NRRI/GMIN-TR-89/11

GEOLOGY, GEOCHEMISTRY, AND STRATIGRAPHY OF A PORTION OF THE PARTRIDGE RIVER INTRUSION

By

Mark J. Severson
and
Steven A. Hauck

March 1990
Technical Report
NRRI/GMIN-TR-89/11

Funded by Minerals Diversification Plan
of the Minerals Coordinating Committee

Natural Resources Research Institute
University of Minnesota Duluth
5013 Miller Trunk Highway
Duluth, MN 55811-1442

This publication is accessible from the home page of the Economic Geology Group of the Center for Applied Research and Technology Development at the Natural Resources Research Institute, University of Minnesota, Duluth (http://www.nrri.umn.edu/egg) as a PDF file readable with Adobe Acrobat 6.0.

Date of release: March 1990

Recommended Citation
Severson, M.J., and Hauck, S.A., 1989, Geology, Geochemistry, and Stratigraphy of a Portion of the Partridge River Intrusion: University of Minnesota Duluth, Natural Resources Research Institute, Technical Report NRRI/GMIN-TR-89/11, 136 p.

Natural Resources Research Institute
University of Minnesota, Duluth
5013 Miller Trunk Highway
Duluth, MN 55811-1442
Telephone: 218-720-4272
Fax: 218-720-4329
e-mail: shauck@nrri.umn.edu

Web site: http://www.nrri.umn.edu/egg

ABSTRACT

Detailed relogging of drill holes (83 holes totalling 100,630 feet of core) and reconnaissance mapping have delineated three major rock groups within a portion (T.58-59 N., R.13-14 W.) of the Partridge River intrusion (PRI), Duluth Complex, Northeastern Minnesota. These have been informally designated as the Partridge River Troctolitic Series (PRTS), Partridge River Gabbro Complex (PRGC) and Oxide-bearing Ultramafic Intrusions (OUI). The PRTS consists of at least eight major igneous units which are correlatable in drill holes over an indicated eleven mile strike length extending (NE to SW) from the Dunka Road Cu-Ni deposit to the Wyman Creek Cu-Ni deposit. From the base up, these units are characterized by: Unit I - sulfide-bearing augite troctolite with minor picrite to peridotite layers; Unit II - troctolite and augite troctolite, with abundant picrite to peridotite layers (Wetlegs Cu-Ni area) and/or minor sulfide-bearing zones; Unit III - mottled textured anorthositic troctolite exhibiting a highly irregular olivine oikocryst distribution; Unit IV -augite troctolite with a picritic base and grading upwards into Unit V; Unit V - coarse-grained anorthositic troctolite; Unit VI - augite troctolite to anorthositic troctolite with a picritic base; and Unit VII - augite troctolite with a well-bedded peridotite-picrite base. Field mapping suggests that an eighth unit (Unit VIII) and possibly additional units are present above Unit VII. Unit VIII consists of troctolite to anorthositic troctolite with a well-bedded peridotite base. Most of the upper units (III-VIII) represent single cooling units in that they are floored by a bedded ultramafic member; whereas, other units (I and II) near the footwall exhibit an overall heterogeneous nature and contain

abundant internal members reflecting continuous magma replenishment. Some of the units also exhibit downcutting relationships and lateral "facies" changes along strike indicating a complex intrusive history.

Structural studies of the basal contact of the Partridge River intrusion have indicated more structure than previously recognized. Structure contour maps of the footwall rocks at the basal contact of the Duluth Complex and on the top of the Biwabik Iron-Formation, and isopach maps of the Virginia Formation beneath the PRI indicate that pre-existing folds in the basement rocks at both Minnamax and Dunka Road exerted a strong control over the form of the base of the intrusion. Cross-sections illustrating the internal "stratigraphy" indicate that in both the Dunka Road and Wetlegs areas, numerous NE-trending normal faults parallel to the Mid-continent Rift are present. These faults support the half-graben model (Weiblen and Morey, 1980) which envisions a step-and-riser geometry at the base of the Duluth Complex due to extensional tectonics. However, most of the faults delineated show corresponding offsets in both the troctolitic and footwall rocks and are, thus, not true half-graben faults as envisioned in the model. The only exception is within the Wetlegs area where a NE-trending fault exhibits substantial offset in the footwall rocks, but no offset is present in the overlying troctolite rocks. An inferred window of Biwabik Iron-Formation is in direct contact with the PRI along this fault. Three late-stage Oxide-bearing Ultramafic Intrusions (OUI) are also located along this zone that suggests they may be genetically related to areas where massive iron-formation assimilation has occurred.

The OUIs are later pegmatitic intrusives consisting of dunite, peridotite, clinopyroxenite, and lesser picrite and melagabbro; all are oxide-bearing (> 10%) and contain semi-massive to massive oxide horizons. These bodies are intrusive into the PRTS and include the Longnose, Longear, Section 17, Wyman Creek, and Skibo Fe-Ti prospects.

The PRGC is situated at the southeastern portion of the investigated area and consists dominantly of oxide-bearing gabbroic and troctolitic rocks; both locally exhibit excellent modal bedding, which may be related to magmatic density currents. The Colvin Creek "Gabbro" (CCG) is part of the PRGC and was originally interpreted to be a hornfelsed basalt. However, reconnaissance mapping indicated that similar fine-grained CCG-type "gabbro" is present within the coarse-grained rocks of the Powerline Gabbro and vice versa. Because the Powerline Gabbro is located near the CCG, the two bodies may be intricately related. Within the Colvin Creek "Gabbro" are several unusual sedimentary-like structures that are not indicative of typical North Shore Volcanic basalts. However, textures resembling vesicles/amygdules are locally present. The unusual sedimentary-like structures suggest a magmatic density current origin but the exact origin of these textures is enigmatic. Also within the Colvin Creek "Gabbro" is a mile-long 1,000 foot-thick belt of cross-bedded rocks. Several internal features of these cross-bedded rocks, e.g., lack of rock fragments, no quartz, are not indicative of typical interflow sandstones and their relationship to the surrounding rocks suggests they may have also been deposited by magmatic density currents.

The unmineralized portions of all the units were sampled (155 samples) in order to establish background geochemical levels and lithogeochemical signatures for each unit and to investigate possible origins for the different units. Background Pd, Pt, and Au values in the major rock groups average 10 ppb, 20 ppb, and 5 ppb, respectively. However, slightly elevated background values are associated with Unit II (15 ppb, 24 ppb, and 9 ppb, respectively), and the OUI rock group (15 ppb, 24 ppb, and 17 ppb respectively). In the course of sampling unmineralized rock (<1% sulfides), five anomalous samples (>200 ppb combined Pd and Pt) were revealed with a maximum of 910 ppb. The OUI units are the most geochemically unique in that they have elevated background values for TiO_2, V, Cr, Co, Cu, Cd, C, Be, Sc, Sb, Pb, Te, Au, and W relative to the other igneous units.

Geochemical data support the various rock units identified during relogging of the PRI. Units I and II exhibit a markedly different geochemical signature when compared to the other PRTS units. One interpretation of this difference is that magma contamination due to assimilation of footwall material was important in their genesis. All rock units of the PRGC have the same geochemical signature and, in turn, this geochemical signature is similar to the geochemical signature for the lower half of Unit I. The OUI units exhibit a markedly different geochemical signature when compared to all the other PRI units.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

INTRODUCTION

Several studies have been conducted on the various subeconomic mineral deposits (Cu-Ni and Fe-Ti±Cu) located within the Partridge River intrusion (PRI) of the Duluth Complex. However, to date there has been little attempt to correlate these works due to a lack of recognizable stratigraphy within the PRI. Also, only a limited amount of geochemical data pertinent to unmineralized rocks of the PRI have been available and even these data have not been representative of the wide variety of rock types present.

The goals of this project were to: 1) establish background geochemical values for a variety of unmineralized rock types within and surrounding the various mineral deposits; 2) establish an internal stratigraphy for the PRI that is present over a wide range of drill holes; 3) establish respective geochemical values for stratigraphically correlative igneous units; 4) establish geochemical values for mappable units within the PRI; 5) provide additional data in the form of cross-sections, outcrop maps, and structural data to aid in understanding the origin of the Duluth Complex and its related mineral deposits; and 6) provide new geological and geochemical data to aid mineral exploration. This report is the culmination of a 1.5 year investigation involving relogging drill holes, conducting reconnaissance mapping, and conducting geochemical sampling within a portion of the PRI (T.58-59 N., R.13-14 W.). Some initial observations and data pertaining to the structure of the footwall rocks of the PRI were previously presented in Severson (1988).

Geologic Setting

The Duluth Complex is a series of tholeiitic intrusions of Keweenawan age (1.1 b.y.) that formed with associated basaltic volcanism along a portion of the Mid-continent 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 (Fig. 1). 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/Thomson Formations, and at some localities the underlying Biwabik Iron-Formation. Northeast from Babbitt to the Gunflint Trail, the footwall rocks of the Complex consist of Archean (2.7 b.y.) granites and greenstones. East from the Gunflint Trail, at the basal contact are the Middle Precambrian metasediments of the Rove Formation. At the eastern upper contact (hanging wall) of the Duluth Complex are the mafic volcanics of the North Shore Volcanic Group; however, since gradations between the two are often present, the "upper contact" of the Complex is arbitrarily chosen in places (Weiblen and Morey, 1975).

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 intrusive bodies which have been given the informal names of: South Kawishiwi intrusion (SKI), Partridge River intrusion (PRI), and Bald Eagle intrusion (Foose and Weiblen, 1986). Within this region, several large, though subeconomic, Cu-Ni deposits have been delineated at the base of the South Kawishiwi and Partridge River intrusions. 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) are also present

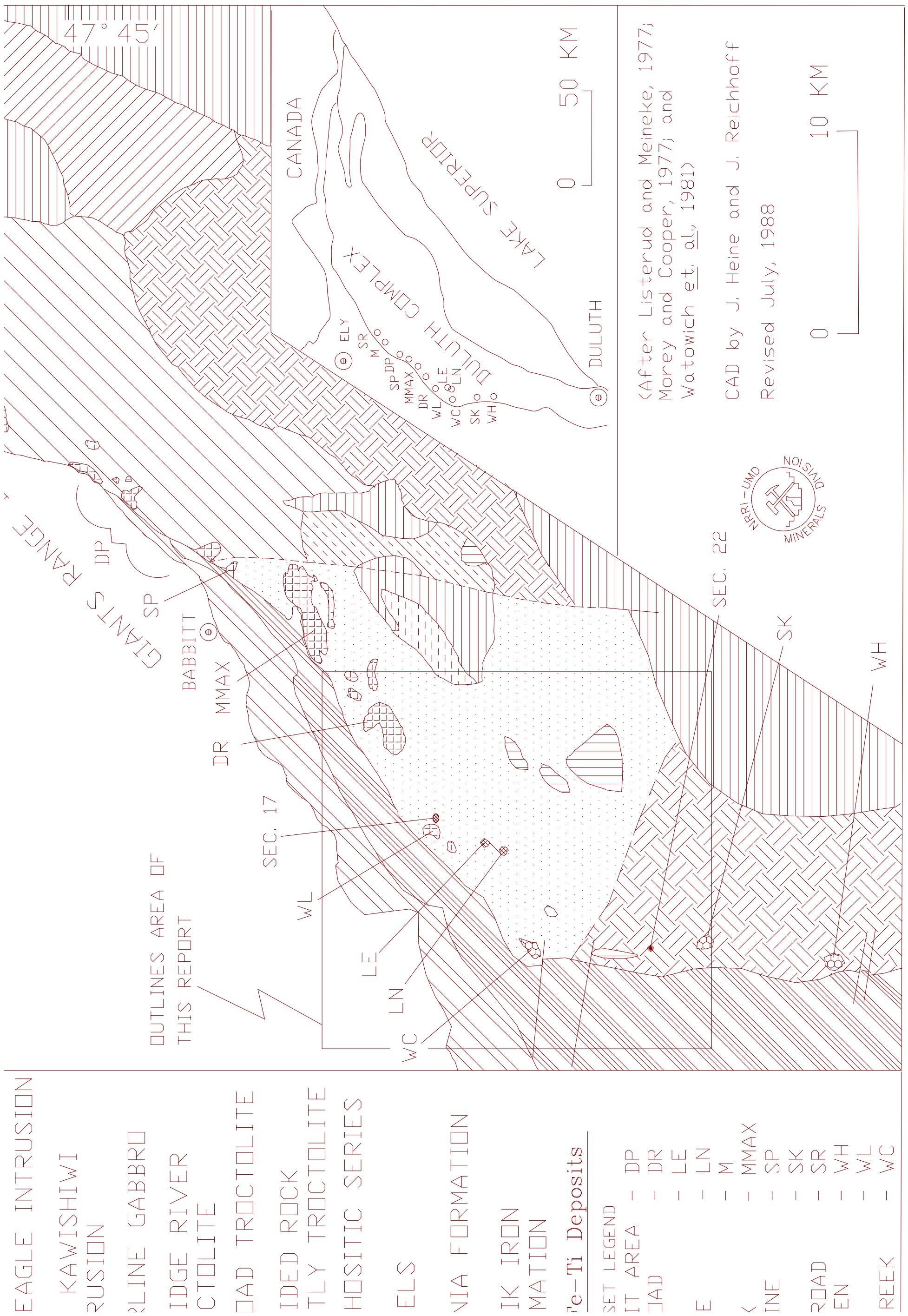


Figure 1: Location of Cu-Ni and Fe-Ti deposits within the Duluth Complex, N.E. Minnesota.

within the PRI and include from north to south: Section 17 (Wetlegs), Longear, Longnose, "Section 22", Skibo, and Water Hen. Ilmenite is the primary oxide phase. The Skibo and Water Hen deposits also contain Cu-Ni mineralization. Primary and secondary PGE mineralization have been documented in several drill holes in the South Kawishiwi and Partridge River intrusions (Ryan and Weiblen, 1984; Sabelin, *et al*, 1986; Dahlberg, 1987; Morton and Hauck, 1987). Occurrences of chromium spinel have also been reported (Weiblen, 1965; Stevenson, 1974; Fukui, 1976; Mainwaring and Naldrett, 1977; Ross, 1985; Miller, 1986; Sabelin, 1987)

Emplacement of the Duluth Complex occurred during an episode of extensional tectonism which produced the Mid-continent Rift. Weiblen and Morey (1975, 1980) have presented a half-graben model for the overall structural geometry of the Complex. They envision a step and riser configuration of the basal contact due to steep, southeast-dipping, northeast-trending normal faults underlying the Complex. According to the model, magma was injected into foundered, fault-bounded voids formed during rifting to produce the multiple intrusions that make up the Complex (Foose and Weiblen, 1986). They (Weiblen and Morey, 1980) also suggest that these northeast-trending faults may be offset by a series of northwest-trending strike-slip (transform) faults. This model is consistent with two fault directions recognized in the SKI (Foose and Cooper, 1981) and in a lineament study conducted by Cooper (1978). The abundance of faults within this postulated half-graben geometry may have been important in localizing the Cu-Ni mineralization. However, Green (1982, 1983) has pointed out "a number of problems with the model and suggests an alternative model of subsiding sequences of plateau lavas." (Holst, *et al*, 1986, p. I-3).

Recent studies of faulting in the Middle Precambrian basement rocks of the Hoyt Lakes - Kawishiwi area (Holst, *et al*, 1986) have delineated several north-south and northwest-trending faults in open pit mines of the Mesabi Range to the north of the Complex. However, no evidence was found within the pit walls for the northeast-trending faults as suggested by the half-graben model. Studies of the basal contact in the Minnamax area indicate that pre-Keweenawan structures in the footwall rocks exerted a major control over the form of the base of the Duluth Complex and possibly over localization of the Cu-Ni deposits (Mancuso and Dolence, 1970; Watowich, 1978; Holst, *et al*, 1986).

Structure contours at the base of the PRI and on top of the Biwabik Iron-Formation indicate that in addition to pre-Keweenawan structures, several NW-trending faults can be delineated (Severson, 1988). NE-trending faults however are not readily expressed by these same data.

Correlation of igneous units in the Wetlegs area (Severson, 1988) has, for the first time, allowed cross-sections to be constructed showing the relationships between the footwall rocks and the overlying troctolitic rocks of the PRI. These cross-sections indicate the presence of several NE-trending normal faults (down to the SE) which exhibit offsets in both the footwall and troctolitic rocks. Though many NE-trending faults were delineated, only one of them exhibits a substantial offset in the footwall rocks with no corresponding offset in the overlying igneous rocks. Severson (1988) proposed a pre-Keweenawan age for this feature. However, the fault may represent a "true" half-graben fault formed during intrusion of the PRI. Overall, Severson's (1988) study indicated the presence of both NE-trending and NW-trending faults in accord with the half-graben model proposed by Weiblen and Morey (1980).

This report is concerned chiefly with rocks of the Partridge River intrusion (PRI) exposed within T.58-59 N., R.13-14 W. Major rock groups present within the PRI consist of (informal names): 1) the Partridge River Troctolitic Series (PRTS), which is the dominant rock group and includes various troctolitic rocks with minor olivine gabbro, picrite, peridotite, dunite, and anorthosite; 2) the Partridge River Gabbro Complex (PRGC), which is present at the southeastern and eastern portion of the PRI and includes the Colvin Creek "Gabbro" and Powerline Gabbro; and 3) the Oxide-bearing Ultramafic Intrusions (OUI), which are pegmatitic clinopyroxenites, peridotites and dunites intruded into the PRTS (Fig. 1; Longnose, Longear, Section 17, Wyman Creek, and Skibo Fe-Ti deposits). The classification scheme used for rock identification (Fig. 2) was adapted from Phinney (1972).

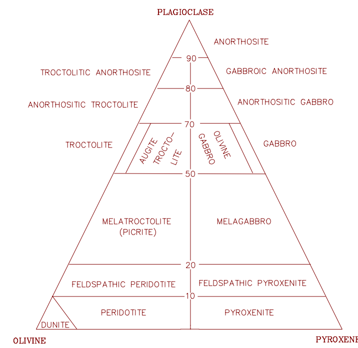


Figure 2: Rock classification (after Phinney, 1972).

Due to an extensive glacial cover, most of the previous rock descriptions of the PRTS have been conducted on various drill holes in the Cu-Ni deposits, some of which include: Hardyman (1969; 1 hole - Minnamax); Boucher (1975; 1 hole - Minnamax); Molling (1979; 1 hole - Minnamax); Tyson (1979; 4 holes - Minnamax); Rao (1981; 7 holes - Dunka Road); Al-Alawi (1985; portions of 18 holes - Minnamax); Chalokwu (1985; 1 hole - Minnamax); Mills-Ervin (1988; 2 holes - Minnamax) and Linscheid (in prep; 4 holes - Longnose). Due to drill hole spacing and a general lack of recognizable marker beds, no correlations between these author's works have been attempted. However, despite any recognized internal stratigraphy, these studies divided the PRI into various magmatic units on the basis of textural, modal, and chemical differences. Within the Minnamax area, Grant and Molling (1981) divided the PRI into 3 major units; Tyson and Chang (1984) described 5 different units; Ripley and Alawi (1986) divided the PRI into 3 units; Chalokwu and Grant (1987) divided it into 4 units, and Mills-Ervin (1988) divided it into 4 units. Within the Dunka Road deposit area, located within 2 miles to the southeast, Rao and Ripley (1983) subdivided the PRI into at least 3 major units. Severson (1988) described at least 5 major units within drill core from the Wetlegs area and has since expanded this to 8+ major igneous units extending from the Wyman Creek deposit to the Dunka Road deposit (this report). No attempt has been made to extend this correlation into the various holes that have been studied at the Minnamax deposit.

Present Investigation

This report is a summary of activities conducted from January, 1988 to July, 1989. Core logging was initiated for 83 holes out of a possible 244 holes (274,228 ft.) within the study area. The 83 holes (100,630 feet) included: 25 holes from the Wetlegs Cu-Ni deposit; 5 holes from the Section 17 Fe-Ti deposit; 3 holes from the Longear Fe-Ti deposit; 1 hole from the Longnose Fe-Ti deposit; 16 holes from the Wyman Creek Cu-Ni deposit; and 33 holes from the Dunka Road Cu-Ni deposit (Plate I). Detailed relogging of these holes indicated that the basal 3000+ feet of the PRTS can be subdivided into at least 8 major subhorizontal igneous units that are correlative over an 11 mile strike-length. A "hung" stratigraphic section (Plate II) was prepared to illustrate the correlations present in 42 drill holes. Structural contour maps of the basal contact, top of the Biwabik Iron-Formation, and an isopach map of the Virginia Formation were also compiled and were included in Severson (1988).

One hundred and twenty drill core samples of unmineralized rock were collected from the various igneous units and footwall rocks. In addition, twenty days were spent conducting reconnaissance mapping in a four township area of the PRI. Previous published open file geologic maps were used as a base for additional geological mapping (Morey and Cooper, 1977; Holst, *et al*, 1986; Linscheid, in prep). About one half of the area was remapped and certain areas were omitted due to the presence of either previous detailed geologic maps, e.g., Linscheid's area in sections 29, 30, 31, T.59 N., R.13 W., or areas with abundant drill holes that could be relogged. A total of 35 field samples were collected.

Acknowledgements

This project has been funded through the Minerals Diversification Plan of the Minerals Coordinating Committee. Special thanks are extended to Mr. Cedric Iverson (USX), Mr. William Ulland (American Shield Corp.), and Mr. John McGoran (Fleck Resources Ltd.) for allowing access to private company records and/or permitting drill core to be logged and sampled. Drill logs and drill core for about one quarter of the holes are located at the Department of Natural Resources, Minerals Division, Hibbing, Minnesota. The general geology of the Hoyt Lakes - Kawishiwi area was obtained from maps and publications of the

Minnesota Geological Survey. Discussions with Dr. John Green (UMD) and Dr. Penny Morton (UMD) proved valuable in unraveling some of the complexities inherent within the Duluth Complex. Thanks are also extended to Jayne Reichhoff (NRRI) for aid in completing the figures, tables, and plates of this report.

PETROGRAPHY OF THE PARTRIDGE RIVER INTRUSION

The vast majority of rock descriptions, petrographic descriptions, and geochemical samples of this investigation are from PRTS drill hole samples. The overall petrographic characteristics of both cumulus and intercumulus minerals, which comprise the PRTS and to a lesser extent the PRGC and OUI, are briefly summarized. Detailed megascopic and microscopic characteristics that are unique to the various igneous units are discussed in subsequent chapters. 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 peridotite and dunite horizons.

A voluminous amount of literature presents descriptions of the modal and textural characteristics of silicates and sulfides in the troctolites from various parts of the Partridge River intrusion; notably the PRTS (Al-Alawi, 1985; Bonnichsen, 1972; Chalokwu, 1985; Churchill, 1978; Hardyman, 1969; Linscheid, in prep; Mills-Ervin, 1988; Molling, 1979; Rao, 1981; Tyson, 1979; Weiblen and Morey, 1975, 1976, 1980). Many of their observations are confirmed by this investigation and are subsequently reiterated. Since only unmineralized rocks were sampled for this study, a description of the sulfide minerals is not presented. For a detailed description of the sulfides, the reader is referred to the above sources. The descriptions presented here are drawn from the observations of 156 polished thin sections and 63 thin sections.

Plagioclase

Plagioclase is the major cumulus mineral in the rocks of the PRTS and PRGC 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. Very minor amounts of bent twins are present. Commonly, a small proportion of the plagioclases are optically zoned. Anorthite contents of plagioclase were determined petrographically by either the Michel-Levy or combined Carlsbad-albite twin methods. Within the troctolitic rocks of the PRTS, the anorthite content ranges from An_{45}-An_{81}.

The plagioclase often contains 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 or in isolated patches within the crystal is also common. Most plagioclase shows varying degrees of deuteric alteration to sericite. The highest degree of alteration occurs in close proximity to fractures or in areas of core also exhibiting uralization.

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 olivine 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 between olivine grain size and crystal habit and both types can be found in near equal amounts in the same section.

Lastly, olivine occurs as large (2-12 mm) optically continuous oikocrysts which occupy more that three adjacent void spaces within a fine-grained plagioclase-rich framework. These poikilitic olivines are petrographically unique to Unit III of the PRTS. Mills-Ervin (1988) describes poikilitic olivine within troctolitic rocks at the Minnamax (Babbitt) Cu-Ni deposit as "raindrop texture." Miller (1986) reports olivine oikocrysts in the anorthositic rocks of the Snowbank Lake Quadrangle.

All varieties of olivine are generally partially to completely surrounded by orthopyroxene kelyphitic rims due to the reaction of the earlier cumulus olivine with later intercumulus liquid. Portions of clinopyroxene (Cpx) oikocrysts also partially rim a small amount of the olivine. Present in trace quantities are olivine symplectites which 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. Optically, the olivines are unzoned and twinning is rare.

Within picrite, peridotite, and dunite horizons of the PRTS, olivine almost always occurs as subrounded, subhedral to anhedral, equant grains (with triple point junctions), poikilitically enclosed in minor Cpx and/or plagioclase. An alignment of cumulus plagioclase laths is also often encountered in these 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.

<u>Clinopyroxene (Cpx)</u>

Augite is the dominant intercumulus mineral of the PRTS 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 can occur in the same thin section. Biotite is commonly associated with the 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), are also present within the clinopyroxene.

Orthopyroxene (Opx)

Hypersthene is present in all PRTS samples where it occurs as partial coronas around olivine in amounts generally less that 2%. Rare to minor quantities of anhedral interstitial Opx is also present with the PRTS. The overall amount of Opx in the PRTS rocks is generally very low except for a gradational increase in Opx adjacent to the basal contact of the Complex and adjacent to hornfels inclusions. However, there are numerous instances where Opx does not increase near these contacts.

Symplectite

Two types of symplectite occur within the troctolitic rocks 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 grains 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 common constituent of PRTS Units I, IV, and V (0.5-5.0%) and is rare in the other PRTS units.

"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 rock units of the PRTS in trace amounts.

Biotite

Biotite is a common constituent of all rock types within the PRI but composes <1%, except within the basal zone of the PRTS (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 the biotite exhibits a reddish-brown color due to the high titanium content. Greenish-brown epitaxial biotite is also present at augite-plagioclase boundaries.

Accessory Minerals

Euhedral, short prismatic crystals of apatite enclosed in plagioclase or associated with coarse sulfides are a very minor constituent of the PRI. Apatite generally occurs in only rare amounts. A higher apatite content (0.5-1.5%) is present within the basal unit of the PRTS (Unit I) as well as the Colvin Creek "Gabbro", Powerline Gabbro, and Oxide-bearing Ultramafic Intrusions.

Ilmenite is the most common oxide mineral in the troctolites of the PRTS. The ilmenite generally is interstitial to the cumulus silicate minerals except in the OUI units where it is a cumulus mineral. Magnetite is also present but to a much lesser extent. Magnetite occurs as either subhedral to anhedral grains with spinel needle inclusions and/or ilmenite lamellae, or it may occur with ilmenite in composite grains. In addition, titanomagnetite is present within the OUI, the Colvin Creek "Gabbro", and Powerline Gabbro.

The principal sulfide minerals include pyrrhotite, chalcopyrite, cubanite, pentlandite and locally bornite. Additional "ore-forming" minerals noted by others (Bonnichsen, 1972; Morton and Hauck, 1987; Mills-Ervin, 1988) within the mineralized rocks include: covellite, cuprite, mackinawite, digenite, chalcocite, tenorite, talnakhite, maucherite, nickeline, parkerite, sphalerite, violarite, froodite, michenerite, and native Au, Ag, Cu, and Bi.

Deuteric Alteration

Patches of deuteric alteration ("uralitization") were present within all units of the PRTS. The alteration was characterized by replacement of interstitial Cpx by fine-grained mats of radiating bundles of chlorite, hornblende, actinolite, sericite, ± tremolite which often interpenetrate with adjacent plagioclase crystals. Strongly sausseritized plagioclase laths and moderately to strongly altered olivine (serpentine + chlorite + magnetite) were also associated with this type of alteration. The dimensions of the uralitized patches in core varied from about one inch to several tens of feet thick and often both uralitized and "fresh" rock alternate within these zones. Sulfide content showed an increase in these patches but a lack of sulfides also occurred. This type of alteration was not: 1) restricted to any particular igneous unit within the PRTS; 2) associated with any particular horizon within a unit; and 3) necessarily associated with sulfide-bearing zones. Though the presence of these alteration patches was noted on drill hole logs, no systematic distribution related to either mineralization and/or faulting was established. Uralitized zones were noted in holes from all three Cu-Ni deposits within the study area. However, uralitized zones were the most common and attain thicker dimensions within the Wetlegs area.

The presence of slimy, rust-colored fluid drops on both unsplit core and split core occur in several drill holes. These drops are reported from other holes within the PRI and South Kawishiwi intrusion (Dahlberg, *et al*, 1988). Analysis of the drops indicates high chlorine values up to 3000 ppm (Dahlberg, 1987; Dahlberg, *et al*, 1988). 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 the OUI dunites and peridotites, but the drops are also observed in cyclic peridotites, troctolites, and uralitized zones of the PRTS.

LITHOLOGIC DESCRIPTIONS OF THE PARTRIDGE RIVER TROCTOLITE SERIES (PRTS)

Introduction

Detailed relogging of core and outcrop mapping of the troctolitic rocks (PRTS) of the PRI identified eight major subhorizontal lithologic units within the basal 3,000+ feet of the intrusion (Plates II and III). Most of these units were present in 83 holes over an 11 mile strike-length extending from the Dunka Road deposit to the Wyman Creek deposit. Rock types were classified according to the classification scheme depicted in Figure 2. Therefore, the igneous rock names were based on estimated modal percentages of plagioclase, olivine and pyroxene. Furthermore, the modal percentages of the minerals exhibited either dramatic fluctuations within small internal zones of a particular rock unit or exhibited a large variability within a unit such that a particular assigned rock name was not valid for the entire unit. In each case, either the dominant rock type name was selected or a range of two rock type names was assigned for a particular drill core interval or a series of outcrops. The modifier "oxide-bearing" and "sulfide-bearing" refer to zones with >10% oxides and >0.5-1.0% sulfides, respectively.

Of the 83 drill holes relogged, some of the deepest holes (42) are plotted on Plate II, which is arranged in a general SW to NE direction from Wyman Creek through the Wetlegs area to the east end of Dunka Road. A generalized strike length correlation of major igneous units of the PRTS is also presented in Figure 3. Note that Plate II is a "hung" stratigraphic section rather than a true cross-section in that all holes are hung on the basis of the contact between Units II and III. Unit III is the most important in terms of recognition and acts as a "marker" bed in unraveling the multitude of "troctolitic" rocks present throughout the PRTS section. Generalized descriptions of the eight major units, starting from the basal unit (I) and working upward follows. Note that the unit numbers of this report are reversed relative to Severson's (1988) report in order to take into account a revised description of the upper igneous units. Thus Unit I of this report correlates with Unit V of Severson (1988), etc. The spatial distribution of the various PRTS units shown on the accompanying geologic map (Plate III) is based primarily on drill hole collar

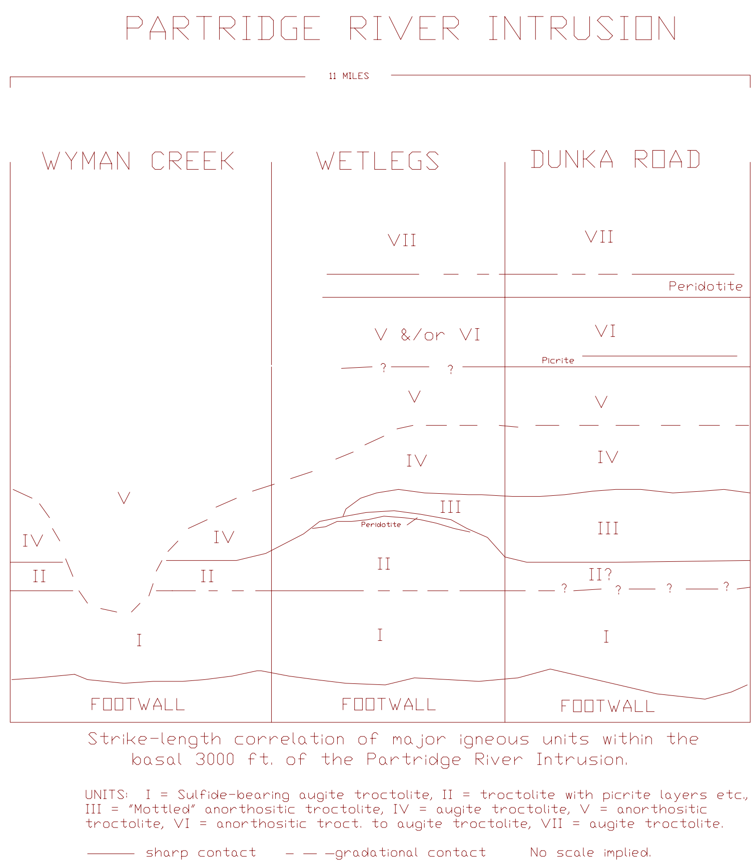


Figure 3: Generalized stratigraphy of the Partridge River Intrusion.

lithologies. The descriptions of igneous units are generalized as they are based on conditions present in a majority of holes. However, particular drill holes can partially deviate from the described "norm." Descriptions of major down-strike lithologic changes of the PRTS units have been attempted; however, lesser lateral lithologic changes in the form of pinch-outs, variable unit thicknesses, and gradational rock type changes are not described but are depicted in Plate II.

Unit I - Sulfide-Bearing Augite Troctolite

The lowest unit of the Partridge River intrusion in the study area consists dominantly of sulfide-bearing, augite-rich (>15% augite) augite troctolite that often grades to olivine gabbro due to the high augite content. Lesser amounts of troctolite, and anorthositic troctolite (all sulfide-bearing) and rare picrite/peridotite layers are also present within Unit I. Grain size is extremely 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 percentages and average grain size that change rapidly in zones from a few feet to tens of feet thick. Due to this heterogeneous texture, numerous internal contacts divide Unit I into several subunits that apparently cannot be correlated from drill hole to drill hole. Thus, Unit I is a conglomeration of various troctolitic subunits related to continuous magma replenishment; all or most of which contain augite and interstitial sulfides. The thickness of Unit I is also highly variable (175-1570 ft. thick) due to a nearly horizontal but undulating top and a divergent southeast deepening base. The top "contact" of Unit I is defined by a general decrease in sulfide content (<1%) or the appearance of picritic layers that are characteristic of the overlying Unit II (at Wetlegs). However, in some instances the upper contact of Unit I is arbitrarily chosen due to the presence of >1% sulfides in Unit II, lack of abundant picrite layers at the base of Unit II, or presence of picrite/peridotite layers associated with sulfide-bearing augite troctolites in the top portion of Unit I. A two pyroxene (Opx and Cpx) olivine gabbro grading to fine-grained norite is usually present at the basal contact or near hornfels inclusions, but numerous exceptions to this have been noted in drill core.

Sulfide-"rich" zones (>1%) in Unit I (Plate II) are variably distributed from hole to hole. In some drill holes, almost all of the entire section of Unit I is sulfide-"rich", whereas a spotty distribution is present in other holes. The majority of sulfides present include pyrrhotite, chalcopyrite, and pentlandite, which occur as interstitial grains ranging from <1 mm to 1.5 cm across. Chalcopyrite is commonly the dominant sulfide whenever coarse-grained anorthositic troctolite subzones are encountered in Unit I. These subzones are distinguished by: 1) a decrease in augite and olivine content; 2) an increase in plagioclase grain size and amount (often bleached-sausseritized appearance in core); and 3) an increase in chalcopyrite ± bornite content over pyrrhotite. Whenever the modal percentage of olivine increases, e.g., in picrites, the average sulfide grain size decreases and pyrrhotite is the dominant sulfide. The sulfides generally average ~1.0-3.0% but internal zones with 3-5% sulfides, and zones with only trace-0.5% sulfides are also common; local zones (<3 ft.) with up to 10% sulfides are also present locally. Coarse apatite crystals are commonly associated with large (>1 cm) interstitial sulfide blebs. Local sulfide enrichment occurs at the basal contact (pyrrhotite >> other sulfides) and/or around hornfels inclusions. However, there is no apparent consistent trend.

Inclusions of Virginia Fm. are the most common within Unit I and vary from > 275 ft. thick to one inch thick. A zone of abundant Virginia Fm. inclusions is present approximately midway up within Unit I in the Wyman Creek and Wetlegs areas. The distribution of this hornfels-rich zone implies that the inclusions were once at the floor of the Complex, but a later magmatic pulse (lower half of Unit I) was intruded sill-like below this zone into the Virginia Fm. Bedding planes of the inclusions within this zone vary from highly contorted to 30-50E (most common) indicating that some rotation of these sedimentary rafts occurred during emplacement of the lower half of Unit I. Interestingly, a somewhat consistent picritic zone is also present at this same horizon. This relationship suggests that the picritic zone was once the basal contact of Unit I and a later intrusive pulse of similar magma was emplaced beneath it. The troctolites beneath the consistent picritic horizon are shown on Plate II as the "lower half" of Unit I. The lower half of Unit I exhibits a geochemical signature that is different from all the other PRTS units (see geochemistry section, page 61).

Several picrite-peridotite layers also occur sporadically within the bottom half of Unit I in the Dunka Road area (see Plate II). Their distribution in drill holes indicates that spatially they are laterally discontinuous and probably grade or pinch-out along strike. These layers vary from 1-13 ft. thick and exhibit gradational to sharp tops and sharp bases. These rocks are commonly serpentinized, which imparts a strong foliation with dips of around 10-20 degrees.

Petrographical characteristics unique to Unit I relative to the other PRTS units are: 1) presence of trace to 2% plagioclase symplectite; 2) presence of up to 2% apatite laths within plagioclase (mantles) and Opx; 3) increased biotite content (up to 5%); 4) increase in Opx content (close to some hornfels inclusions); and 5) interstitial, anhedral olivine is the dominant morphology. Many of these characteristics have also been recognized in the basal portions of other drill holes within the PRI (Bonnichsen, 1972; Grant and Molling, 1981; Tyson and Chang, 1984; Chalokwu, 1985). Anorthite content ranges from An_{54}-An_{73}.

In summary, Unit I is characterized by: 1) the above petrographic features; 2) sulfide-bearing and augite-rich (>15% augite) rocks; 3) the heterogeneity and numerous internal contacts; and 4) an unusually high amount of hornfels inclusions with or without adjacent noritic rocks. The effects of contamination from the Virginia Fm., at the basal contact and near hornfels inclusions, is discussed by several authors (Bonnichsen, 1972; Rao and Ripley, 1983; Tyson and Chang, 1984).

<u>Unit II</u>

Unit II is variable along its strike length. In the Wetlegs area, Unit II is characterized by abundant cyclic units (troctolite grading downwards into picrite-peridotite-dunite layers) within medium-grained troctolite and/or augite-poor (5-10%), augite troctolite (Severson, 1988). The basal ultramafic layers (picrite and peridotite dominant) of this cyclic units are fine- to medium-grained and vary from 8 inches to 36 feet thick, although most of the layers average either 5-18 feet or 1-2 feet thick. These layers often exhibit internal banding (alternating olivine and plagioclase-rich laminae down to 1 cm thick) and/or a serpentinized foliation with dips of approximately 5-20E (range of 5-40E). Sharp bases are almost always present and tops have both sharp and gradational contacts with the enclosing troctolitic rocks indicating crystal settling. Internally, some of the ultramafic layers exhibit modal grading characterized by picritic tops and dunite bases. The ultramafic layers are laterally discontinuous and rarely can any single layer be correlated in more than 2 drill holes. The number of ultramafic layers in individual drill holes is also extremely variable due to their discontinuous nature. In some cases, the modal percentage of olivine changes laterally and therefore, the basal ultramafic rock type may change along strike from peridotite to picrite to olivine-rich troctolite (40-45% olivine).

The rocks in which the ultramafic layers are enclosed are generally medium-grained troctolite but augite-poor (5-10% augite), augite troctolite is more common in some drill holes. Sulfide-"rich" (>1%) zones are sporadically distributed throughout both the troctolitic rocks and ultramafic layers. In the Wetlegs area, hornfels inclusions are also sporadically distributed throughout Unit II. Near the top of Unit II, a pegmatitic anorthositic troctolite occurs in some drill holes.

The top of Unit II at Wetlegs is marked by a persistent peridotite layer that averages 5 ft. thick. The excellent lateral continuity of this layer (present in 10 out of 13 deep drill holes within the Wetlegs area) also establishes a local marker horizon between Unit II and the overlying Unit III. The peridotite layer is commonly strongly serpentinized/foliated with dips of 10-30E (20E average) and has sharp top and bottom contacts. Toward the east, the peridotite pinches out and is absent in the Dunka Road area.

Changes in the thickness and character of Unit II occur to the east and west of the Wetlegs area. West toward Wyman Creek, Unit II thins dramatically to a 20-40 ft. thick picrite and olivine-rich troctolite horizon. In the Dunka Road area, Unit II again thins (40-200 ft.) and the abundant ultramafic horizons which are ubiquitous in the Wetlegs area are absent. At Dunka Road, Unit II is characterized by an augite-poor (5-10% augite), augite troctolite with minor scattered sulfide-bearing zones. A somewhat persistent 5-35 ft. thick basal picrite layer is present in 15 out of the 33 drill holes logged at Dunka Road. This picrite generally has a gradational top and sharp base but variations occur.

There are no petrographic characteristics unique to the Unit II troctolitic rocks in the Wetlegs area. Within some thin sections from Dunka Road, olivine oikocrysts (which are unique to Unit III) are present within Unit II in addition to the other olivine morphologies. Overall, anorthite contents of plagioclase range from An_{58}-An_{75} in the troctolitic rocks. The picrite-peridotite horizons are characterized by fine- to medium-grained, subrounded, equant olivine grains that often exhibit 120E triple point junctions and are intermixed with varying amounts of: subrounded plagioclase laths, subhedral magnetite, and subophitic clinopyroxene ± plagioclase.

In summary, Unit II exhibits lateral variations but can be distinguished from the other PRTS units by: 1) presence of abundant ultramafic layers (cyclic) within sulfide-poor troctolites in the Wetlegs area; 2) sulfide-poor troctolite with a moderately persistent picrite base at Dunka Road; and 3) a single picrite horizon at Wyman Creek.

Unit III

Unit III is the major "marker bed" of the PRTS. The texture of this unit is characterized by a fine-grained anorthositic troctolite that consistently grades into irregular patches (<1 ft.) of anorthosite, troctolitic anorthosite, troctolite, and minor picrite giving the rock an overall mottled appearance. This mottled appearance is due to the highly irregular distribution of olivine oikocrysts (up to 3 cm across). Since the distribution of olivine is so erratic, the core has to be "looked at from a distance" in order to assign an overall rock name. Plagioclase is generally lath-shaped (1-2 mm) and arranged in a decussate texture; overall, the rock is finer-grained than any of the other PRTS units. Locally, pyroxene and oxides also occur as oikocrysts.

At Wetlegs, Unit III is a mottled anorthositic troctolite-troctolitic anorthosite that averages about 250 ft. thick (135-450 ft. range) and commonly grades down into medium- to coarse-grained anorthositic troctolite and/or augite troctolite in the bottom 20-80 ft. of several holes. The base of Unit III is in sharp contact with the persistent peridotite layer of Unit II in most holes. The top of Unit III is in sharp contact with Unit IV.

At Dunka Road, Unit III is a mottled anorthositic troctolite that averages about 315 ft. thick. In several drill holes, it grades into medium- to coarse-grained augite troctolite and anorthositic troctolite at the center of Unit III. An increase in the modal percentage of Cpx oikocrysts occurs at the eastern end of Dunka Road and thus lateral gradations into weakly mottled augite troctolite and olivine gabbro are common. A gradational contact at the base of Unit III into Unit II is present in 65% of the holes relogged at Dunka Road; however, sharp contacts make up the remaining 35%. The top of Unit III exhibits a sharp contact with Unit IV and is sulfide-bearing (>1% sulfides with cp>>po) in some holes at Dunka Road.

Petrographically unique to Unit III is the occurrence of ophitic olivine oikocrysts, which constitute the only olivine morphology present in the rock. This type of olivine morphology is restricted solely to Unit III but in some instances may also be found within Unit II at Dunka Road. Similar olivine oikocrysts have also been reported as "raindrop texture" within the Minnamax area (Mills-Ervin, 1988) but the stratigraphic position of these olivine oikocrysts is unknown. Anorthite contents range from An_{47}-An_{77}.

In summary, Unit III serves as a unique marker bed within the PRTS stratigraphy and differs from all the other troctolitic units due to: 1) finer-grained texture; 2) presence of olivine oikocrysts; and 3) a mottled texture due to the highly erratic distribution of olivine.

<u>Unit IV</u>

Unit IV is characterized by a homogeneous, coarse-grained, augite-poor, augite troctolite. The rock is relatively uniform in texture and modal proportions although gradations to olivine gabbro and thin pegmatitic zones occur locally. Sulfide-bearing zones are rare and sedimentary hornfels inclusions are a minor constituent. Unit IV averages about 300 ft. thick but ranges from 0-550 ft. thick. This extreme thickness variation is, in part, due to the highly gradational nature of the upper contact of Unit IV with Unit V. Thus the exact position of the upper contact has been arbitrarily chosen in several drill holes. The base of Unit IV generally exhibits a sharp contact with Unit III, or Unit II when III is absent. A picritic horizon (0.5-25 ft. thick) with minor interbeds of troctolite and peridotite (bedding averages about 20-25E) occurs at or near the base of Unit IV in several holes at Dunka Road and Wetlegs (see Plate II).

There are no unique petrographic characteristics in Unit IV. Minor amounts of plagioclase-symplectite occur in the Wyman Creek and Wetlegs areas. Anorthite contents range from An_{62}-An_{71}.

In summary, Unit IV is a homogenous, coarse-grained augite troctolite that is very similar in appearance to overlying Units V through VIII. The only unique characteristics of Unit IV are: 1) an upper gradational contact with Unit V; and 2) a picritic horizon at or near the base in some holes within the Dunka Road-Wetlegs area.

Unit V

Unit V is characterized by a homogeneous textured, coarse-grained (locally pegmatitic), augite-bearing anorthositic troctolite that locally grades to troctolitic anorthosite, augite troctolite, and olivine gabbro. A highly gradational lower contact, over intervals of 20-100 ft., occurs with Unit IV and the upper contact is sharp. Very rare sulfide-bearing zones are present within Unit V in the

Wetlegs and Dunka Road areas. Unit V varies from 150-520 ft. thick in the Wetlegs-Dunka Road area.

At Wyman Creek, Unit V is up to 800 ft. thick and exhibits a dramatic downcutting relationship into Units I and II (see Plate II). This relationship indicates that Unit V is later than and intrusive into the lower units and that a local conduit of Unit V may be present in the Wyman Creek area. The presence of a conduit in this area is also suggested by Holst, *et al*, (1986) based on an extreme steepening of the basal contact to over 60E in an area about one mile to the south of Wyman Creek (also see Plate II - Severson, 1988). In addition, reconnaissance mapping indicates a broadening of Unit V in the Wyman Creek area (see Plate III) that may also be related to a local conduit. Yet to be demonstrated is the relationship between the downcutting Unit V in the Wyman Creek area and the sill-like Unit V in the Wetlegs and Dunka Road areas.

Petrographically unique to Unit V is the presence of up to 5% plagioclase-symplectite in the Wyman Creek and Wetlegs areas. Plagioclase-symplectite is present in only a few of the samples collected at Dunka Road and is totally lacking in the Unit V(?) outcrop samples collected to the south of the Wyman Creek area. Also important is that minor plagioclase-symplectite occurs in Unit IV, which exhibits a gradational contact with Unit V. Anorthite contents range from An_{52}-An_{72}.

In summary, Unit V is characterized by: 1) coarse-grained, augite-bearing anorthositic troctolite, which has a highly gradational contact with Unit IV; 2) plagioclase-symplectite is unique to Unit V at Wyman Creek and Wetlegs but not at Dunka Road; and 3) Unit V crosscuts lower units and a possible conduit for Unit V magma is present in the Wyman Creek area.

Unit VI

Unit VI is characterized by a homogeneous textured, medium- to coarse-grained, augite-poor (<10%), augite troctolite that commonly grades into thick zones of anorthositic troctolite-troctolitic anorthosite. At Dunka Road, a picritic horizon with internal bedding dips of 5-20E occurs at the base of Unit VI. This basal layer averages about 12 ft. thick and exhibits a consistently sharp base with a sharp to gradational top. Minor "cloud zone" sulfides are present at the western edge of the Dunka Road area. At Dunka Road, Unit VI is about 400-600 ft. thick but it thins to 200-400 ft. thick at Wetlegs. Unit VI is apparently not present within drill hole BA-6 in the Longnose area (see Plate II) and has been shown as a pinched-out unit on the geologic map of this report (Plate III). There are no petrographic features characteristic of Unit VI. Anorthite contents range from An_{45}-An_{80}.

Unit VII

Unit VII was intersected in the upper portions of only 15 drill holes that have been relogged in the Wetlegs and Dunka Road areas. Unit VII is similar to Unit VI in that Unit VII is a homogeneous medium- to coarse-grained, augite-poor, augite troctolite. In a few Dunka Road drill holes, zones remarkably similar to the mottled anorthositic troctolite of Unit III were intersected. The presence of these inclusions(?) of Unit III "up-section" suggests that Unit VII was intruded later than Unit III. However, additional work is needed to fully ascertain the intrusive timing of the PRTS units. A persistent basal horizon consisting of well-layered peridotite-picrite-troctolite (10-20E dips) is present in all holes that have been relogged (see Plate II). This horizon ranges from 5-44 ft. thick at Dunka Road and thickens to 100 ft. thick in the Wetlegs and Longnose areas. The top of this basal ultramafic horizon consists of interlayered troctolite, picrite, and peridotite which grade into thick peridotite and dunite layers at the base. The bottom contact of this horizon is sharp in all drill holes. The nature of the upper contact of Unit VII is unknown. No sulfide-bearing zones were encountered in Unit VII.

The thickness of Unit VII, including the basal ultramafic member, is unknown as all holes studied to date were collared within Unit VII; a minimum of 450 ft. is present in drill hole #26117 at Dunka Road. The geographic distribution of Unit VII to the south of the Longnose area (Plate III) is based on the tentative continuation of the drilled basal ultramafic member to a peridotite outcrop located at the base of a cliff in Section 1, T.58 N., R.14 W. (geochemical sample PRT-13). Similar to Unit VI, Unit VII has no distinguishing petrographic characteristics. Anorthite contents range from An_{47}-An_{81}.

In summary, Units IV, VI, and VII are all homogeneous medium- to coarse-grained, augite-poor, augite troctolites that are remarkably similar to each other. Each unit grades into thick zones of anorthositic troctolite and each unit has a basal ultramafic horizon. Due to these petrological similarities, unit assignment is difficult unless the drill hole has penetrated the marker bed unit (Unit III), and the hole has been "hung" accordingly.

Unit VIII

Unit VIII has not been encountered in any of the drill holes. Reconnaissance mapping indicates that Unit VIII resembles Units IV through VII in all characteristics. Poor exposures of serpentinized peridotite-picrite were located in Section 29, T.59 N., R.14 W. (Linscheid, in prep.) and Section 6, T.58 N., R.13 W. (geochemical sample PRT-11) and are presumed to represent the basal member of Unit VIII. The geographic distribution of this ultramafic member (Plate III) is based on a corresponding sinuous magnetic high present on the Allen quadrangle aeromagnetic map. Since no internal contacts have been located in the field, all of the troctolitic rocks situated between this sinuous peridotite member and outcrops of the Partridge River Gabbro Complex (PRGC) have been tentatively lumped into Unit VIII. Anorthite contents range from An_{57}-An_{71}.

Footwall Rocks

Within the study area, the bottom 20-400 ft. of Virginia Formation has been intersected in most drill holes. The rock is generally well bedded and is characterized by graphitic argillites, argillites, and siltstone with minor recrystallized biotite schist, graywacke, calc-silicate beds, massive cordierite-bearing argillite and rare chert. The graphitic argillites commonly exhibit weakly to highly contorted bedding planes and contain 5 - 10% very finely disseminated and bedded pyrrhotite. Planar to ptygmatic pyrrhotite beds averaging 1 - 2 mm thick (up to 1 cm) are also present in some graphitic argillite horizons. Planar "undeformed" beds in the argillites and graphitic argillites commonly exhibit dips ranging from 20-45E. Interestingly, the planar bedding planes in the large hornfels inclusions have the same dip range - rarely are near vertical beds encountered unless intense small-scale folding is present. Recrystallized biotitic argillite with decussate arranged biotite flakes/plates are commonly intermixed with the argillites. Primary bedding is occasionally preserved (planar to highly contorted) but these recrystallized sediments commonly exhibit a massive decussate texture. Both inclusions and interbeds of well-bedded siltstones, exhibiting sharp contacts with the surrounding rock, are commonly found in the recrystallized biotitic argillite indicating a mobile partial melt nature. Partial melt granites ranging from irregular-shaped wisps (<1 cm thick) to 10-20 ft. thick bodies (rare) occur within the Virginia Formation. The contact with the underlying Biwabik Iron-Formation is generally sharp.

The upper slaty member of the Biwabik Iron-Formation (BIF) was intersected in many drill holes. Submembers present within the BIF (after Gundersen and Schwartz, 1959) include: A - coarse-grained, bedded to massive marble (present in about one half of the holes drilled into the BIF indicating a pinch-out or facies change); B - layered diopside-chert taconite; and C - thinly laminated quartz taconite with ferrohypersthene, fayalite and magnetite. Bedding plane dips are generally 10-30E; however, steeper dips (35-70E) indicate the presence of local deformation.

A large hornfelsed basalt inclusion is located within Sections 2 and 10, T.58 N., R.14 W. and is referred to as the Moose Mountain Hornfels (MMH). In outcrop MMH is characterized by a very fine-grained, biotite-free, Opx-rich, massive rock that at restricted locales exhibits crude beds (flow banding?), spherical amygdules (plagioclase-filled), and ropey flow tops containing intermixed, discontinuous, highly contorted white calc-silicate(?) beds. Four samples of the MMH collected in this investigation exhibit a granoblastic texture. The modal percentages of minerals between samples varies dramatically. Plagioclase laths are the dominant mineral phase (45-55%) followed by 30-50% orthopyroxene (inverted pigeonite), 5-10% clinopyroxene (50% Cpx and 50% plag. in one section), 0-2% apatite (inclusions in Cpx and plag.), and 5-10% olivine (in two sections). The MMH occurs as a thin tabular body situated on the dip slope of a NE-trending ridge and is estimated to be at least 20 ft. thick with an overall dip of 5E to the southeast. Sharp contacts with surrounding anorthositic troctolite of Unit V(?) are present in outcrop. No sulfide enrichment occurs at any of the observed contacts.

About four miles north of the MMH is a large railroad cut (Section 18, T.59 N., R.14 W.) of hornfelsed basalt known as the Erie Hornfels. Tyson (1976) suggests the Erie Hornfels is a metamorphosed basalt of the North Shore Volcanic Group. The hornfels is characterized by plagioclase lath phenocrysts and relict amygdules set in a granoblastic plag. + Cpx + ol. + Opx groundmass. The Erie Hornfels presumably overlies the Virginia Formation at this locality as the Virginia Formation is present in the collars of peripheral drill holes. A thin lense of hornfelsed gabbro (granular/granoblastic texture) is located in outcrops in Sections 16 and 17, T.59 N., R.14 W. (see Plate III).

<u>Miscellaneous</u>

Numerous pegmatitic bodies in sharp contact with the troctolitic rocks are present in all units of the PRTS. They are extremely variable in composition ranging from anorthosite to augite troctolite and olivine gabbro. Their size is also extremely variable ranging from 1 ft. thick to larger bodies measured in tens of feet (see Plate II). Some of the pegmatite bodies contain abundant sulfides whereas others are barren - there is no clear-cut distinction between rock type and presence of sulfides. Pegmatitic, oxide-bearing (>10%) intrusives (OUI) are also dispersed throughout all the PRTS units.

Numerous fault zones occur in several holes. The fault zones are characterized by a brecciated to crumbly, slickensided, chlorite-serpentine mixture plus or minus calcite-plagioclase-quartz veins and veinlets. Fault contacts with the surrounding rocks exhibit both a gradational (into progressively less altered country rock) and a sharp nature.

Inclusions of Virginia Formation are present throughout the entire PRTS section up to Unit V. The number of sedimentary hornfels inclusions increases with depth and reaches a maximum in Unit I. The rock types are the same as described for the footwall rocks. There is not a 1:1 relationship of hornfels inclusions to sulfide-bearing troctolite.

STRUCTURAL EXAMINATION OF THE PARTRIDGE RIVER TROCTOLITE SERIES

The structure of the Partridge River intrusion in regards to the basal contact and the top of the Biwabik Iron-Formation is summarized in Severson (1988). These data indicate that pre-existing structures in the footwall rocks played an important role in how the lower part of the PRTS was intruded. Units I and II apparently are intruded sill-like along bedding planes within the Virginia Formation, which accounts for: 1) abundant sedimentary hornfels inclusions in both units; 2) the presence of hornfels inclusions concentrated at a particular stratigraphic horizon (middle of Unit I); and 3) the presence of troughs and ridges at the basal contact that correspond to pre-existing fold axes in the footwall rocks (indicated by the structure contours at the top of the Biwabik Iron-Formation; Severson, 1988).

Division of the PRTS into major units has provided an excellent opportunity to construct cross-sections through the various copper-nickel mineral deposits. These cross-sections can then be used to view the deposits in three dimensions to examine: 1) the relationships of the ore horizons to the various PRTS units; 2) the relationship of altered (uralitized) zones to ore horizons; and 3) examine the nature of fault offsets. Only the latter examination has been attempted. Eight cross-sections through three of the mineral deposits have been constructed to illustrate the relationship of the PRTS units to the footwall rocks.

The cross-sections are shown on Figures 4, 5, and 6 and on Plate IV; the locations of the cross-sections are shown on Plate I. Immediately evident in most of the cross-sections is the presence of normal faults (southeast side down) that intersect both footwall and troctolitic rocks. Within the Wetlegs area, these faults are arranged in a NE-trending pattern (see Severson, 1988, for a more detailed description). Several faults at Dunka Road have an inferred NE trend, but additional work is required to determine the overall extent and pattern of these faults. Faults with appreciable movement do not occur in the Wyman Creek area.

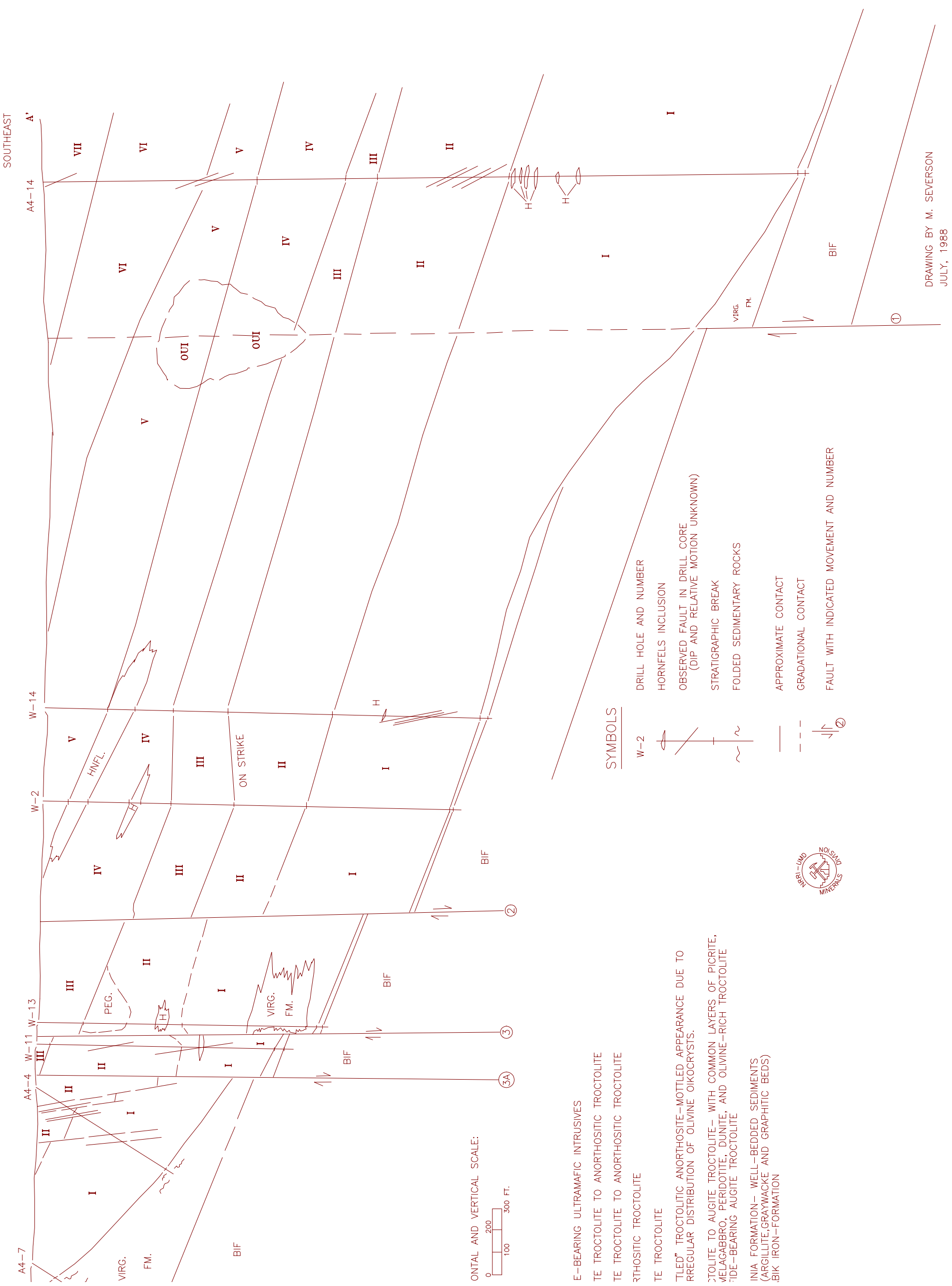


Figure 4: Wetlegs area cross-section A-A[1].

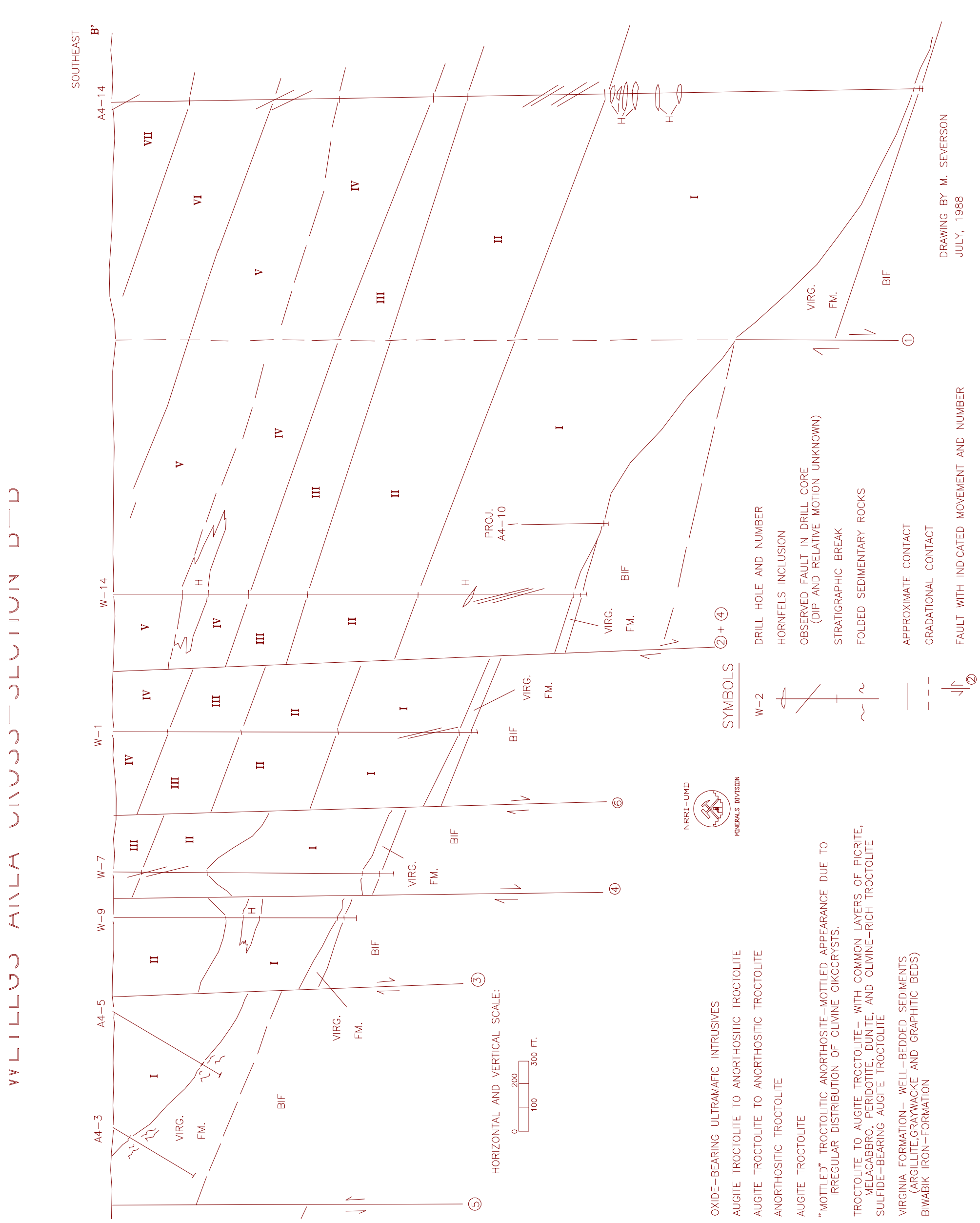


Figure 5: Wetlegs area cross-section B-B[1].

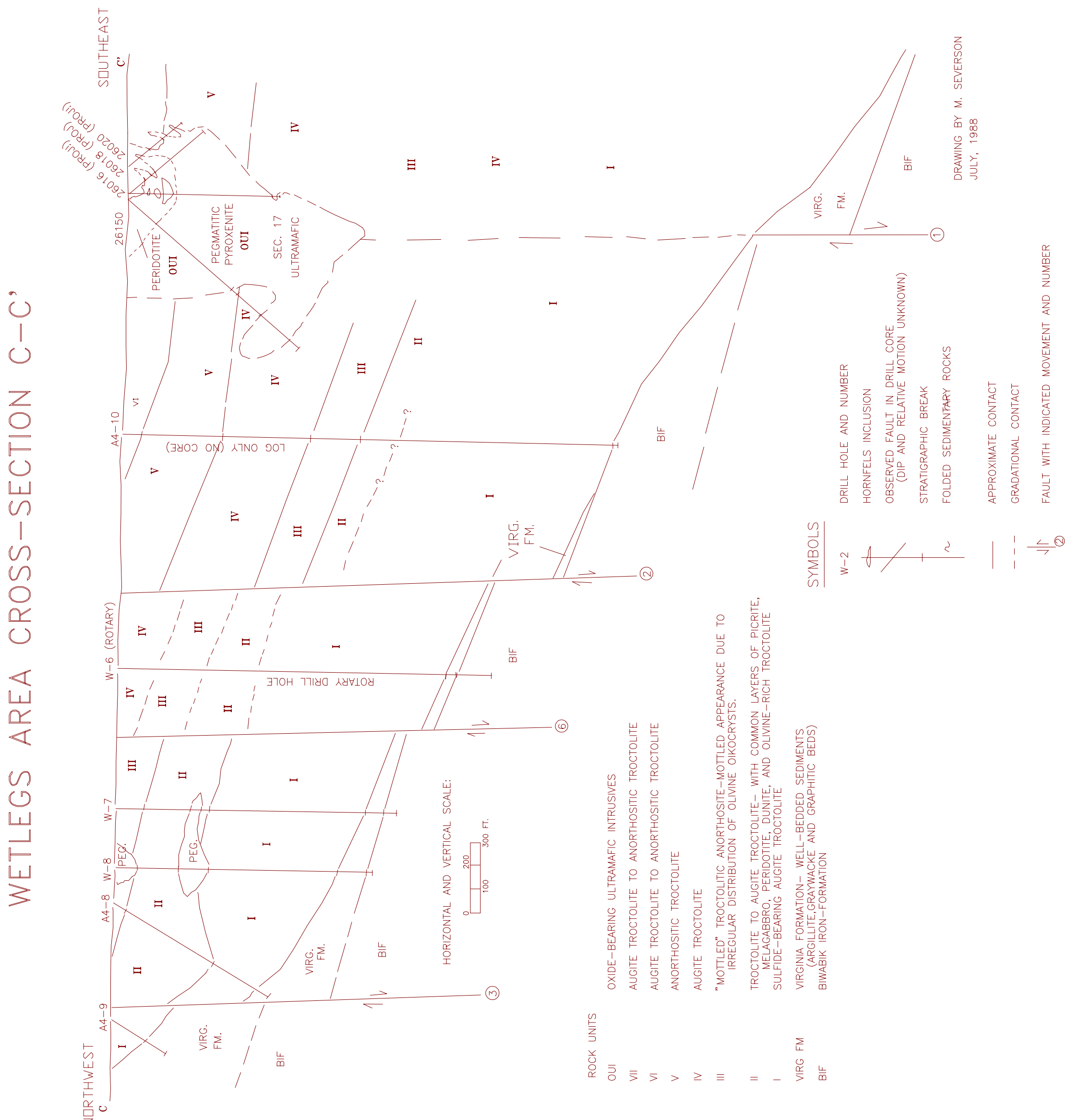


Figure 6: Wetlegs area cross-section C-C[1].

OXIDE-BEARING ULTRAMAFIC INTRUSIONS (OUI)

Introduction

Several Oxide-bearing Ultramafic Intrusions (OUI) are delineated within the Partridge River intrusion. They are intrusive into all units of the PRTS and range in size from large bodies (>200 ft. thick) that are discordant to the general PRTS stratigraphy to small bodies/lenses (<30 ft. thick) that repeatedly occur along a particular stratigraphic horizon. Rock types are characterized by pegmatitic dunite, peridotite, and clinopyroxenite (referred to as pyroxenite hereafter), with minor amounts of picrite and melagabbro. These rock types contain varying amounts of ilmenite and titanomagnetite ranging from 10-15% to semi-massive (50-80%) and massive (>80%) oxide zones. Internal contacts between these rock types varies from abrupt (over 3 inches) to sharp (multiple pulses) and it is not uncommon to find small peridotite intervals (6 in - 2 ft) in pyroxenite and vice versa.

In almost all cases, the OUI bodies in sharp contact with the PRTS units are clearly younger. This is demonstrated in drill core by: 1) near vertical, sharp contacts (most cases); 2) abundance of small ultramafic lenses (apophyses) in the PRTS; 3) presence of small PRTS inclusions within the interior of thick intervals of OUI (rare); and 4) where in sharp contact with serpentinized-foliated PRTS units, the adjacent OUIs are "fresh" and generally void of serpentinization and foliation.

Olivine, whether in dunite or pyroxenite, occurs as subrounded equant grains that often exhibit 120E triple point junctions. The olivine is often enclosed in Cpx indicating it was first to crystallize. Although serpentinization is not usually very intense within the OUI units, minor, subparallel, hairline serpentine-chlorite filled cracks are common within olivine-rich zones. Whenever one of these cracks crosses a Cpx crystal, the crack thins dramatically. Rust colored, Cl-rich drops that coat the core are often associated with weakly to moderately serpentinized olivine.

Fe-Ti oxides (ilmenite and titanomagnetite) are an important constituent of all rock types present in the OUI rocks. The oxides occur as either: 1) subrounded, equant, subhedral to euhedral, cumulus grains that are concentrated in clusters and crude bands (rare); or 2) as irregular grains interstitial to olivine. Skeletal crystals and long slender blades between Cpx crystals also occur. Ilmenite is generally present in much greater quantities than titanomagnetite.

Within the pyroxenites, augite occurs as anhedral grains that exhibit mutually sinuous to consertal grain boundaries. The augite crystallized later than both olivine and Fe-Ti oxides in that subhedral, equant grains of both phases are often totally enclosed in larger Cpx grains. Within the dunites and peridotites, augite occurs as irregular, interstitial grains. The augite typically has a "moth-eaten" appearance due to the presence of unoriented internal blebs of titanaugite (red-brown pleochroism). Titanaugite also occurs as individual grains (up to 5%), and as thick rinds on augite where augite is in contact with oxides. The augite crystals commonly contain exsolved rods and plates of ilmenite, magnetite, rutile, and biotite which occur along the major cleavage planes. Both inclusion-rich and inclusion-poor augites can occur in the same thin section. In some thin sections, early formed, inclusion-poor, equant Cpx crystals are enclosed in later inclusion-rich Cpx and/or plagioclase.

Minor constituents of the OUI are orthopyroxene (cumulus and intercumulus), plagioclase and calcite which are interstitial to the framework grains. Anorthite contents range from An_{50}-An_{77} (Linscheid, in prep.). Minor amounts of biotite (<3%) are also present and are associated with oxides and interstitial Cpx and Opx. Hornblende is present but rare.

Sulfide content generally ranges from trace to 3% in the upper portions of the larger bodies and exhibits a downhole decrease to trace amounts. In general, sulfide content increases whenever the olivine and/or oxide content increases. Pyrrhotite and chalcopyrite are the dominant sulfides and occur as <1 mm round droplets within olivine and Cpx, or as interstitial grains (up to 5 mm) adjacent to Cpx and oxides.

Small lenses of OUI are present within the PRTS at Dunka Road and Wetlegs. Larger OUI bodies have been drilled at Section 17, Longnose, Longear, Wyman Creek, Section 22, and Skibo. The Section 17, Longnose, and Longear bodies are spatially distributed along a NE-trend that corresponds to a NE-trending half-graben fault and an inferred window of Biwabik Iron-Formation at the basal contact (Severson, 1988). The correspondence of these three bodies of OUI to the BIF window suggest that they may be related to areas where massive iron-formation assimilation has occurred at depth.

<u>Section 17</u>

The OUI body in Section 17 (T.59 N., R.13 W.) consists dominantly of pegmatitic pyroxenite with a small interior core zone of peridotite. Semi-massive (50-80%) oxide horizons up to 7 feet thick are present in some drill holes, but they cannot be correlated as continuous stratigraphically controlled zones. Ilmenite content is generally greater that titanomagnetite.

Sulfide content generally ranges from trace to 3% at the tops of some holes and decreases downhole to rare quantities. Pyrrhotite is by far the most dominant sulfide and occurs as both <1 mm round droplets within Cpx and olivine, and as coarse interstitial grains adjacent to Cpx and oxides. Chalcopyrite, and rare bornite, almost always occur at the periphery of pyrrhotite. Two occurrences of massive pyrrhotite (<1.5 inches) were noted (# 26016 213 ft., and # 26018 399.5 ft.).

<u>Longear</u>

The Longear body (three drill holes) is characterized by alternating coarse-grained and pegmatitic pyroxenites that exhibit both abrupt and sharp contacts indicating a multiple pulse origin. Overall, rock types are similar to Section 17, except that only minor, thin peridotite intervals were intersected. Semi-massive and massive (>80%) oxide horizons up to 10 feet thick commonly occur in the pyroxenites and a crude correlation between drill holes is possible. Sulfides are present as trace amounts to 0.5% in the upper half of the body but decrease downhole to rare amounts. Chalcopyrite is the dominant sulfide. The highest percentages of sulfides are generally associated with oxide-rich and/or olivine-rich zones.

Longnose

Twelve holes were drilled into the Longnose OUI body. A review of four holes by Linscheid (in prep.) indicates that this body is intrusive into the PRI. The ultramafic body is crudely concentrically zoned with a dunite core grading downward and outward through peridotite to pyroxenite. Several massive to semi-massive oxide zones up to 50 feet thick are present within the dunite core and apparently can be correlated between drill holes. Sulfides are a minor constituent at Longnose (trace-2%). Linscheid (in prep.) reports that chalcopyrite accounts for about 99% of the sulfides.

Wyman Creek

Several bodies of OUI occur in the Wyman Creek Cu-Ni deposit. The OUIs occur dominantly as large lensoidal bodies (100-200 ft. thick) intrusive into Unit I of the PRTS, but small lenses (1-30 ft. thick) are also present higher up in the stratigraphic section within Units IV and V. The bodies within Unit I are discordant to the stratigraphy. Rock type is characterized by peridotite and pyroxenite, but picrite and melagabbro is also common. No compositional zonation patterns are evident within these large OUI bodies. Oxide content averages 5-15% and minor massive oxide horizons also occur (14 feet in drill hole 26133). Sulfide content is extremely variable in each of the bodies/lenses and ranges from rare amounts to 3%. Chalcopyrite is generally the dominant sulfide except in the oxide-enriched zones where pyrrhotite is dominant.

Abundant chlorine drops covered the core in a 160 foot thick oxide-rich peridotite of drill hole 26133.

Dunka Road

Abundant small lenses of OUI are present throughout the entire PRTS stratigraphic section at Dunka Road. These bodies average about 2-5 feet thick (up to 50 feet thick in two drill holes) and dominantly consist of pegmatitic pyroxenite and melagabbro with 5-10% oxides and 1-5% biotite. Sulfide content is extremely low (rare to trace amounts) but some lenses contain 0.5% to 5% sulfides.

The spatial distribution of these small bodies of OUI suggest that they occur as thin lenses concordant to the PRTS stratigraphy. However, the stratigraphic position and amount of these bodies present in any particular drill hole is extremely variable (at least 18 lenses intersected in drill hole 26117) making exact correlations between drill holes tenuous (see Plate II). Logging of drill holes at Dunka Road is ongoing (1989 GMC Project - Steve Geerts) and to date no OUI lenses have been encountered in the shallow holes of the deposit. Thus, their position at Dunka Road is confined to deep holes that are along the southern periphery of the deposit, in an area where the Virginia Formation has thinned to about 10 feet at the basal contact. If the thinning of the Virginia Fm. "cap" continues, eventually the Biwabik Iron-Formation will be in contact with the Partridge River intrusion. Thus, as at Wetlegs, an empirical relationship may also exist at Dunka Road between the spatial location of OUI bodies and where iron-formation may have been assimilated at the basal contact.

Section 22

Outside of the reported occurrence of "ferro dunite" in the log for drill hole A-4, little is known of the Section 22 body. The drill core from five holes in this vicinity have yet to be relogged by the authors.

Skibo

Sixteen drill holes were put down by INCO to test a OUI body situated in the Skibo area (Section 34, T.58 N. - T.14 W). A drill hole put down by United States Steel (#27016) represents the only core preserved for this area and is currently being studied by J. Seitz at Virginia Polytechnical Institute, Blacksburg, VA. The following description of the Skibo body is from Seitz and Pasteris (1988). The OUI is a subhorizontal sill-like body that is intrusive into troctolitic rocks and consists dominantly of dunite to feldspathic peridotite. Olivine (Fo_{57}-Fo_{63}) is cumulus, whereas plagioclase and augite are intercumulus. Oxides (ilmenite > magnetite) occur interstitially to major cumulate silicate phases and as rounded lobate grains. Pods or mats of massive ilmenite are common. Graphite is often found in some of the oxide-enriched zones. In numerous cases, sulfide horizons occur near oxide horizons. Sulfides occur as massive pyrrhotite mats (which are also enriched in ilmenite) and as intercumulus Cu-enriched blebs. The textures of sulfide and oxide minerals suggest the existence/co-existence of immiscible oxide and sulfide liquids. Geochemical analysis (funded by NRRI) indicate strong positive correlations between FeO and C and between C and S. Since C is associated with oxide mineralization, then the positive correlation between C and S directly relates to oxide and sulfide mineralization. The high C and S contents of the Virginia Formation footwall should be considered as a possible dual source of these elements.

LITHOLOGIC DESCRIPTIONS OF THE PARTRIDGE RIVER GABBRO COMPLEX (PRGC)

Introduction

The Partridge River Gabbro Complex (PRGC) is used in this report to informally designate gabbroic and troctolitic rocks present in the southeast portion of the study area (see Plate III). The PRGC includes the Colvin Creek "Gabbro", the Powerline Gabbro, a body of anorthositic gabbro, and intervening troctolitic rocks situated between the Colvin Creek and Powerline bodies. Descriptions of each subunit of the PRGC are based on very limited reconnaissance mapping and thus they are preliminary at this time.

Colvin Creek "Gabbro"

The Colvin Creek "Gabbro" (CCG) is exposed in two bodies (Plate III) situated near the boundary between rocks of the Anorthositic Series and the Partridge River intrusion. Due to a thick mantling of glacial overburden (especially over the southernmost body) the dimensions of the bodies are largely inferred from aeromagnetic highs.

The Colvin Creek rocks were first described by Bonnichsen (1972) who concluded that the "Colvin Creek Hornfels" was a basaltic hornfels inclusion due to the rare presence of recrystallized plagioclase phenocrysts and fine-grained plagioclase-filled ovoids that were thought to represent metamorphosed amygdules. Tyson (1976) also looked at the Colvin Creek material as well as three other hornfelsed basalt inclusions (Erie Hornfels 18-59N-13W, Reserve Hornfels 32-60N-12W, and Dunka Railroad Hornfels 33-60N-12W). He concluded that the Colvin Creek was a basaltic hornfels but noted that the mineral assemblage (plag.+augite+magnetite, with no olivine) differed from the other three hornfels bodies (augite + plag. ± ilmenite ± olivine ± inverted pigeonite). Based on a triangular mineralogic plot (mafics vs. plagioclase vs. opaques), Tyson (1976) divided the hornfels bodies into two types: type I = Erie, Reserve and Dunka Railroad bodies that were equivalent to reduced North Shore Volcanic basalts; and type II = Colvin Creek material that was equivalent to oxidized North Shore Volcanic basalts. He noted that the Colvin Creek material presented a problem due to the absence of olivine and excess amount of magnetite, but he felt that these unusual features may have been due to weathering of the basalt prior to metamorphism. However, reconnaissance mapping conducted in this study discovered several new outcrops that conflict with a typical hornfelsed basalt protolith. These features will be discussed later.

Though outcrops are scarce, the majority of the southern Colvin Creek body is characterized by a dark gray, fine-grained, sugary-textured rock composed of plagioclase (40-65%), augite (20-35%), and magnetite (10-25%), with local veins of medium to coarse-grained augite. In thin section, the texture is typically granular (granoblastic) and plagioclase occurs as polygonal grains that meet at 120E triple point junctions. Augite occurs as inclusion-poor equant grains that may contain Ca-poor pyroxene lamellae (rare) and also tend to meet at triple point junctions. Up to 10% orthopyroxene occurring as equant grains occurs in two samples. Minor olivine oikocrysts (<1%) also occur (no olivine was noted in the eight sections studied by Tyson). Abundant apatite needles/rods are ubiquitous to all samples and occur as unoriented inclusions in plagioclase, Cpx and Opx. Magnetite is the dominant opaque and occurs as rounded, equant subhedral grains. Embayed interstitial blebs of titanomagnetite, with ilmenite patches and/or ilmenite oxidation-exsolution lamellae, make up the remaining opaques. No plagioclase phenocrysts nor plagioclase-filled ovoids ("amygdules") are noted in the outcrops of the southern body.

In contrast, the northern Colvin Creek body (Sections 27, 28, 33, 34, T.59 N., R.13 W.) is characterized by abundant outcrops that contain several different mappable units that trend approximately N40-60EE with near vertical dips and northwest-topping directions. Within this body are conflicting outcrops that are suggestive of both magmatic layered rocks and "amygdaloidal" volcanics. These are described below starting with the top of the body (NW side) and progressing downward across the body (to the SW). A generalized geologic map of the northern body with specific outcrop locations is shown on Figure 7.

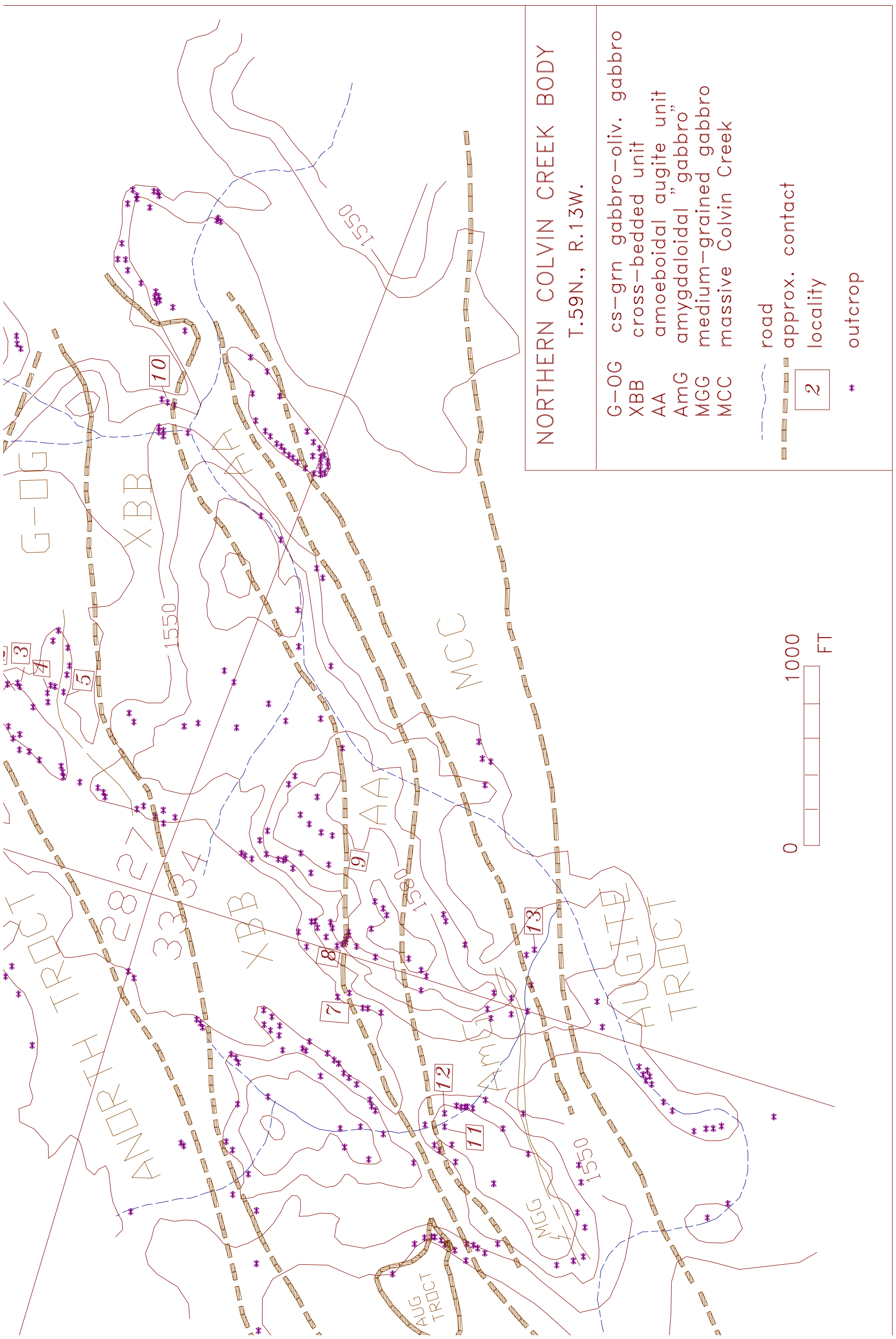


Figure 7: Generalized geology of the northern Colvin Creek body.

The northernmost mapped unit (G-OG unit on Figure 7) is characterized dominantly by coarse-to medium-grained, magnetite-bearing gabbro that is similar to outcrops of the Powerline Gabbro located within a mile to the northeast. Within the G-OG unit are several outcrops that display excellent modal laminations that trend N40-60EE with near vertical dips. Within the upper 2/3 of unit G-OG are several subunits which are characterized by: Locality 1 = modally layered anorthositic gabbro with aligned plagioclase; Locality 2 = medium-grained olivine gabbro with 15% plagioclase phenocrysts and minor rounded anorthosite inclusions (up to 5 inches across) derived from Locality 3 (indicates top directions to the northwest); and Locality 4 = coarse-grained gabbros, melagabbros, and olivine gabbros that exhibit "inch-scale" layering and north-topping cross-beds (Fig. 8A) indicating the presence of magmatic density currents. Also at Locality 4 is a north-trending vein (3x10 feet) of massive, coarse-grained, octahedral magnetite with minor malachite (sample PRT 23-7). To the south of Locality 4, olivine gabbro grades downward into augite troctolite which is the dominant rock type in the lower 1/3 of the G-OG unit. The troctolitic rocks at Locality

5 are a heterogeneous mixture of modally layered fine- and medium-grained rocks with olivine gabbro "interbeds" and local rounded inclusions of troctolite. At Locality 6 (at the west end of Fig. 7), a downward transgression from olivine gabbro to modally layered (50E dip) picrite with troctolite occurs. The basal contact of the G-OG unit is not, as yet, located in the field.

Below the G-OG unit is a 1000 foot thick unit that is herein referred to as the "cross-bedded belt" (unit XBB on Fig. 7) that was traced for about 2 miles along a N60EE trend with near vertical dips. Rocks of the XBB are strikingly similar to sedimentary rocks in that they display features that include (Figs. 8B and 8C) bedding planes/modal laminations defined by alternating plagioclase and augite±magnetite bands, cross-beds, sculpting, troughs, and local convoluted layers suggestive of "soft-sediment" slumpage. Internal beds within the XBB range from N40-85EE with dips of 50-70E north, but shallow dips up to 5E and variations in strike are also encountered indicating that slumpage and/or folding is also locally present within the belt. Top directions, as defined by the cross-beds and troughs, are generally to the northwest, but local variations due to slumpage/folding also occur.

In thin section (PRT-24), the rock is characterized by a fine-grained, granular-textured rock composed of polygonal, equant plagioclase (exhibits triple point junctions and abundant apatite inclusions), equant inclusion-poor augite (triple point junctions), rounded equant magnetite (with minor exsolved spinel patches), and minor olivine oikocrysts (<1%). There are also irregular-shaped and embayed composite grains of titanomagnetite-ilmenite. Preliminary microprobe analyses indicate that the ilmenites have high MgO contents (5-8%) and they contain minor minute exsolved patches of an unknown mineral ($Mg_{O.7}Fe_{O.3}Mn_{O.1}Ti_{0.9}O_3$) that is intermediate between geikielite ($MgTiO_3$) and pyrophanite ($MnTiO_3$).

The presence of the XBB is somewhat problematic if the Colvin Creek body represents a hornfelsed North Shore basalt unless the belt is assumed to be an interflow sediment. However, the XBB is not a typical interflow sediment in that: 1) it is much thicker (1000 ft.) and has a longer strike-length (at least 2 miles) than typical interflow sediments exposed along the North Shore; 2) no ripples or rock fragments could be located anywhere in the field and, in fact, the rock is characterized by a very homogeneous grain size; and 3) no micas, quartz, nor cordierite are noted in thin section - these should be present in an interflow sediment whose provenance would have included the Archean Giants Range Batholith (located within seven miles to the northwest). For these reasons and because both the XBB and G-OG units display sedimentary features and similar mineralogy (albeit differences in grain size and textures), the "cross-bedded belt" is herein interpreted to be a contact metamorphosed, chilled gabbroic unit that was deposited via magmatic density currents. Similar "sedimentary" features have been interpreted as magmatic density currents (Irvine, 1987) in the Cross-Bedded Belt of the Skaergaard Intrusion (Wager and Brown, 1967). The basal contact of the XBB unit crops out at four locations. At Localities 7, 8, and 9 (Fig. 7), the cross-bedded material is in sharp contact with a 2-3 foot thick, layered, coarse-grained melagabbro that in turn grades downward (SE) into unit AA (to be discussed later). At these localities, the contact often exhibits some broad undulations (folds, convoluted beds, infilled troughs) that are suggestive of "soft-sediment" deformation due to slumpage.

However, local axial-planar cleavage and "stringy"/sheared augite along the bedding within the basal 2 inches of the XBB unit suggest that tectonic deformation may also have been important along the contact.

Figure 8:

A: "Inch scale" layered and cross-bedded unit (1.5 ft. thick) within coarse-grained gabbro (G-OG unit) of the northern Colvin Creek body. Sample PRT 23-8, NE-SW-SW Section 27, T.59 N., R.13 W. (Locality 4 in Fig. 7)

B and C: Sedimentary-type features of the "cross-bedded belt" (XBB unit) within the northern Colvin Creek body. Sample PRT-24, NW-NW-NW, Section 34, T.59 N., R.13 W.

At Locality 10 (Fig. 7), the contact is also sharp, but the melagabbro unit here is fine-grained and locally cross-bedded. Near to the contact, the melagabbro contains minor coarse-grained augite lenses that are hook-shaped (small Z folds) and convoluted. Features of both "soft-sediment" slumpage and tectonic deformation are also present at Locality 10. No rock fragments or conglomerates are present in any of the contact outcrops.

Rocks beneath the XBB unit can be further subdivided into three mappable units which are shown on Figure 7 (units AA, AmG, and MCC). The MCC (massive Colvin Creek) is similar to rocks of the southern Colvin Creek body described previously. The MCC is the dominant rock type along the southeastern edge of the northern body, but it is also present as interbeds within the AA and AmG units.

The AA unit (amoeboidal augite) is characterized by medium to very coarse-grained augites set in a MCC "matrix". The coarser augites exhibit a highly variable morphology consisting of amoeboid-shaped, rounded, hook-shaped, and interstitial forms. At some localities the augite is plagioclase-cored and plagioclase-rimmed. Modal layering on the order of 1-4 feet is common; the coarse augite is generally reverse size-graded in some of these layers.

The AmG unit ("amygdaloidal" gabbro) is characterized by plagioclase-filled ovoids up to 1.5 cm across and wispy plagioclase stringers dispersed within a MCC "matrix". The AmG unit is also often layered/bedded on the order of 2 to 10+ feet thick. At some localities, the plagioclase ovoids are concentrated in up to 5 x 5 foot patches that cannot be traced with certainty; whereas at other localities, plagioclase stringers parallel the bedding trend. The presence of plagioclase ovoids suggests that the AmG unit is a hornfelsed basalt, whereas the thin beds and plagioclase stringers are not typical of other hornfelsed basalt inclusions described elsewhere in the PRI. At present, it is difficult to ascertain whether the plagioclase ovoids represent amygdules in basalt flows or are related to degassing of volatiles in a magma chamber that experienced magmatic density currents (which may explain the plagioclase stringers and thin bedded nature of the AmG unit). Compounding the protolith origin are conflicting outcrops of: Locality 11 = augite-filled "pipe vesicles" at the base of a north-topping 3 ft. thick bed (see Fig. 9A); Locality 12 = "load cast" structures within a massive magnetite base(?) of a MCC unit that tops to the south at this particular locality (see Fig. 9B); and an interbed of MGG (medium-grained gabbro) within the AmG unit (Fig. 7) that contains approximately 15% plagioclase phenocrysts up to 4.0 cm long (similar to locality 2 in the G-OG unit).

The most unique feature of the entire northern Colvin Creek body is exposed in a road cut at Locality 13 (Fig. 7). At this locality, MCC-type material has been "autobrecciated" to varying degrees (due to slumpage?) and a fine-grained magnetite-rich material has been "injected" into the interstices. At one point (shown in Fig. 9C), the magnetite-rich material has been "injected" along a contact between MCC material and a unit with pegmatoidal, tabular plagioclase producing a highly irregular and undulating contact. Tabular plagioclase has been literally "stripped" from the pegmatoidal unit and has been incorporated in the adjacent magnetite-rich material indicating that the process of "autobrecciation" and "injection" occurred while the rocks were still in a semi-molten state.

The rocks of the northern Colvin Creek body are diverse in nature and problematic in their origin. Magmatic density current features are present within the G-OG unit, the XBB unit(?), and possibly the AA and AmG units (thin bedded nature and presence of plagioclase stringers). However, the overall thickness of the fine-grained granular-textured XBB, AA, AmG, and MCC units is difficult to envision if the units were deposited in a chilled basal setting of a magma chamber by magmatic density currents. On the other hand, volcanic features (amoeboidal augite and plagioclase ovoids) are present in the AA and AmG units, but the thin nature of the internal beds is not characteristic of typical North Shore Volcanic basalts as reported in the literature. Finally, the thickness, lack of rock fragments and quartz, and homogeneous grain size of the XBB unit is not characteristic of typical interflow sediments; whereas, similar mineralogy to the overlying G-OG unit (which also contains sedimentary features) suggests that the two units were deposited by magmatic density currents. These problems are beyond the scope of this investigation and much more detailed mapping, petrographic work, geochemistry, structural investigations, and comparisons to other surrounding rock types are necessary in order to resolve this enigmatic rock unit. At present, the bodies are tentatively classed as the Colvin Creek "Gabbro" and a deposition mechanism of magmatic density currents is suggested. As will be seen in the following discussions, and from mapped units of Plate III, similar zones of MCC-type material are located within what has previously been mapped as the Powerline Gabbro which is a coarse-grained, magnetite-bearing gabbro that is similar to the G-OG unit of the northern Colvin Creek body.

If the CCG body is intrusive, its relationship to the other PRTS units, e.g., timing, and what mechanism/intrusion produced the contact metamorphic textures as well as turning the entire northern Colvin Creek package on end, is unknown. Based on magnetic modeling, Chandler and Ferderer (in press) reiterate Bonnichsen's concept (1972) that the Colvin Creek body, etc., (referred to as the Railroad Troctolite by Chandler and Ferderer) was delaminated from the floor of the Duluth Complex and elevated to its present position by repeated underplating intrusions of troctolitic material of the Partridge River intrusion.

Figure 9:

A: Augite-filled "pipe vesicles" at the base(?) of a 3 ft. thick bed within the AmG unit. On logging road in the NW-SE-NE, Section 33, T.59 N., R.13 W. (Locality 11 on Fig. 7)

B: Sharp, scoured base of massive magnetite that modally grades upward (to the south) into fine-grained MCC material indicating deposition by magmatic density currents. Borrow pit to the east of logging road in NW-SE-NE, Section 33, T.59 N., R.13 W. (Locality 12 on Fig. 7).

C: Irregular contact between pegmatoidal plagioclase-rich unit (A) and "injected" magnetite-rich material. Note large plagioclase laths within the magnetite-rich material. Borrow pit on the north side of logging road in the center-SW-NW, Section 33, T.59 N., R.13 W. (Locality 13 on Fig. 7)

Powerline Gabbro

The Powerline Gabbro (PLG), as first mapped by Bonnichsen (1974), is a relatively small body of olivine gabbro with appreciable amounts of magnetite and apatite. The PLG's dimensions, like the Colvin Creek "Gabbro", are largely based on associated aeromagnetic highs (Babbitt SW aeromagnetic quadrangle). Rock types encountered during this study include: medium to coarse-grained gabbro, olivine gabbro grading into augite troctolite, and fine-grained hornfelsed "gabbro" (same rock type as encountered in the southern Colvin Creek body and the MCC material of the northern Colvin Creek body). All rock types of the Powerline Gabbro contain variable amounts of magnetite (5-20%). A shallow-dipping zone of "cross-bedded belt" material is located in Section 25 (T.59 N., R.13 W.) and was erroneously(?) mapped as being within a Powerline Gabbro body (see Plate III). In thin section, the fine-grained hornfelsed "gabbro" exhibits the same granular texture as rocks of the Colvin Creek bodies. The coarser-grained gabbros are characterized by varying amounts of plagioclase (subhedral laths with abundant apatite inclusions), augite (occurs as both equant inclusion-poor crystals and as inclusion-rich oikocrysts), orthopyroxene (equant crystals and rims on olivine), olivine (equant cumulus grains, amoeboid interstitial grains, and oikocrysts), magnetite, and trace amounts of sulfides (composite interstitial grains of chalcopyrite and pyrrhotite). Contacts with augite troctolite of the PRTS on the western edge of the Powerline Gabbro are not exposed and may be gradational. Contacts with troctolites within the PRGC (TGC - to be described later) are both cross-cutting and interbedded at various localities.

Both the Powerline Gabbro and Colvin Creek "Gabbro" are similar in many respects. These similarities include: 1) both are associated with aeromagnetic highs and have an appreciable amount of magnetite; 2) both contain an appreciable amount of apatite as inclusions in plagioclase; 3) the Colvin Creek "Gabbro" contains minor amounts of coarse-grained oxide-bearing gabbro, e.g., G-OG unit, and the Powerline Gabbro contains isolated pods of fine-grained "gabbro", e.g., MCC unit; and 4) both contain isolated zones of modally laminated rock. Based on these field relationships, both the Colvin Creek and Powerline bodies appear to be the same gabbroic body - the main difference being the relative grain size of the rock types characterizing each body, e.g., fine-grained rock and coarse-grained rock, respectively.

Anorthositic Gabbro

A northeast-trending wedge of anorthositic gabbro (unit AG on Plate III) occurs in Sections 5, 7, and 8, T.58 N., R.14 W. The AG unit is characterized by 70-80% plagioclase, 5-15% augite (occurring as equant inclusion-poor grains and inclusion-rich oikocrysts), 3-15% olivine (occurring as equant cumulus and irregular interstitial grains), 2-5% magnetite, and trace amounts of orthopyroxene, biotite, and sulfides. The northern half of the body is typically coarse-grained, whereas medium-grained rocks are more dominant in the southern half. Close to the contact with the Colvin Creek "Gabbro" there is an increase in magnetite content (10%) and also abundant apatite inclusions (sample PRT-18). Therefore, the anorthositic gabbro body (AG) may be related to the Colvin Creek "Gabbro" and is tentatively lumped with other rocks of the Partridge River Gabbro Complex (PRGC).

Several outcrops of anorthositic gabbro are also located to the north along the Dunka road (Section 1, T.59 N., R.13 W.). At present, the relationship of these outcrops to the PRGC is unknown.

Troctolitic Rocks of the Partridge River Gabbro Complex

Abundant outcrops of medium- to coarse-grained augite troctolite grading to olivine gabbro (TGC unit of Plate III) occurs in the intervening areas between the Colvin Creek "Gabbro" and Powerline Gabbro bodies. The age relationships between the TGC, CCG, and PLG units are unknown at this time due to the conflicting lines of evidence disclosed by reconnaissance mapping. For example, an outcrop of augite-rich troctolite (sample PRT-44; 33-59N-13W) is present that contains excessive amounts of magnetite and minor apatite, which is the characteristic mineralogy of the nearby PLG and CCG units (indicating that a gradational contact is present?). At another location (SW,NE,SE,25-59N-13W), alternating outcrops of augite troctolite and olivine gabbro are present that exhibit a gradational nature between the two rock types; one of the troctolitic outcrops exhibits excellent modal laminations (40E dip to the north) with minor olivine gabbro interbeds. Stratigraphically below these outcrops (15 feet lower in elevation and 800 feet to the south) are "cross-bedded belt" outcrops that also dip to the north at about 5E. It is possible that the TGC outcrops conformably(?) overlie the "cross-bedded belt" material and is, therefore, time correlative with similar appearing rocks in the lower 1/3 of the G-OG unit (northern Colvin Creek body). At another location (SE,SW,SW,24-59N-13W), a large outcrop of augite troctolite contains an east-west trending, near-vertical lense (approximately 20 x 100+ feet) of fine-grained troctolite exhibiting "inch-scale" modal olivine layers. Conformably(?) situated within this lense is a 3 foot thick bed of cross-bedded belt material suggesting that the TGC and CCG units may be time correlative. However, within this same outcrop, the western edge of the lense is cut by a 5 foot thick, north-trending augite troctolite indicating that a portion of the outcrop was intruded during a later phase. Thus, both syn-CCG-PLG (interbedded and gradational contacts) and post-CCG-PLG (cross-cutting relationships) may be collectively present within the TGC. Furthermore, two distinct geochemical signatures are present within the TGC and may be related to these bimodal intrusive events.

GEOCHEMISTRY

Introduction

There have been no previous geochemical studies on a wide variety of rock types present within the Duluth Complex. Therefore, this program was initiated in order to conduct a regional geochemical study of unmineralized rocks in and around the Cu-Ni deposits and Fe-Ti deposits of the Partridge River intrusion. By systematically sampling correlative igneous rock units, and the various rock types present within these units, corresponding background geochemical values can be established to a limited extent, depending on the number of samples collected from each unit. These background values can then be used for comparison purposes in determining if "mineralized" rocks contain anomalous amounts of a specific element relative to the unmineralized rocks. Also, the background data can be used to determine if the various igneous rock units exhibit a specific lithogeochemical signature. The geochemical data can also be used to study the origin of the various igneous rock types and units.

Sampling

One hundred and fifty-five rock samples of unmineralized rocks were collected from the various rock units present within the PRI, e.g. PRTS, PRGC, and OUI and the footwall Virginia Formation. The distribution of samples relative to the igneous rock units is depicted in Table 1. Sample numbers of drill core are represented by the footage of the sampled interval followed by the drill hole number. Field sample numbers are prefixed PRT. In almost all cases, the samples represent unmineralized rocks that contain only rare amounts of sulfides; two of the samples contain up to 1% sulfides (# 26042 973-978 ft., and # 26143 320-325 ft.). Unmineralized oxide-bearing samples, e.g., OUI and PRGC units, were selected from zones that contain less that 20% oxides (visual estimate), except for sample PRT 23-7 that was collected from a massive magnetite vein.

The majority of the samples were collected from drill core and an attempt was made to sample homogeneous intervals that were void of: 1) intense fracturing or jointing; 2) pegmatitic lenses; 3) deuteric alteration (uralitization); and 4) strong serpentinization (this was somewhat unavoidable in the picrite-peridotite members; however, the least serpentinized zones were sampled in these cases). The core was split and 5 foot to 10 foot intervals were sampled in most instances, except for strongly serpentinized zones where less that 5 foot long zones were sampled. Large field samples were also collected for geochemical analyses (samples PRT-6 through PRT-46). Weathered portions of the field samples were trimmed off with a diamond saw and all traces of metal from the saw were ground off. Representative thin section samples were also made of all geochemical sample material.

All samples were sent to the NRRI Coleraine Research Laboratory in Coleraine, Minnesota for crushing and pulverizing. The samples were split before the final pulverizing phase and the respective splits were then ground with steel rings and ceramic rings (the latter was analyzed for Ni, Co, Cr, FeO). The steel ring pulverized sample was split and one half was sent to Bondar-Clegg, Inc. (Vancouver) for REE, Pt, Pd, Au, C, Cl, and F analyses. All other analyses were performed by Mr. John Engesser of Coleraine Research Laboratory.

To indicate the accuracy of the results, blind analyses for international geochemical standards (MRG-1, NIM-G, and SY-3) were submitted to Bondar-Clegg. Geochemical standards were run at the Coleraine Lab (Appendix A

V	4	12	14	INCLUDES ONE TRIPLICATE SAMPLE
/	5	18	20	INCLUDES ONE TRIPLICATE SAMPLE
/I	6	11	11	INCLUDES ONE SEMI-MINERALIZED SAMPLE (320-325' 26143)
/II	7	11	11	INCLUDES THREE PERIDOTITES
/III	8	5	5	INCLUDES ONE PERIDOTITE
AG	9	6	6	INCLUDES ONE BLIND UMPIRE (PRT-52)
CCG	10	6	6	INCLUDES ONE BLIND UMPIRE (PRT-51) AND MAGNETITE "VEIN" (PRT 23-7)
PLG	11	7	7	
GC	12	4	4	
OUI	13	13	15	INCLUDES TWO DUNITES, THREE PERIDOTITES, TWO PICRITES, AND EIGHT PYROXENITES (ONE TRIPLICATE SAMPLE). SAMPLES COLLECTED FROM LONGNOSE (5), LONGEAR (2), SECTION 17 (3), AND WYMAN CREEK (3) BODIES
/F	14	6	6	INCLUDES ONE HORNFELS INCLUSION
AGU	15	1	1	(PRT-45)
HB	16	1	1	MOOSE MOUNTAIN HORNFELS
		158	164	

BLIND UMPIRE SAMPLES: PRT-51 = PRT 23-8
PRT-52 = PRT-42
PRT-53 = PRT-43

35 FIELD SAMPLE LOCATIONS (e.g. PRT-#)
120 DRILL CORE SAMPLES (e.g. 320-325' 26042)

TRIPLICATE SAMPLES: SAMPLE NUMBER FOLLOWED BY a AND b

Table 1: Grouping of Geochemical Samples

-3-1 and A-3-2).

The agreement with the recommended values is ±5% for whole rock and ±15% for trace element samples (see Appendix A-3). Precision of whole rock and trace element analyses at Coleraine is based on triplicate analyses of 3 randomly selected samples (see Table 1; Appendix A-1). As a final precision check, three blind umpire samples (large field samples sawn into half) were also included (Appendix A-2). The accuracy of the Te values of this report is somewhat questionable and could not be cross-checked as no accepted values for the standards are available. These analyses are felt to be too high (possibly by a factor of 10); however, relative differences in the Te values between the various rock units may be useful.

<u>Results</u>

Analytical results of all the samples are provided in Appendix B and Appendix C (computer disk in the back pocket) where they are grouped according to rock unit and rock type. Note that on the analytical list, units 1 through 8 correspond to PRTS Units I through VIII. Units 9 through 12 correspond to the PRGC units (AG, CCG, PLG, TGC), and units 13, 14, 15, and 16 correspond to map units OUI, VF, AGU, and HB, respectively. For a cross-reference between map units and analytical list units the reader is referred to Table 1.

Notable high values within the analytical list are (see Tables 2-5): 1) high Zn values (310-1265 ppm) from the Virginia Formation; 2) high chlorine contents associated with the peridotite submembers of the PRTS as well as dunite, peridotite, and picrite of the OUI unit (note that all these rock types commonly exhibit Cl-rich drops which coat the drill core); 3) high F contents associated with the basal unit of the PRTS (specifically the lower half of Unit I) as well as the CCG and PLG units; and 4) elevated Pd+Pt+Au values (>200 ppm) in five samples of "unmineralized" rock collected from the PRTS (note that samples 26042 973-978 ft. and 26143 320-325 ft. were collected from weakly mineralized zones with . 1% sulfide content). Average whole rock analyses are presented in Table 2. Background Pd, Pt, and Au values in most of the rock units average about 10 ppb, 20 ppb and 5 ppb, respectively (see Table 3). Slightly elevated background values for these three elements are associated with Unit II and the OUI units (see Table 3).

Background Values

Average background major and trace element values for unmineralized rocks of the various rock units of the PRI are shown in Tables 2 through 5. Note that because a large number of units and rock types were sampled, each individual unit has a low population density. Therefore, lognormal statistical analysis was not attempted and the reported background values are arithmetic averages. Several generalizations can be made about these values and are briefly discussed below.

Within the PRTS, Units I and II have higher background values for Zn, S, Cu, Pd, Au and TiO_2 relative to all the other PRTS units (Units III through VIII). Slightly higher background values for Cd, P_2O_5, F, and C are also indicated in Units I and II (Note that the values for these elements are notably higher in samples collected from the bottom half of Unit I which has not been averaged as a separate entity in the Tables of this report). High fluorine contents in Unit I are probably related to the high apatite (fluorapatite?) content. Cu:Ni ratios also indicate a difference in Units I and II (generally Cu>Ni, 1:1 to 2:1) relative to Units III through VIII (Cu<Ni, 1:1 to 1:2). The most primitive material (high MG Number) of the PRTS rocks are the peridotite submembers which exhibit Cu:Ni ratios of 1:4 to 1:7. These submembers are "enriched in TFe_2O_3, Cr, Co, Cl, and Pb and "depleted" in Ba and TiO_2 relative to the troctolitic rocks of the PRTS.

Unit II has slightly higher Pd and Au values when compared to the other units, but the Cu, Ni, and S values for Unit II are similar to Unit I. Whereas Unit I contains the most sulfide mineralization, there is only scattered sulfide mineralization in Unit II. These relationships suggest: 1) Unit II may be a source for the anomalous Pd and Au values in the PRI; and 2) that sulfide saturation did not occur in Unit II.

The PRGC units (especially the CCG and PLG units) are very similar to Units I and II in that they have high background values for Zn, P_2O_5, and Cu and they exhibit the same Cu:Ni ratios (Cu>Ni, 1:1 to 2:1). The PRGC units are also similar to Unit I (specifically the lower half) in that they have high fluorine contents which are probably related to the abundant apatite (fluorapatite?) noted in the rocks. The PRGC units have the highest rare-earth content other than Unit I and the Virginia Formation. The Colvin Creek Gabbro (CCG) is the only unit where $Fe^{+3}>Fe^{+}$ (Table 2).

The OUI unit is the most unique in that background values for Sb, Cd, Pb, Zn, Cu, Ni, Cr, Co, V, Pd, Au, S, C, Cl, TFe_2O_3, TiO_2, and Te are much higher that the PRTS and PRGC units. Cu:Ni ratios range from 2:1 to 4:1 for the OUI suite. Unpublished data obtained from Fleck Resources (Vancouver, B.C.) indicate that the OUI body in Section 17 also contains anomalous W values (330-720 ppm) relative to the troctolitic rocks (generally 1-100 ppm).

Overall, some background values for Units I and II are high relative to all the other PRTS units. This in part is probably related to a higher degree of magma contamination due to assimilation of the footwall rocks in these two basal units. Some of the PRGC units also have similar high background values and have similar Cu:Ni

Table 2

AVERAGE UNMINERALIZED WHOLE ROCK COMPOSITIONS

Rock Unit	#	SiO_2	Al_2O_3	TiO_2	TFe_2O_3	Fe_2O_3	FeO	CaO	MgO	MnO	Na_2O	K_2O	P_2O_5	Cr_2O_3	LOI	CO_2	$H2O^+$	S	Total
PRTS																			
Unit I																			
AGT	13	46.33	18.18	2.05	13.87	3.08	9.70	8.98	7.55	0.156	2.73	0.53	0.123	0.03	0.74	0.16	0.73	0.14	101.23
T	2	45.42	19.22	0.86	12.50	2.18	9.29	8.97	8.52	0.140	2.42	0.52	0.055	0.03	1.57	0.24	1.48	0.09	100.19
Unit II																			
AGT	7	46.56	18.25	1.00	13.28	2.86	9.38	8.76	8.68	0.147	2.60	0.49	0.101	0.02	1.17	0.33	1.03	0.15	101.03
T	5	45.69	18.81	1.03	13.50	2.03	10.32	8.69	9.51	0.146	2.74	0.39	0.053	0.05	1.03	0.14	0.60	0.12	101.59
PIC	5	43.79	13.70	1.91	17.16	3.09	12.66	8.37	12.73	0.190	1.90	0.35	0.080	0.03	1.34	0.12	1.08	0.15	101.52
PER	5	37.40	7.02	0.27	23.01	7.52	13.94	3.14	22.32	0.242	0.67	0.17	0.019	0.05	7.57	0.12	6.27	0.07	101.84
Unit III																			
AT	5	47.55	22.61	0.64	8.48	1.84	5.98	10.57	6.62	0.103	2.82	0.43	0.064	0.03	1.05	0.28	0.85	0.08	100.95
TA	4	47.43	22.70	0.59	8.14	2.06	5.47	10.74	6.25	0.093	2.73	0.47	0.069	0.03	1.37	0.27	0.63	0.03	100.58
Unit IV																			
AGT	8	47.05	20.65	0.96	10.96	2.04	8.03	9.95	7.55	0.131	2.73	0.43	0.061	0.04	0.96	0.20	0.99	0.07	101.43
T	3	47.20	22.44	0.70	8.59	3.33	4.74	10.73	6.30	0.105	2.86	0.42	0.074	0.02	0.96	0.13	0.96	0.09	100.08
Unit V																			
T	4	47.55	21.20	1.00	10.71	1.80	8.02	9.77	7.18	0.121	2.81	0.46	0.064	0.04	0.37	0.10	0.62	0.22	101.23
AT	11	47.25	22.00	0.60	9.50	1.66	7.06	10.27	7.24	0.111	2.69	0.41	0.059	0.03	1.08	0.16	0.98	0.07	101.21
TA	2	47.58	21.62	0.63	9.78	1.65	7.32	10.18	6.60	0.112	2.98	0.38	0.062	0.02	0.90	0.17	0.95	0.07	100.83
Unit VI																			
AT	5	47.78	22.30	0.49	8.85	1.58	6.54	9.97	7.33	0.107	2.72	0.36	0.039	0.03	1.31	0.24	1.13	0.06	101.27
T	3	46.46	21.02	0.60	10.67	1.73	8.04	9.60	8.60	0.123	2.63	0.43	0.040	0.03	0.99	0.13	0.84	0.07	101.16
TA	2	48.09	22.18	1.09	9.19	2.03	6.45	10.54	5.81	0.108	2.65	0.50	0.129	0.02	0.61	0.05	0.57	0.03	100.89
Unit VII																			
AGT	7	45.57	20.60	1.19	11.90	2.33	8.62	10.25	7.83	0.136	2.44	0.33	0.037	0.04	1.12	0.32	0.93	0.08	101.39
PER	3	36.94	7.83	0.27	18.82	8.62	9.18	2.64	22.32	0.211	0.60	0.19	0.026	0.13	11.07	0.67	7.98	0.11	100.91
Unit VIII																			
AT	3	47.46	21.21	0.96	10.94	1.94	8.10	9.88	6.86	0.121	2.64	0.50	0.102	0.01	0.65	0.09	0.58	0.02	101.33
PRGC																			
Unit IX																			
AG	4	47.90	21.61	2.13	9.92	2.94	6.28	10.83	4.51	0.113	2.87	0.47	0.104	0.02	0.58	0.10	0.70	0.03	101.04
CCG																			
G	4	42.91	15.53	4.35	18.44	11.38	6.35	10.78	5.65	0.251	2.57	0.15	0.316	0.01	0.34	0.09	0.22	0.02	101.29
PLG																			
OG	6	44.42	16.84	3.06	16.66	6.63	9.03	10.07	5.91	0.196	2.45	0.44	0.371	0.04	0.36	0.17	0.51	0.06	100.77
TGC																			
AGT	4	46.48	18.60	1.84	13.53	2.86	9.61	9.61	7.58	0.154	2.46	0.53	0.217	0.02	0.41	0.08	0.43	0.03	101.40
OUI																			
Unit XIII																			
DUN	2	18.26	1.20	20.04	41.96	11.81	27.14	0.68	14.88	0.328	0.08	0.10	0.016	0.19	4.44	0.21	3.20	0.20	101.99
PER	3	27.01	1.72	12.25	35.60	8.84	24.99	4.29	16.03	0.353	0.17	0.23	0.121	0.14	3.10	0.45	2.62	0.50	101.87
PIC	2	32.97	5.67	9.29	29.55	8.57	18.88	5.53	14.05	0.313	0.62	0.32	0.020	0.09	3.37	0.33	2.92	0.34	101.69
PY	6	35.57	3.02	10.49	27.44	13.82	12.26	10.88	12.11	0.282	0.28	0.24	0.086	0.04	1.29	0.48	0.94	0.22	101.48
VA FM																			
Unit XIV	6	56.81	16.09	0.68	11.19	1.73	8.52	0.78	2.90	0.041	1.70	3.54	0.110	0.02	6.41	0.80	2.97	3.42	100.25

Note: # denotes number of samples in averages. Averages only shown for rock types with 2 or more samples. All values are in wt. %. Fe_2O_3 is calculated. Totals calculated using TFe_2O_3 and LOI instead of Fe_2O_3, FeO, Co_2, $H2O^+$, S, and Cr_2O_3. AGT = Augite Troctolite, T = Troctolite, A = Anorthosite, G = Gabbro, PER = Peridotite, Py = Pyroxenite, DUN = Dunite, PIC = Picrite, AT = Anorthositic Troctolite, OG = Olivine Gabbro, etc.

Table 3

AVERAGE BASE METAL, CL, F, FERROUS AND PRECIOUS METAL BACKGROUND VALUES

Rock Unit	#	Cu	Ni	Cr	Co	V	Pt	Pd	Au	Mo	Sc	Se	Cl	F	
PRTS															
Unit I															
AGT	13	463	232	180	82	173	16	6	3	<1.5	17.3	<1.6	<200	147	
T	2	215	257	203	71	91	<15	<2	2	<1.5	9.0	<1.6	<200	73	Unit II
AGT	7	545	292	167	74	111	24	16	9	<1.5	13.0	<1.6	<200	128	
T	5	409	310	313	79	101	23	9	4	<1.5	8.7	<1.6	137	53	
PIC	5	855	497	196	111	223	23	16	8	<1.5	23.3	<1.6	113	98	
PER	5	180	955	341	139	51	25	19	5	<1.5	9.4	<1.6	1521	17	
Unit III															
AT	5	120	211	203	52	77	32	5	2	<1.5	9.4	<1.6	<200	89	
TA	4	72	187	198	43	62	21	4	2	1.4	8.0	<1.6	<200	71	
Unit IV															
AGT	8	137	229	262	60	111	24	17	3	<1.5	12.0	<1.6	<200	65	
T	3	136	202	131	50	63	22	7	3	<1.5	8.5	<1.6	<200	73	
Unit V															
T	4	78	192	287	58	93	21	2	1	<1.5	9.2	<1.6	<200	75	
AT	11	119	228	222	54	71	25	4	4	<1.5	8.5	<1.6	<200	56	
TA	2	112	197	145	52	68	14	2	4	<1.5	8.3	<1.6	<200	78	
Unit VI															
AT	5	102	224	222	53	57	22	7	3	<1.5	6.7	<1.6	<200	42	
T	3	144	285	199	58	72	17	5	2	<1.5	8.2	<1.6	<200	50	
TA	2	119	155	131	47	77	20	4	2	1.6	10.5	<1.6	<200	140	
Unit VII															
AGT	7	197	258	245	64	146	22	5	3	<1.5	13.6	<1.6	<200	53	
PER	3	15	854	901	113	67	20	<2	2	<1.5	7.7	<1.6	1180	52	
Unit VIII															
AT	3	113	232	78	58	68	17	<2	2	<1.5	9.3	<1.6	<50	117	
PRGC															
Unit IX															
AG	4	190	122	125	56	167	20	2	3	<1.5	17.7	<1.6	<50	123	
CCG															
G	4	243	63	99	95	432	15	12	6	<1.5	41.6	1.3	<200	333	
PLG															
OG	6	281	212	280	89	254	15	2	5	<1.5	27.9	<1.6	<200	317	
TGC															
AGT	4	149	246	110	79	138	14	<2	2	<1.5	16.7	<1.6	<200	169	
OUI															
Unit XIII															
DUN	2	1652	595	1297	317	1075	25	25	37	<1.5	39.4	<1.6	360	40	
PER	3	1392	647	939	262	682	28	14	8	<1.5	45.4	<1.6	900	67	
PIC	2	1827	445	586	206	627	23	10	19	<1.5	41.0	<1.6	113	58	
PY	6	529	284	298	292	997	19	12	5	<1.5	82.9	<1.6	<200	101	
VA FM															
Unit XIV	6	172	158	167	32	179	18	3	5	22.1	21.9	2.9	<200	483	

Note: # denotes the number of samples in averages. Au, Pt, Pd in ppb; remainder in ppm.

Table 4

AVERAGE TRACE ELEMENT AND BASE METAL (Con't) BACKGROUND VALUES

Rock Unit	#	Sb	As	Ba	Bi	Cd	Pb	Sn	Te	Zn	Be	Li	Rb	Sr	Y	Zr	C
PRTS																	
Unit I																	
AGT	13	7.1	1.9	145	4.2	19.0	<1	1.1	42.5	106	1.3	15.9	36.0	267.0	11.3	43.7	0.05
T	2	11.1	<3	104	3.8	14.7	<1	2.6	21.9	53	1.1	9.8	<50	277.8	5.3	24.5	0.09
Unit II																	
AGT	7	6.3	<3	126	1.7	20.1	<1	1.9	32.9	101	1.1	11.4	<50	270.5	8.7	34.9	0.08
T	5	6.8	4.1	837	4.7	20.2	<1	1.6	16.3	556	0.9	10.0	<50	279.1	4.6	29.6	0.06
PIC	5	<4	<3	107	0.9	27.3	<1	2.3	30.2	122	1.2	9.8	46.9	214.2	8.3	43.2	0.06
PER	5	<4	<3	55	4.3	38.8	1.8	1.7	24.7	141	1.2	7.0	<50	72.9	2.1	15.4	0.07
Unit III																	
AT	5	6.2	<3	115	2.7	8.5	<1	1.7	8.3	74	0.8	9.1	<50	321.7	5.4	24.8	0.04
TA	4	10.4	4.1	118	1.3	11.5	<1	<1	6.0	65	0.7	12.8	<50	299.4	6.3	45.4	0.08
Unit IV																	
AGT	8	4.1	<3	113	1.9	13.1	<1	1.5	23.9	79	0.9	10.1	<50	286.2	6.0	26.0	0.04
T	3	<4	<3	116	5.9	9.5	<1	<1	10.8	68	0.8	11.0	<50	288.6	6.1	29.2	0.04
Unit V																	
T	4	2.7	<3	110	4.9	13.5	<1	<1	22.4	57	0.9	8.2	<50	291.0	5.8	28.0	0.03
AT	11	<4	<3	106	4.3	11.5	<1	2.1	10.7	66	0.8	10.1	<50	299.5	4.8	29.3	0.04
TA	2	9.8	<3	106	4.5	12.2	<1	3.7	2.4	71	0.8	9.4	<50	299.9	5.4	27.6	0.05
Unit VI																	
AT	5	<4	<3	97	2.9	8.9	<1	4.6	10.2	75	0.7	8.3	<50	298.0	2.6	14.6	0.05
T	3	6.4	<3	95	1.1	9.1	<1	<1	19.0	57	0.9	7.6	<50	292.0	3.3	14.1	0.03
TA	2	8.7	<3	122	4.8	13.4	<1	<1	31.8	62	1.0	6.8	49.8	269.9	8.3	40.5	0.05
Unit VII																	
AGT	7	<4	<3	85	<0.7	14.6	<1	11.9	40.1	95	1.0	7.3	<50	300.1	3.3	19.4	0.05
PER	3	5.6	<3	22	8.6	26.3	2.6	3.7	44.6	103	1.1	34.2	<50	87.9	1.3	10.7	0.08
Unit VIII																	
AT	3	<4	<3	122	3.8	16.3	<1	<1	21.5	80	0.8	7.5	<50	324.4	7.3	36.3	0.04
PRGC																	
Unit IX																	
AG	4	<4	<3	129	3.0	14.9	<1	1.3	36.5	76	0.9	7.8	<50	316.7	8.8	40.0	0.04
CCG																	
G	4	9.4	2.1	120	2.3	30.6	<1	<1	110.3	149	1.4	3.9	<50	310.0	23.8	68.2	0.04
PLG																	
OG	6	<4	<3	155	4.8	29.0	<1	<1	61.9	154	1.3	7.7	<50	269.6	24.8	74.5	0.03
TGC																	
AGT	4	<4	6.2	154	3.1	22.9	<1	1.3	38.4	110	1.0	9.0	<50	287.1	14.0	56.8	0.02
OUI																	
Unit XIII																	
DUN	2	11.8	<3	7	<0.7	43.4	16.3	<1	556.1	204	2.3	2.6	<50	8.7	1.0	83.8	0.12
PER	3	49.2	<3	16	<0.7	53.0	15.5	<1	362.7	171	2.2	8.1	<50	20.5	7.6	63.2	0.10
PIC	2	42.8	4.7	31	7.4	45.0	11.8	<1	223.0	121	1.8	8.8	<50	73.6	8.6	72.5	0.08
PY	6	35.3	<3	25	4.2	43.1	11.3	<1	300.7	135	1.6	6.8	<50	25.2	14.1	78.1	0.07
VA FM																	
Unit XIV	6	9.8	47.6	686	<0.7	20.4	20.0	4.2	15.5	713	2.0	59.6	61.5	119.8	12.8	129.9	1.70

Note: # denotes the number of samples in averages. All samples in ppm, C which is in wt. %.

Table 5

AVERAGE RARE EARTH ELEMENTS, U, and Th BACKGROUND VALUES

Rock Unit	#	Ce	Dy	Er	Eu	Gd	Ho	La	Lu	Nd	Pr	Sm	Tb	Th	Tm	U	Yb
PRTS																	
Unit I																	
AGT	13	21	2.7	<100	1.6	<200	<1	10.1	0.2	12	<50	2.8	<1	1.0	<2	<1	1.4
T	2	10	<1	<100	1.0	<200	<1	5.6	0.1	<10	<50	1.5	<1	<0.5	<2	<1	<0.5
Unit II																	
AGT	7	16	1.7	<100	1.4	<200	<1	7.9	0.1	9.3	<50	2.2	<1	0.8	<2	<1	1.0
T	5	9	0.9	<100	0.9	<200	<1	4.5	0.1	<10	<50	1.2	<1	<0.5	<2	<1	0.6
PIC	5	10	1.0	<100	1.2	<200	<1	5.3	<0.1	<10	<50	1.9	<1	<0.5	<2	<1	0.9
PER	5	<5	<1	<100	<1	<200	<1	1.2	<0.1	<10	<50	0.3	<1	<0.5	<2	<1	<0.5
Unit III																	
AT	5	11	1.1	<100	<1	<200	<1	5.5	<0.1	<10	<50	1.3	<1	<0.5	<2	<1	0.6
TA	4	12	1.5	<100	<1	<200	<1	5.9	<0.1	<10	<50	1.5	<1	0.5	<2	<1	0.7
Unit IV																	
AGT	8	11	1.3	<100	0.8	<200	<1	5.2	0.1	<10	<50	1.5	<1	<0.5	<2	<1	0.7
T	3	12	1.3	<100	0.8	<200	<1	6.3	<0.1	<10	<50	1.6	<1	0.6	<2	<1	0.7
Unit V																	
T	4	13	1.6	<100	1.1	<200	<1	6.0	0.1	<10	<50	1.6	<1	0.5	<2	<1	0.7
AT	11	10	<1	<100	0.8	<200	<1	4.8	<0.1	<10	<50	1.3	<1	<0.5	<2	<1	0.5
TA	2	11	1.0	<100	1.0	<200	<1	5.1	<0.1	<10	<50	1.4	<1	<0.5	<2	<1	0.7
Unit VI																	
AT	5	6	<1	<100	<1	<200	<1	3.4	<0.1	<10	<50	0.8	<1	<0.5	<2	<1	<0.5
T	3	6	<1	<100	<1	<200	<1	3.5	<0.1	<10	<50	0.9	<1	<0.5	<2	<1	<0.5
TA	2	19	2.0	<100	1.0	<200	<1	8.5	0.2	10	<50	2.4	<1	1.0	<2	<1	1.2
Unit VII																	
AGT	7	5	<1	<100	<1	<200	<1	3.0	<0.1	<10	<50	0.9	<1	<0.5	<2	<1	<0.5
PER	3	<5	<1	<100	<1	<200	<1	1.4	<0.1	<10	<50	0.3	<1	<0.5	<2	<1	<0.5
Unit VIII																	
AT	3	15	1.5	<100	1.0	<200	<1	7.4	0.1	10	<50	1.9	<1	<0.5	<2	<1	0.8
PRGC																	
Unit IX																	
AG	4	16	2.1	<100	1.8	<200	<1	7.6	0.2	10	<50	2.3	<1	<0.5	<2	<1	1.1
CCG																	
G	4	30	5.3	<100	2.3	<200	1.0	11.9	0.3	23	<50	6.1	0.8	<0.5	<2	<1	2.4
PLG																	
OG	6	40	5.7	<100	2.5	<200	1.2	18.0	0.4	26	<50	6.2	<1	<0.5	<2	<1	2.7
TGC																	
AGT	4	25	3.3	<100	1.5	<200	<1	12.2	0.2	17	<50	3.6	<1	0.6	<2	<1	1.6
OUI																	
Unit XIII																	
DUN	2	<5	<1	<100	<1	<200	<1	1.0	0.1	<10	<50	0.4	<1	<0.5	<2	<1	0.4
PER	3	9	1.8	<100	<1	<200	<1	3.3	0.2	<10	<50	1.8	<1	<0.5	<2	<1	1.0
PIC	2	6	1.5	<100	<1	<200	<1	2.8	0.2	<10	<50	1.6	<1	<0.5	<2	<1	1.1
PY	6	12	3.2	<100	<1	<200	<1	3.9	0.3	8	<50	3.1	<1	<0.5	<2	<1	1.7
VA FM																	
Unit XIV	6	71	5.3	<100	1.8	<200	1.4	36.3	0.4	35	<50	6.5	<1	9.3	<2	15	3.1

Note: # denotes the number of samples in averages. All samples in ppm.

ratios when compared to Units I and II. The similarity between the PRGC and Units I and II suggests that the PRGC units may have also been contaminated by assimilation of footwall rocks. This is in accord with Chandler and Ferderer's (in press) concept that the PRGC (referred to as Railroad Troctolite) originated near the floor of the PRI and was then delaminated and elevated to its present position.

Spider Diagrams

Plots of chondrite normalized incompatible elements for each of the PRTS, PRGC, and OUI units are illustrated on the spider diagrams (Figs. 10 to 15). 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). However, no YB normalization was performed. Several of the samples had no available Yb values (below detection limit) and thus a "Yb correction" was used in plotting the tail end of these samples. This was accomplished by determining the slope between Y and Yb in samples which contained Yb values for an igneous unit, and then applying this slope to obtain an approximate Yb value for the remaining samples of the particular igneous unit that lacked Yb. For each spider diagram, all individual samples that were collected from a particular igneous unit were originally plotted but only the collective area, or field, of the samples are shown in the diagrams of this report. The spider diagram fields for each of the major rock groups (PRTS, PRGC, OUI) exhibit different lithogeochemical "fingerprints".

PRTS All of the troctolitic units of the PRTS, excluding the peridotite submembers, are shown in the spider diagrams of Figure 10. With the exception of the lower half of Unit **I** (to be discussed later), the fields for all the other PRTS units

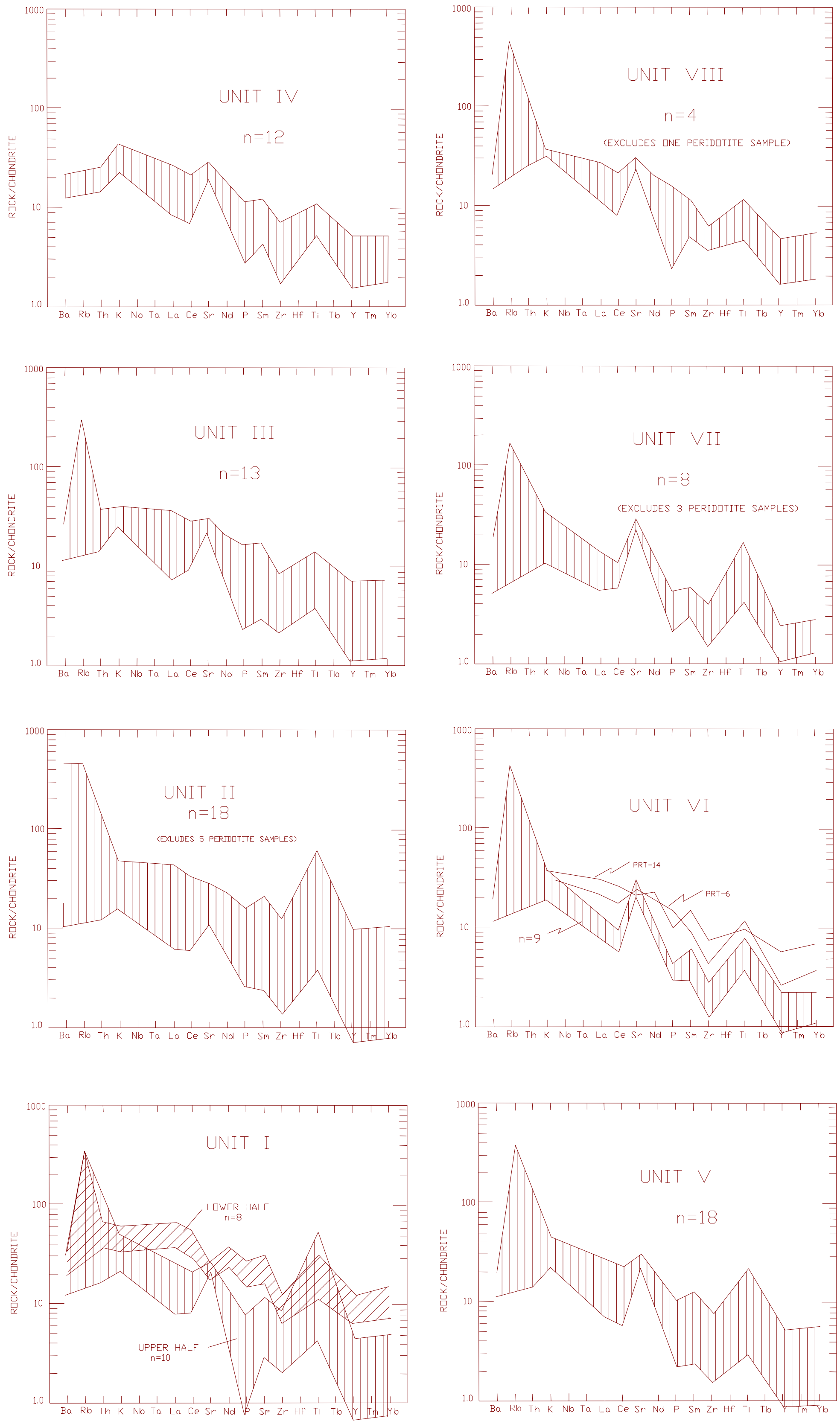


Figure 10: Spider diagrams of PRTS Units I through VIII.

exhibit similar patterns and slopes with only minor fluctuations for a particular element e.g., Rb and Ti. Due to this similarity, there is no distinct lithogeochemical signature that can be used to "fingerprint" any of the internal igneous units of the PRTS, but the diagrams support a common origin. Notable differences on the spider diagrams of the PRTS units include: 1) the field for Unit II is much broader; 2) Rb values are notably lower for Unit IV; and 3) the fields for both Units VI and VII are much tighter than the other PRTS units due to generally lower values for La, Ce, P, and Sm. Figure 10, illustrates two additional individual samples for the Unit VI. These are outcrop samples and are shown separately because they were originally and erroneously(?) grouped with Unit VI when the geochemical data base was compiled. However, later review of the drill hole correlation of Plate II indicated that Unit VI pinched-out at, or north of, the Longnose Fe-Ti body. Since the two outcrop samples are located south of Longnose they should probably have been included with the Unit V samples. A Unit V "fingerprint" is indicated by the similar pattern and slope of these two samples in the spider diagram.

Two distinctly different patterns are present on the spider diagram for Unit 1. A check of the stratigraphic position of these samples indicates that one group was collected from the bottom half of Unit I, which are augite troctolites below a variably persistent picritic horizon (see Plate II). Though the rocks of the upper and lower half of Unit I are texturally the same and can not be categorized as different units during logging, the spider diagram (Fig.10) shows the upper and lower halves of Unit I to be chemically distinct. In fact, the lower half of Unit I exhibits an entirely different "fingerprint" that is distinctly different from all the other PRTS units. The difference in pattern is due to higher values of La, Ce, Nd, P, and Sm (as well as lesser "enrichments" in Ti, Zr, Y, and Yb; see Tables 4 and 5) relative to all the other PRTS units. Because of increased amounts of these elements, the lower half of Unit I plots higher on the spider diagram area and exhibits a negative Sr anomaly "fingerprint", whereas all the other PRTS units exhibit a positive Sr anomaly. As the lower half of Unit I is volumetrically in contact with the most footwall material (basal contact and inclusions), this different "fingerprint" is probably related to magma contamination due to assimilation of the Virginia Formation (see Tables 4 and 5 and Fig 15). The "fingerprint" for the lower half of Unit I is situated midway between the Virginia Formation and the other PRTS units suggesting that assimilation of footwall was important in the genesis of the lower half.

Outcrops of augite troctolite located in Section 34, T.58 N., R.14 W. were previously mapped as "troctolite undivided" (Morey and Cooper, 1977). A spider diagram of sample PRT-43 (and its umpire PRT-53) collected from this outcrop area is shown on Figure 11. The signature of this sample is very similar to the "fingerprint" for the lower half of Unit I.

The "fingerprint" of the peridotitic submembers of the PRTS (sampled from Units II, VII and VIII) are shown separately on Figure 12. They display the same general pattern as the PRTS units (excluding the lower half of Unit I), except that they are "depleted" in the plotted elements due to their more primitive nature.

Overall, the spider diagrams do not distinguish differences between the troctolitic units of the PRTS except for the lower half of Unit I. However, as a group, the PRTS units collectively have a "fingerprint" that is different from the PRGC and OUI units.

PRGC "Fingerprints" for the units of the Partridge River Gabbro Complex (PRGC) are shown in Figure 13. A striking similarity to the "fingerprint" of the lower half of Unit **I** is readily apparent in the Colvin Creek "Gabbro" and Powerline Gabbro.

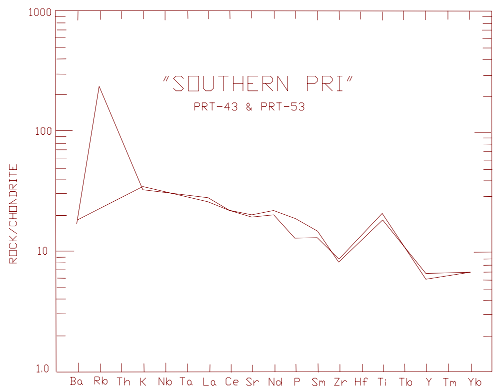


Figure 11: Spider diagram of "troctolite undivided" (south of PRI confines).

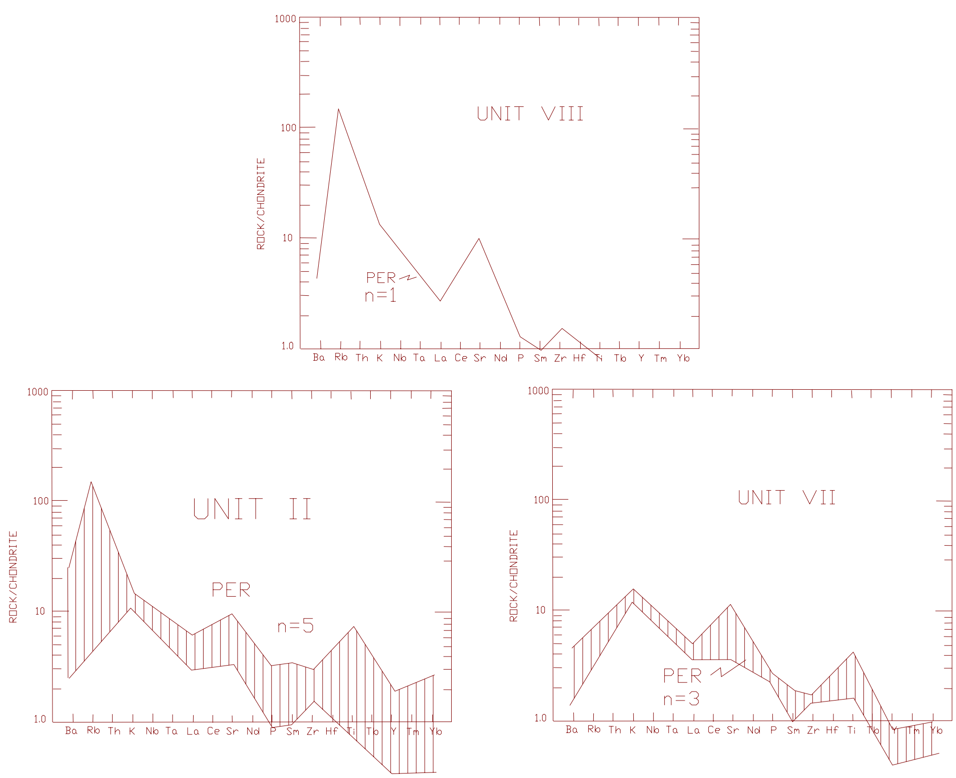


Figure 12: Spider diagrams of peridotite submembers in Units II, VII and VIII.

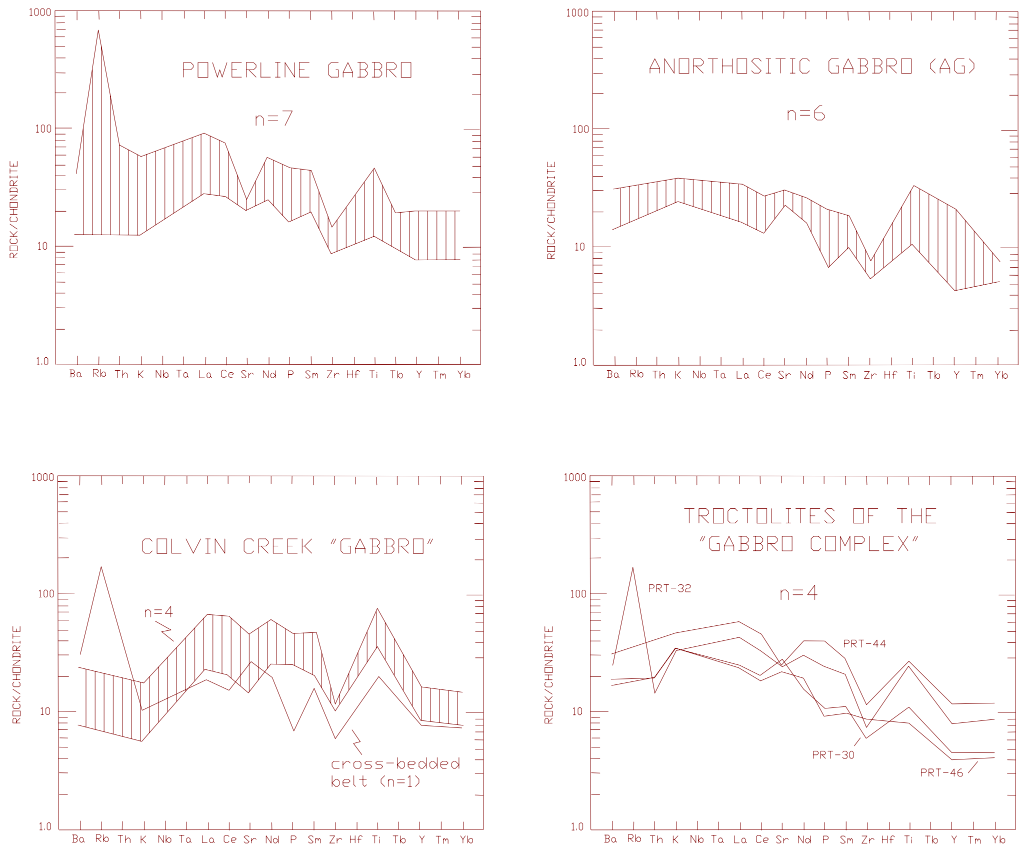


Figure 13: Spider diagrams of the PRGC units.

Both exhibit the same overall "enrichment" in incompatibles and the negative Sr anomaly that are characteristic of the lower half of Unit I. The Colvin Creek "Gabbro"(CCG) and Powerline Gabbro(PLG) "fingerprints" are generally the same, except for differences in the Rb, Th, and K portions. This difference, however, may be related to geographical location and/or magma evolution and not to rock type. For example, sample PRT 23-7 (and its umpire PRT-51) is a coarse-grained gabbro that is remarkably similar to the Powerline Gabbro, but since the sample is located in the northern Colvin Creek body, it is categorized as CCG. The spider diagrams of this sample are the same as the fine-grained granular material (MCC) that was also sampled from the Colvin Creek body. Likewise, three samples of fine-grained material (similar to MCC) were collected from the PLG, and these show no pattern difference when compared to coarse-grained gabbroic rocks also collected from the PLG. Thus in both instances, the fine-grained material collected from either the CCG or PLG have the same "fingerprints" as their coarse-grained counterparts. The similarity in "fingerprints" for the fine-grained and coarse-grained material of both the CCG and PLG suggests that the fine-grained granular material is related to the gabbroic rocks and is not a hornfelsed basalt as previously believed. For comparison, spider diagrams of the North Shore Volcanic Group (data from Green, 1986) are shown in Figure 15.

As discussed previously, some outcrop evidence has been found that indicates that the Troctolitic Rocks of the Gabbro Complex (TGC) are both syn- and post- CCG-PLG and thus at least two different age relationships may be present. Two different spider patterns are also present within the TGC (Fig. 13). Samples PRT-32 and PRT-44 exhibit the same "fingerprint" as the CCG, PLG, and lower half of Unit I. Samples PRT-46 and PRT-30 exhibit a "fingerprint" that is typical for the PRTS units (excluding

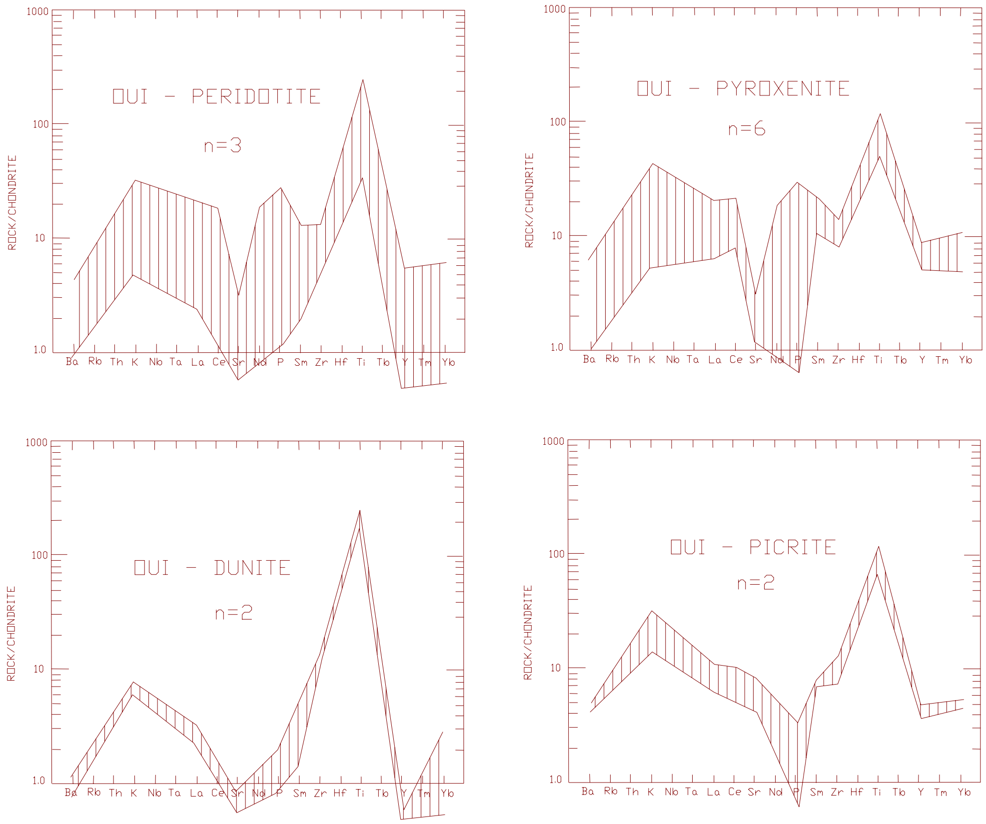


Figure 14: Spider diagrams of the Oxide Ultramafic Intrusives (OUI).

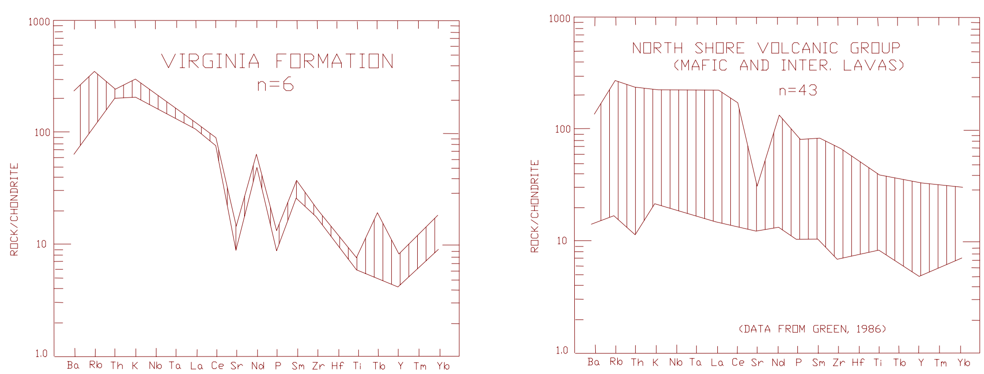


Figure 15: Spider diagrams of Virginia Formation and North Shore Volcanic Group.

the lower half of Unit I). Therefore, PRT-44 and 32 may be syn-CCG-PLG and samples PRT-46 and 30 may be correlative with later troctolites (PRTS?). The later troctolites may have delaminated, metamorphosed, and elevated the earlier PRGC units, e.g., CCG, PLG, portions of the TGC, to their present elevation as envisioned by Chandler and Ferderer (in press).

The geochemical "fingerprint" for the Anorthositic Gabbro (AG) of the PRGC is shown in Figure 13. This unit's signature is intermediate between the "fingerprints" for the CCG-PLG units and the PRTS units.

In summary, the CCG, PLG, and portions of the TGC all have the same "fingerprint" in the spider diagrams and are, therefore, related to the same intrusive event. This "fingerprint" is also the same as the one exhibited by the lower half of Unit I that has been contaminated via assimilation of the footwall rocks. This implies that the PRGC may have also been near the basal contact and has since been delaminated and elevated to its present position. If this hypothesis is correct, then the PRGC may have Cu-Ni-precious metal sulfide potential similar to the lower half of Unit I.

OUI Spider diagrams of the four major rock types with the Oxide-bearing Ultramafic Intrusions (OUI) are shown in Figure 18. All rock types exhibit the same general "fingerprint" that is vastly different from the PRTS and PRGC "fingerprints". They all show an extremely positive Ti anomaly and negative Sr anomaly. They are chemically different than the ultramafic horizons (peridotite) within, or at the base of, Units II, VII and VIII (Fig. 12).

X-Y Scatter Plots

X-Y scatter plots of MgO versus various whole rock values are presented in Figures 16 through 31. All sample points within each individual igneous unit were originally plotted using IGPET II (Carr, 1987) that normalized the major oxides to 100% on a water-free basis; trace element values were not normalized by the same factor. The X-Y plots were simplified by showing only the respective fields in which the igneous unit sample points are contained - the number of sample points within these fields are indicated on each diagram. Additional plots of MG Number vs AL_2O_3, Y vs Zr, P_2O_5 vs F, Ni vs Zr, are illustrated in Figures 28, 29, 30, and 31. In most cases, distinct fields (with varying degrees of overlap) for the various rock units are apparent. Some of the fields are based on a high amount of sample points, whereas others are based on a very limited amount of samples and thus are less clearly defined at this time. Because the Colvin Creek bodies (and similar fine-grained portions of the Powerline Gabbro) have been previously classed as hornfelsed basalt (Bonnichsen, 1972; Tyson, 1976), data on the mafic to intermediate lavas of the North Shore Volcanic Group (Green, 1986) are included for comparison. One sample of the Moose Mountain Hornfels (basaltic hornfels) is also plotted for comparison. Six samples of the footwall Virginia Formation, collected near the footwall contact or from inclusions within the PRI (one sample) are also included in some of the plots.

PRTS The PRTS units fall into three distinct fields in many of the X-Y plots. The fields represented are for: 1) Units I and II that have the highest degree of variability, but in general clustered together; 2) Units III through VIII that clustered together in a much tighter field; and 3) the peridotite submembers of all the PRTS units (collected from Units II, VII, and VIII) that plot in a separate more primitive field (higher MgO content). A differentiation trend is suggested by the linearity between the primitive ultramafic submembers and the more evolved troctolitic rocks. However, a gap exists between the troctolites and peridotites. At present, this gap may be the

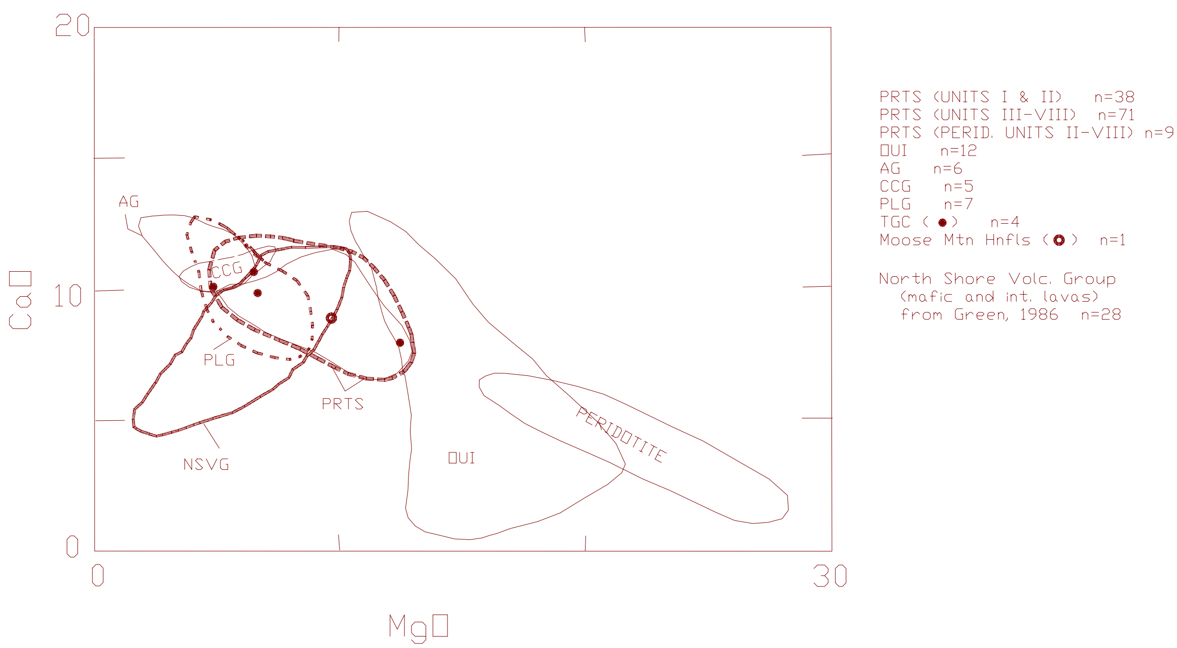


Figure 16: MgO versus CaO, Partridge River Intrusion.

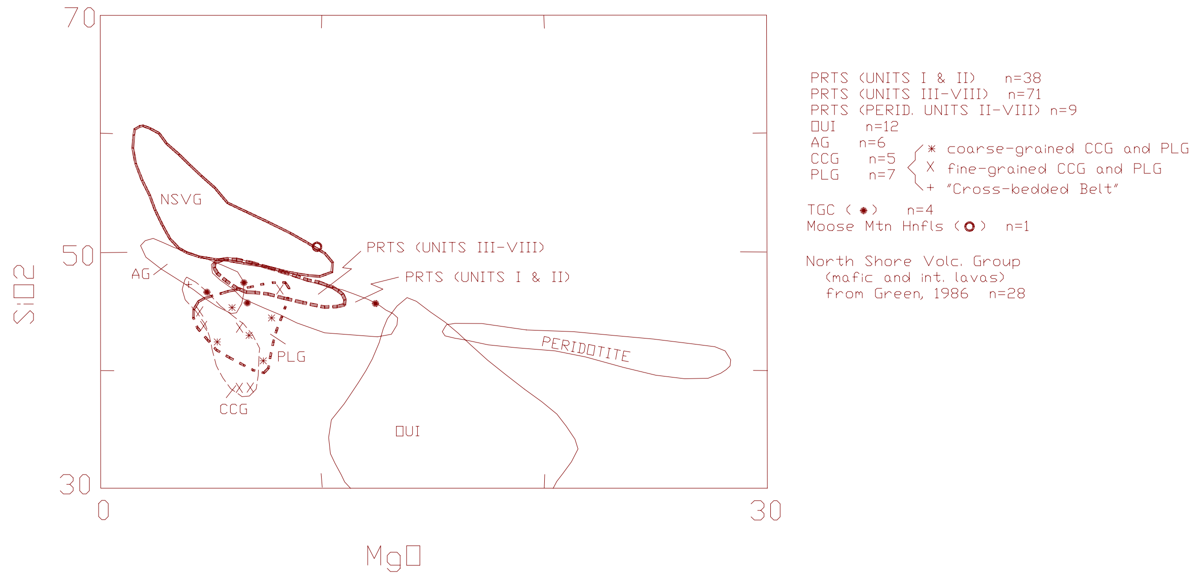


Figure 17: MgO versus SiO_2, Partridge River Intrusion.

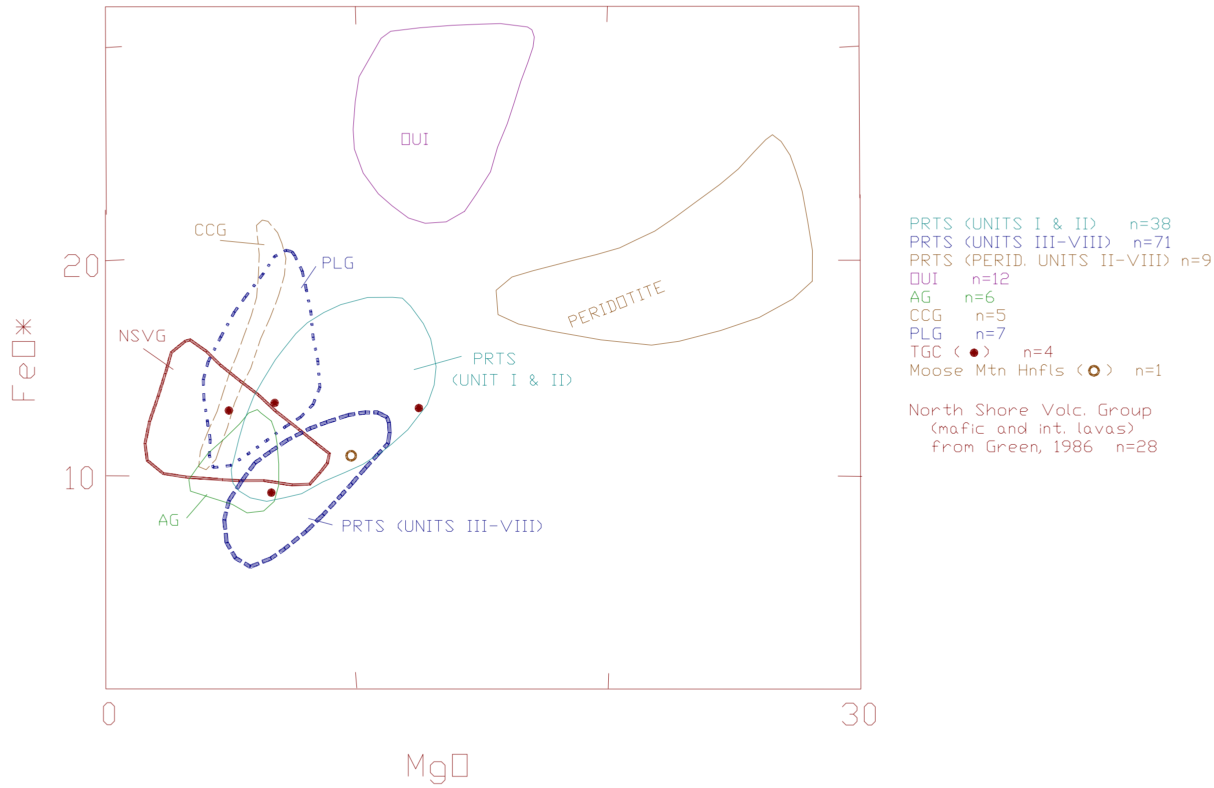


Figure 18: MgO versus FeO*, Partridge River Intrusion.
($FeO^* = FeO + 0.8998\ Fe_2O_3$)

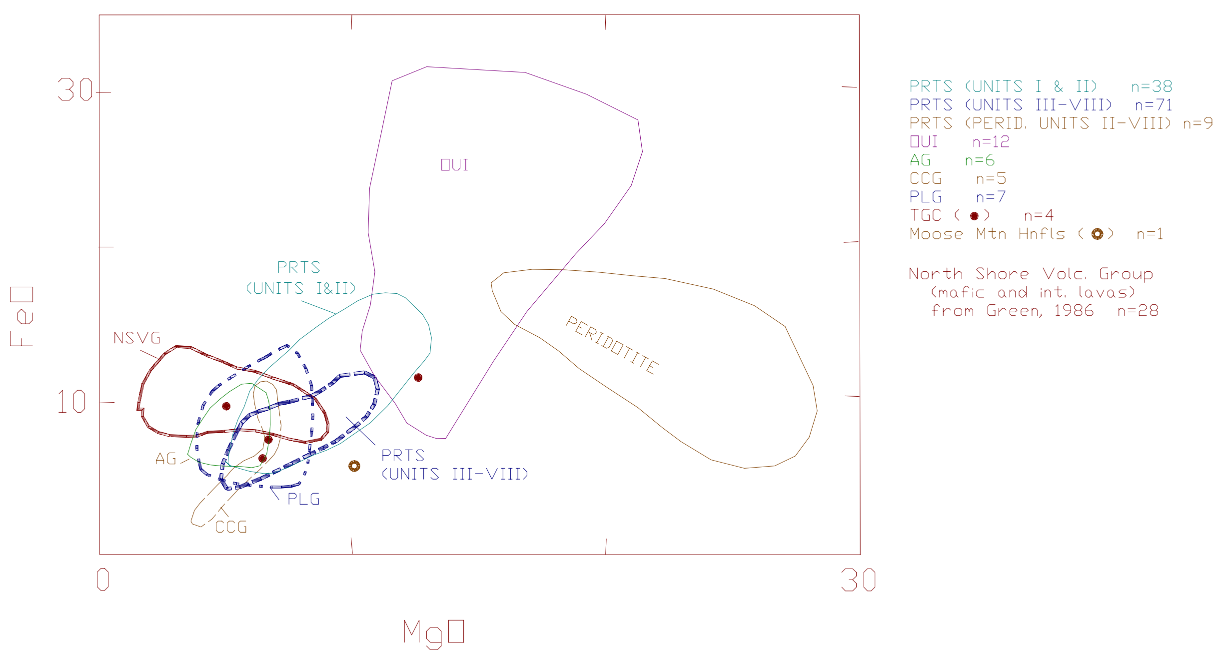


Figure 19: MgO versus FeO, Partridge River Intrusion.

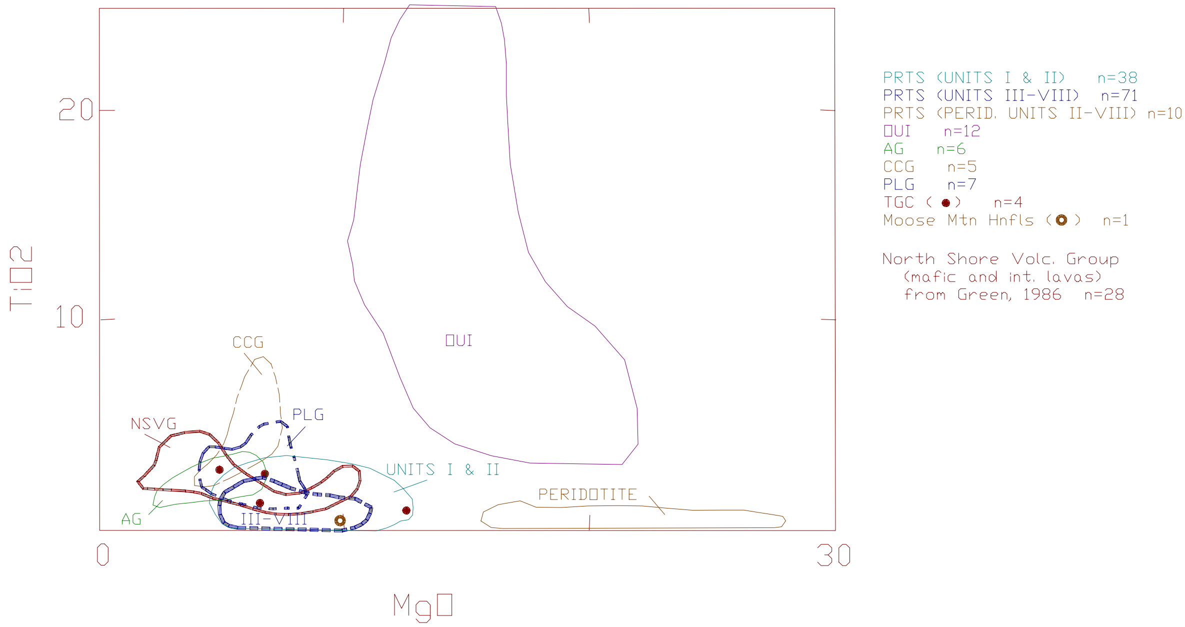


Figure 20: MgO versus TiO_2, Partridge River Intrusion.

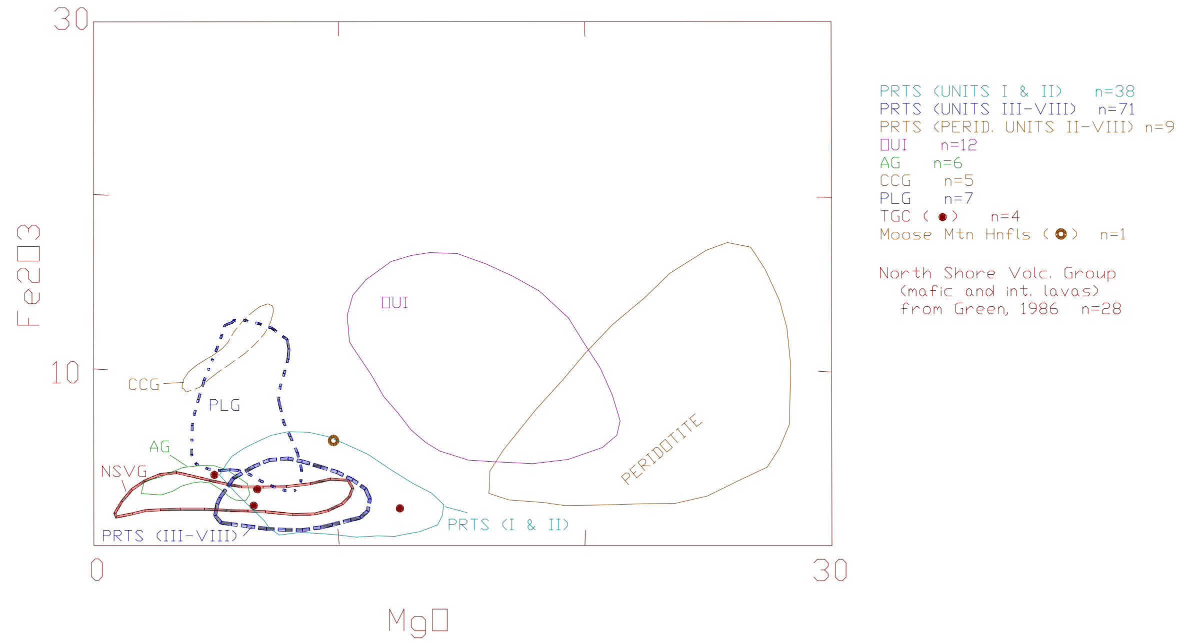


Figure 21: MgO versus Fe_2O_3, Partridge River Intrusion.

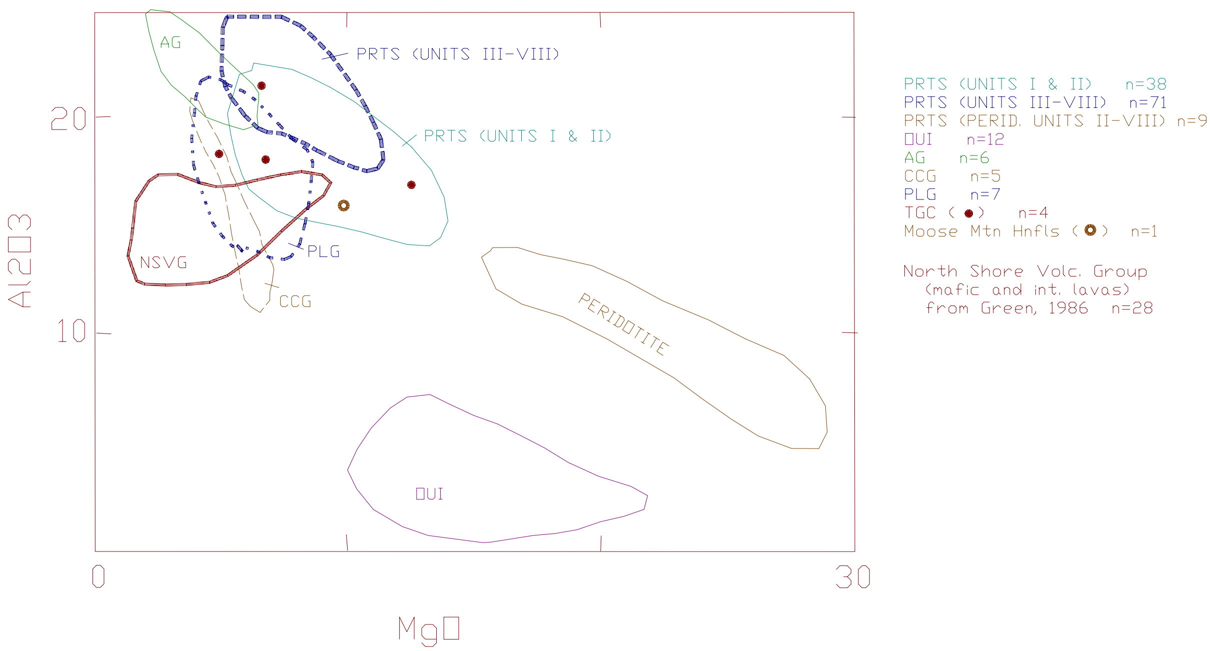


Figure 22: MgO versus Al_2O_3, Partridge River Intrusion.

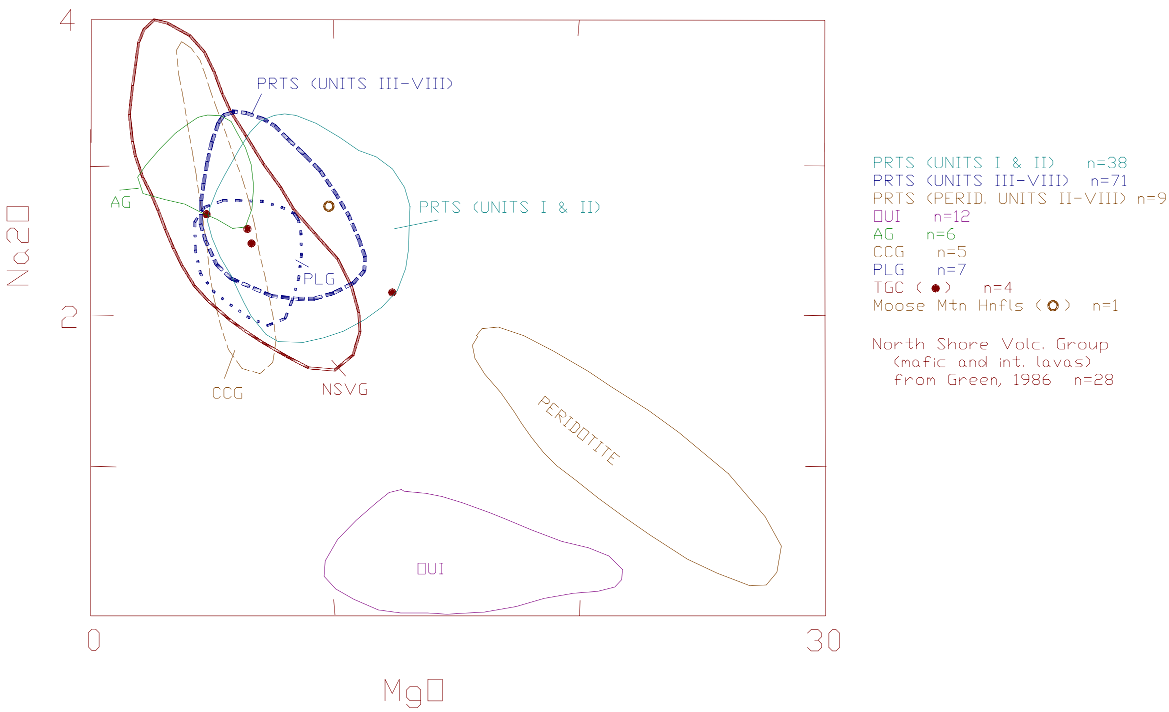


Figure 23: MgO versus Na_2O, Partridge River Intrusion.

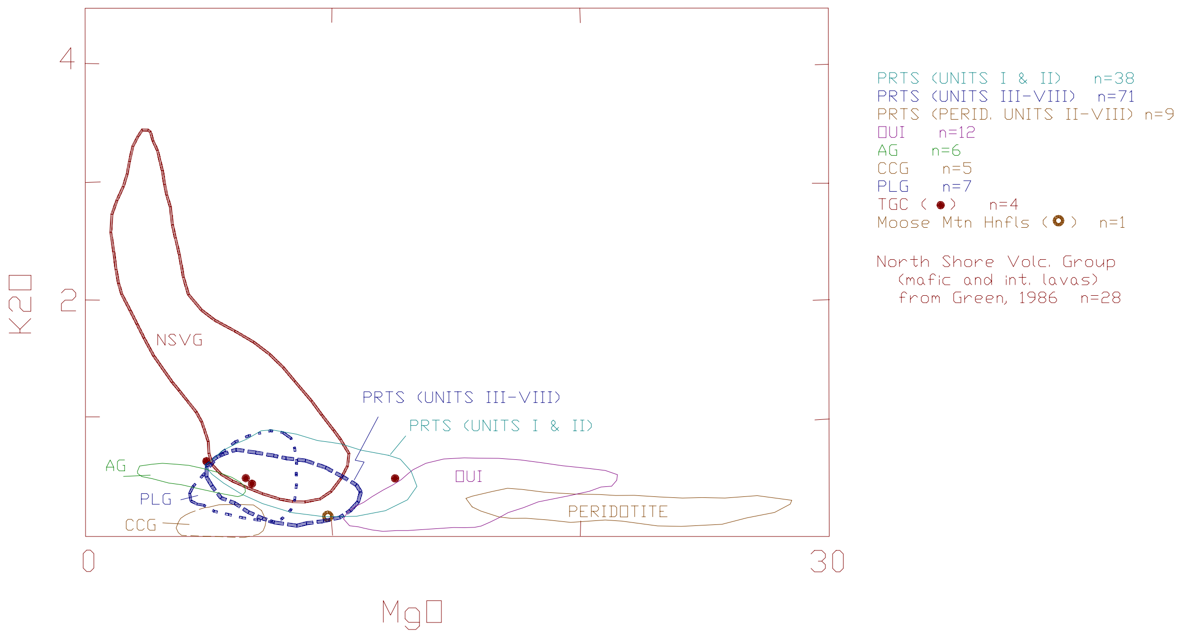


Figure 24: MgO versus K_2O, Partridge River Intrusion.

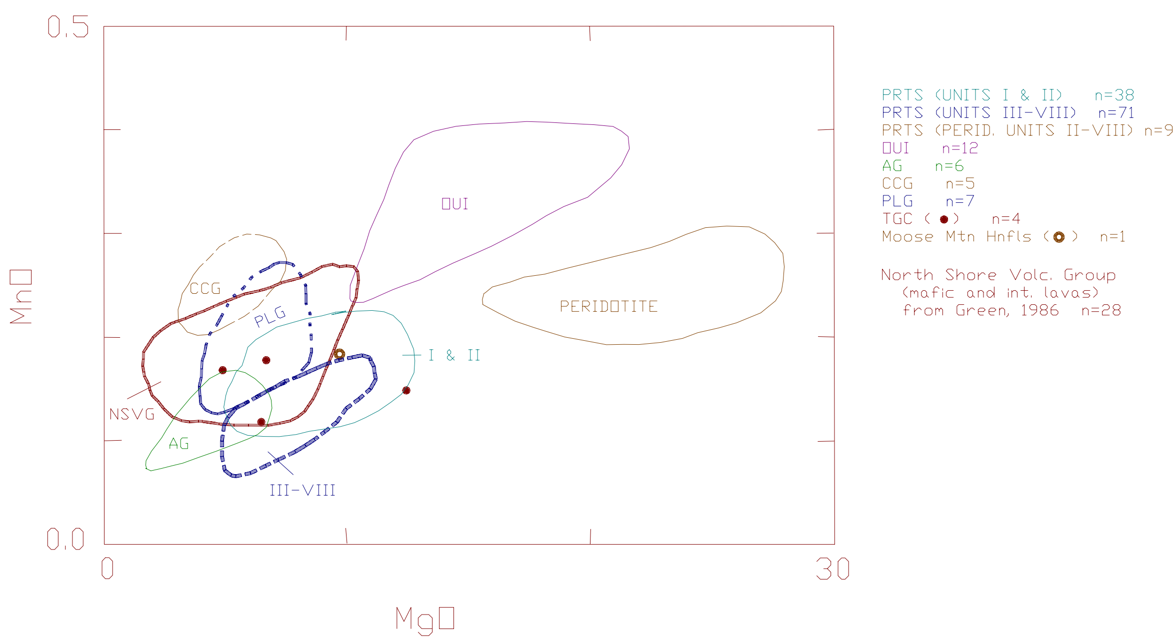


Figure 25: MgO versus MnO, Partridge River Intrusion.

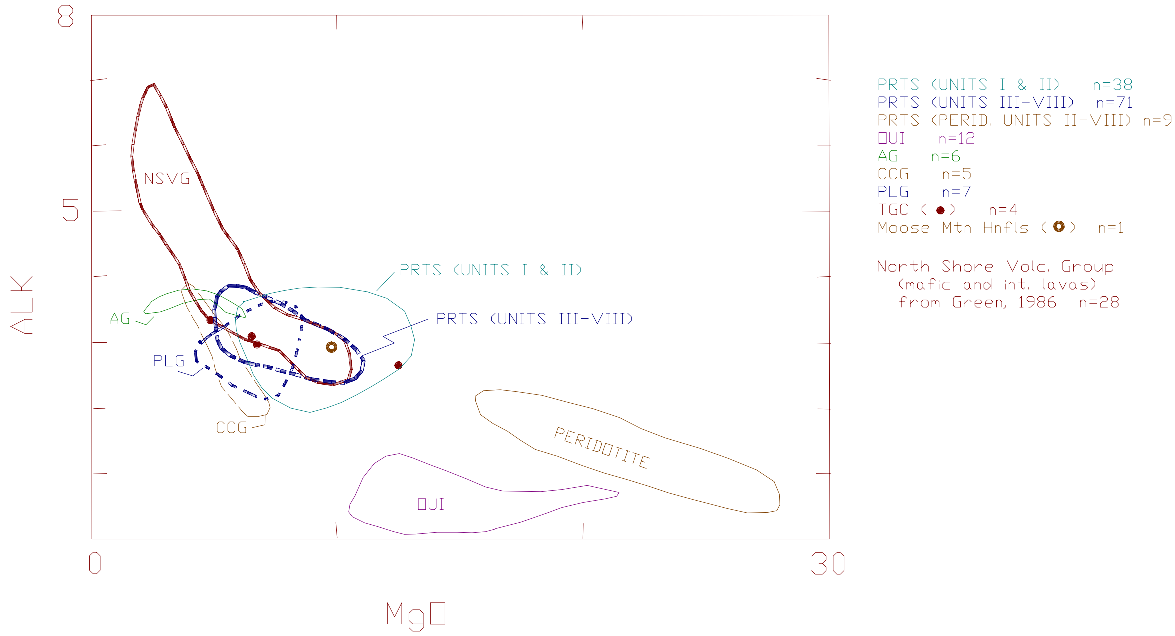


Figure 26: MgO versus Alkalies, Partridge River Intrusion.
(ALK = $Na_2O + K_2O$)

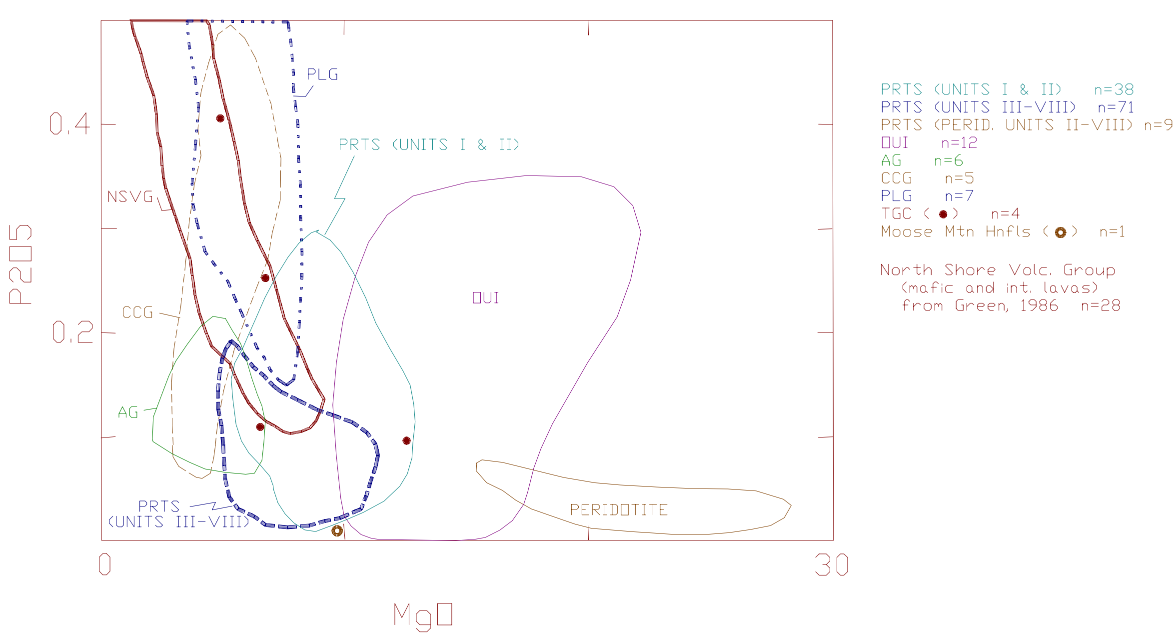


Figure 27: MgO versus P_2O_5, Partridge River Intrusion.

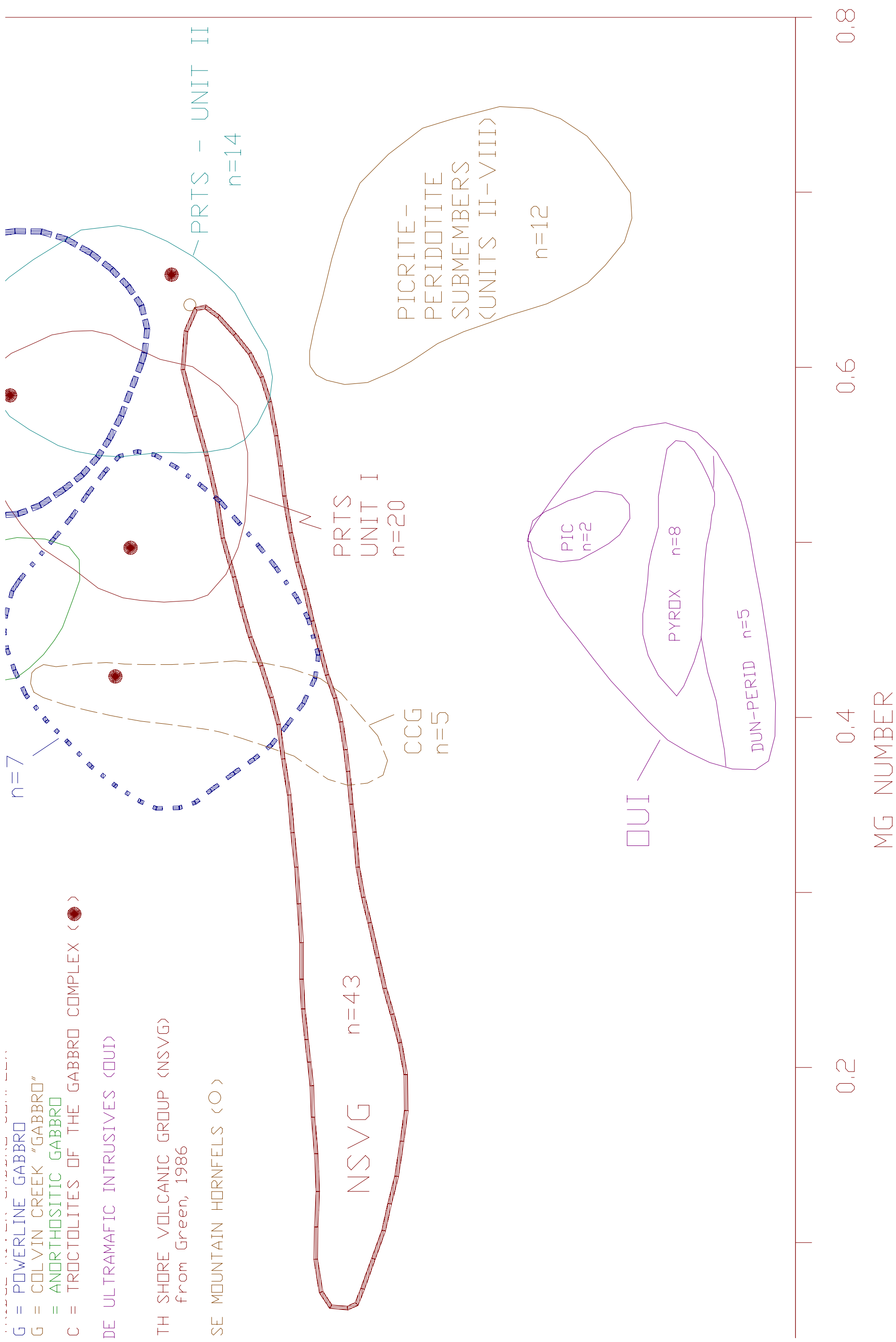


Figure 28: MG number versus Al_2O_3, Partridge River Intrusion.

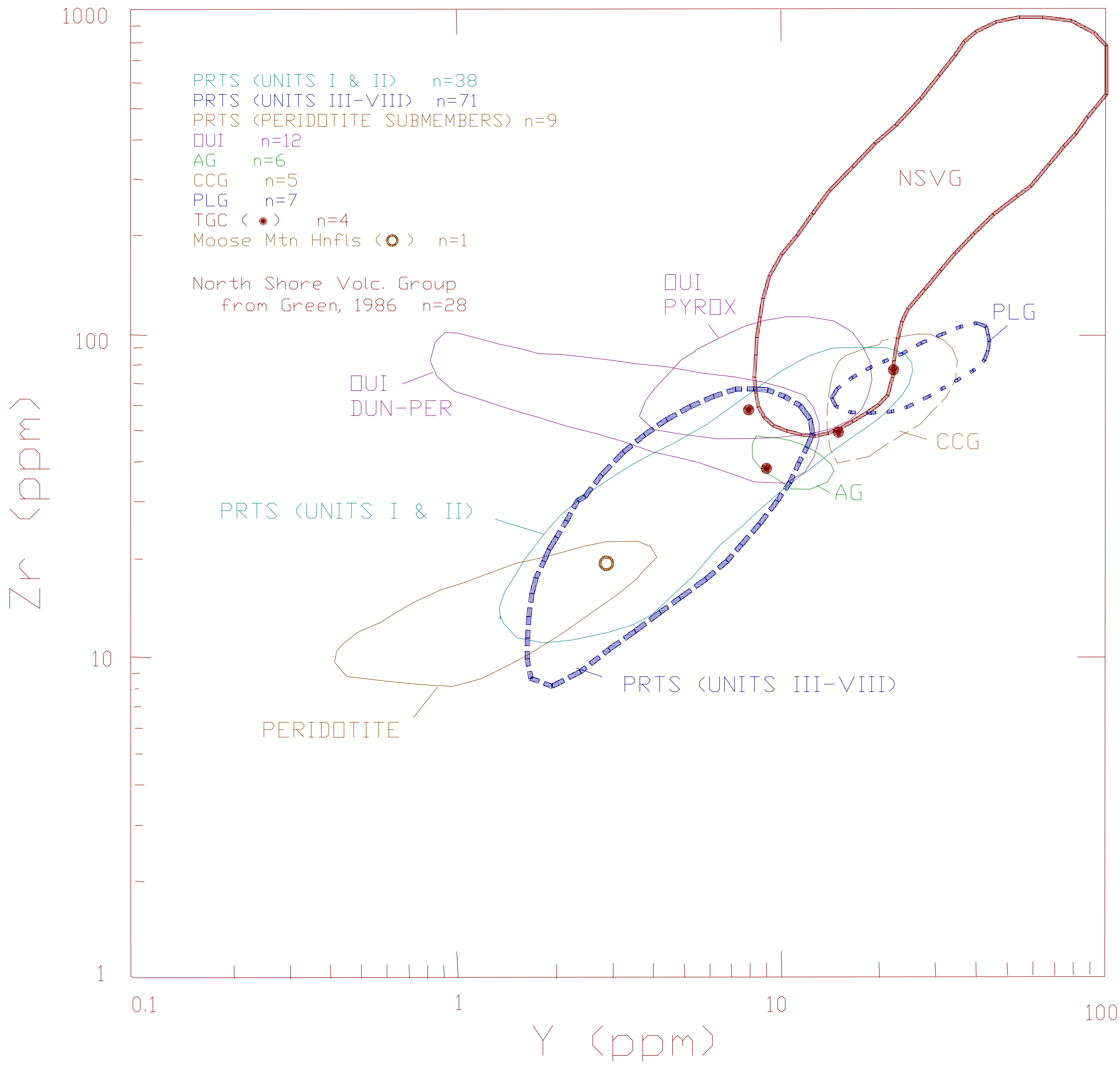


Figure 29: Y versus Zr, Partridge River Intrusion.

result of sampling bias in that only a few peridotites were sampled (9) relative to abundant troctolitic samples (109) collected from the PRTS units.

As discussed previously, the lower half of Unit I is geochemically different from all the other PRTS units. This difference is also seen in the X-Y plots but has not been illustrated (except in Figs. 30 and 31) as the plots are too cluttered with data already. In all the MgO plots, the lower half of Unit I plots within the left half of the "Unit I and II" field (MgO content is generally less than 8% for the lower half of Unit I). On Figure 28, the lower half of Unit I plots on the left half of the "Unit I" field. The lower half of Unit I plots in an isolated field in Figure 30 as the fluorine contents of the lower half of Unit I are consistently high (>180 ppm) due to the high apatite content (fluorapatite?). In the Y vs Zr diagram (Figure 29), the lower half of Unit I plots in the top portion of the "Unit I and II" field (Zr >44 ppm, Y >13 ppm). The lower half of Unit I also plots in a separate field, relative to the other troctolitic rocks of Units I and II, in the Ni vs Zr diagram (Fig. 31).

Therefore, the lower half of Unit I is chemically distinct from Unit II and the upper half of Unit I. Because the lower half of Unit I is in contact with the footwall Virginia Formation and contains abundant hornfels inclusions, the difference between the lower half of Unit I and the upper half of Unit I reflects a greater degree of magma contamination due to the close proximity and assimilation of the footwall rocks. This is indicated on Figure 31 by the plotted position of the lower half of Unit I relative to the Virginia Formation and all the other PRTS units. The lower half of Unit I is situated midway between the PRTS units and the Virginia Formation along a "mixing line" (Fig. 31) suggesting that magma contamination from the Virginia Formation was important in its genesis. Furthermore, the lower half of Unit I often plots within or near the CCG and PLG units suggesting that they too may have also undergone similar magma contamination.

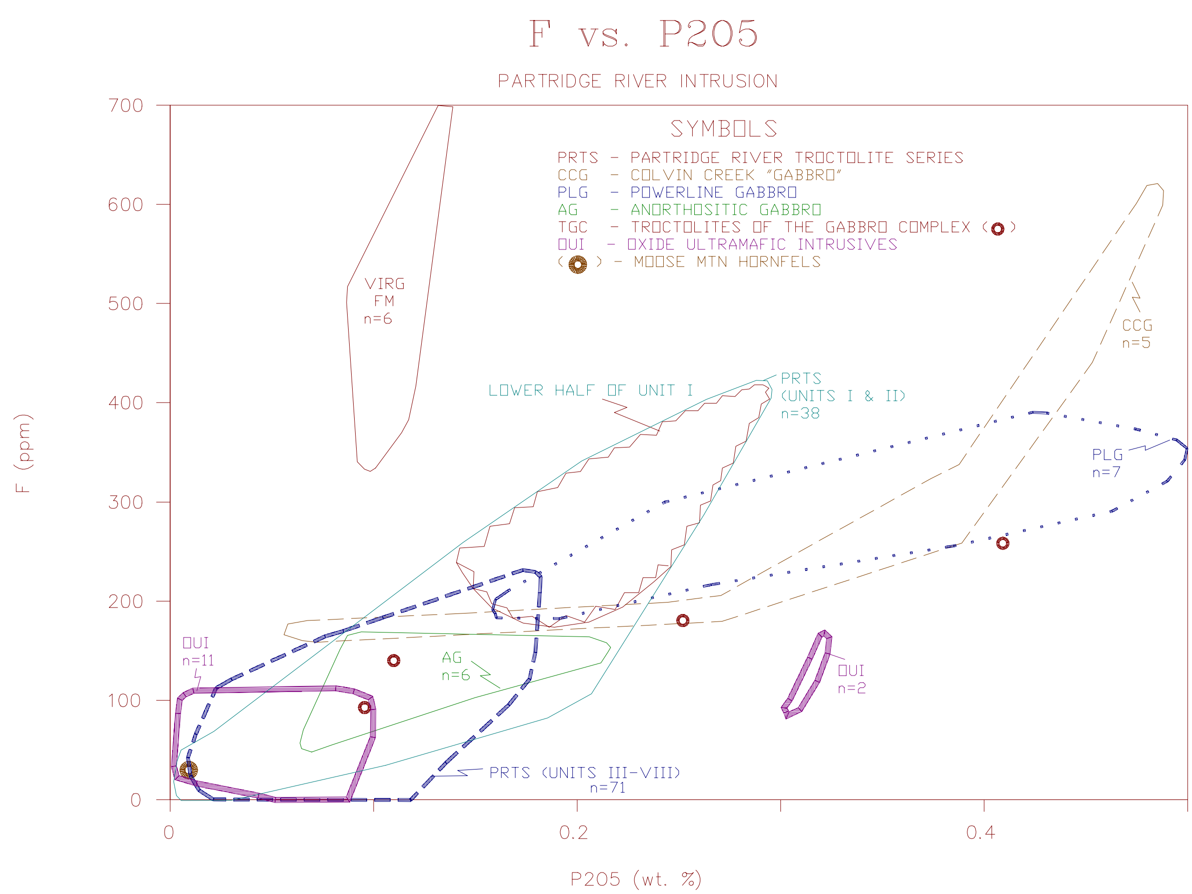


Figure 30: P_2O_5 versus F, Partridge River Intrusion.

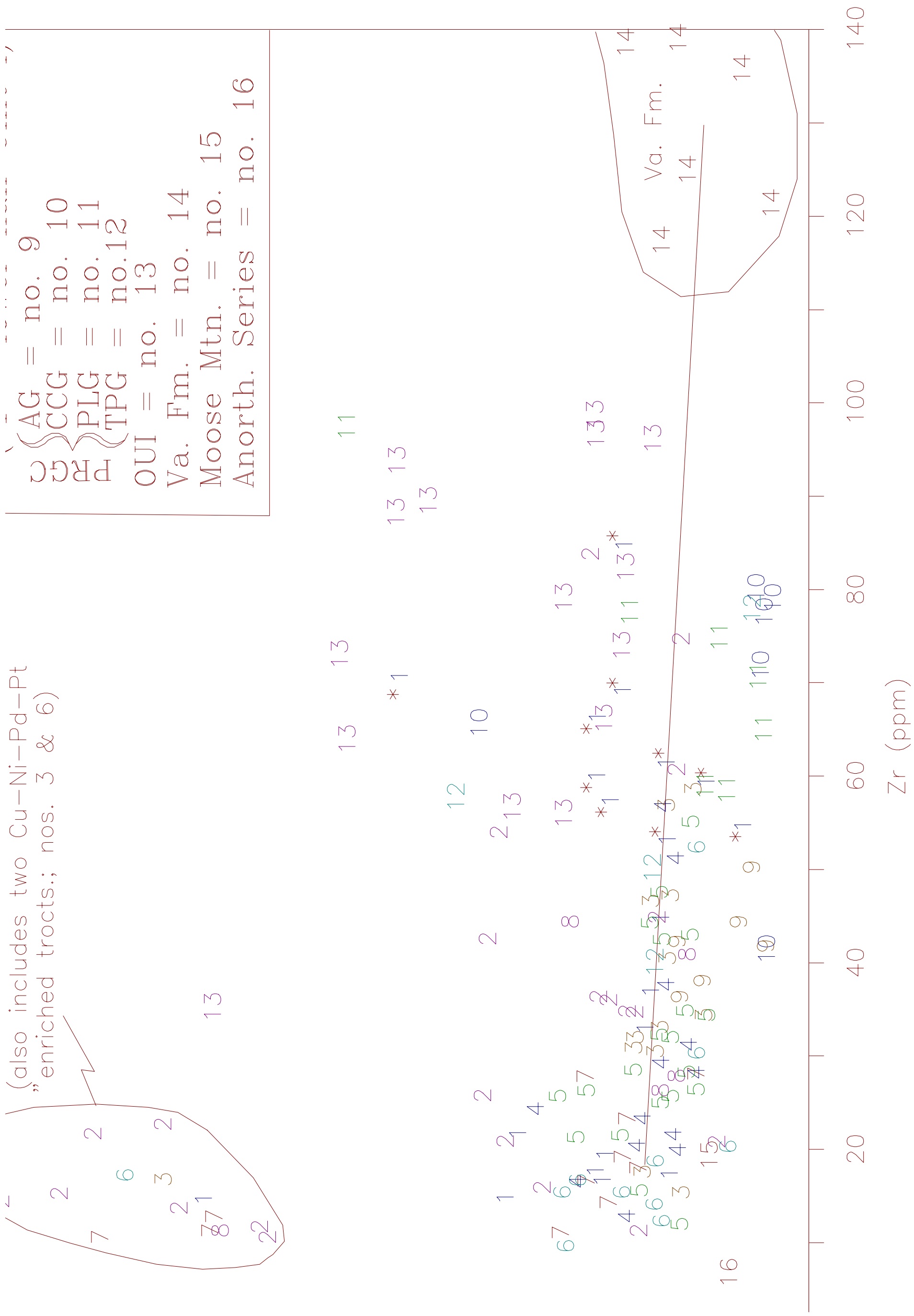


Figure 31: Ni versus Zr, Partridge River Intrusion.

PRGC Geochemically the CCG, PLG, and AG units are often distinctly different than most of the PRTS units, with the exception of the lower half of Unit I. The CCG geochemistry (previously believed to be a hornfelsed basalt) is almost always similar to the PLG, suggesting that the two units are intricately related. Reconnaissance mapping supports this evidence in that CCG-type material is often found included within the PLG and PLG-type material is within the CCG.

The overlap of the PLG and CCG geochemistry was at first thought to be a result of how the sampled material was categorized in the field. In other words, if fine-grained granular material was located within the PLG outcrop area it was categorized as "PLG" even though it is similar to CCG-type material. Conversely, coarse-grained gabbroic rock within the CCG outcrop area was categorized as "CCG" even though the rock is similar to the Powerline Gabbro (PLG). A manual check was conducted to see if the fine-grained material plotted in an isolated field regardless of whether it was categorized as CCG or PLG. The results, though only shown in Figure 17 this report, indicated that the fine-grained material has a "shotgun" pattern within the combined fields for the CCG and PLG units. Similarly, the coarser gabbroic rocks (regardless of whether categorized as CCG or PLG) were also evenly dispersed within the combined fields. Therefore, it is interpreted that, neither the fine-grained nor the coarse-grained portions of the CCG and PLG have different origins but are related.

Since the Colvin Creek "Gabbro" (CCG), and similar fine-grained portions of the PLG, have been previously inferred to be hornfelsed basalt, analyses of mafic to intermediate lavas from the North Shore of Lake Superior (Green, 1986) are included for comparison. There is little similarity between the North Shore Volcanic

Group (NSVG) and the PLG and CCG units. The only overlap between the NSVG and CCG-PLG fields are those in which fields for all the PRI units are clustered together initially, e.g., MgO vs Na_2O (Fig. 23). Also, the fine-grained material (closest analog of hornfelsed basalt) of the CCG and PLG shows no correlation with the NSVG field. This suggests that either the CCG is not a typical NSVG unit, or that the CCG is indeed gabbroic, and if so, the features noted within the northern Colvin Creek body are, therefore, related to magmatic density currents. However, only a limited number of geochemical samples have been collected and additional sampling is needed in order to resolve these questions.

The Moose Mountain Hornfels (MMH) is also plotted for comparison to the NSVG and CCG-PLG. In almost all cases, the MMH sample plots away from the CCG-PLG field and within or near the NSVG field (plots near samples of olivine tholeiite).

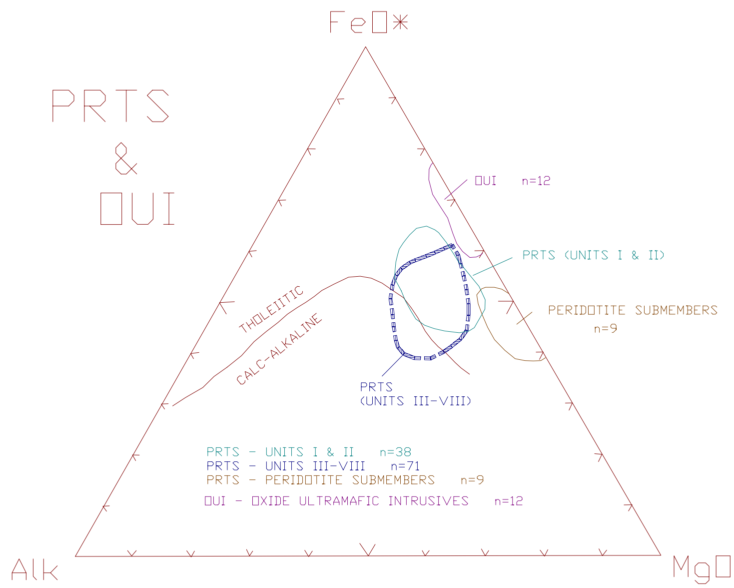
Samples (4) collected from the Troctolites of the Gabbro Complex (TGC) are plotted individually due to the two different trends noted on Figure 13. A similar relationship occurs in Figures 16-31. Two of the samples (PRT-44, PRT-32) usually plot within the CCG-PLG fields and the other two samples (PRT-46, PRT-30) plot within the PRTS fields. Therefore, samples PRT-46 and PRT-30 may be post CCG-PLG and may be related to the PRTS troctolites which are inferred to have delaminated and underplated the CCG-PLG package. Samples PRT-44 and PRT-32 are believed to by syn-CCG-PLG. However, this conclusion is based on extremely meager data (mapped relationships and geochemistry) and much more work is needed to resolve the nature of the two different trends (geochemical) in the TGC, and whether it indeed exists. The Anorthositic Gabbro (AG) geochemistry indicates that it is somewhat isolated but often partially overlaps the CCG-PLG and/or the PRTS fields.

On most of the scatter plots, there is a good correlation between the lower half of Unit I, CCG, PLG, and TGC (two samples). This correlation strongly suggests that magma contamination due to assimilation of footwall rocks was important in their genesis.

OUI The Oxide-bearing Ultramafic Intrusions (OUI) exhibit sharp contacts with, and are clearly later than, the PRTS units. In Figures 16-31, the OUI's are geochemically distinct from all other units within the PRTS and thus they represent a unique rock type. Because geochemical modelling was not attempted, little more can be said about whether the OUI's are late stage differentiates of the PRTS, or about how assimilation of the Biwabik Iron-Formation at depth, if at all, may be related to their origin.

AFM Diagram

All PRI rocks are tholeiitic (Figure 32). Similar geochemical relationships between the units, as previously discussed, are supported by the AFM plots.



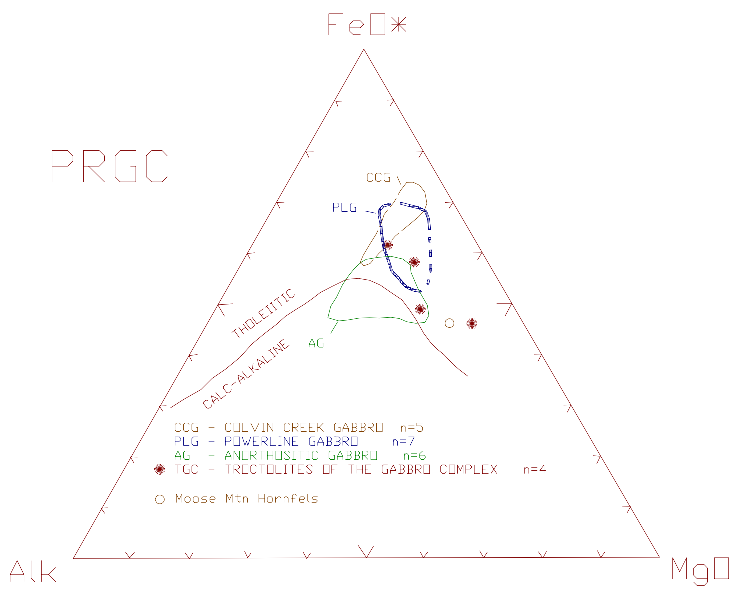


Figure 32: AFM diagrams of rocks within the Partridge River Intrusion.
($FeO^* = FeO + 0.8998\ Fe_2O_3$; $ALK = Na_2O + K_2O$)

SUMMARY AND CONCLUSIONS

Summary of the PRTS Units

To date, eight igneous units have been delineated within the PRTS of the Partridge River intrusion. A "sea of troctolite" is still present within the PRTS; however, each unit displays unique characteristics that become apparent when the drill holes have been stratigraphically "hung". Though vertical and lateral gradational changes are present, each individual unit collectively exhibits uniform characteristics. The major characteristics of each unit of the PRTS are summarized in Table 6.

What has emerged during this investigation is that several of the upper igneous units (Units VIII, VII, VI, and V-IV) are characterized by thick intervals of homogeneous textured "troctolite" that contain persistent basal picrite and/or peridotite horizons. Each ultramafic unit has modally graded tops and sharp bases produced by crystal settling. The ultramafic base of these units indicates that : 1) each 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 which then mixed with an earlier pulse. Unit III (marker bed) exhibits considerable textural and mineralogic variations relative to the upper PRTS units and apparently was intruded as a single pulse. Units I and II appear to reflect an entirely different intrusive style than all the other overlying units. Collectively, both units are highly heterogeneous (abundant laterally discontinuous cyclic layers in Unit II, and abundant internal contacts between sundry troctolitic rocks in Unit I) that suggests a mechanism 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). Also unique to Unit

	MINOR "CLOUD" ZONES AT DUNKA ROAD	NONE	NONE	45–80 (11 SECTIONS)		
					SHARP	
	RARE ZONES	PLAGIOCLASE–SYMPLECTITE COMMON AT WETLEGS AND WYMAN CREEK; RARE AT DUNKA ROAD	RARE (MOOSE MTN HORNFELS)	52–75 (12 SECTIONS)		DOWNCUTTING RELATIONSHIP AT WYMAN CREEK (CONDUIT?)
					GRADATIONAL	
EAR S D	RARE ZONES	MINOR PLAGIOCLASE–SYMPLECTITE AT WETLEGS AND WYMAN CREEK	MINOR (TWO THICK SECTIONS IN 2 HOLES AT WETLEGS)	62–71 (10 SECTIONS)		
					SHARP	
	"CLOUD" ZONE IN TOP PORTIONS OF SOME HOLES	OLIVINE OIKOCRYSTS	MINOR	47–77 (14 SECTIONS)		NOT AT WYMAN CREEK
					PERIDOTITE AT WETLEGS, SHARP – GRAD. @ DUNKA ROAD	
C S T	SECOND MOST IMPORTANT UNIT	MINOR OLIVINE OIKOCRYSTS AT DUNKA ROAD	MODERATELY ABUNDANT	58–75 (12 SECTIONS)	↑ –PERSISTENT PICRITE AT DUNKA ROAD AND WYMAN CR. –CYCLIC UNITS @ WETLEGS	
					SULFIDE–BEARING ↓	
	MAIN ORE ZONE	INCREASED BIOTITE AND CPX CONTENT INCREASED OPX CONTENT LOCALLY APATITE COMMON PLAGIOCLASE–SYMPLECTITE PRESENT IN MOST SAMPLES	ABUNDANT SUBHORIZONTAL HORNFELS–RICH ZONE IN THE MIDDLE OF THE UNIT	54–73 (11 SECTIONS)	NORITE LOCALLY	

Table 6: Summary of distinguishing characteristics pertinent to the various igneous units of the Partridge River Troctolitic Series (PRTS).

I and II is the abundance of Virginia Formation hornfels inclusions indicating a different intrusive style relative to the more homogeneous-textured overlying units (Units IV through VIII) that contain relatively rare hornfels inclusions.

The timing of each magmatic pulse present in the PRTS is unknown. Several authors (Grant and Molling,1981; Rao and Ripley, 1983) propose that the PRI 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 PRTS 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 minerals were not conducted as a part of this investigation and thus it is difficult to determine how the mineral chemistries change with depth in each unit of the PRTS or how they vary from unit to unit is difficult. However, Rao (1981) did produce a mineral chemistry profile of drill hole 26056 which was relogged during this investigation. Based on mineral compositional variation patterns, Rao (1981) proposes several magmatic cycles. His data are presented in Figure 33 along with his proposed "stratigraphic" breaks in the cycles (right side of Fig. 33). Lithologic breaks corresponding to the various PRTS units of this investigation are also superimposed on the diagram. There is a fair amount of agreement between the lithologic and mineral chemistry breaks. Rao also notes that

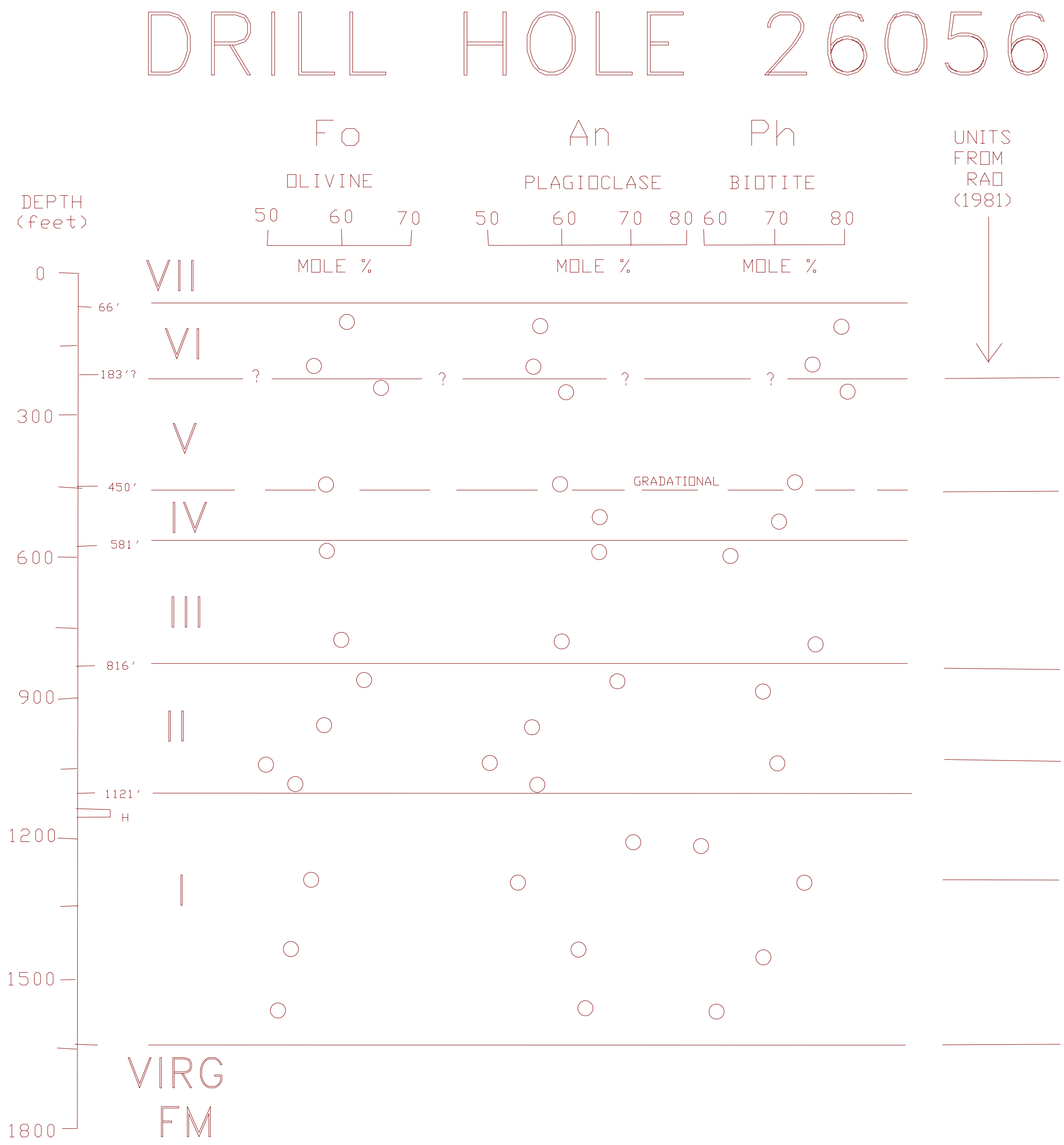


Figure 33: Correlation of igneous units to compositional variations of olivine, plagioclase, and biotite. Microprobe data and diagram (modified) from Rao (1981), p. 85.

in each cycle, there is a reverse trend in the differentiation from bottom to top. This however, is based on a very limited sample density per cycle/unit. Therefore, additional mineral chemistry data are necessary to fully evaluate any cryptic layering patterns.

In regards to the timing of igneous units delineated in this investigation, a sequential intrusion of magma pulses from top to bottom is not totally indicated. Instead, a more complex pattern of mixed intrusions is suggested by the presence of Unit III-type inclusions(?) higher up-section within Unit VII, and more important, by the downcutting relationship of Unit V into Units I and II at Wyman Creek. However, the exact timing of the various PRTS units has yet to be determined and clearly more work is needed. In addition to the complicated timing of magmatic pulses, a difference in the style of emplacement is also indicated. Units IV through VIII are characterized by a monotonous sequence of homogeneous-textured troctolites that may be related to widely spaced pulses into a large magma chamber. Thus, these units may have undergone little *in situ* contamination due to assimilation of the footwall rocks.

Units I and II, however, exhibited a different intrusive history. These units formed by rapid magmatic pulses emplaced along bedding planes in the footwall rocks. Intrusion was accompanied by assimilation of larger volumes of footwall rock (indicated by presence of abundant hornfels inclusions in these two units relative to all the other PRTS units).

Construction of cross-sections through the various Cu-Ni prospects (utilizing the heretofore defined stratigraphy), indicates the presence of several NE-trending normal faults. These faults support the half-graben model of Weiblen and Morey

(1980). However, the vast majority of these faults cut the entire section and do not represent the true half-graben faults as envisioned in the model. The only possible true half-graben fault located in this investigation is present in the Wetlegs area. This fault is characterized by a substantial offset in the footwall rocks and no offset in the overlying troctolitic rocks. A pre-Keweenawan age for this fault is proposed by Severson (1988); however, the fault may have formed during intrusion of Unit I, whereby magma was injected into a foundered, fault-bounded void envisioned by the half-graben model.

Summary of OUI Units

Several bodies of OUI are present within the PRI and in almost all cases exhibit sharp intrusive contacts with the PRTS units. The bodies vary from small lenses (Dunka Road) to subhorizontal sill-like bodies (Wyman Creek and Skibo) to large discordant spherical bodies (Section 17, Longnose, Longear). Dunite, peridotite and pyroxenite are the dominant rock types but picrite and melagabbro are present. Some of the bodies contain an interior dunite-peridotite core. Massive oxide zones are common in dunite and peridotite but are also present in the pyroxenites. Ilmenite is generally greater than titanomagnetite/magnetite. Sulfide content generally increases in oxide-rich and or olivine-rich zones but is generally present throughout in minor amounts. Pyrrhotite is the dominant sulfide in some OUI, whereas chalcopyrite is dominant in others. The spatial distribution and correspondence of the Section 17, Longnose, and Longear bodies to an inferred window of Biwabik Iron-Formation at the basal contact suggests a genetic link with areas of massive iron-formation assimilation. A similar empirical relationship is also present at Dunka Road in that OUI lenses become more common in deep drill holes as the Virginia Formation "cap" thins at the basal contact. The strong correlation between FeO and C, and between C and S at Skibo (Seitz and Pasteris, 1988) suggests that assimilation of the Virginia Formation also played an important role in the formation of these bodies.

Summary of the Partridge River Gabbro Complex

Gabbroic and minor troctolitic rocks in the southeast portion of the study area are tentatively assigned to the PRGC. Field relationships indicate that the Colvin Creek "Gabbro" and Powerline Gabbro are similar in many respects but differ in the relative volumes of rock types present. Granular-textured, fine-grained "gabbro" typifies the Colvin Creek bodies, whereas coarse-grained gabbro is dominant in the Powerline Gabbro. However, rock types indigenous to one body are often found in lesser amounts in the other body, and vice versa, suggesting that the two bodies are related to the same intrusive event. The presence of hornfelsed gabbro indicates contact metamorphism by a still later intrusive. Whether or not the contact metamorphic event is related to: 1) the multiple intrusions of the PRGC e.g., portions of the TGC unit; or 2) to underplating by intrusions of the Partridge River intrusion, e.g., PRTS units, is unknown.

Sedimentary-type features occur within the Colvin Creek "Gabbro" (Sections 27, 33, and 34, T.59 N, R.13 W) and the Powerline Gabbro (25-59N-13W). The sedimentary textures are hard to reconcile if the Colvin Creek body represents a typical hornfelsed basalt or a typical interflow sediment (combined strike-length of these cross-bedded outcrops is at least four miles). Sedimentary features are also present in overlying coarse-grained rocks and collectively they both may be related to magmatic density currents. However, based on reconnaissance mapping, a more detailed investigation of these features is needed.

Geochemistry Summary

Average background values are established for all the various rock types and units present within the Partridge River intrusion; however, sampling is limited for each rock type. Within the PRTS rock units, Units I and II exhibit markedly different background values relative to Units III through VIII. This "anomalous" behavior of Units I and II is not too surprising in lieu of the fact that they are more heterogeneous textured, sulfide-rich, biotite-rich, and contain more hornfels inclusions than all the overlying homogeneous textured Units III through VIII. These differences suggest that magma contamination due to assimilation of footwall material is more important in the genesis of Units I and II. Furthermore, some units of the PRGC also exhibit the same background values as Units I and II suggesting that magma contamination may have also been important in their genesis as well. Background values for the OUI units exhibit a marked variation in several elements and thus they represent a unique rock group relative to other units of the Partridge River intrusion.

In regards to precious mineral content, five samples with anomalous PGE values (>200-910 ppb combined Pd and Pt) were obtained during the course of sampling "unmineralized" rock. This indicates that overall sulfide content is not always related to "mineralized" PGE zones. The five samples were obtained from several of the PRTS units (Units I, II, III, and VI).

The spider diagrams and X-Y scatter plots support the lithologic grouping of igneous units. Specific igneous units that have a similar origin include: 1) Units I, II, CCG, PLG, and TGC (two samples out of four); 2) Units III through VIII and TGC (two samples); 3) the lower half of Unit I which is different than the upper half but similar to the CCG and PLG; and 4) rocks of the OUI group.

The CCG, PLG and TGC (two samples) units all have similar spider diagram "fingerprints", and all three of their respective fields show considerable overlap on the x-y plots. Because the geochemistry of these units is similar, a lumping of the units into the informally designated Partridge River Gabbro Complex (PRGC of this report) is warranted. This grouping is based on limited outcrop evidence in that coarse-grained gabbros similar to the Powerline Gabbro (PLG) are located within the fine-grained Colvin Creek "Gabbro" (CCG) outcrop area and vice versa. Also, modally layered troctolites of the TGC are often found overlying, or intermixed with, both CCG and PLG-type material, respectively. Therefore, both field and geochemical evidence indicate that all three units, and possibly the AG unit, are all part of the PRGC intrusive body. The similarity in geochemistry of the PRGC units to Units I and II of the extensively drilled portion of the PRTS suggests that "Unit I-type sulfide mineralization" may also be present within the unexplored PRGC. Lastly, the possibility that the CCG is a hornfelsed basalt is not supported here because of the dissimilar geochemical signatures between the CCG and the NSVG and MMH. This dissimilarity indicates that either the CCG is not a typical North Shore basalt, or that it is a fine-grained chilled basal equivalent of the PLG. If the latter is true, then the sedimentary features of the cross-bedded belt (XBB) originated from magmatic density currents.

The initial geochemical plots of the various igneous units of the PRI indicate that they occupy distinct geochemical fields. This supports the proposed breakdown of the PRI into major rock groups, e.g., PRTS, PRGC, OUI, each with internal members (eight units within the PRTS), as is indicated by detailed core logging and reconnaissance mapping. However, the geochemical relationships noted above, are based on limited sample densities and additional sampling of the various rock types is needed.

Conclusions

During the 1.5 year investigation period, a voluminous amount of data was obtained in regards to the Partridge River intrusion (PRI). A heretofore unknown stratigraphy for the basal portion of the PRI was established that is correlated over an 11 mile strike-length and includes 83 drill holes (over 100,000 feet of core). At least eight units within the Partridge River Troctolitic Series (PRTS) were recognized due to both megascopic and microscopic differences. This stratigraphic package indicated that the basal +3000 feet of the PRI was emplaced as several subhorizontal sheets with shallow dips towards Lake Superior. Some of these igneous units (Units III through VIII) may represented single cooling units in that they were homogeneous and floored by a persistent ultramafic member; whereas, other units near the basal contact (Units I and II) were more heterogeneous and contain abundant, compositionally different 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 than simply "sheets successively emplaced beneath previous sheets" was indicated. Further complicating the "style of emplacement" picture were the Oxide-bearing Ultramafic Intrusions (OUI) which in almost all cases are intrusive into the entire PRTS stratigraphic package. Lastly, the PRGC units were geochemically and petrographically similar to Units I and II, and may have been underplated and intruded by later (younger) PRTS units.

Establishment of an internal stratigraphy, instead of a "sea of troctolite", has for the first time established the presence of fault offsets within the PRI. Both NE-trending and NW-trending faults have been recognized in several of the Cu-Ni deposits. These data support the half-graben model of Weiblen and Morey (1980). However, most of the faults recognized in this investigation show corresponding offsets in both troctolitic and footwall rocks and are thus, not true half-graben faults as envisioned in the model. The relationship of these faults to higher grade Cu-Ni zones within the deposits is possible but has not been investigated. An empirical relationship of the spatial occurrence of the OUI bodies to areas where the Biwabik Iron-formation is present at the footwall contact has been indicated. The OUI units also exhibit a marked variation in geochemistry when compared to all other units of the PRI. Whether these OUI bodies originated as late-stage differentiates of the PRTS, in combination with assimilation of iron-formation at depth, is a matter reserved for future investigations and geochemical modelling.

Several "interesting" features occur in the Partridge River Gabbro Complex (PRGC). Fine-grained "gabbroic" rocks, which previously were inferred to be hornfelsed basaltic hanging-wall material, and coarse-grained gabbroic rocks are located within both the Colvin Creek "Gabbro" (CCG) and Powerline Gabbro (PLG) outcrop areas. Within the outcrop areas are "sedimentary" type features that are not indicative of <u>typical</u> North Shore Volcanics as described in the literature. These features may be related to magmatic density currents but their true origin remains enigmatic and additional work is required. The nature of the metamorphic/intrusive event which produced the fine-grained, (possibly originally chilled?) granular-textured material and turned the entire northern Colvin Creek body on end also remains to be resolved. At present, the similarity in geochemistry for the CCG, PLG, AG(?), and portions of the TGC, suggest that they are all part of the same intrusive body/event. However, field relationships and geochemical differences in the TGC suggest that some of the troctolitic rocks of the TGC may be related to the upper PRTS units (IV through VIII etc) and may have been intruded at a later time or during underplating. If the bimodality in geochemistry for the TGC unit is real (based on only four samples), a mechanism of emplacement of the PRGC near the base of a magma chamber followed by emplacement of the upper PRTS units beneath it is possible. The later emplaced PRTS units may have thus delaminated and elevated the PRGC to its present position as envisioned by Chandler and Ferderer (in press).

Background geochemical values and geochemical diagrams substantiate the various rock divisions of the PRI as established in this investigation. Units I and II exhibit a markedly different geochemistry when compared to the other PRTS units.

The difference in geochemistry, coupled with the fact that these two basal units differ megascopically from all the overlying homogeneous troctolitic units (III-VIII), suggests that magma contamination due to assimilation of footwall material played an important role in their genesis. The data suggest that *in situ* assimilation was more important in Units I and II that contain volumetrically more inclusions of the Virginia Formation than the overlying troctolitic rocks. This is in contrast to a concept proposed by Ripley (1986), and Ripley and Al-Jassar (1987), whereby assimilation of footwall material occurred within a secondary or auxiliary magma chamber at depth. Units I and II may have intruded the earliest and "armored" the Virginia Formation from a later overlying magma chamber (Units III through VIII). This may have limited the amount of subsequent contamination in Units III through VIII.

Within the PRGC, the internal units (CCG, PLG, etc) all exhibit similar geochemical relationships suggesting that they are intricately related and are different "facies" of a singular intrusive body. Even the geochemical similarity of the fine-grained "gabbroic" material, e.g., CCG, to the coarse-grained gabbros (typically referred to as Powerline Gabbro) is indicated. A geochemical similarity of the fine-grained "gabbroic" material to basalts of the NSVG or to the Moose Mountain (basaltic) Hornfels has not been established. These data indicate that the fine-grained "gabbroic" material (CCG) is either: a basalt inclusion that is not <u>typical</u> of the NSVG, or that it is a fine-grained equivalent of the Powerline Gabbro. Interestingly, the overall geochemistry of the PRGC is similar to the Unit I and II geochemistry (specifically the lower half of Unit I) suggesting that Unit I type sulfide mineralization may be present within the PRGC. However, geochemical data is very limited within the PRGC and much more sampling is needed in order to fully understand the relationships of internal units within the PRGC and the relationship of the PRGC to the PRTS.

In summary, several similarities and differences among a wide variety of rock types and geological settings are present within the Duluth Complex. In short, our understanding of the Duluth Complex has just become even more complex and care should be exercised when applying the results obtained from a "one or two drill hole" study to the remainder of the Duluth Complex.

REFERENCES

Al-Alawi, J.A., 1985, Petrography, sulfide mineralogy and distribution, mass transfer and chemical evolution of the Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Unpubl. Ph.D. thesis, Indiana Univ., Bloomington, Indiana, 350 pp.

Bonnichsen, B., 1972, Southern part of Duluth Complex: *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume; Minnesota Geological Survey, pp. 361-387.

Bonnichsen, B., 1973, Geologic log of Bear Creek drill hole A4-12: DNR open file CN-7136, 16 pp.

Boucher, M.L., 1975, Copper-nickel mineralization in a drill core from the Duluth Complex of northern Minnesota: U.S. Bureau of Mines Rept. of Invest. 8084, 55 pp.

Carr, M.J., 1987, IGPET II computer program, RockWare, Inc., Wheat Ridge, Colorado.

Chalokwu, C.I., 1985, A geochemical, petrological and compositional study of the Partridge River intrusion, Duluth Complex, Minnesota: Unpubl. Ph.D. thesis, Miami University, Oxford, Ohio, 230 pp.

Chalokwu, C.I. and Grant, N.K., 1987, Reequilibration of olivine with trapped liquid in the Duluth Complex, Minnesota: Geology, v. 15, pp. 71-74.

Chandler, V.W. and Ferderer, R.J., in press, Copper-nickel mineralization of the Duluth Complex, Minnesota -- A gravity and magnetic perspective: Econ. Geol.

Churchill, R.K., 1978, A geochemical and petrological investigation of the Cu-Ni sulfide genesis in the Duluth Complex, Minnesota: Unpubl. M.S. thesis, University of Minnesota, Minneapolis, Minnesota, 101 pp.

Cooper, R.W., 1978, Lineament and structural analysis of the Duluth Complex, Hoyt Lakes-Kawishiwi area, northeastern Minnesota: Unpubl. Ph.D. thesis, University of Minnesota, Minneapolis, Minnesota, 280 pp.

Dahlberg, E.H., 1987, Drill core evaluation for platinum group mineral potential of the basal zone of the Duluth Complex: Minnesota Department of Natural Resources, Div. of Minerals, Report 255, 60 pp.

Dahlberg, E.H., Saini-Eidukat, B., Peterson, D., Seyfried, W.E., and Weiblen, P.W., 1988, Evidence for precipitation from chlorine brines in drill core from the

Duluth Complex: [abs.] Annual Institute Lake Superior Geology, 34th Proc., (handout).

Davidson, D.M., Jr., 1972, Eastern part of the Duluth Complex: *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume; Minnesota Geological Survey, pp. 354-360.

Foose, M.P., and Cooper, R.W., 1981, Faulting and fracturing in part of the Duluth Complex, northeastern Minnesota: Can. Jour. Earth Sci., v. 18, pp. 810-814.

Foose, M.P., and Weiblen, P.W., 1986, The physical and chemical setting and textural and compositional characteristics of sulfide ores from the South Kawishiwi Intrusion, Duluth Complex, Minnesota, USA: *in* 27th Int. Geol. Congress (Moscow), Special Copper Symposium, Springer-Verlag, New York, pp. 8-24.

Fukui, L.M., 1976, The mineralogy and petrology of the South Kawishiwi intrusive, Duluth Complex, Minnesota: Unpubl. M.S. thesis, University of Illinois, Chicago Circle, 110 pp.

Grant, N.K., and Molling, P.A., 1981, A strontium isotope and trace element profile through the Partridge River troctolite, Duluth Complex, Minnesota: Contrib. Mineral. Petrol., v. 77, pp. 296-305.

Green, J.C., 1982, Geology of Keweenawan extrusive rocks: *in* Wold, R.J., and Hinze, W.J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America, Memoir 156, pp. 47-56.

Green, J.C., 1983, Geological and geochemical evidence for the nature and development of the middle Proterozoic (Keweenawan) Midcontinent Rift of North America: Tectonophysics, v. 94, pp. 413-437.

Green, J.C., 1986, Lithogeochemistry of Keweenawan Igneous Rocks: Unpubl. report to the Minnesota Department of Natural Resources, Division of Minerals.

Gundersen, J.N., and Schwartz, G.M., 1959, The geology of the metamorphosed Biwabik Iron-Formation, eastern Mesabi district, Minnesota: Minnesota Geological Survey, Bulletin 43, 139 pp.

Hardyman, R.J., 1969, The petrography of a section of the basal Duluth Complex, St. Louis County, northeastern Minnesota: Unpubl. M.S. thesis, University of Minnesota, Minneapolis, Minnesota, 132 pp.

Holst, T.B., Mullenmeister, E.E., Chandler, V.W., Green, J.C., and Weiblen, P.W., 1986, Relationship of structural geology of the Duluth Complex to economic mineralization: Minnesota Department of Natural Resources, Div. of Minerals, Report 241-2.

Irvine, T.N., 1982, Terminology for layered intrusives: Journal Petrology, v. 23, n. 2, pp. 127-162.

Irvine, T.N., 1987, Layering and related structures in the Duke Island and Skaergaard Intrusions: similarities, differences, and origins: *in* Parsons, I., ed., Origins of Igneous Layering, D. Reidel Publ. Co., Dordrecht, Holland, pp. 185-245.

Linscheid, E.K., (in prep.), The petrography of the Longnose peridotite deposit and its relationship to the Duluth Complex: Unpubl. M.S. thesis, University of Minnesota, Duluth, Minnesota.

Listerud, W.H., and Meineke, D.G., 1977, Mineral resources of a portion of the Duluth Complex and adjacent rocks in St. Louis and Lake Counties, northeastern Minnesota: Minnesota Department of Natural Resources, Div. of Minerals, Hibbing, MN, Report 93, 49 pp.

Mainwaring, P.R., and Naldrett, A.J., 1977, Country-rock assimilation and the genesis of Cu-Ni sulfides in the Water Hen Intrusion, Duluth Complex, Minnesota: Econ. Geol., v. 72, pp. 1269-1284.

Mancuso, J.D., and Dolence, J.D., 1970, Structure of the Duluth Gabbro Complex in the Babbitt area, Minnesota: [abs.] Annual Institute Lake Superior Geology, 16th Proc., p. 27.

Miller, J.D., 1986, The geology and petrology of anorthositic rocks in the Duluth Complex, Snowbank Lake Quadrangle, northeastern Minnesota: Unpubl. Ph.D. thesis, University of Minnesota, Minneapolis, Minnesota, 525 pp.

Mills-Ervin, S., 1988, The relationship between the cloud zone and basal zone Cu-Ni sulfides, and the significance of mafic pegmatites, Minnamax Property, Duluth Complex, Minnesota: Unpubl. M.S. thesis, University of Minnesota, Duluth, Minnesota, 146 pp.

Molling, P.A., 1979, Petrology of a drill core (DDH 295) from the Partridge River troctolite of the Duluth Complex, Minnesota: Unpubl. M.S. thesis, Miami University, Oxford, Ohio, 150 pp.

Morey, G.B., and Cooper, R.W., 1977, Bedrock geology of the Hoyt Lakes-Kawishiwi area, St. Louis and Lake Counties, northeastern Minnesota: Minnesota Geological Survey, open-file map, 1:48,000.

Morton, P., and Hauck, S.A., 1987, PGE, Au and Ag contents of Cu-Ni sulfides found at the base of the Duluth Complex, northeastern Minnesota: Natural Resources Research Institute Technical Report, NRRI/GMIN-TR-87-04, Duluth, Minnesota, 85 pp.

Phinney, W.C., 1972, Duluth Complex, history and nomenclature: *in* Sims, P.K. and Morey, G.B., eds., Geology of Minnesota: A Centennial Volume; Minnesota Geological Survey, pp. 333-334.

Rao, B.V., 1981, Petrogenesis of sulfides in the Dunka Road copper-nickel deposit, Duluth Complex, Minnesota with special references to the role of contamination by country rock: Unpubl. Ph.D. thesis, Indiana University, Bloomington, Indiana, 372 pp.

Rao, B.V., and Ripley, E.M., 1983, Petrochemical studies of the Dunka Road Cu-Ni deposit, Duluth Complex, Minnesota: Econ. Geol., v. 78, pp. 1222-1238.

Ripley, E.M., 1986, Origin and concentration mechanisms of copper and nickel in Duluth Complex sulfide zones - a dilemma: Econ. Geol., v. 81, pp. 974-978.

Ripley, E.M., and Al-Jassar, T.J., 1987, Sulfur and oxygen isotope studies of melt-country rock interaction, Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Econ. Geol., v. 82, pp. 87-107.

Ripley, E.M., and Alawi, J., 1986, Sulfide mineralogy and chemical evolution of the Babbitt Cu-Ni deposit, Duluth Complex, Minnesota: Canadian Mineralogist, v. 24, p. 347-368.

Ross, B.A., 1985, A petrologic study of the Bardon Peak peridotite, Duluth Complex: Unpubl. M.S. thesis, University of Minnesota, Minneapolis, Minnesota, 161 pp.

Ryan, P.J., and Weiblen, P.W., 1984, Pt and Ni arsenide minerals in the Duluth Complex [abs.]: 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, p. 58-60.

Ryan, R.M., 1984, Chemical isotopic and petrographic study of the sulfides in the Duluth Complex cloud zone: Unpubl. M.S. thesis, Indiana University, Bloomington, Indiana, 88 pp.

Sabelin, T., 1987, Association of platinum deposits with chromium occurrences: An overview with implications for the Duluth Complex: Skilling's Mining Review, Nov. 21, pp. 4-7.

Sabelin, T., Iwasaki, I., and Reid, K.J., 1986, Platinum group minerals in the Duluth Complex and their beneficiation behaviors: Proceedings 59th Annual Meeting, Minnesota Section AIME, 12 pp.

Seitz, J.C., and Pasteris, J., 1988, Oxide and sulfide mineralization at the base of the Duluth Complex -- Skibo Tower, Minnesota: [abs.] Fifth Annual Current Minerals Forum, Chisholm, Minnesota.

Severson, M.J., 1988, Geology and structure of a portion of the Partridge River intrusion: A progress report: Natural Resources Research Institute, Technical Report, NRRI/GMIN-TR-88-08, Duluth, Minnesota, 78 pp.

Stevenson, R.I., 1974, A mafic layered intrusion of Keweenawan age near Finland, Lake County, Minnesota: Unpubl. M.S. thesis, University of Minnesota, Duluth, Minnesota, 160 pp.

Thompson, R.N., 1982, Magmatism of the British Tertiary Volcanic Province: Scott. J. Geol., v. 18, pp. 49-107.

Tyson, R.M., 1976, Hornfelsed Basalts in the Duluth Complex: Unpubl. M.S. thesis, Cornell University, Ithaca, New York, 85 pp.

Tyson, R.M., 1979, The mineralogy and petrology of the Partridge River troctolite in the Babbitt-Hoyt Lakes region of the Duluth Complex, northeastern Minnesota: Unpubl. Ph.D. thesis, Miami University, Oxford, Ohio, 179 pp.

Tyson, R.M., and Chang, L.L.Y., 1984, The petrology and sulfide mineralization of the Partridge River troctolite, Duluth Complex, Minnesota: Canadian Mineralogist, v. 22, pp. 23-38.

Wager, L.R., and Brown,G.M., 1968, Layered Igneous Rocks: W.H. Freeman and Co., San Francisco, 588 pp.

Watowich, S.N., 1978, A preliminary geological view of the Minnamax copper-nickel deposit in the Duluth gabbro at the Minnamax Project: *in* Graven, L.K., compiler, Productivity in Lake Superior Mining (39th Proceedings, Annual Minnesota Mining Symposium), University of Minnesota, Minneapolis, Minnesota, pp. 19.1-19.11.

Watowich, S.N., Malcolm, J.B., and Parker, P.D., 1981, A review of the Duluth Gabbro Complex of Minnesota as a domestic source of critical and strategic metals: SME-AIME Fall Meeting, Denver, Colorado, 9 pp.

Weiblen, P.W., 1965, A funnel-shaped gabbro-troctolite intrusion in the Duluth Complex, Lake County, Minnesota: Unpubl. Ph.D. thesis, University of Minnesota, Minneapolis, Minnesota, 161 pp.

Weiblen, P.W., and Morey, G.B., 1975, The Duluth Complex - A petrologic and tectonic summary: Duluth Mining Symposium, pp. 72-95.

Weiblen, P.W., and Morey, G.B., 1976, Textural and compositional characteristics of sulfide ores from the basal contact zone of the South intrusion, Duluth Complex, northeastern Minnesota: 37th Annual Mining Symposium, University of Minnesota, Minneapolis, Minnesota, 22 pp.

Weiblen, P.W., and Morey, G.B., 1980, A summary of the stratigraphy, petrology and structure of the Duluth Complex: American Journal of Science, v. 280, pp. 88-133.