of the North Shore Volcanic Group (NSVG). The CC-type inclusions exhibit a different mineralogy (oxide-bearing) than the "pic"-type inclusions, but both exhibit the same chemical signatures (Figs. 13, 14, and 17 through 28). However, neither rock type exhibits chemical signatures similar to geochemical samples of basalts from the North Shore Volcanic Group (in Severson and Hauck, 1990). The CC-type inclusions were designated as such, due to their similarity to outcrops of the Colvin Creek hornfels. However, chemical signatures between the two are not similar.

The protoliths of both types of inclusions are unknown. Clearly, they both exhibit vesicle-like features, have common chemical signatures, and occur at the same stratigraphic level within the troctolitic rocks. For these reasons they are inferred to be basalts, but a NSVG connection has not been completely demonstrated, or at least a "typical" NSVG basalt connection is not completely demonstrated. Major discrepancies between a typical NSVG basalt and these inclusions resides mostly in the CC-type inclusions. These inclusions contain zones that contain modally bedded magnetite. Some of these bedded magnetite zones were sampled for thin sections and exhibit cumulus features. Thus, the nature of all the bedded magnetite zones within, and adjacent to, the CC inclusions needs to be further investigated. Also, the magnetite grains (MAG-III type) of both CC inclusions and bedded magnetite zones exhibit the same internal extremely fine, cloth-like net of ulvospinel (± green pleonaste) parallel to (100). These features suggest a common parentage. Thus, once again, both cumulus(?) and granular features are found occurring in the same vicinity -- a similar dilemma was reported by Severson and Hauck (1990) for the Colvin Creek area that contains a 1,000 foot thick cross-bedded granular-textured unit. Because of these problems, and because more detailed observations are lacking, the hanging wall inclusions remain an enigmatic rock and much more research is needed to fully understand their origin.

The stratigraphic level of the two inclusion types indicates that the CC-type inclusions are more common with depth than the "pic"-type inclusions. This places the CC inclusions at the base of the hanging wall material where the Virginia Formation and NSVG were in contact before intrusion of the Duluth Complex. Actual assignment of the CC material to either the Virginia Formation, the NSVG, or some other unit(?) may be critical to understanding its origin.

SUMMARY OF FOOTWALL UNITS

The Virginia Formation is present within hornfels inclusions and at the basal contact of the Minnamax deposit area. The rock types are dominantly bedded argillites and massive graywackes (more common near the bottom of the Virginia Formation), with minor interbeds of calc-silicate, chert, and marble. Several marker horizons were delineated within the Minnamax deposit area and include: 1) c-cs unit - well bedded chert and calc-silicate that is persistently present about 5-10 feet above the Biwabik Iron-Formation (BIF); 2) chert+calc-silicate+massive diopside horizon about 250-350 feet above the BIF; 3) graphitic argillites that are present within the large raft-like inclusions, and at 1-3 stratigraphic levels within the footwall rocks; and 4) an unusual hornblende ± olivine-bearing rock that has been termed the sill(?).

The graphitic argillite horizons are only locally present in the footwall rocks and may pinch out, only to reappear later at the same stratigraphic level in another group of drill holes. Bedding is often well developed in the graphitic argillites and is often highly contorted due to the less structurally competent nature of the graphitic argillites relative to the surrounding metasediments. A strongly folded and sheared graphitic argillite bed was intersected in several of the underground drill fans; specifically the D drift fans. This same graphitic argillite bed was mapped as a fault zone in the underground drifts by several geologists (AMAX geologists, corporate files at MDNR; Kirstein, 1979; Matlack, 1980) due to its sheared nature.

Several large hornfelsed inclusions of footwall sediments occur stacked above each other within Unit I in the Local Boy area. Inclusions of such immense areal extent have not been encountered anywhere else within the PRT. Within these inclusions are several correlative graphitic argillite beds. Interesting, the graphitic argillites are most commonly present at the exterior edge of the inclusions. These data collectively suggest that a larger amount of graphitic argillite interbeds may have been originally present in the Local Boy area. The continuous intrusion of Unit I may have been preferentially along the bedding planes of the graphitic argillites due to their incompetent nature. Subsequent assimilation, associated with the repeated intrusive activity, may have been more intense within the graphitic argillite beds as well. The result of this scenario is large preserved hornfels inclusions with only a small proportion of the original graphitic argillite beds now present on their exterior. The graphitic argillites commonly have interbedded pyrrhotite beds that may have served as an additional local source for sulfur that was utilized during Cu-Ni mineralization.

A unique hornblende ± olivine-bearing unit was encountered in the bottom-most portion of the footwall Virginia Formation. This unit has been referred to as a sill(?) due to: 1) the anomalous presence of hornblende and olivine relative to the other metasedimentary rocks; 2) local gradations into serpentinized picrite or peridotite, with hornblende, are present at the same stratigraphic level in several drill holes; 3) the presence of high Cr values; 4) the presence of high Cl values; and 5) the presence of an extremely high MG number. If this unit is indeed a sill, it now exhibits gradational contact relationships with the surrounding metasediments. This may indicate that the sill(?) was intruded either during late Proterozoic or early Keweenawan time and both the sill(?) and the footwall were hornfelsed during emplacement of the Duluth Complex. The basal massive sulfide ore has never been observed within or below the sill(?).

CONCLUSIONS

A voluminous amount of data was obtained on the geology of the Minnamax deposit area. A heretofore unknown igneous stratigraphy was established that is correlated in 61 surface drill holes. This stratigraphy is continuous with the previously established stratigraphy for the Dunka Road, Wetlegs, and Wyman Creek Cu-Ni deposits (Severson and Hauck, 1990). The stratigraphic package indicates that the basal +3,000 feet of the PRT was emplaced as several sub-horizontal sheets with shallow dips toward Lake Superior. Some of these igneous units (Units III through VII) may represent single cooling units in that they are homogeneous and floored by persistent ultramafic horizons. Other units, specifically Unit I, are more heterogeneous and contain abundant internal members reflecting continuous magma replenishment. The age relationships of these units to each other has not been established. However, a much more complicated pattern is indicated rather than simply "sheets successively emplaced beneath previous sheets." Further complicating the stratigraphic picture are the Oxide-bearing Ultramafic Intrusions (OUI) that in almost all cases are intrusive into the entire troctolitic package. Two different types of enigmatic hanging wall rocks were delineated, but much more detailed work is needed to fully understand their origin. Lastly, a hornfelsed sill is inferred to be present within the bottom portion of the Virginia Formation. (Similar sills are found in the top of the Biwabik Iron-Formation in the open pit mines to the north of Minnamax.)

In conclusion, a semi-regular layered pattern is present within the Partridge River Troctolite, designated the Partridge River Troctolite Series by Severson and Hauck (1990). Specific marker beds are present in the troctolitic rocks and can be utilized to help delineate this layering. However, caution must be applied when depending solely on one marker bed, as pinch outs or lateral gradational changes in rock type are inevitable. Also, there are numerous cases where a particular drill hole does not contain all the igneous units described in this investigation. Usually only one or, at most, two of the units may be omitted, or not recognizable. Thus care must be exercised when drawing conclusions from a "one or two drill hole" study and applying them to the rest of the Duluth Complex.

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APPENDIX A

WHOLE ROCK GEOCHEMISTRY

The following file is provided on the floppy diskette in the back pocket.

MNMXRK.WK1 (55,311 k, 06-29-91, 7:27 a.m.)
Whole rock chemical data: results are grouped according to the rock unit and/or rock type.