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PETROGRAPHY, GEOCHEMISTRY AND PLATINUM-GROUP ELEMENT
DISTRIBUTION OF PART OF THE UPPER CENTRAL LAYERED ZONE, MAIN
LAYERED SERIES, FOX RIVER SILL, NORTHEASTERN MANITOBA

BY

PAMELA LEE SCHWANN

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS OF THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

CARLETON UNIVERSITY

OTTAWA, ONTARIO

MARCH 13, 1989

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The undersigned recommend to the Faculty
of Graduate Studies and Research
acceptance of the thesis
"Petrography, Geochemistry and Platinum-Group Element
Distribution of Part of the Upper Central Layered Zone, Main
Layered Series, Fox River Sill, Northeastern Manitoba"
submitted by Pamela Lee Schwann, B.Sc. Hons.,
in partial fulfillment of the requirements
for the degree of Master of Science.

Thesis Supervisor

Chairman,
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Carleton University

March 13, 1989

ABSTRACT

The Proterozoic (1882.9 MA) Fox River Sill (FRS) is a 275 km long, 2 - 2.5 km thick mafic - ultramafic intrusion located along the Churchill-Superior Boundary Zone of northeastern Manitoba. It has been subdivided into a lower Marginal Series, a Layered Series and an upper Hybrid Series. The Layered Series is further subdivided into the Lower Central Layered Zone (LCLZ) and the Upper Central Layered Zone (UCLZ). The study interval covers the LCLZ/UCLZ contact and the lower 600 m of UCLZ strata. Within this interval a minimum of 32 cyclic units are recognized, composed of variations in dunite (cumulus ol +/- chr), peridotite (cumulus ol +/- cpx +/- chr), pyroxenite (cumulus cpx +/- ol +/- chr) and gabbro (cumulus pl + cpx +/- ol). Disseminated sulphides (po + pn + ccp + cbn + mkw + py) occur throughout the stratigraphic successions as polymineralic or monomineralic grains. Sulphide assemblages range from Ni-rich in peridotite to more Cu-rich in pyroxenite. Primary sulphides have been replaced and/or recrystallized by silicate, oxide and second-generation Cu-rich sulphide assemblages.

Within the 32 cyclic units there are three main intervals of anomalous platinum-group element (PGE) concentrations (Pt + Pd > 100 ppb); Lower Mineralized Unit, (70 m), Middle Mineralized Unit (50 m), and Upper

Mineralized Unit (5 m). Within these intervals, PGE abundances occur predominantly within sulphide-bearing, medium to coarse-grained olivine clinopyroxenite and are commonly associated with high Cu, S and Se abundances. However correlation coefficient analyses for 1 m long drill core intervals indicates a moderate to poor correlation between PGE and base metal element abundances.

Pt/(Pt + Pd) ratios and Chondrite Normalized Profiles (CNP) indicate that with increasing stratigraphic height, Pd is depleted relative to Pt. S isotope data is notably heavy (+9.2 --> +17.4) indicating that crustal S has been incorporated into the magma.

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CHAPTER I: INTRODUCTION

I.1 LOCATION OF STUDY AREA

The Fox River Sill (FRS) is a 275 km long, 2.0 km thick layered ultramafic intrusion located in northeastern Manitoba. The FRS extends from 94°35', 56°55' to 92°20', 55°45', (Fig. 1). The area investigated is a 600 m thick section at the westernmost extent of the Sill, 1 km directly north of the Fox River at 94°25', 55°51' 45", approximately 55 km by air from Gillam, Manitoba (Fig. 2), (Scoates, 1981; section 462 W.) Thick layers of till and alluvium blanket the study area, restricting outcrop to minor river sections. The area is accessible by air from Gillam or Thompson, although landing is restricted to lakes as there are many rapids in the Fox River. Summer access is further restricted by the shallow depths of many of the lakes in the area.

The FRS was the target of exploration for massive Ni-Cu sulphide deposits by INCO during the 1960's and is currently being explored for concentrations of platinum-group elements (PGE) by BP Resources, Canada Ltd and International Platinum.

FIGURE 1: Geographic Location of the Fox River Sill, (after Scoates and Eckstrand, 1986).

FIGURE 2: Geologic map illustrating the position of 462 W Section Line and drill holes, (after Scoates and Eckstrand, 1986).

FIGURE 3: Composite stratigraphic section of the Fox River Sill, (after Scoates, 1981).

1.2 METHOD OF STUDY

All data presented in this thesis are based on 6 drill core sections due to the lack of bedrock exposure in the area. During August 1986, split core from three diamond drill holes (DDH; Fox 86-1, Fox 86-2, Fox 86-5) in the study area were logged in detail at the Manitoba Department of Mines Core Library in Thompson, Manitoba. Assay results for Cu, Ni, Pt, Pd, and Au were provided by BP Resources.

Representative rock types and sections where $Pt + Pd > 100$ ppb were sampled at this time. Pulps and powders (each representing 1 m intervals) of the PGE anomalous sections were subsequently made available by BP Resources. Data from telescoped core of three INCO drill holes, drilled during the 1960's, were made available by Dr. R.F.J. Scoates of the Geological Survey of Canada. A generalized cross-section of the drill holes is presented in Fig. 4.

Information from these 6 drill holes was used to construct a stratigraphic succession of the layered igneous rocks, (Fig. 5). In September, 1987, further information on the FRS was gained from participation in a drilling program in the eastern part of the west lobe and outcrops of the base of the intrusion along the Stupart River Section.

Detailed petrography of silicate and sulphide minerals was studied in thin, polished-thin and polished sections. Selected pieces of core were polished to enhance the silicate, oxide and sulphide textures.

Geochemical data used in this study included 112 major,

GENERALIZED DRILL HOLE CORRELATION OF THE UPPER CENTRAL LAYERED ZONE, 462W SECTION, FOX RIVER SILL

LOOKING WEST

FIGURE 4: Generalized Drill Hole Correlation of the Upper Central Layered Zone, 462W Section, Fox River Sill.

VERTICAL SCALE 1:3100

HORIZONTAL SCALE 1:2000

minor and trace element analyses (Appendix ii, iii), 89 precious metal analyses (Os, Ir, Ru, Rh, Pt, Pd, and Au; Appendix iv), and 11 S isotope analyses (Appendix v).

Basic statistical tests (correlation coefficients) were used to assess the relationship between PGE concentration and rock type, trace elements and base metal sulphides. Definitions and acronyms used throughout the text are defined in Table 1.

1.3 PREVIOUS WORK

Ultramafic rocks in the area were first recognized by Merritt (1925) who noted "a serpentine rock outcrop about 6 miles below the lower junction of Bigstone and Fox Rivers". Quinn (1955) also described the occurrence of "ultrabasic" rocks on the Fox River which Potter (1962) correlated with ultrabasic rocks he had observed on the Stupart River to the east. Based on aeromagnetic data Potter (1962) also proposed the eastward continuation of the ultrabasic rocks. More recently Scoates (1969, 1971, 1981, 1989) has undertaken a detailed study of the petrology of the FRS and Fox River Belt. Raudsepp and Turnock (1986) have reported on the cryptic variation of primary minerals in the FRS. Major subdivision and nomenclature of the FRS strata follows that initially proposed by Scoates (1981) and modified by Scoates and Eckstrand (1986).

TABLE 1: DEFINITIONS AND ACRONYMS

CSB	Circum-Superior Belt
FRB	Fox River Belt
TNB	Thompson Nickel Belt
FRS	Fox River Sill
MS	Marginal Series
LS	Layered Series
UCLZ	Upper Central Layered Zone
LCLZ	Lower Central Layered Zone
HRS	Hybrid Roof Series
UMU	Upper Mineralized Unit
MMU	Middle Mineralized Unit
LMU	Lower Mineralized Unit
PGE	Platinum-group elements (Pt, Pd, Rh, Os, Ir, Ru)
PGM	Platinum-group minerals
PR	(Pt/(Pt + Pd))
P/OIR	(Pt + Pd)/(Os + Ir + Ru)
BMS	Base metal sulphide

cumulus minerals - minerals which have fractionally crystallized from a magma. Fractionation can have occurred by crystals separating from the liquid (by settling or floating), by the liquid separating from the crystals (by convecting away), or by some other mechanism (through intermediary gas phase) (Irvine, 1982), (Campbell, 1978). Gravitational settling is not required.

Descriptive classification of cumulate rocks by the nature of postcumulus minerals: (Wager et al., 1960).

orthocumulate: contains abundant postcumulus material, cumulus minerals exhibit original crystallization habit (25 - 50% postcumulus material).

mesocumulate: contains less postcumulus material and cumulus grains adjoin in part along mutual interference boundaries developed by overgrowth (7 - 25% postcumulus material).

adcumulate: contains minor discrete postcumulus minerals and exhibit mutually interfering grain boundaries (0 - 7% postcumulus material).

cumulate - igneous rock characterized by cumulus framework (Irvine, 1982).

rhythmic unit - succession of layer types that are repeated stratigraphically in a regular way.

cyclic unit - a rhythmic unit in which the cumulus mineral sequence reflects the order of fractional crystallization from the magma.

laminae - thin (<25 cm), sharply defined layers.

layer - broadly conformable sheet (>25 cm) of individual rock type.

oikocryst - an individual postcumulus crystal which is host to smaller cumulus crystals.

chadacryst - relatively small cumulus crystals scattered as poikilitic inclusions throughout a host crystal (oikocryst).

chondrite normalized profile - diagrammatic representation

of PGE concentrations normalized with respect to chondritic abundances. PGE are plotted from left to right in order of decreasing melting point of the metals, (Barnes et al., 1985).

primary sulphide - sulphides which have directly precipitated from a melt.

secondary sulphide - sulphides which have either been mobilized or replaced primary sulphide or silicate or sulphides resulting from alteration of primary sulphide.

mineralized samples - refers to samples in which Pt + Pd > 100 ppb.

mineral abbreviations - (modified from Kretz, 1983, mineral names are not capitalized).

ol = olivine; cpx = clinopyroxene; opx = orthopyroxene; pl = plagioclase; chr = chromite; po = pyrrhotite; ccp = chalcopyrite; cbn = cubanite; pn = pentlandite; py = pyrite; mkw = mackinawite; bn = bornite; sph = sphalerite; gn = galena; tcl = tochilinite; mll = millerite; mgn = magnetite; ilmgn = ilmenomagnetite;

I.4 PURPOSE AND SCOPE

Ultramafic - mafic intrusions host a variety of mineral deposit types, most notably concentrations of PGE (e.g., Bushveld and Stillwater Complexes), chromite (Bushveld), massive Ni-Cu sulphides (Sudbury, Thompson). These deposit types are commonly formed during the magmatic stage, although there is much debate as to which stage and by what process in the evolution of crystallization of the magma do metals, and PGE in particular, become concentrated. As the generation of economic concentrations of PGE appears to be closely associated with magmatic processes (including late deuteric activity) studying the petrography and petrochemistry of the mafic-ultramafic intrusive rocks permits attempts at reconstructing past magmatic processes and potential modelling of the behavior of PGE during crystallization processes.

The objectives of this investigation are to establish:

- (1) The petrology of the rock type succession.
- (2) The distribution of PGE and correlated elements in intervals throughout the stratigraphic succession.
- (3) The sulphide mineralogy and distribution.
- (4) A model to determine the relationships between the different rock types, the relationship of the sulphides to the rock types and to better understand the controls on PGE concentrations within the layered succession of rocks in the Upper Central Layered Zone (UCLZ) of the FRS.

CHAPTER II: GENERAL GEOLOGY

II.1 REGIONAL GEOLOGY

The Fox River Sill (FRS) is a major layered, predominantly ultramafic intrusion located within the Fox River Belt of the Churchill Superior Boundary Zone. The Fox River Belt is one of nine Archean (2450 - 1700 MA) segments of the Circum-Superior Belt (Thomas and Gibb, 1977, Baragar and Scoates, 1981). In areas of poor outcrop it may be traced by gravity and magnetic anomalies (Klasner and Bomke, 1978).

Correlation of the segments of the Circum-Superior Belt is based on the presence of a combination of stratigraphic and magmatic features summarized by Baragar and Scoates (1981). Major aspects common to these segments include: deposition on Archean basement of supracrustal rocks which conformably change from shallow water, clastic-dominated sequences to deeper water volcanic sequences, the presence of iron formation, and mafic and ultramafic rocks. In northeastern Manitoba, the Circum-Superior Belt is composed of the Fox River and Thompson Nickel Belts (Opwagan Group). They have similar sedimentary sequences and both contain a high proportion of intrusive and extrusive ultramafic rocks. Correlation of the two belts is provisional as Thompson Nickel Belt rocks are deformed, metamorphosed to middle amphibolite facies and intruded by Hudsonian granitic rocks, whereas Fox River Belt rocks are relatively undeformed and consist of low grade

subgreenschist facies assemblages. Ultramafic sills of the Thompson Nickel Belt tend to be little differentiated; Fox River Belt sills are commonly differentiated (Eckstrand, pers comm., 1986). Northeast-striking Molson dykes are not present in the Fox River Belt, but their deformed and metamorphosed equivalents occur in the Thompson Nickel Belt (Scoates and Macek 1978; Cranston and Turek 1976; Hubregtse 1980; Weber 1977, Weber et al., 1978). Molson dykes range from mafic to ultramafic in composition.

II.2 AGE RELATIONSHIPS

The similarity in the range of composition of the Molson dykes and mafic/ultramafic rocks of the Fox River and Thompson Nickel Belts has led to the suggestion that the Molson dykes acted as feeders to the mafic igneous rocks of the Fox River and possibly the Thompson Nickel Belts (Scoates and Macek, 1978). Precise U-Pb zircon ages for Molson dykes at Cross Lake (1,883.7 [+1.7, -1.5] Ma) and Cuthbert Lake (1,883 [+2, -2] Ma) and from a gabbroic pegmatoid from the Marginal Series of the FRS (1,882.9 [+1.5, -1.4] Ma) are similar (Heaman et al., 1986) indicating that Molson dyke magmatism was likely related to the emplacement of the FRS. A precise U-Pb zircon age for the Thompson Nickel Belt has not been determined; however, the presence of Molson dykes, albeit deformed, indicates that emplacement must precede 1883 Ma. Cumming et al., (1982) suggested an age of 2320 ± 30 Ma for the time of emplacement of Thompson Nickel Belt ultramafic rocks and related Ni-sulphide

deposits, based on Pb isotope ratios of nickel sulphides.

Previous attempts to date the rocks of the Fox River Belt based on Rb-Sr systematics yielded ages of 1735 Ma and 1720 Ma (Weber and Scoates, 1978). These ages are similar to the 1740 Ma age of the Churchill paragneiss adjacent to the FRS and likely reflect a metamorphic rather than magmatic event (Scoates 1981).

II.3 GEOLOGY OF THE FOX RIVER BELT

The Fox River Belt is a 15-20 km wide, steeply dipping, north-facing homoclinal sequence composed of sedimentary, ultramafic to mafic differentiated sills and volcanic rocks. Metamorphism is low grade, ranging from sub-greenschist facies at the stratigraphically highest levels increasing to lowermost greenschist facies at the stratigraphically lowest levels. The following is summarized from Scoates (1981, 1971), and Baragar and Scoates (1981), (refer to Fig. 2).

Sedimentary rocks occur in three positions in the stratigraphic section and are informally referred to as the Lower (5 km), Middle (1 km) and Upper (1 km) Sedimentary formations. They consist primarily of fine-grained, finely laminated quartz-rich siltstone, argillite, and shale interlayered with sandstone, quartzite and dolomite. Lithic components are notably absent. Iron formation and carbonaceous shale occur in the Lower Sedimentary formation.

Differentiated sills intrude the upper part of the Lower Sedimentary formation, and the larger FRS intrudes a siltstone-sandstone sequence of the Middle Sedimentary formation. The smaller sills within the Lower Sedimentary formation are simply differentiated from a pyroxene-rich contact zone overlain in succession by a peridotitic zone, a pyroxenitic zone, a gabbroic and hybrid granophyre-bearing roof zone. The more voluminous FRS is composed of the same major units as the smaller sills, but it has undergone more complex differentiation as a result of repeated injections of basic magma pulses (Scoates, 1981; 1989). The FRS has been subdivided into three lithostructural Series; Marginal Series, Main Layered Series, and Hybrid Roof Series, (Fig. 3).

Volcanic rocks are intercalated with the sediments at two stratigraphic positions and are informally referred to as the Lower (3 km) and Upper (2 km) Volcanic Formations. The volcanic rocks exhibit a progressive change in character from ultramafic (komatiitic) to mafic (tholeiitic), suggesting derivation from a differentiating source (Scoates, 1981; Baragar and Scoates, 1981). The Lower Volcanic formation is related to magma expelled from the smaller differentiated intrusions in the Lower Sedimentary sequence; the Upper Volcanic formation is related to magma expelled from the FRS magma chamber during its crystallization.

II.4 GEOLOGY OF THE FOX RIVER SILL

The Fox River Sill (FRS), which at present erosional levels is 2 km thick, extends E-W along strike for 200 km, and dips steeply to the north. It is separated into an east and west lobe. Distinctive aeromagnetic anomalies which continue into Paleozoic Hudson Bay Basin rocks beyond the east lobe suggest eastward continuation of the FRS for 100 km, and segmented anomalies 25 km to the NW of the west lobe suggest the westward continuation of the FRS. Westward termination of the Sill corresponds to structural pinching out of the Fox River Belt against Churchill paragneisses to the north and the Pikwitonei granulite domain to the south.

II.4.i Internal Stratigraphy

The FRS has been subdivided into the Marginal Series, Main Layered Series, and Hybrid Roof Series, each characterized by distinctive rock type associations, (Fig. 3), (Scoates 1981, Scoates et al., 1988). The Marginal Series and Main Layered Series are further distinguished by a regular cyclic arrangement of rock types, (Scoates, 1981). A brief description of the three Series is summarized from Scoates, (1981) and Scoates and Eckstrand (1986). For a more detailed description of these Series, the reader is referred to Scoates (1989).

4.1.i Marginal Series

The Marginal Series is a repeated succession of layered peridotite (cumulus ol +/- cpx), pyroxenite (cumulus cpx +/- ol) and gabbro (cumulus pl + cpx +/- ol) which ranges up to 300 m in thickness. Peridotite and pyroxenite are plagioclase bearing, and gabbros contain minor amphibole.

The contact between the Marginal Series and Layered Series has been proposed to be intrusive, but locally faulted (Scoates 1981). Recent drilling by BP Resources in the eastern part of the west lobe at two localities through this contact has intersected intensely brecciated material and metre intervals of unrecoverable core suggesting a faulted contact between the Marginal and ultramafic lower Main Layered Series.

4.1.ii Main Layered Series

The Main Layered Series consists of a 2000 m succession of cumulate rocks. It has been subdivided into the

- A) Lower Central Layered Zone (LCLZ), a 1000 m succession of predominantly ultramafic rocks composed of repeated cyclic units of thick dunite layers (cumulus ol +/- chr) alternating with thinner peridotite (cumulus ol +/- cpx +/- chr) and pyroxenite layers (cumulus cpx +/- ol +/- chr) .
- B) Upper Central Layered Zone (UCLZ), an 1100 m succession of ultramafic and mafic rocks consisting of numerous repetitive, small scale cyclic units composed of variations of dunite (cumulus ol +/- chr), peridotite (cumulus ol +/-

cpx +/- chr), pyroxenite (cumulus cpx +/- ol +/- chr) and gabbro (cumulus pl + cpx +/- ol).

4.1.iii Hybrid Roof Series

The Hybrid Roof Series is the thin (50 m) uppermost zone of the FRS. It is primarily composed of quartz granophyre-bearing gabbronorite, medium-grained to pegmatitic gabbro, and hosts inclusions of partially assimilated sedimentary rocks.

This thesis concerns the upper 50 m of LCLZ, the LCLZ /UCLZ contact and the lower 600 m of UCLZ strata.

CHAPTER III: PETROGRAPHY OF ROCK UNITS

III.1 NOMENCLATURE OF ROCK UNITS

Classification of mafic-ultramafic igneous rock types is particularly controversial. Various classification schemes have been proposed based on cumulus and intercumulus mineralogy, modal mineralogy and whole rock chemistry. Resultant terminology is inconsistent between individual intrusions and amongst coworkers in the field of igneous petrology. The problem of naming cumulate rocks has been discussed by Wager et al., (1960); Jackson (1971); Irvine (1982); and Zientek et al., (1985). In this study rocks are classified on the basis of cumulate mineralogy and traditional names (as suggested by Irvine, 1982). Mineral abbreviations conform to Kretz (1983). In the study area, cumulus mineral assemblages ol +/- chr; ol +/- cpx +/- chr; cpx + ol +/- chr; and pl + cpx +/- ol form the rock sequence dunite, peridotite, olivine clinopyroxenite and the olivine gabbro-gabbro series, respectively (Table II). Normative mineralogy was plotted after Streckeisen (1976), (Fig. 6) using rock-type fields defined by cumulus phases present (as in Table II).

FIGURE 6: Classification of Rock Type Based on Normative Mineralogy and Observed Cumulus Phases.

TABLE II: CUMULUS MINERAL ASSEMBLAGES AND ROCK TYPE NOMENCLATURE

Cumulus Phase*	Conventional Rock Name
ol + chr (ol > 90%)	Dunite
ol +/- chr (ol < 90%)	Peridotite
ol +/- cpx +/- chr (ol > cpx)	Peridotite
cpx + ol +/- chr (cpx > ol)	Olivine clinopyroxenite
pl + cpx +/- ol	Olivine gabbro-Gabbro
*Cumulus minerals are listed in order of decreasing abundance.	

Intercumulus minerals were not used in classification of rock types as intercumulus mineralogy has been commonly documented as changing along strike (e.g., Zientek et al., 1985). Orthopyroxene is not a cumulus mineral although it occurs as a minor intercumulus phase which becomes more prominent in rocks derived from more highly fractionated magma: i.e., olivine clinopyroxenite and, particularly, gabbroic rocks. Primary minerals have been extensively altered and commonly their identification is based on alteration assemblages, relict mineral habits and textures. Alteration processes include serpentinization, uralitization and saussuritization.

PLATE I Examples of ultramafic rock types

1.A Foliated dunite (ol + chr cumulate) with large pyroxene oikocrysts; (DH1-7268).

1.B Photomicrograph of foliated dunite. Alteration products outline serpentized cumulus olivine grains. Cumulus chromite grains occur as inclusions within cumulus olivine. Opaque material occurs in intercumulus area; (DH2-7298).

1.C Peridotite (ol + chr cumulate) (DH2-7298)

1.D Sulphide-bearing olivine clinopyroxenite (cpx + ol cumulate). Olivine grains are black, clinopyroxene are gray, sulphides are white; (DH2-7547).

1.E Photomicrograph of peridotite. Serpentized cumulus olivine are host by clinopyroxene oikocryst. (DH2-7534).

III.1.1 DUNITE

Dunite (Plate I a,b) is an olivine cumulate composed of >90% cumulus olivine, minor (<2%) cumulus chromite and <10% intercumulus material. Dunite is grayish green and may exhibit a patchy, mottled appearance which reflects the distribution of coarse grained (0.5 - 1.5 cm) clinopyroxene oikocrysts. Densely packed equigranular cumulus olivine grains (0.50 - 3 mm) are subround to tabular and often display preferential orientation. Cumulus chromite occurs as disseminated clusters of idiomorphic octahedral crystals (0.25 mm) both as inclusions within cumulus olivine and in the interstitial areas between olivine grains. Pyroxene and plagioclase are minor (<10%) primary intercumulus minerals.

III.1.2 PERIDOTITE

Peridotite (Plate I c,e) is composed of cumulus ol +/- cpx +/- chr with >10% intercumulus material. Peridotite is dark black to green (olivine) with gray flecks (clinopyroxene). Cumulus olivine grains are equant to subround and range from 0.25 - 1.5 mm. They may contain spherical inclusions infilled with chlorite (Plate VI a). Clinopyroxene may be either a cumulus or postcumulus phase. Cumulus clinopyroxene exhibits adcumulus growth and commonly contains altered orthopyroxene exsolution. Postcumulus clinopyroxene is poikilitic and forms stubby, ovoid, 3 - 10 mm xenomorphic oikocrysts which contain 0.25 - 0.50 mm olivine chadacrysts (Plate III c,d). Chromite is a minor

cumulus mineral (<1%), occurring as idiomorphic clusters within either cumulus olivine or intercumulus material. Orthopyroxene and plagioclase are minor (<10%) intercumulus phases.

III.1.3 OLIVINE CLINOPYROXENITE

Olivine clinopyroxenite (Plate I d) is composed of cumulus cpx + ol +/- chr. The transition from peridotite to olivine clinopyroxenite is defined by a change from olivine to clinopyroxene as the predominant cumulus phase. Olivine clinopyroxenite varies from grayish black (olivine-rich) to a light greenish gray (clinopyroxene-rich) reflecting the variable proportion of cumulus clinopyroxene to olivine. Clinopyroxene grains are commonly twinned with fine exsolution of orthopyroxene (herringbone pattern). Orthopyroxene (10 -15%) also commonly forms stubby 10 - 50 mm oikocrysts which host both olivine and clinopyroxene. Plagioclase (5 - 15%) is also postcumulus and is most prevalent in olivine-poor pyroxenite.

III.1.4 GABBRO

There is both cumulus (olivine gabbro-gabbro series) and non-cumulus gabbro (ilmenomagnetite-bearing gabbro, gabbroic pegmatite) in the study interval.

PLATE II EXAMPLES OF MAFIC ROCK TYPES

II.A "Salt & pepper" olivine gabbro. Dark black spots are olivine, gray: clinopyroxene and white: plagioclase. Weakly defined modal laminae of melanocratic gabbro at right hand side of picture; (DH1-7039)

II.B Photomicrograph of "salt & pepper" olivine gabbro. Cumulus plagioclase is pseudomorphously replaced by prehnite, hydrogrossular and epidote; large rounded olivine grains by serpentine; clinopyroxene is partially replaced by chlorite; (DH5-7975).

II.C "Mottled" olivine gabbro. Olivine grains (black) form mottled texture and define textural lamination; (DH5-7814).

II.D Photomicrograph of "mottled" olivine gabbro. Secondary replacement minerals as in II.B; (DH5-7808)

II.E Ilmenomagnetite-bearing gabbro. Coarse - medium grained gabbro grades into fine grained gabbro which is abruptly overlain by coarse grained gabbro; (DH2-7397).

II.F Photomicrograph of ilmenomagnetite-bearing gabbro exhibiting sub-ophitic texture. Pyroxene, amphibole and magnetite are replaced by chlorite, and plagioclase contains dusty inclusions of clay alteration products; (DH2-7397).

II.G Pegmatitic, amphibole-bearing gabbroic material in olivine clinopyroxenite; (DH1-7025).

II.H Coarse grained orthopyroxene-bearing gabbroic material in plagioclase-bearing olivine clinopyroxenite; (DH1-7010).

1.4.i Olivine Gabbro - Gabbro Series (Plate II a,b,c,d)

Gabbro is composed of cumulus pl + cpx +/- ol.

Orthopyroxene is a common postcumulus phase which forms stubby oikocrysts. Gabbro ranges from medium gray to milky white and exhibits a wide variety of textures from a fine-grained, equigranular, "salt and pepper" (Plate II a) to a laminated "olivine mottled" (Plate II c) to a massive aphanitic creamy white rock (Plate V h). Cumulus plagioclase laths are 0.5 - 1.0 mm. Clinopyroxene grains are variable in size and shape and commonly exhibit adcumulus growth. Cumulus olivine grains (0.5 - 1.5 mm) are subround (Plate II b). Smaller olivine grains (0.25 - 0.5 mm) are often linked together to form a "mottled" texture (Plate II d).

1.4.ii Ilmenomagnetite-bearing Gabbro (Plate II e,f)

Ilmenomagnetite-bearing gabbro is composed of non-cumulus equigranular plagioclase, pyroxene, amphibole and ilmenomagnetite. It is distinct from the olivine gabbro - gabbro series by its subophitic texture and the presence and abundance (5 - 10%) of ilmenomagnetite grains (Plate II e). Plagioclase laths and bladed pyroxenes are interpenetrant. Within an interval of gabbro, the grain size of all constituents may abruptly and proportionally decrease or increase. The gabbro texture is well preserved, but the primary silicate mineralogy is altered. Plagioclase is partially converted to hydrogrossular and epidote, pyroxene is altered to amphibole and chlorite, and magnetite is

replaced by biotite and chlorite.

1.4.iii Gabbroic Pegmatite (Plate II g,h)

Within the stratigraphic succession there are minor, thin (~20 cm) zones of coarse-grained gabbro. Contacts with surrounding rocks are irregular. They are randomly located and commonly separate individual rock layers. They do not display intrusive relationships with adjacent rocks and appear similar to "segregation pockets" described by Helz (1980); i.e., they represent "in situ" crystallization of trapped intercumulus magma.

III.2 POSTCUMULUS MODIFICATION

Most cumulates have undergone varying degrees of postcumulus modification, either by adcumulus growth or resorption.

III.2.1 Adcumulus Processes (Plates III a)

The process of adcumulus growth, first proposed by Hess (1939) to explain the enlargement of original cumulus grains, has been continually refined by workers including Wager et al., (1960); Jackson (1971); and Tait et al., (1984). Olivine + chromite cumulates (dunites) exhibit extreme adcumulus growth of olivine to form a virtually monomineralic rock. Clinopyroxene + olivine cumulates (olivine clinopyroxenite) commonly exhibit adcumulus growth of clinopyroxene. Original cumulus clinopyroxene may form monomineralic accumulations of fine to medium grained (0.5 mm) clinopyroxene, with triple point grain boundary

PLATE III POST CUMULUS MODIFICATION

III.A Adcumulus growth of clinopyroxene grains in olivine clinopyroxenite; (DH1-7253m).

II.B Subround olivine chadocrysts in clinopyroxene oikocryst (plane polarized light); (DH1-7021).

III.C As above with crossed nicols. The proportion of cumulus olivine inside the oikocryst is less than that outside the oikocryst. This observation and the subround nature of the olivine grains suggest that olivine has been resorbed, resulting from reaction of cumulus olivine with intercumulus liquid to form clinopyroxene; (DH1-7021).

PLATE IV STRUCTURAL DEFORMATION

IV.A Matrix-supported breccia in peridotite. Matrix consists of fine grained, foliated tectonic breccia and carbonate which contains angular peridotite fragments of variable size. The matrix comprises 50 - 90 volume % of the breccia; (DH1-7079).

IV.B Clast-supported breccia in oikocrystic peridotite. Angular fragments consist of rodingite (altered gabbro). The matrix comprises 30 - 50 volume % of the breccia; (DH1-7229).

junctions.

In gabbro, plagioclase chadacrysts in clinopyroxene oikocrysts are fine grained and randomly oriented. Pseudomorphed plagioclase laths outside the oikocryst are coarser grained and locally exhibit a preferential orientation. This observation was also noted by Mathison (1987) from a layered gabbroic intrusion in Australia. As the plagioclase chadacrysts have no preferential alignment he concluded that the plagioclase lamination was a product of postcumulus modification (adcumulus growth) on original cumulus plagioclase.

III.2.2 Resorption Processes (Plate III c,d)

In peridotite irregular, ovoid to round olivine grains (chadacrysts) are common within clinopyroxene or orthopyroxene oikocrysts. The number of cumulus olivines within the oikocryst is less than that outside the oikocryst. This distribution suggests that the pyroxene has formed from reaction of the cumulus olivine with intercumulus liquid, as was noted by Jackson (1971) in rocks from the Stillwater Complex.

III.3 PRIMARY INTERNAL STRUCTURES; Layering, Layer contacts, Laminae, Lamination & Cyclic Units

III.3.1 Layering

Compositional layering is defined by changes in the appearance/disappearance and proportion of olivine, clinopyroxene and plagioclase as cumulus phases and manifest by changes in lithology from dunite to peridotite to olivine clinopyroxenite and olivine gabbro. Layers vary in thickness from <1 cm to 25. Modal, grain-size, and texturally graded layers occur, and are best developed in gabbroic rocks, although peridotite and pyroxenite also commonly display these features. Modal layering is commonly gradational over metre-length intervals. In gabbroic rocks, modal layering is illustrated by the alternation of leucocratic to mesocratic to melanocratic layers. Modally graded layers often mark the transition from peridotite (ol +/- cpx) to pyroxenite (cpx + ol) as clinopyroxene becomes the more dominant cumulus phase. Textural layering is especially common in gabbro, with fine-grained olivine "salt and pepper" gabbro grading into a slightly coarser grained "flecked" olivine gabbro and subsequently into a "mottled" olivine gabbro, over metre-length intervals. Peridotite also has texturally graded layers. Poikilitic peridotite (ol +/- chr) with clinopyroxene oikocrysts may abruptly change to non-poikilitic peridotite (ol +/- cpx +/- chr) as clinopyroxene becomes a cumulus mineral. Grain-size graded layers are not common. They are most commonly observed in peridotite where cumulus olivine grains are gradually

PLATE V PRIMARY INTERNAL STRUCTURES

V.A Phase contact between peridotite (ol + chr cumulate) and overlying olivine clinopyroxenite (cpx + ol cumulate). Note the sharpness and irregularity of the contact; (DH1-7238).

V.B Photomicrograph of phase contact between olivine clinopyroxenite adcumulate (at base) and overlying coarse grained peridotite mesocumulate; (DH2-7485).

V.C Sharp grain size contact between fine-grained olivine clinopyroxenite and overlying coarse-grained olivine clinopyroxenite; (DH5-7835)

V.D Interlaminated peridotite (black) and olivine clinopyroxenite (gray) containing both phase (pyroxenite lamina bordered by oikocrystic peridotite) and modal contacts (upper contact between peridotite and overlying olivine clinopyroxenite is marked by an increase in the proportion of cumulus clinopyroxene); (DH2-7503).

coarser grained as the proportion of intercumulus material increases. A sharp grain-size contact was noted in an olivine clinopyroxenite where clinopyroxene grains changed from a fine-medium (<0.25 mm) to a coarse grained (>0.5mm) phase (Plate V c). The abrupt rather than gradational nature of this contact may suggest that the abrupt change in grain size is a result of postcumulus metasomatism and recrystallization rather than reflecting a primary crystallization feature.

III.3.2 Layer contacts are both phase and modal (Irvine, 1982). Phase contacts (Plate V a,b) are characterized by a change in the mineral assemblages, modal contact (Plate V c) by the change in the proportion of mineral assemblages. Phase contacts (e.g., peridotite (ol +/- chr) --> olivine clinopyroxenite (cpx + ol +/- chr) are sharp and may be irregular. They may also be subtle, [e.g., plagioclase-bearing olivine clinopyroxenite (cpx + ol +/- pl) --> olivine gabbro (pl + cpx +/- ol)], and the point at which plagioclase becomes the dominant cumulus mineral is not readily evident. Modal contacts are gradational over 10 to 100 cm and are best exemplified by contacts between peridotite (ol +/- cpx +/- chr) and olivine clinopyroxenite (cpx + ol +/- chr).

III.3.3 Laminae are thin, sharply defined layers. For convenience, an arbitrary layer thickness of < 25 cm is referred to as a lamina, > 25 cm as a layer. Peridotite and pyroxenite laminae of similar thickness are commonly finely

interlaminated (Plate V d). Pyroxenite and gabbro are also interlaminated. Thick pyroxenite sequences are commonly interrupted by gabbroic laminae (10 cm). In thick gabbroic intervals, thin (5 - 15 mm) melagabbro to plagioclase-bearing pyroxenite laminae occur.

III.3.4 Lamination refers to subtle features which are pervasive throughout a cumulate fabric. Textural lamination is common in gabbroic and peridotitic rocks, where chains of olivine and clinopyroxene grains form a mottled texture which define the lamination.

III.4. ALTERATION (Plate VI)

Hydrous alteration of primary silicate assemblages is pervasive and precluded a systematic study of primary mineral chemistry. Identification of primary minerals is commonly based on alteration assemblages, relict mineral shapes and textures. Alteration processes include serpentinization, uralitization and saussuritization. A detailed study of these processes is beyond the scope of this thesis.

III.4.1. Serpentinization (Plate VI a,b,c,d,e,)

Serpentinization is the most prevalent and pervasive form of alteration of the ultramafic rocks. Olivine and orthopyroxene are partially to completely converted to serpentine minerals and minor magnetite. Serpentine polymorphs may be pseudomorphic, non-pseudomorphic or vein-filling minerals.

PLATE VI ALTERATION

VI.A Serpentinization: Photomicrograph of pseudomorphic hourglass serpentinization of cumulus olivine grains with spherical inclusions infilled with chlorite (possible melt inclusion); (DH1-7218).

VI.B Serpentinization: Photomicrograph of oriented idiomorphic inclusions (garnet, melilite) in serpentinized cumulus olivine grains; (DH1-7218).

VI.C Serpentinization: Photomicrograph of non-pseudomorphic, fine-grained flakes of serpentine replaces peridotite (ol + chr cumulate); (DH1-7084).

VI.D Serpentinization: Serpentine vein(picrolite) crosscuts peridotite; (DH1-7251).

VI.E Serpentinization: Bastite alteration of postcumulus orthopyroxene grain. Secondary magnetite occurs along cleavage planes; (DH1-7188).

VI.F Saussuritization: Partial replacement of primary mineralogy and texture in gabbro by prehnite, hydrogrossular and epidote; (DH5-7806)

VI.G Saussuritization: Complete replacement of primary mineralogy and texture in gabbro by dense aphanitic, milky white alteration products, (prehnite + hydrogrossular + epidote); (DH5-7885).

4.1.i Pseudomorphic Textures (Plate VI a,b,e)

Serpentine minerals have pseudomorphed cumulus olivine and postcumulus orthopyroxene. Serpentinization originated along grain boundaries and fractures and advanced toward the core of the olivine grains to produce the characteristic mesh textures and hourglass structures (Plate VI a). Secondary magnetite, formed from Fe liberated from the olivine lattice during serpentinization, occurs as fine aggregates which rim the serpentine pseudomorphs after former olivine grains and as subhedral grains which occur in their cores. Dunite commonly contains veinlets of fine-grained magnetite. Completely serpentinized olivine grains commonly contain dozens of oriented and unoriented inclusions of idiomorphic, colorless, high relief minerals (garnet/melilite) (Plate VI b). Orthopyroxene lamellae in clinopyroxene may be preferentially replaced by serpentine and postcumulus orthopyroxene grains are altered to intergrown bastite and amphibole (Plate VI e). Orthopyroxene has also been altered to intergrowths of talc and tremolite.

4.1.ii Non-pseudomorphic Textures (Plate VI c)

Non-pseudomorphous serpentine replaces both cumulus and intercumulus minerals and is formed from either primary minerals or from pseudomorphous serpentine textures (Wicks and Whittaker, 1977). Rocks consist of completely amorphous masses and patches of interpenetrant anhedral flakes and blades of serpentine (Plate VI c). Plagioclase is commonly

replaced by chlorite prior to serpentinization (O'Hara, 1967), and Wicks and Whittaker (1977) have documented fine grained interlocking serpentine after plagioclase.

4.1.iii Vein Textures (Plate VI d)

Serpentine veins are late stage features which cross-cut primary and secondary mineral assemblages. They predominantly occur within peridotitic rocks as both "asbestiform" chrysotile veins and as "non-asbestiform" massive, fine-grained picrolite veins which are characteristically turquoise and contain euhedral pyrite cubes.

III.4.2 Uralitization

Recrystallization of clinopyroxene to amphibole is not a widespread phenomena, and is most commonly associated with coarse-grained to pegmatitic olivine clinopyroxenites. Alteration of pyroxene to amphibole began along clinopyroxene grain boundaries and cleavages and proceeded inwards. Clinopyroxene may be completely converted to coarse-grained amphibole, or it may be only partially altered to fine grained aggregates of amphibole and chlorite.

III.4.3 Saussuritization (Plate VI f,g)

Plagioclase has been extensively replaced by hydrogrossular, vesuvianite, epidote, chlorite and prehnite. This alteration assemblage is characteristic of low temperature metasomatic alteration and of a high water:rock mass ratio (Bird et al., 1988). Alteration of plagioclase

commonly destroys primary textural relationships, but in gabbroic rocks, plagioclase is often pseudomorphously replaced, preserving its cumulus texture. Intercumulus plagioclase in dunite, peridotite and pyroxenite is replaced by a bluish-gray to brownish-gray fibrous and bow-tie chlorite. The intensity of saussuritization is reflected by the gabbro colour. Relatively unaltered gabbro is medium gray. With progressive saussuritization of plagioclase, the gabbro changes from medium gray to light green to a pale milky white, the latter representing the most intensely saussuritized rocks. Primary mineralogy may influence the degree of alteration. Plagioclase-rich gabbros preferentially may be more completely saussuritized than melagabbros.

The pervasiveness of serpentization and saussuritization with only minor relict olivine or plagioclase suggests that fluids circulated effectively throughout dunite, peridotite and gabbro. Uralitization is not as pervasive and primary clinopyroxene grains are generally relatively unaltered; unserpentinized cores and entire cumulus olivine grains are common. Consequently dunite, peridotite and gabbro are the most altered whereas olivine clinopyroxenite is the least.

III.5 STRUCTURE

The layered rock succession is commonly interrupted by fault breccia; intervals of rubbly core and gouge and by matrix and clast-supported breccias. Small scale (mm) fault displacements are recorded by interlaminated peridotite - pyroxenite layers (Plate V d). Serpentine/picrolite veins are commonly brecciated and fragments rotated. The relative timing of brittle deformation postdates both consolidation of the layers and serpentinization episode(s). Fault breccias were commonly observed in peridotite and gabbro intervals; dunite often displayed a strong foliation; olivine clinopyroxenite did not commonly contain fault breccia. Contacts between rock types are often unconformable and are marked by fault breccia, suggesting that juxtaposed units may not represent rocks which have crystallized in sequence. Alternatively, the rocks may have had little displacement and faulting at the contact of the adjacent rocks is a function of their contrasting competencies. Variations in layer attitude and thickness as seen in the cross-section (Fig. 4) may reflect displacement due to faulting with subsequent structural thickening of rock packages.

III.6 DESCRIPTION OF STRATIGRAPHIC SECTION

III.6.1 DRILL HOLE CORRELATION

The cross section (Fig. 4) illustrates the variable but steep to vertical to slightly overturned north-facing dips of correlated units. The near vertical dips result in a short interval of overlap between DDH's Fox 1 and Fox 2 and no overlap of units between DDH's Fox 2 and Fox 5.

Correlation was based on lithologies intersected in Fox 1, Fox 2 and Fox 5 and INCO 13231, 13242, and 13240 holes.

Rocks intersected at the base of Fox 1, (LCLZ), represent crystallization products from the most magnesian magma, with rocks derived from more fractionated magma (UCLZ) occurring at successively higher stratigraphic intervals. The rocks intersected at the top of Fox 5 represent the stratigraphically highest UCLZ rocks of the study section.

The vertical stratigraphic succession intersected in drill holes Fox 1, 2 and 5 and INCO 13231, 13242 and 13240 is shown in Figure 2. It represents over 650 m of strata including the upper 50 m of LCLZ rocks, the LCLZ-UCLZ contact and the lowermost 600 m of UCLZ strata.

6.1.i LCLZ/UCLZ Contact

The transition between LCLZ to UCLZ rocks is marked by a change in character of the rock from ultramafic in the LCLZ to a combination of ultramafic and mafic rocks in the UCLZ. Thick sequences of dunite and peridotite commonly capped by thin olivine clinopyroxenite layers in the LCLZ yield to thinner dunite and peridotite capped by thicker

olivine clinopyroxenite and gabbro layers in the UCLZ. Plagioclase occurs as a common, cumulus mineral and sulphides, which are sparsely distributed in LCLZ rocks (Scoates and Eckstrand, 1986) are a ubiquitous, albeit minor (<3% disseminated) component of UCLZ rocks. Another difference between LCLZ and UCLZ rocks is reflected by the whole rock Ni contents of the rocks; LCLZ dunite peridotite near the LCLZ/UCLZ contact contain much higher whole rock nickel contents (2000-4000 ppm) than their counterparts from the UCLZ rocks (600 ppm). The anomalously high Ni in LCLZ rocks which contain relatively low sulphide contents likely reflects the occurrence of Ni in the olivine lattice. In thick, sulphide-poor dunite - peridotite sequences in both the LCLZ and UCLZ, fluctuations in whole rock Ni content likely establishes the sites of new magma influx that are otherwise (megascopically) not evident (as suggested by Irvine and Smith, 1967).

The LCLZ/UCLZ contact is placed at the base of a succession of dunite/peridotite capped by olivine clinopyroxenite. This cyclic unit marks the predominance of pyroxenite relative to peridotite. The base of the dunite is marked by an increase in whole rock Ni from 2700 ppm to 4100 ppm. Both LCLZ and UCLZ rocks at the contact are sulphide-bearing.

III.6.2. DEFINITION OF CYCLIC UNITS

The rock types are interlayered in a systematic, rhythmic succession and the cumulus mineral sequence represents the fractional crystallization order of the magma. These rhythmic units are referred to as cyclic units, (Irvine, 1982). Few of the cyclic units, represented by the rock sequence dunite, peridotite, olivine clinopyroxenite and gabbro, are fully developed. More commonly the rock sequence progresses through two or three rock types before being repeated (beheaded cyclic unit; Jackson, 1970). In many of the interlayered sequences of peridotite --> olivine clinopyroxenite or olivine clinopyroxenite --> gabbro, the layer thickness of the rock type is less than 0.25 m. As this study is based on drill core, the lateral continuity of these relatively thin layers is not certain. At these stratigraphic intervals, every new sequence of more magnesium cumulates overlain by less magnesian cumulates is not considered as a single cyclic unit. Rather, the entire sequence of thinly (<0.25 m) layered rocks is considered as one macrorhythmic cyclic unit. An arbitrary layer thickness of > 0.25 m is set to represent an individual layer in a cyclic unit. Layers < 0.25 m in thickness are referred to as laminae.

III.6.3 DESCRIPTION OF CYCLIC UNITS (C.U.)

Thirty-two cyclic units are recognized from the LCLZ/UCLZ contact to the top of the study section (Fig. 5). The layer thicknesses are indicated in brackets. Cyclic units 1 - 9 consist of rhythmic succession of interlaminated peridotite with olivine clinopyroxenite.

C.U. 1 - Sulphide-bearing oikocrystic dunite-peridotite (7 m) overlain by sulphide-bearing, medium - coarse grained olivine clinopyroxenite (2 m). Grain size of cumulus olivine increases from the base to the top of the dunite - peridotite from 0.5 to 1.0 mm as postcumulus material becomes more abundant. Tochilinite and picrolite are common on brecciated surfaces.

C.U. 2 - Dark black peridotite (2 m) overlain by a sulphide-bearing olivine clinopyroxenite (2 m).

C.U. 3 - Peridotite finely interlaminated with olivine clinopyroxenite. Peridotite laminae vary from 5 - 10 cm in width. Contacts between the two are sharp and magmatic; no sign of structural deformation is evident.

C.U. 4 - Peridotite (1 m) overlain by thick, sulphide-bearing olivine clinopyroxenite. The contact between the two is sharp, and irregular.

C.U. 5 - Rhythmic successions of interlaminated peridotite with picrolitic veins (<0.25 m) and thick sulphide-bearing olivine clinopyroxenite (2 -5 m). Layer contacts are sharp.

C.U. 6 - Rhythmic successions of interlaminated peridotite (0.25 m) and thick sulphide-bearing olivine clinopyroxenite

(0.25 - 4 m). This succession differs from C.U. 5 in that the peridotite laminae are generally thicker and pyroxenite layers thinner. Microrhythmic (cm scale) peridotite - pyroxenite laminae are common in the upper part of this unit. Sulphides are concentrated in the pyroxenite at the contact of C.U. 6 and C.U. 7.

C.U. 7 - Peridotite (2 m) overlain by sulphide-bearing olivine clinopyroxenite (2 m) in which intercumulus sulphide is mobilized into veinlets. Contacts between peridotite and pyroxenite and with overlying C.U. 8 are sharp.

C.U. 8 - Oikocrystic, sulphide-bearing peridotite (2 m) succeeded by sulphide-bearing olivine clinopyroxenite (1.5 m).

C.U. 9 - Sulphide-bearing, oikocrystic peridotite (8 m) overlain by sulphide-bearing olivine clinopyroxenite (8 m). The contact between the two is gradational, marked by a decrease in the proportion of cumulus olivine and an increase in cumulus clinopyroxene over a 50 cm interval. Thin peridotite is gradationally interlaminated with olivine clinopyroxenite in the upper part of C.U. 9.

C.U. 10 - Thick (45 m) succession of dunite - peridotite forms C.U. 10. This macrorhythmic succession is grouped together as one cyclic unit even though it likely contains up to 10 individual cyclic units (based on petrographic descriptions and fluctuations in whole rock Ni content). The lower contact with C.U. 9 is sharp, marked by loss of clinopyroxene as a cumulus phase, and an increase in cumulus

olivine. This succession contains numerous metre-length intervals of poor recovery of rubbly core. Chromite-bearing, foliated, apple-green dunite with magnetite stringers is interlayered with massive, oikocrystic dark green to dark gray peridotite. Layers are thick, ranging from < 1 m to 15 m. Near the base of this macrorhythmic succession dunite layers are thickest; however, peridotite is thicker and more prevalent higher in the unit. Contacts between dunite and peridotite rocks are gradational often over metre-length intervals, and the placements of contacts was subjective. Hence the rocks are collectively grouped as "peridotite". An olivine clinopyroxenite (2 m) marks the top of C.U. 10.

C.U. 11 - Peridotite (10 m) sharply overlies the upper olivine clinopyroxenite of C.U. 10. It is in turn overlain by a mottled olivine gabbro which marks the first significant occurrence of plagioclase as a cumulus phase in the Main Layered Series. A fault breccia at the contact between the two contains angular peridotite clasts and carbonate + hematite + picrolite veining. A fault breccia containing angular gabbroic clasts marks the contact of the olivine gabbro with a plagioclase-bearing oikocrystic olivine clinopyroxenite (1 - 1.5 m). This grades into an olivine gabbro as plagioclase becomes a dominant cumulus mineral.

C.U. 12 - Peridotite, olivine clinopyroxenite and gabbro are represented in C.U. 12, which marks the first significant

appearance of cumulus plagioclase. Sulphide-rich (5 - 7%) oikocrystic peridotite (5 m) is abruptly overlain by sulphide-bearing olivine clinopyroxenite (6 m). This is gradationally overlain by a sulphide-bearing, modally and texturally laminated olivine leucogabbro (10.5 m).

C.U.13 - Macrorhythmic sequence of dominantly thick (3 - 7 m) olivine clinopyroxenite alternating with thin (<0.25 m) olivine gabbro. The basal sulphide-bearing olivine clinopyroxenite (7 m) is gradationally overlain by a weakly, modally laminated, "salt and pepper" textured olivine leucogabbro. Two successive sulphide-bearing olivine clinopyroxenite laminae interlaminated with olivine gabbro laminae are thinner, and more plagioclase rich. Contacts are gradational, and masked by fluctuations in cumulus plagioclase content.

C.U. 14 - Macrorhythmic sequence, similar to C.U. 13, composed of thick sulphide-bearing olivine clinopyroxenite interlaminated with thin olivine gabbro layers. The contact between C.U. 13 and C.U. 14 is marked by the development of an upper gabbroic interval >0.25 m, overlain by a thick (8 m) olivine clinopyroxenite. The upper 6 m of C.U. 14 consists of thin (0.5 cm) interlaminated olivine clinopyroxenite - olivine gabbro. C.U. 14 is capped by a 1.5 m thick medium to coarse-grained texturally laminated (mottled) olivine gabbro.

C.U. 15 - Plagioclase-bearing, weakly modally laminated olivine clinopyroxenite (2.5 m) gradationally overlain by a

sulphide-bearing texturally laminated mottled olivine gabbro.

C.U. 16 - Sulphide-bearing, oikocrystic peridotite finely interlaminated with sulphide-bearing olivine clinopyroxenite. Laminae are <0.25 m thick, and only two repetitions of each lithology are shown in C.U. 16 for clarity. The upper olivine clinopyroxenite contains fault breccia.

C.U. 17 - Cyclic unit of peridotite - olivine clinopyroxenite and olivine gabbro. Peridotite, which is finely interlaminated with olivine clinopyroxenite, sharply overlies C.U. 16. A second, thin (<0.5 m) chromite-bearing oikocrystic peridotite is gradationally overlain by olivine clinopyroxenite which is succeeded by a gabbro interval (3 m). Contacts between the olivine clinopyroxenite and gabbro are irregular and sharp, marked by a coarse-grained gabbro.

C.U. 18 - Thinly interlaminated sulphide-bearing oikocrystic peridotite and oikocrystic olivine clinopyroxenite. Laminae range from 5 cm to 0.25 m. Orthopyroxene forms large, (5 mm) stubby oikocrysts in both the peridotite and pyroxenite. Contacts are marked by either changes in dominant cumulus mineral (phase contact) or modal mineralogy (modal contact).

C.U. 19 - Complete cyclic unit of thin peridotite (0.25 - 1.0 m), plagioclase-bearing olivine clinopyroxenite (1 m) and olivine gabbro (2 m). The pyroxenite - gabbro contact is gradational.

C.U. 20 - Interlaminated olivine clinopyroxenite with minor

peridotite and altered, oikocrystic olivine gabbro. The modal contact between pyroxenite and overlying peridotite lamina is gradational, reflecting an increased proportion of cumulus clinopyroxene. The pyroxenite contact with overlying gabbro is sharp and marked by the appearance of plagioclase as a cumulus mineral.

C.U. 21 - Thick sequence of peridotite with coarse-grained pyroxenite base overlain by altered olivine gabbro (1 m).

C.U. 22 - Altered plagioclase-bearing olivine clinopyroxenite (3 m) sharply overlain by brecciated olivine gabbro (1 m) with a carbonate matrix.

C.U. 23 - Olivine clinopyroxenite (4.5 m) with coarse-grained patches overlain by variably altered olivine gabbro (2.5 m).

C.U. 24 - Olivine clinopyroxenite (3 m) overlain by thick, (12 m) modally laminated "salt and pepper" olivine gabbro. Both the grain size and degree of alteration of the olivine gabbro is variable. The top of C.U. 24 is marked by gabbro in contact with a coarse-grained, brecciated and altered peridotite.

C.U. 25 - Thick (up to 75 m) macrorhythmic succession of dominantly peridotite - dunite similar to C.U. 10. Peridotite is dark black-green, massive and oikocrystic, dunite is a gray to apple green and foliated. The succession is relatively intact in the lower 15 m, but in the upper 50 m, fault breccias are common, and carbonate, hematite, and pyrrhotite commonly vein the peridotite. The

absolute thickness of this macrorhythmic unit is not known, as it is interrupted by a thick (up to 40 m) variably textured, ilmenomagnetite-bearing gabbro. The upper contacts with the peridotite - dunite are sites of intense alteration and recrystallization; the lower contact is brecciated. A modally graded, well-laminated "salt and pepper" gabbro (16 m) overlies the dunite - peridotite. This is also punctuated by ilmenomagnetite-bearing gabbro. C.U. 26 - Thick (13 m) peridotite with minor intercalated olivine gabbro is overlain by a thick (10 m) olivine clinopyroxenite.

C.U. 27 - Peridotite (15 m), plagioclase-bearing olivine clinopyroxenite (11 m) and a thick, oikocrystic, texturally laminated (mottled) olivine gabbro (28 m) form the complete cyclic unit 27. The contact between pyroxenite and gabbro is gradational over 5 - 7 m, marked by an increase in the proportion of cumulus plagioclase. A fault breccia occurs near the base of the gabbro and a thin (20 cm) peridotite breccia with angular fragments cemented by calcite occurs within the upper 15 m of gabbro. A thin wedge of ilmenomagnetite-bearing gabbro is also intersected in the upper 10 m of gabbro.

C.U. 28 - Plagioclase-bearing olivine clinopyroxenite (1.5 m) interlaminated with thin (5 - 10 cm) peridotite layers is overlain by a thick (8 m) olivine gabbro. The gabbro is highly altered, occurring as massive, milky white, aphanitic, anastomosing prehnite veins and patches.

C.U. 29 - Plagioclase-bearing peridotite (3 m) is overlain by thick (11 m) gabbro. Peridotite-gabbro contacts of the peridotite with gabbro are marked by fault breccias and poor core recovery. The peridotite interval is brecciated throughout and powdery core recovery was common. The upper gabbro is also brecciated and pervasively altered.

Relatively unaltered gabbro exhibits a fine-grained, massive salt and pepper texture. Saussuritized gabbro is milky white and aphanitic consisting dominantly of prehnite, and hydrogrossular garnet. Contacts with unaltered gabbro are irregular and gradational. Disseminated galena and galena veinlets occur in the most intensely saussuritized gabbro and along altered fracture surfaces.

C.U. 30 - Plagioclase-bearing peridotite (3 m) overlain by thin (0.5 m) olivine clinopyroxenite which in turn is overlain by a thick (14 m) succession of variably texturally laminated (mottled, salt and pepper), and altered olivine gabbro. The basal peridotite contact with underlying gabbro is marked by fault breccia which persists throughout the peridotite interval. The contact of peridotite with pyroxenite appears gradational, but is masked by prehnite veins.

C.U. 31 - Thick (13 m) interval of sulphide and plagioclase-bearing peridotite, olivine clinopyroxenite (5 m) and gabbro (10 m). Thin peridotite (10 cm) is interlaminated with pyroxenite. The lower contact peridotite layer contact is marked by a fault breccia. Peridotite is commonly

brecciated and talcose with sulphide-bearing picrolite and hematite on slickensided surfaces. Fault breccias also occur in the gabbro. The peridotite - pyroxenite contact is sharp, marked by the appearance of clinopyroxene as a cumulus phase. The contact between pyroxenite and the overlying mottled olivine gabbro is gradational, as plagioclase becomes the predominant cumulus mineral. C.U. 32 - Plagioclase-bearing oikocrystic peridotite (4 m), plagioclase-bearing olivine clinopyroxenite (2 m) and mottled olivine gabbro (> 5 m) form the uppermost cyclic unit of the study interval.

SUMMARY

(1) Cumulus ol + chr; ol +/- cpx +/- chr; cpx + ol +/- chr; and pl + cpx + /-ol; form the respective sequences: dunite, peridotite, olivine clinopyroxenite and gabbro-olivine gabbro.

(2) Thick, homogeneous ilmenomagnetite-bearing gabbro and minor ilmenite-bearing gabbro apophyses occur within the succession. They are non-cumulus in origin and appear to have an intrusive relationship with the layered succession. Thin, coarse-grained gabbroic intervals may represent segregations of relatively evolved intercumulus magma.

(3) Primary minerals were modified by postcumulus processes, and olivine, clinopyroxene, and plagioclase commonly exhibit adcumulus growth. Olivine chadacrysts in pyroxene oikocrysts are subrounded suggesting that they

reacted with intercumulus magma to form pyroxene oikocrysts.

(4) Compositional layering is defined by changes in proportions of olivine, clinopyroxene and plagioclase as cumulus phases. Internally the layers may be modally, grain-size or texturally graded. Layer contacts may be either phase or modal. Laminae are best developed in peridotite - pyroxenite sequences. Olivine and clinopyroxene aggregates commonly form a textural lamination in gabbro and peridotite.

(5) Primary silicate minerals have been pervasively altered. Serpentinization affected both olivine and orthopyroxene; uralitization of pyroxene is not as intense, pyroxene is recrystallized to amphibole in coarse-grained olivine clinopyroxenite; and saussuritization resulted in complete destruction of primary plagioclase and production of a secondary mineral assemblage consisting of hydrogrossular, epidote and prehnite. The above noted alteration processes require large volumes of water to pass through the strata producing pervasive alteration of the more permeable rock types.

(6) Fault breccias are manifest by both clast and matrix supported breccias and fault gouge, and are most commonly developed in peridotite and gabbro.

(7) The stratigraphic succession intersected in drill holes Fox 1, 2 & 5, and INCO 13231, 13242, and 13241 represents over 650 m of strata including the upper 50 m of LCLZ rocks, the LCLZ - UCLZ contact and the lowermost 600 m of UCLZ

strata.

(8) The LCLZ - UCLZ contact marks a change in the character of the rock from ultramafic to ultramafic and mafic. Whole rock Ni in LCLZ peridotite and dunite is notably higher than its UCLZ counterpart.

(9) A complete cyclic unit is represented by the rock sequence dunite, peridotite, olivine clinopyroxenite and olivine gabbro. The complete sequence is generally not present. Thirty - two cyclic units are recognized from the LCLZ/UCLZ contact upward.

CHAPTER IV GEOCHEMISTRY

IV.1 WHOLE ROCK GEOCHEMISTRY

Whole rock analyses (Appendices ii and iii) of 116 samples provide data on stratigraphic geochemical trends and compositionally identify and confirm the rock type nomenclature used in drill hole logging. Major, minor and trace element analyses were examined as a function of PGE concentrations.

IV.2 SAMPLING AND ANALYTICAL METHODS

Whole rock analyses of 116 drill core samples were completed at the Geological Survey of Canada geochemical laboratory in 1986-1987. Powders representing one metre drill core intervals were provided by BP Selco Canada Ltd. Sampling for representative rock type relied on drill hole logging to identify homogeneous intervals suitable for chemical analyses as more than one rock type was commonly represented in the one metre interval.

Sampling covered 1100 m of drill core equivalent to ~ 600 m of strata, and was biased toward collecting PGE-bearing intervals. Analytical methods and detection limits are in Appendix i.

IV.3 PRESENTATION OF DATA AND DISCUSSION

Major and trace element analyses are plotted according to rock type and with increasing stratigraphic height. Selected elements which exhibit well defined trends with stratigraphic height are illustrated in Figs. 7 and 8. Individual PGE-bearing intervals and averages of PGE are indicated to emphasize general trends and differences.

IV.3.1 Major elements - (Fig.7) (The range of concentration in wt% is indicated in brackets following the element.)

SiO₂ (34 - 52 wt%) - Gabbro contains the highest concentrations of SiO₂, peridotite the lowest and olivine clinopyroxenite is intermediate. Rock types become more silica-rich with increasing stratigraphic height.

TiO₂ (0.05 - 2.45 wt%) - Among the mineralized units TiO₂ contents are low and uniform, ranging from 0.05 to 0.55 wt%. TiO₂ contents are greatest in the more highly differentiated ilmenomagnetite-bearing gabbro (up to 2.45 wt %).

MgO (4.5 - 38 wt%) - Peridotite contains the highest MgO content, gabbro the least. MgO content is constant in peridotite but progressively decreases in pyroxenite and gabbro with increasing stratigraphic height.

Fe₂O_{3T} (3.5 - 16.5 wt%) - Peridotite contains the highest contents of Fe₂O_{3T}, gabbro the lowest. Fe enrichment occurs within the peridotite and pyroxenite from the LMU to the MMU reflecting olivine fractionation. The ensuing weak Fe

depletion in all three rock types toward the late stages of crystallization represented by UMU rocks reflects decreasing Fe content of the magma. Ilmenomagnetite-bearing gabbro is distinguished from other gabbro by its high Fe_2O_3 content.

CaO (0.1 - 22.5 wt%) - CaO content in gabbro and pyroxenite increases with stratigraphic height. This reflects the increasing proportion of An-rich plagioclase and the increasing amount of augite precipitation during crystallization. Peridotite at all stratigraphic intervals contains low amounts of CaO.

Al_2O_3 (0.1 - 15.5 wt%) - Al_2O_3 contents are highest in gabbro. Individual rock types are more aluminous with increasing stratigraphic height.

Cr_2O_3 (0 - 1.6 wt%) - High Cr_2O_3 content in peridotite reflects the presence of chromite as a cumulus phase. Cr_2O_3 is most widely distributed within the LMU peridotite but average Cr_2O_3 content remains the same for the LMU and MMU, and decreases in peridotite from the UMU. Cr_2O_3 content abruptly decreases from peridotite to pyroxenite and gabbros. Cr_2O_3 in pyroxenite increases from the MMU to the UMU.

$\text{Na}_2\text{O} + \text{K}_2\text{O}$ (0 - 4.0 wt%) - $\text{Na}_2\text{O} + \text{K}_2\text{O}$ are not illustrated as there is little variation in their contents in the mineralized intervals. This reflects the low abundances of albite-rich plagioclase, K-feldspar and K-bearing mafic minerals. The ilmenomagnetite-bearing gabbro is an

FIGURE 7: Major and Minor Element Variation
with Stratigraphic Position.

Symbols: $\overline{\bullet}$ = Average peridotite abundance
for mineralized interval.
 $\overline{\blacktriangle}$ = Average pyroxenite abundance
for mineralized interval.
 $\overline{\blacksquare}$ = Average gabbro abundance
for mineralized interval.

exception, containing high abundances of $\text{Na}_2\text{O} + \text{K}_2\text{O}$.

Petrographically distinct ilmenomagnetite-bearing gabbro is chemically distinguishable from the olivine gabbro-gabbro series, by higher SiO_2 , TiO_2 , $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and FeO and lower CaO , Al_2O_3 , and MgO contents (Table II).

TABLE II: AVERAGE ABUNDANCES (WT%) OF MAJOR ELEMENT ANALYSES OF GABBROIC ROCKS.		
	Ilmenite-bearing gabbro	Ol gabbro -gabbro
SiO_2	50.70	46.17
TiO_2	1.57	0.29
FeO	9.70	4.80
$\text{Na}_2\text{O} + \text{K}_2\text{O}$	7.60	0.43
Al_2O_3	12.70	14.60
CaO	8.82	16.20
MgO	5.90	15.00

Trends of increasing SiO_2 , Al_2O_3 , CaO and decreasing MgO , Fe_2O_3 , and Cr_2O_3 from peridotite through pyroxenite to gabbroic rocks are apparent. MgO and CaO contents are the best discriminants for distinguishing peridotite (high MgO) and pyroxenite (high CaO); Al_2O_3 and CaO are the best discriminants for discerning gabbro (high Al_2O_3) from pyroxenite (high CaO). The distinctive ranges of MgO , CaO and Al_2O_3 , recalculated to 100%, were used to distinguish the rock type fields (Fig. 9).

The peridotite and minor dunite field occurs near the MgO apex, extending away from MgO towards CaO. The olivine clinopyroxenite field ranges from 83-45% MgO and 38-10% CaO. Gabbro trends away from MgO and CaO towards increasing Al_2O_3 content. Melagabbroic rocks overlap the field of olivine clinopyroxenite. Ilmenomagnetite-bearing gabbro is isolated, plotting closest to the Al_2O_3 apex. The strong linear trend between the field of peridotite and pyroxenite away from MgO towards CaO reflects the control of fractional crystallization of olivine. The curvilinear trend away from the MgO and CaO towards the Al_2O_3 apices reflects the predominance of plagioclase as a crystallizing phase.

IV.3.2 Trace Elements - (Fig. 8)

Trace elements commonly show a greater change with fractionation than major elements and are a better indication of the fractionation stage of the magma when a particular rock crystallized. Trace elements may behave as separate groups as noted by Wager and Brown (1968). Elements such as Ni readily enters cumulus olivine, providing S saturation has not been attained. The amount of these elements should decrease in the liquid with fractionation. If S saturation has occurred, elements such as Cu, Ni, Se, Zn and Pb would be preferentially incorporated into a sulphide liquid. More "incompatible elements" such as As, Te, and Sb remain in the residual liquid and are more abundant in more fractionated rock

types. F and Cl abundances may reflect the influence of late fluid processes. The variation in concentration of the trace elements with stratigraphic height is shown in Fig. 8. Cu (2 - 1600 ppm) - Pyroxenite contains the highest Cu concentration. Cu in pyroxenite increases from the LMU to MMU, decreasing in the UMU. Peridotite and gabbro contain consistent Cu concentrations. Rocks from the UMU contain appreciably lower concentrations of Cu than their counterparts from the LMU and MMU.

Ni (84 - 4200 ppm) - Peridotite contains the highest average Ni concentrations, gabbro the lowest. There is a progressive decrease in Ni content among individual rock type from the LMU to the UMU.

Zn (0 - 160 ppm) - Zn content is variable although the overall average Zn content of each rock type is ~25-30 ppm. Peridotite from the LMU and gabbroic rocks from the UMU have the widest range of Zn content.

Pb (0 - 770 ppm) - The widest range and highest average Pb concentration occur within gabbro of the UMU. Two samples of gabbro from the same stratigraphic interval are notably enriched in Pb. These samples (7935, 7910) also have high Se/S ratios. Pyroxenite from the LMU contain a few high Pb contents, although the average Pb content is <15 ppm. Peridotite averages <15 ppm in all 3 mineralized units.

As (<0.1 - 5 ppm) - As contents are low in all rock types. The widest range and highest As concentrations are contained in gabbro. There is an upward trend of increasing As in all

rock types from the LMU to MMU to UMU.

Sb (0.1 - 17 ppm) - Gabbro has the highest content and widest range of Sb concentration. Sb content is low and uniform in peridotite but erratic in pyroxenite and gabbros.

F (10 - 400 ppm) - F content is consistently about 80 ppm regardless of rock type or stratigraphic position.

Cl (50 - 4100 ppm) - Serpentinized peridotite contains the highest concentration of Cl in the LMU, MMU and UMU; gabbro contains the least. Cl concentrations decrease with increasing stratigraphic height likely reflecting the decreasing proportion of serpentinized dunite/peridotite with increasing stratigraphic height.

Te - Te values are not diagrammatically illustrated as they are near detection limits.

S (56 - 20,824 ppm) - The distribution of S among mineralized units and rock types is very similar to that of Se and Cu. Pyroxenite contains the highest and widest range of S concentration, and S contents in pyroxenite increases from the LMU and MMU and then abruptly decrease in the UMU. Gabbro contains notably lower abundances of S than peridotite and pyroxenite.

FIGURE 8: Trace Element Variation with Stratigraphic Position.

Symbols: $\bullet$ = Average peridotite abundance
for mineralized interval.
 $\blacktriangle$ = Average pyroxenite abundance
for mineralized interval.
 $\blacksquare$ = Average gabbro abundance
for mineralized interval.

Se (0.005 - 3.4 ppm) - Peridotite and pyroxenite contain wider ranges and higher concentrations of Se than gabbro. Se concentrations within individual rock type decrease with increasing stratigraphic height.

Se/S*10⁶ (19.7 - 2347) - Se/S ratios have previously been used as a method of distinguishing the origin of sulphide deposits (Edwards and Carlos, 1954). More recently this ratio has been used as an indicator of S source, and environments favourable for PGE enrichment (Eckstrand et al., 1989). Se/S*10⁶ whole rock ratios greater than 350 and less than 250 are considered indicative of crustal contamination and a favorable indicator of PGE enrichment. Those in the range of 250 - 350 are considered to be strictly of mantle derivation. Se/S*10⁶ ratios from the study interval range from 19.7 to 2347. The widest range and highest ratios occur in gabbroic rocks from the UMU. The high Se/S ratios from the UMU are a function of low S contents of the samples rather than anomalously high Se content of the rocks.

The distribution of sulphides with rock type is illustrated in Fig. 10. MgO contents are used to distinguish the different rock types. Pyroxenite has the highest concentrations and the widest range of S. Peridotite is also S-rich, gabbroic rocks contain notably less S, (Fig. 10a). Peridotite-hosted sulphides are Ni-rich, olivine clinopyroxenite and gabbro host sulphides

FIGURE 9: Major Element Compositional Fields for Rock Type.

FIGURE 10: Distribution of Sulphides with Rock Type.

10.A MgO vs S
10.B MgO vs Cu/(Cu + Ni)

which range from Cu to Ni-rich; ilmenomagnetite-bearing gabbro is S-poor, sulphides which are present are Cu rather than Ni-rich, (Fig. 10b).

IV.4 Summary of Major and Trace Element Distribution

There is a progressive evolution toward a less mafic composition within individual rock types with increasing stratigraphic height (Figs. 7 & 8). Among individual rock types, SiO_2 , CaO , Al_2O_3 , As and Pb contents increase while MgO , and Cr_2O_3 decrease with increasing stratigraphic height. FeO content increases in peridotite and pyroxenite from the LMU to MMU, but decreases in all three rock types from the MMU to UMU.

The behavior of these elements is consistent with continued fractional crystallization of the magma(s) with increasing stratigraphic height. Ilmenomagnetite-bearing gabbro represents the most highly fractionated rock type, with high concentrations of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and As, Sb, F and TiO_2 .

Peak Cu, Ni, S, and Se concentrations occur in pyroxenite from the MMU, and subsequently decrease with increasing stratigraphy. Cu/Cu + Ni ratios indicate peridotite is Ni-rich; pyroxenite and gabbro range from Cu to Ni rich.

CHAPTER V: SULPHIDE AND OXIDE DISTRIBUTION

V.1.SULPHIDES

Sulphide minerals within the FRS are minor but ubiquitous, seldom exceeding 3 volume per cent. The overall sulphide mineralogy is relatively simple, principally consisting of iron-nickel-copper-sulphur assemblages. Pyrrhotite (po), pentlandite (pn), chalcopyrite (ccp), cubanite (cbn), and mackinawite (mkw), are the prevalent sulphide minerals. They commonly form polymineralic grains with po or pn cores bordered by ccp. Galena (gn), sphalerite (sph) and bornite (bn) are minor sulphide phases. Sulphide minerals are described in Section I.1A. Disseminated sulphides are most common in pyroxenite and peridotite and appear to be homogeneously distributed throughout the stratigraphic succession. On a smaller scale, however, sulphides are commonly preferentially concentrated at the top of peridotite layers in contact with pyroxenite.

Sulphide assemblages vary with rock type (Table IV, Fig. 10b). Peridotite is Ni-sulphide rich, and contains po-pn assemblages which have been partially replaced by pyrite (py) and magnetite (mgn). Cu-bearing sulphide minerals are notably absent. Pyroxenite is Cu-sulphide rich, containing

TABLE IV: Sulphide Assemblages with Rock Type

ROCK TYPE: PERIDOTITE															
S.NO	Po	Pn	Ccp	Cbn	Mkw	Py	Gn	Sph	Bn	Mll	Chr	Il	Mgn	COMMENT	
F5-1			X			X							X	Sec.	
F2-5	X					X2					X		X2	Loss S	
F1-2	X					Xpn					X		X2	Loss S	
F1-4	X					X2							X2	Loss S	
F1-5	X	X				X2							X2	Loss S	
F1-7	X					X2					X		X2	Loss S	
ROCK TYPE: PYROXENITE															
S.NO	Po	Pn	Ccp	Cbn	Mkw	Py	Gn	Sph	Bn	Mll	Chr	Il	Mgn	COMMENT	
F5-2	X	X ₂	X		X _{pn}								X	Poly+Mgn	
F5-3	X	X	X _{1,2}			X _M				X _{pn}			X	Polymin	
F5-4	X	X	X	X		X ₂							X	Polymin,	
														Sl + S	
F2-1	X	X ₂	X	X	X _{pn}								X	Polymin	
F2-2	X	X	X _{1,2}	X	X									Polymin,	
													Sl R S		
F2-3	X	X _b	X	X	X _b								X _{pn}	Polymin	
F2-4	X		X		X								X	Polymin Sl R S	
F2-6	X	X	X _{1,2}	X	X _b		X	X					X	Polymin	
														2 gen S	
F2-7	X	X	X _{1,2}		X	X ₂							X	Polymin	
F2-8	X	X	X _{1,2}		X								X	Polymin	
F2-9	X	X	X		X _{csp}								X	Polymin	
														Sl + S	

F2-10	X	X ₂	X _{1,2}	X				X					X	Polymin
F1-1B	X	X											X	Loss S
F1-6	X	X	X		X _b								X	Polymin
F1-8	X	X	X		X _{ccp}	X							X	Loss S
F1-9	X	X	X		X	X _M						X	X	Loss S
														Sl + S
F1-10	X		X _{1,2}	X	X	X _M	X	X						Polymin
														Sl + S
F1-11	X	X	X _{1,2}	X	X									Polymin
F1-12	X	X _b	X		X								X	Polymin
ROCK TYPE: GABBRO														
S.NO	Po	Pn	Ccp	Cbn	Mkw	Py	Gn	Sph	Bn	Mll	Chr	Il	Mgn	COMMENT
F5-5			X2	X		X						X	X	
F5-6			X2											Low S
F5-7			X2			X	X		X					V Alt.

Pn_b = massive monomineralic grains and as exsolution in po or as polymineralic grains

Ccp 1 = primary

Ccp 2 = remobilized/replacement

Mkw -X_b = alteration in both pn and ccp

Py -X_M = marcasite

Py₂ = py + mgn association

Poly = polymineralic grains

Sl + S = intergrowth of silicate and sulphide at grain boundary.

Sl R S = secondary silicate replaces sulphide

Loss S = sulphide replaced by mgn +/- py

po-pn-ccp-cbn-mkw; gabbro is relatively sulphide deficient containing fine, disseminated ccp-gn-sph-bn or in highly saussuritized samples, secondary veinlets of gn-bn.

Pn was only recognized in one peridotite sample; (Table IV),

however, from Fig. 10b, which indicates that peridotite contains higher abundances of Ni sulphides than pyroxenites, it is evident that pn must occur in peridotite more commonly than was identified. Ni-sulphide-bearing minerals (pn) decrease and Cu-sulphide-bearing phases (ccp,cbn,bn) and Pb-sulphide-bearing phases (gn) increase with stratigraphic height reflecting the greater proportion of pyroxenite and gabbroic with increasing stratigraphic height. Grain size ranges between 0.01 and 0.5 mm and may reach 5 mm in peridotite with net-textured sulphides. Mgn is the predominant alteration product of sulphide minerals, although py and small amounts of marcasite, tochilinite (tcl) and millerite (mll) have been noted.

V.2 SULPHIDE MINERALS

V.2.1 PYRRHOTITE (Po)- Po is the principal sulphide, and may occur either as isolated monomineralic "blebs" which typically exhibit a well developed parting or as polymineralic grains with exsolved pn, ccp, and cbn. Po also occurs within serpentine veins in association with py and ccp. Po grains in mutual contact with each other generally form a ragged interlocking mosaic texture. Mgn commonly replaces po.

V.2.2 PENTLANDITE (Pn) - Pn is the dominant Ni-bearing sulphide phase. It occurs as subrounded monomineralic grains, as central massive patches within polymineralic sulphide grains or as "feathery flames" of exsolution in po. As massive monomineralic grains and massive patches, pn

exhibits a distinctive octahedral cleavage which is commonly accentuated by being occupied by mgn. Massive pn is often altered to "wormy" mkw which is preferentially oriented along pn cleavage planes.

V.2.3 CHALCOPYRITE (Ccp) - Ccp is the most abundant Cu-bearing sulphide mineral. It occurs as granular masses at the periphery of polyminerale sulphide grains (po and pn), as irregularly distributed fine grained granules within the polycrystalline grain, and as monomineralic coarse grains and fine, hair-like, veinlets connected to coarse ccp-rich grains. Ccp serves as host to cbn lamellae, and flames of mkw.

V.2.4 CUBANITE (Cbn) - Cbn, a subordinate Cu-bearing sulphide, occurs as fine to coarse-grained well defined exsolution lamellae in ccp grains. Cbn is most abundant in Cu-rich sulphide assemblages.

V.2.5 MACKINAWITE (Mkw) - Mkw, a minor sulphide mineral, is widely distributed as "wormy" alteration material and flames in po, pn and ccp. It is a common constituent of second generation po grains. In pn, feathery mkw alteration is preferentially oriented in a trellis network.

V.2.6 PYRITE (Py) - Py occurs as a secondary mineral associated with mgn as a replacement product of primary sulphides. Fe released from the olivine lattice during serpentization combines with S-bearing fluids to form pyrite. Pyrite also occurs as idiomorphic cubes along fractures, and within picrolite veins. Marcasite was

identified as a replacement of pn.

V.2.7 SPHALERITE (Sph) - Sph is a minor sulphide mineral which occurs as anhedral grains characterized by numerous ccp inclusions. It is found in association with ccp, cbn and gn in highly uralitized pyroxenite.

V.2.8 GALENA (Gn) - Gn, a minor sulphide, is associated with ccp, bn, cbn, and sph. It commonly occurs as isolated, disseminated fine grains or as massive veinlets up to 1 cm in width in highly saussuritized gabbroic rocks in the upper part of the stratigraphic study interval.

V.2.9 BORNITE (Bn) - Bn, a trace sulphide, occurs as fine grained disseminated grains which replaces ccp and also as fine grains intimately associated with massive gn veinlets. Bn distribution is limited to highly saussuritized gabbroic rocks in the upper part of the stratigraphic study interval.

V.2.10 MILLERITE (Mll) - Mll, an alteration product of pn occurs as fine acicular blades along pn cleavage.

V.2.11 TOCHILINITE (Tcl) - Tcl is a hydrous iron sulphide mineral ($2\text{Fe}_{0.9}\text{S}_{1.67}[(\text{Mg},\text{Fe})(\text{OH})_2]$) which was identified by X-ray diffraction methods. It has been previously identified in other mafic-ultramafic rocks including the Muskox and Duluth intrusions (Jambor, 1969)). In hand specimen it resembles graphite in that it is submetallic, dark grey and greasy. It occurs as thin flakes or as semi-massive veins along fractures in serpentized peridotite.

V.3 SULPHIDE DISTRIBUTION

Sulphides are classified as primary or secondary depending on; (i) their relationship to associated silicate minerals, and to a lesser extent (ii) the sulphide assemblage.

V.3.1 PRIMARY

Sulphides of "primary" magmatic origin are fine-grained and disseminated. They are generally cusped and bleb-like, conforming to the shape of the area between cumulus grains. Examples of primary textures include the presence of polymineralic sulphide grains, unmixing and exsolution features such as exsolution lamellae and blebs of one sulphide phase within another. These features as well as the polymineralic Cu-Fe-Ni sulphide assemblages (po + pn + ccp + cbn) are consistent with exsolution of minerals upon cooling of a monosulphide solid solution (MSS) as suggested by Craig and Kullerud, (1969). These textures, which have been described in detail above are shown in Plate VII.

V.3.2 SECONDARY

Five modes of secondary sulphide distribution were identified;

- 1) Sulphide for sulphide replacement
- 2) Sulphide for silicate replacement
- 3) Silicate for sulphide intergrowths/recrystallization
- 4) Oxide + sulphide replacement of sulphide
- 5) Sulphide-bearing veins

Examples of these are illustrated in Plate VIII

2

MICRO

PLATE VII TEXTURES OF PRIMARY SULPHIDES

- (a) Intercumulus sulphide blebs in olivine clinopyroxenite
- (b) Intercumulus sulphide blebs and remobilized sulphide stringers in peridotite.
- (c) Intercumulus sulphides. Grains conform to shapes of areas between serpentized cumulus olivine. (R.L.)
- (d) Monomineralic grains of po with characteristic parting. (R.L.)
- (e) Polymineralic grains of po with ccp, cbn, and wormy mkw alteration in ccp (R.L.)
- (f) Polymineralic grains of ccp, cbn, sph and pn. (R.L.)
- (g) Polymineralic grains of po, pn, and ccp with py replacing primary pn. (R.L.)
- (h) Disseminated gn, bn and ccp in saussuritized gabbro. (R.L.)

R.L.= Reflected Light

PLATE VIII TEXTURES OF SECONDARY MODES OF SULPHIDES

- (a) Assemblage 1: Sulphide for Sulphide Replacement
Polymineralic grain of ccp, cbn, sph and pn. Note that ccp displays relict pn cleavage suggesting ccp has replaced pn.
- (b) Assemblage 1: Sulphide for Sulphide Replacement
Polymineralic grain of po, ccp, mkw with remobilized veinlet of po and ccp.
- (c) Assemblage 3: Silicate for Sulphide Replacement
Chlorite blades replace primary pn grain along crystallographic directions during recrystallization. The outline of the original pn grain is still discernible.
- (d) Assemblage 3 + 5: Silicate for Sulphide Intergrowth cut by Sulphide-bearing Serpentine Vein
Note (i) ragged edges of sulphide grain resulting from intergrowth of chlorite with sulphide
(ii) polymineralic nature of sulphide grain in serpentine vein (po + ccp + mkw).
- (e) Assemblage 4: Oxide for Sulphide Replacement
Direct replacement of polymineralic sulphide grain by mgn.
- (f) Assemblage 4: Oxide for Sulphide Replacement
Mgn + py replacement of primary sulphide grain in serpentinized peridotite.
- (g) Assemblage 5: Py in serpentine vein
- (h) Assemblage 5: Po + ccp intergrown with amphibole in late vein.

*All photomicrographs taken in reflected light.

i) Sulphide for Sulphide Replacement (Plate VII Ia,b)

Replacement of one sulphide by another generally proceeds inward from crystal boundaries or along fractures and grain boundaries. Examples include caries texture, irregular islands of sulphide in a matrix of secondary sulphide and relict primary or pseudomorphs of primary phases. Sulphides of secondary/replacement origin are Cu-rich. Ccp is the dominant sulphide, and occurs as irregular hair-like veinlets connected to larger ccp-rich grains. The ccp-rich grains commonly exhibit relict po cleavage, relict pn octahedral cleavage and/or remnant islands of porous po and pn suggesting that ccp replaced primary sulphide grains.

ii) Sulphide for Silicate Replacement

Replacement of silicate by sulphide was accompanied by intense deuteric alteration of the silicate assemblage, (uralitization and saussuritization). Replacement of silicate by sulphide proceeded along altered grain boundaries and cleavages. Sulphide grain size ranges from 5 mm to 0.25 mm. Different generations of sulphide replacement are recorded by overprinting of one sulphide phase by another.

iii) Silicate for Sulphide Intergrowth/ Recrystallization (Plate VIII c,d)

Intergrowths of hydrous silicates with sulphides are common in rocks which have undergone hydrous alteration (serpentinization, uralitization, saussuritization) and recrystallization. Sulphide minerals retain their primary

interstitial nature during the early stages of alteration and recrystallization of silicates; however, with progressive alteration and recrystallization of silicate minerals, sulphide grains commonly lose their original outline.

(a) Silicate - Sulphide Intergrowth: Sulphide grains are penetrated by secondary hydrous silicates (serpentine, chlorite, amphibole) resulting in jagged and irregular sulphide-silicate grain boundaries (Plate VIIId)

(b) Silicate Replacement of Sulphide: Sulphides may be dissected by chlorite and serpentine (Fig. VIIc). The outline of the original sulphide is retained suggesting that they are being replaced by silicates (with accompanied loss of S).

iv) Oxide (Mgn)+ Sulphide (Py) for Sulphide Replacement (Plate VIII e,f)

Replacement of Fe-bearing sulphides (po, ccp, pn) by mgn is common, varying from negligible to virtually 100% replacement of original sulphide. Mgn directly replaced sulphides in some cases; in others, mgn + py replaced primary sulphides. Where mgn directly replaced sulphide, the textural nature of the sulphide was preserved with no intergrowth between sulphide and silicate along grain boundaries. Sulphides replaced by mgn + py have a "spongy" texture and grain boundaries are commonly interdigitated with secondary silicates (serpentine and chlorite). Mgn replacement has also occurred at grain boundaries and along

cleavage planes and fractures of altered olivine and pyroxene grains. Fine-grained disseminated mgn occurs in peridotite as a byproduct of serpentinization.

v) Vein Sulphides (Plate VIIIg,h)

Sulphide-bearing veins are late features which crosscut primary sulphide assemblages. Sulphide-bearing serpentine/picrolite veinlets are common in peridotite and to a lesser extent in pyroxenite which may also contain sulphide-bearing amphibole veinlets. Py is the predominant sulphide, occurring as idiomorphic cubes. Po-ccp-pn-mkw assemblages also occur in "picrolitic" veins, and gn-bn veins occur in highly altered gabbroic rocks.

V.1C CRYSTALLIZATION HISTORY OF SULPHIDE MINERALOGY

The interstitial/intercumulus nature of the Cu-Fe-Ni sulphide assemblages as well as the internal textural relationships of the grains suggest that monosulphide solid solutions (MSS) have precipitated from sulphide melts and upon further cooling have exsolved from the monosulphide solid solutions. Original high temperature phases have undergone subsolidus reequilibration to produce the lower temperature assemblages referred to above as primary mineralogical and textural assemblages. Sulphide distribution is lithologically controlled; Ni-rich assemblages are associated with peridotite and Cu-rich assemblages with pyroxenite and gabbro. Sulphides were subsequently mobilized and recrystallized with silicate minerals to give the secondary mineralogical and textural

sulphide assemblages. Secondary assemblages 1 and 2, which are associated with altered/uralitized pyroxenite and appear to have formed relatively early in the recrystallization sequence. Replacement of these sulphides by mgn (Assemblage 4) suggests oxidizing conditions perhaps associated with the first episode of serpentinization. Assemblages 4 (mgn + py) and 3 postdate assemblages 1 and 2 and occur within intensely deuterically altered and recrystallized rocks. Interdigitated silicate and sulphide at grain boundaries are similar to sulphide textures of metamorphosed disseminated sulphides, (Dillon-Leitch, 1988; Kilburn et al., 1969). The presence of this texture in highly altered rocks (peridotite, pyroxenite and gabbro) suggests that the sulphides have recrystallized during hydrous alteration of enclosing silicates, possibly during low-grade metamorphism of the FRS rocks. Sulphides in serpentine and amphibole veins (Assemblage 5) crosscut all other assemblages and are related to the last stage of serpentinization. Py is the predominant sulphide in these veins, but polymineralic grains of po, crp and cbn were also present in pyroxenite with the same primary sulphide assemblages, suggesting late local remobilization of sulphides.

V.2 OXIDE DISTRIBUTION

Oxide minerals, which are a minor constituent of FRS rocks, consist of chromite (chr), ilmenomagnetite (ilmgn), and magnetite (mgn), (Plate IX). The former are of magmatic

PLATE IX TEXTURES OF PRIMARY OXIDE MINERALS

- (a) Chr grains as inclusions in cumulus olivine grains and in intercumulus area. (R.L.)
- (b) Intercumulus chr grains and clusters. Note mgn lining along fractured chr grains. (R.L.)
- (c) Relict ilmenite lamellae in altered ilmgn grain. Note second generation anhedral blebs of ilmenite which contain fine sulphide, and second generation trellis mgn lamellae and anhedral mgn blebs which overprint ilmenite lamellae. Sulphide is py. (R.L)
- (d) Altered ilmgn grain. Mgn has been replaced by chlorite/biotite (P.P.L)

R.L. = Reflected Light

P.P.L. = Plane Polarized Light

origin, whereas mgn is a product of alteration processes.

V.5.1 CHROMITE (Chr) - Chr is present as disseminated (<3%) cumulus grains in dunite, peridotite and pyroxenite. It occurs as fine-grained (0.25 - 0.50 mm) idiomorphic to subrounded grains in cumulus olivine (Plate IXa), or pyroxene or surrounded by intercumulus minerals (Plate IXb). Chr occurs alone or as clusters of grains.

V.5.2 ILMENOMAGNETITE (Ilmgn) - Ilmgn crystals are restricted to a thick, coarse-grained, compositionally evolved gabbroic rock which occurs at approximately 400 m in the stratigraphic section (Fig. 5). The gabbro is equigranular, composed of plagioclase, pyroxene, amphibole and ilmgn. It is not a cumulate rock. Ilmgn crystals are idiomorphic and their size varies proportionally to that of the associated silicate minerals ranging from fine (1 mm) to coarse-grained (7.5 mm). Ilmgn grains are altered so that the only primary remnant is a network of ilmenite exsolution lamellae (Plate IXc). Presumably, mgn has been replaced by chlorite and biotite (as suggested by Ramdohr 1969), (Plate IXd). In polished section the ilmenite lamellae are corroded, and are enveloped by secondary mgn which may also exhibit the habit of a very fine network of lamellae. These lamellae overprint coarser ilmenite lamellae. A second generation of ilmenite occurs as irregularly shaped blebs between and also overprinting the ilmenite lamellae. Fine-grained (0.1 - 1 mm) po, py and ccp are disseminated between ilmenite lamellae and as inclusions in second generation

ilmenite and mgn blebs.

V.5.3 MAGNETITE (Mgn) - Mgn is of secondary origin. It is the most dominant alteration of sulphide and primary oxide minerals. Its various modes of occurrence have already been described. In highly serpentized rocks, mgn also forms massive 1 - 2 mm veinlets.

CHAPTER VI: DISTRIBUTION OF THE PLATINUM-GROUP ELEMENTS

VI.1 INTRODUCTION

This chapter presents information on the distribution of PGE and associated elements. Drill core samples representing consecutive 1 m intervals were assayed for Pt, Pd and Au. Samples from identified PGE mineralized intervals of three boreholes (Fox 86-1, 86-2 and 86-5) were reanalyzed for the total suite of PGE (Os, Ir, Ru, Rh, Pt, Pd) and Au. Polished thin sections were studied but no platinum-group minerals (PGM) were observed. Consequently statistical analyses of PGE with elements with which they are commonly associated in similar environments (eg. Bushveld, Stillwater), were used to infer their mode of occurrence.

VI.2 GEOCHEMISTRY OF THE PGE

During igneous processes, there is a tendency for the PGE to behave as two distinct groups, one retaining the predominantly siderophile character (Os, Ir and Ru; oxide-silicate association), whereas the other (Rh, Pt and Pd) has a more chalcophile character (sulphide association), (Crocket, 1979, Cabri and Naldrett 1981). Cousins and Vermaak (1976) noted that during differentiation of a mafic magma, $Pt/(Pt+Pd)$ increases sympathetically with Fe suggesting that Pt has a greater siderophile tendency than Pd. By contrast, they also noted that with increasing "acidification" of a magma, Pd follows Cu along with more volatile metals to concentrate in fluids which form

components of volcanogenic or hydrothermal ores and that any mobilized primary ore would be enriched in Pd relative to Pt. Naldrett and Cabri (1976) also suggested that Pd:Pt increases with increasing differentiation of a tholeiitic magma towards a granitic pole. The behavior of PGE with stratigraphic position and rock type is illustrated using ratios among the PGE and chondrite normalized profiles (CNP), (Figs. 13 & 15).

VI.3 DISTRIBUTION OF PGE WITH ROCK TYPE

VI.3.1 Introduction

PGE mineralization ($Pt + Pd > 100$ ppb) is predominantly associated with sulphide-bearing pyroxenite (Fig. 11). Pyroxenites host both the most positively anomalous and the widest range of PGE as well as Cu, S and Se.

VI.3.2 Petrographic Descriptions of Mineralized Units

Anomalous concentrations of PGE ($Pt + Pd > 100$ ppb) occur at three stratigraphic intervals and are referred to as the Lower Mineralized Unit (LMU), Middle Mineralized Unit (MMU) and the Upper Mineralized Unit (UMU). Examples of mineralized core are shown in Plate X. The cyclic units (C.U.) which constitute the mineralized intervals are indicated in brackets below. (Refer to Chapter II, pp. 41 - 56 for detailed description of C.U.)

VI.3.2.i Lower Mineralized Unit (LMU) (C.U. 1 - 9) (Plate X.A,B)

PGE abundances ($Pt + Pd$) range from $<25 - 800$ ppb in the LMU. The LMU is a 70 m succession of thinly interlayered rhythmic units of peridotite and pyroxenite which overlaps

**PLATE X Representative samples of PGE mineralized core
from the Lower, Middle and Upper Mineralized Units.**

- X.A Coarse-grained olivine clinopyroxenite, LMU
 DH1-7180, 484.2 ppb PGE
- X.B Olivine clinopyroxenite, LMU. Note the increase in
 grain size from left to right. DH1-7186, 280.7 ppb PGE.
- X.C. Coarse-grained to pegmatitic olivine clinopyroxenite,
 MMU. DH2-7540, 315.5 ppb PGE.
- X.D Interlaminated peridotite and olivine clinopyroxenite,
 MMU. DH1-7027, 527.7 ppb PGE.
- X.E Pegmatitic olivine clinopyroxenite, UMU. Note coarse-
 grained nature of sulphide "blebs". DH5-7835, 527.7
 ppb PGE.

1=PERIDOTITE 3=OLIVINE CLINOPYROXENITE 5=GABBRO

FIGURE 11: Box and Whisker Plot illustrating the Distribution of Total PGE Concentrations for the Lower, Middle and Upper Mineralized Units.

SYMBOLS: --- = Average; — = Median; area inside box = middle 50% of data values; Whiskers extend to minimum and maximum values.

the LCLZ/UCLZ contact. Olivine clinopyroxenite laminae and layers are predominant and tend to be thicker (5 cm - 5 m) than peridotite laminae and layers (10 cm - 2.5 m). Although the range of PGE abundances is greater in the peridotite, both the median and average PGE concentration are higher in the pyroxenite. Contacts between the peridotite and pyroxenite layers are generally sharp and do not show any sign of tectonic disruption. There is no gabbro in the LMU.

VI.3.2.ii Middle Mineralized Unit (MMU)
(C.U. 13 - 18) (Plate X.C,D)

PGE abundances (Pt + Pd) range from < 100 ppb to 625 ppb in the MMU. The MMU occurs over a 50 m stratigraphic succession of dominantly thick olivine clinopyroxenite layers interlaminated with thin peridotite and locally with olivine gabbro. Pyroxenite, the predominant mineralized rock type within this interval, exhibits the greatest range, and has the highest median and average of PGE abundances. The MMU has been intersected at the top of Fox 1 and the lower 60 m of Fox 2 (Fig. 4). Contacts are generally not faulted, although a minor fault breccia occurs within the upper olivine clinopyroxenite of C.U. 5.

VI.3.2.iii Upper Mineralized Unit (UMU)
(C.U. 27 - 32) (Plate X.E)

Sporadic anomalous (Pt + Pd > 100 ppb) PGE concentrations occur throughout DH Fox 5 and range up to 980 ppb. The UMU contains the highest proportion of gabbroic rocks and represents products of the most fractionated magma. Peridotite, pyroxenite and gabbro in the UMU all contain PGE

abundances, with pyroxenite again being the preferential host of PGE mineralization. The highest PGE concentrations occur within a 5 m thick olivine clinopyroxenite layer of C.U. 31. A thick peridotite containing fault breccia is overlain by a 5 m thick olivine clinopyroxenite which contains a thin (5 cm) peridotite lamina near its base. The olivine clinopyroxenite changes abruptly upsection to a coarse-grained to pegmatitic interval (1 m thick) which abruptly changes back to a homogeneous medium-grained olivine clinopyroxenite for the upper 0.5 m. The olivine clinopyroxenite is capped by gabbro. Peak PGE abundances are concentrated in the sulphide-bearing, coarse-grained to pegmatitic part of the olivine clinopyroxenite. In the UMU, contacts between gabbroic rocks and overlying peridotite are often marked by fault breccia or gouge in the peridotite, and extensive recrystallization of the upper gabbro member. Fault breccias within individual rock types are also common.

Although pyroxenite is the dominant host rock for PGE, the proportions of rock types hosting PGE changes with increasing stratigraphic height. Peridotite is commonly host to PGE in the LMU; however, within the MMU and UMU there is a progressive decrease in the proportion of PGE-bearing peridotite. Conversely, PGE mineralized gabbroic rocks which are absent in the LMU become successively more common within the MMU and UMU respectively. This trend suggests that with increasing stratigraphic height PGE abundances occur in more fractionated rock types.

VI.4 VARIATION AMONG PGE

PGE analyses of 89 samples indicate that Pt, Pd and Rh are more abundant than Os, Ir and Ru. The range and mean of each PGE and Au in the mineralized samples are listed in Table V.

TABLE V: PGE ASSAY STATISTICS							
SUMMARY OF PGE CONCENTRATIONS							
	#	MIN	MAX	X	MEDIAN	D.L.	% < D.L.
Os	89	1.5	8	1.8	1.5	(3)1.5	78/89=88%
Ir	89	0.3	14	2.1	1.9	(0.1)0.1	0/89=0%
Ru	89	2.5	51	9.2	4	(5)2.5	36/89=40%
Rh	89	1	19	5.6	5	(1)1	9/89=10%
Pt	89	5	530	113.5	97	(5)2.5	1/89=1%
Pd	89	2.5	690	172	140	(5)2.5	6/89=6.7%
Au	89	1	100	12.5	9	(1)1	5/89=5.6
(*note D.L.= detection limit, the number in brackets refers to the value used in calculating ratios if the sample value was < d.l., % < D.L. states the percentage of samples which assayed below the quoted d.l., # = no. of samples)							

The variation in abundances of PGE concentrations are shown in Figs. 12A & B. The variation with rock type and stratigraphic position is indicated. The more siderophile elements Os, Ir and Ru are grouped together at one apex in Fig. 12A. Pt and Pd label the remaining two apices

SYMBOLS: ▼ peridotite; ○ pyroxenite; □ gabbro

FIGURE 12.A: Variation of Pt, Pd and (Os + Ir + Ru) Concentrations Among Individual Mineralized Units.

12.B: Variation of Pt, Pd and Rh Concentrations Among Individual Mineralized Units.

respectively; Rh is not represented in this Figure. The relative low Rh levels in all samples is evident in Fig. 12B. Examination of Fig. 12A indicates a wide range of ratios although Os, Ir and Ru levels are consistently less than Pt and Pd. The variation in ratios appears grossly related to rock composition and stratigraphic position. Peridotite is more enriched in Os, Ir and Ru than either pyroxenite or gabbro, and rocks from the LMU contain higher levels of Os + Ir + Ru than those of the MMU or UMU. The relative proportion of Pt to Pd abundances are illustrated in Fig. 12B. Peridotite is generally Pd enriched; pyroxenite and gabbro range from Pd to extremely Pt enriched. Pyroxenite and gabbro from the UMU contain higher proportions of Pt to Pd than similar rocks from the MMU and LMU.

VI.5 GEOCHEMICAL AFFINITY OF PGE

As mentioned previously, no platinum-group minerals from the FRS were identified. PGE, Cu, Ni, S, Se and Cr abundances in the FRS were plotted against stratigraphic height to determine which elements displayed similar distribution patterns (Figs. 13A-C).

VI.5.1 Lower Mineralized Unit

In the LMU, PGE, Cu, Se and S abundances exhibit similar profiles. Ni distribution roughly approximates that of the PGE. Cr distribution does not resemble PGE or BMS abundances. Increases in $Pt/(Pt + Pd)$ generally do not

correspond to increases in $\text{Cu}/(\text{Cu} + \text{Ni})$. $\text{Se}/\text{S} \times 10^6$ ratios are consistently low. Increases in PGE abundances seem to correspond to the presence of pyroxenite rather than peridotite, and the $\text{Cu}/(\text{Cu} + \text{Ni})$ profiles indicates that pyroxenite is more Cu-rich than peridotite which is Ni-rich.

VI.5.2 Middle Mineralized Unit

In the MMU, PGE, Cu, Se and S abundances again display similar distribution patterns. Profiles of Ni abundances do not correspond as well to the PGE profiles; however, some Ni peaks do correlate with peaks in PGE abundances. Profiles of Cr abundances do not resemble those of PGE suggesting that distribution of the two are interdependent of each other. $\text{Pt}/(\text{Pt} + \text{Pd})$ and $\text{Cu}/(\text{Cu} + \text{Ni})$ profiles do not vary sympathetically; peaks in $\text{Pt}/(\text{Pt} + \text{Pd})$ commonly correspond to lows in $\text{Cu}/(\text{Cu} + \text{Ni})$ suggesting that Pt-rich rocks are not necessarily Cu-rich. The $\text{Se}/\text{S} \times 10^6$ is notably flat. Peak PGE, Cu, S, and Se abundances occur in pyroxenite.

VI.5.3 Upper Mineralized Unit

In the UMU the relationship between element profiles is not well established as there are fewer data points; however, it is still evident that peak PGE abundances positively correlate with peaks in Cu, Ni, S and Se abundances. $\text{Pt}/(\text{Pt} + \text{Pd})$ and $\text{Cu}/(\text{Cu} + \text{Ni})$ profiles are not similar. Peak $\text{Pt}/(\text{Pt} + \text{Pd})$ values often correspond to low $\text{Cu}/(\text{Cu} + \text{Ni})$ values. The $\text{Se}/\text{S} \times 10^6$ values fluctuate, with some peak values corresponding to increases in PGE

FIGURE 13.A: Stratigraphic Distribution of PGE Concentrations and Associated Elements in the Lower Mineralized Unit. Stratigraphic Legend as in Figure 5.

FIGURE 13.B Stratigraphic Distribution of PGE Concentrations and Associated Elements in the Middle Mineralized Unit. Stratigraphic Legend as in Figure 5.

FIGURE 13.C: Stratigraphic Distribution of PGE Concentrations and Associated Elements in the Upper Mineralized Unit. Stratigraphic Legend as in Figure 5.

abundances. Pyroxenite and gabbro host anomalously high PGE abundances.

From these profiles it appears that there is a positive relationship between the distribution of PGE with Cu, S, Se and to some extent Ni. Peak PGE abundances generally positively correlate with peaks in Cu abundances, although this is not necessarily a reciprocal relationship as peaks in Cu are not always matched by peaks in PGE abundances. This suggests that rocks with anomalous PGE abundances are Cu-sulphide bearing, but that not all Cu-sulphide bearing rocks contain elevated PGE abundances. $Pt/(Pt + Pd)$ and $Cu/(Cu + Ni)$ profiles do not closely correspond with each other, suggesting that Cu-rich rocks are not necessarily Pt-rich.

VI.6 PGE RATIOS - $(Pt+Pd)/(Os, Ir, \& Ru)$, $(Pt/Pt+Pd)$ & (Pd/Ir)

PGE ratios are useful in assessing the variations of PGE within mineralized intervals. Ratios and profiles of the mineralized units are presented in Table VI and Fig. 14 respectively.

TABLE VI: AVERAGE PGE RATIOS IN MINERALIZED UNITS IN DIFFERENT ROCK TYPES *

Rock Type (Pt+Pd/(Os+Ir+Ru)		Pt/(Pt+Pd)	Pd/Ir	
UMU	(5)	22.9	0.6	59.8
	(3)	15.8	0.5	48.5
	(1)	9.5	0.6	53.3
MMU	(5)	20.1	0.3	141.5
	(3)	37.4	0.4	59.3
	(1)	57.2	0.3	169.2
LMU	(3)	34.7	0.4	81.0
	(1)	23.1	0.4	89.0
Average PGE concentration of all samples with rock type:				
	(5)	22.1	0.5	83.8
	(3)	34.5	0.4	66.6
	(1)	24.6	0.4	92.2
Rock Type: (1) = peridotite; (3) = pyroxenite; (5) = gabbro				

V.6.1 (Pt+Pd)/(Os+Ir+Ru) - (P/OIR)

The (P/OIR) ratio indicates the strength of the sulphide versus oxide-silicate affiliation of the PGE. All samples have ratios >1 indicating the prominent sulphide association of PGE (Fig. 14). Other workers (Naldrett and

FIGURE 14: Variation of PGE Ratios among the Lower, Middle, and Upper Mineralized Units.

Symbols: $\overline{\bullet}$ = Average peridotite ratio.
 $\overline{\blacktriangle}$ = Average pyroxenite ratio.
 $\overline{\blacksquare}$ = Average gabbro ratio.

Stratigraphic Legend as in Figure 5.

Duke 1980; Naldrett 1981; von Gruenewaldt et al. 1988) have used P/OIR ratios to characterize source magmas: low P/OIR (<13) indicate derivation from primitive magmas ($\text{MgO} > 20\%$) and high P/OIR ratios (>13) indicated derivation from more fractionated magmas ($\text{MgO} < 12\%$). According to these authors and assuming the process of fractional crystallization from the one magma chamber, P/OIR ratios from the FRS should progressively increase with overall stratigraphic position and rock type; i.e., rocks from the LMU should have lower P/OIR ratios than rocks from the MMU and UMU. Peridotite should have the lowest ratio, pyroxenite intermediate, and gabbro should exhibit the highest P/OIR ratios. The data from the mineralized samples do not confirm this hypothesis (Fig. 14). P/OIR ratios among rock type and mineralized intervals are erratic; only peridotite from the UMU has P/OIR value < 13 compatible with crystallization from a primitive magma. All other rocks have P/OIR > 13 implying derivation from a more fractionated source rock melt or other process. P/OIR ratios do increase with more fractionated rock type in the LMU and UMU but decrease from peridotite to gabbro in the MMU. Behaviour among the same rock types is also inconsistent, P/OIR ratios of pyroxenite increase from the LMU to MMU but decrease from the MMU to UMU. Another controlling variable on the P/OIR ratio may be the presence of chromite in the host rock. Os, Ir and Ru may be preferentially associated with chromite, (likely as minute inclusions incorporated into chromite grains, Gain

1985; Kinloch 1982; Cousins and Vermaak 1976, Talkington et al., 1983), resulting in low P/OIR ratios in chromite - bearing rocks. Hence the presence of chromite in the rocks may influence the Os + Ir + Ru abundances and the resultant P/OIR ratio.

VI.6.2 Pt/(Pt+Pd)

There is an overall trend of Pt enrichment and Pd depletion with both increasing overall stratigraphic height and within individual mineralized units, (Fig. 14).

In the LMU the Pt/(Pt + Pd) averages 0.42 (Fig. 14A). Although reversals are common there is an overall trend of decreasing Pt concentration with increasing stratigraphic height. In the basal portion of the LMU, Pt/(Pt + Pd) is consistently < 0.50. The ratio is ~0.5 in the central portion; however, in the upper 30 m the ratios are again < 0.5 indicating relative enrichment of Pd relative to Pt.

In the MMU (Fig. 14B) the average Pt/(Pt + Pd) is similar to that of the LMU, averaging 0.45. However, there is a strong overall trend of Pt enrichment with increasing stratigraphic position. In the basal portion of the MMU, the Pt/(Pt + Pd) is < 0.5 and constant. In the central portion, there are marked reversals in Pt/(Pt + Pd) from ~0.5 to < 0.5. In the upper portion, Pt/(Pt + Pd) > 0.5.

In the UMU, (Fig. 14C) the average Pt/(Pt + Pd) is much greater than in the LMU or MMU (0.58). There is an overall trend of Pt enrichment with increasing stratigraphic position. This trend is repeated on a smaller scale within

individual mineralized cyclic units. Generally peridotite and pyroxenite have $Pt/(Pt + Pd) < 0.7$, gabbro typically exhibit $Pt/(Pt + Pd) > 0.7$ indicating that Pt enrichment/Pd depletion is a function of increasing fractionation of the magma.

VI.6.3 Pd/Ir

Lowest average Pd/Ir ratios are from the stratigraphically highest and most fractionated rocks (UMU). The highest Pd/Ir ratio is from peridotite in the MMU, (Fig. XIV). These values contrast with the observations of Naldrett and Duke (1980) and Barnes et al. (1985) who used Pd/Ir ratios to relate PGE concentrations to partial melting and crystal fractionation processes respectively. In their investigation, they concluded that during partial melting of mantle material Ir partitions into olivine, whereas Pd partitions into the magma, and during crystal fractionation, Os, Ir and Ru may form alloys prior to Fe-Ni-Cu-S saturation and settle out with co-precipitating phases from the magma. The result of both partial melting and crystal fractionation processes is to concentrate Os, Ir and Ru in "primitive" rock types, with Pd being concentrated in more chemically evolved rock types. Their observations contrast with the behavior and diverse Pd/Ir range ($<1 - 240$) in rocks from the FRS. The discrepancy between Pd/Ir ratios in the FRS and the proposed behavior of Pd/Ir during partial melting and fractional crystallization processes suggest that a process other than only magmatic has played a role in the

distribution of PGE. Barnes et al. (1985) note that Pd is more mobile than other PGE in a hydrothermal solution. It is possible that late fluids have preferentially removed Pd from stratigraphically higher rocks resulting in their apparent Pd depletion. However, as indicated from $Pt/(Pt + Pd)$, Pd distribution appears systematic from the LMU through to the UMU. $Pt/(Pt + Pd)$ progressively decrease with stratigraphic position from the base of the MMU to the top of the UMU and in some cases from the base to the top of individual cyclic units. An alternative and more likely explanation for the wide range of Pd/Ir ratios is a combination of the low abundance of Ir in the FRS and its erratic distribution, resulting from the distribution of accessory chromite which may contain minute Os-Ir-Ru alloy inclusions. The low abundance of Os and Ru as well as Ir (Table V) suggests that if these inclusions do exist they are not a common phenomenon.

VI.7 STATISTICAL ASSOCIATION OF PGE

Statistical analysis¹ was used to further evaluate the geochemical and mineralogical associations of PGE.

Correlation analyses of the 89 mineralized samples was done on the basis of log normal distribution² of the PGE and associated elements (S, Se, Cu, Ni, As, Sb), (Table VII).

¹Statistical techniques from Statsgrah Version 2 package were used for correlation and regression analyses.

²Log normal distribution was used as these elements occur in low concentrations and their distribution more closely approximates that of a log normal than normal distribution O.R. Eckstrand, pers comm., 1989.

Correlation coefficient values > 0.5 were considered to be moderately correlated, values > 0.7 were the most strongly correlated. Significance levels for the correlation coefficients are indicated in Table VII. A factor which must be considered when reviewing the correlation coefficient analyses is the 1 m sample size interval. Geochemical material supplied for this study consisted of powdered sample representing 1 m lengths of drill core. True correlations between PGE and associated elements may become homogenized by the distribution of elements throughout the entire 1 m section rather than solely the area of PGE concentration.

There is a moderately positive correlation among PGE and base metal sulphide (BMS) elements of the 89 mineralized samples, notably between the total PGE (TPGE), Pt, Pd concentrations and Cu, (Table VIIA). The total PGE concentration and absolute S abundances are poorly correlated as are Cu and S.. In the LMU, MMU and UMU there is no correlation between PGE and elements of "late magmatic/hydrothermal" affinity, (As and Sb), (Tables VIIB-D).

When examined separately, the relationship between elements of the individual mineralized intervals vary (Tables VIIB-D). The discrepancy in correlation analyses among the overall 89 PGE mineralized samples and individual mineralized intervals suggests PGE affiliation among the LMU, MMU and UMU differs as follows.

TABLE VII : CORRELATION COEFFICIENT TABLES* (Based on log normal distribution)

A: Correlation Coefficients: ALL DATA (n = 89)
(At the 95% confidence level, correlation coefficients >0.21 are considered significant).

	TPGE	Ir	Ru	Rh	Pt	Pd	Au	S	Se	Cu	Ni	Cr	Co	Sb
TPGE														
Ir	.68													
Ru	.18	.29												
Rh	.72	.66	.11											
Pt	.86	.69	.14	.64										
Pd	.89	.57	.21	.58	.59									
Au	.31	.22	-.08	.30	.46	.11								
S	.39	.48	.25	.30	.32	.35	.23							
Se	.54	.52	.24	.34	.46	.49	.28	.90						
Cu	.60	.38	.09	.39	.55	.52	.50	.67	.79					
Ni	.34	.54	.25	.20	.26	.30	-.10	.79	.75	.38				
Cr	-.17	.07	.17	-.11	-.10	-.16	-.04	.28	.25	-.08	.36			
Co	.40	.50	.19	.27	.30	.38	-.06	.82	.76	.45	.94	.25		
Sb	-.09	-.22	.01	-.11	-.13	-.04	-.15	-.21	-.19	-.06	-.18	-.23	-.19	
As	-.15	-.33	-.08	-.18	-.16	-.14	-.09	-.54	-.42	-.28	-.47	-.25	-.46	.52

B: Correlation Coefficients: Lower Mineralized Unit (n = 38)
(At the 95% confidence interval, correlation coefficients > 0.33 are considered significant).

	TPGE	Ir	Ru	Rh	Pt	Pd	Au	S	Se	Cu	Ni	Cr	Sb
TPGE													
Ir	.44												
Ru	.15	.26											
Rh	.75	.40	.00										
Pt	.92	.60	.15	.74									
Pd	.95	.27	.15	.66	.77								
Au	.33	.29	.16	.51	.49	.18							
S	.13	.46	.02	-.09	.17	.04	-.21						
Se	.60	.58	.09	.26	.62	.47	.03	.75					
Cu	.63	.36	-.08	.45	.72	.47	.46	.41	.68				
Ni	.20	.49	.08	-.10	.15	.17	-.48	.80	.70	.16			
Cr	-.33	.13	.11	-.43	-.33	-.34	-.37	.37	.06	-.23	.40		
Sb	.07	.10	.26	.08	.04	.06	.03	.02	.10	.11	.06	.08	
As	.18	.25	.38	.16	.12	.19	-.08	.01	.16	-.12	.22	-.12	.74

C: Correlation Coefficients: Middle Mineralized Unit (n = 34)
(At the 95% confidence interval, correlation coefficients > 0.35
are considered significant).

	TPGE	Ir	Ru	Rh	Pt	Pd	Au	S	Se	Cu	Ni	Cr	Sb
TPGE													
Ir	.89												
Ru	-.16	-.23											
Rh	.76	.75	-.21										
Pt	.78	.90	-.29	.64									
Pd	.88	.62	-.03	.55	.47								
Au	.46	.59	-.39	.33	.67	.22							
S	.56	.63	.05	.53	.62	.36	.41						
Se	.65	.67	.01	.61	.61	.50	.42	.95					
Cu	.63	.61	.06	.56	.54	.64	.49	.75	.84				
Ni	.35	.52	-.27	.41	.45	.07	.27	.60	.58	.27			
Cr	-.38	-.08	-.01	.28	.08	-.56	.07	-.06	-.21	-.47	.15		
Sb	-.04	-.15	.07	-.02	-.34	.05	-.16	-.17	-.13	-.10	.01	-.25	
As	-.28	-.37	.09	-.25	-.48	-.13	-.20	-.37	-.38	-.22	-.28	-.34	.65

D: Correlation Coefficients: Upper Mineralized Unit (n = 17)
(At the 95% confidence interval, correlation coefficients > 0.48
are considered significant).

	TPGE	Ir	Ru	Rh	Pt	Pd	Au	S	Se	Cu	Ni	Cr	Sb
TPGE													
Ir	.86												
Ru	.67	.80											
Rh	.70	.74	.71										
Pt	.82	.88	.67	.62									
Pd	.83	.62	.50	.47	.43								
Au	-.09	.01	.05	-.08	.17	-.38							
S	.06	.17	.48	.01	.06	.09	.25						
Se	.01	.10	.41	-.18	-.01	.12	.39	.79					
Cu	-.03	-.01	.23	-.30	-.03	.02	.44	.64	.84				
Ni	.05	.17	.45	.05	.01	.07	.07	.88	.66	.50			
Cr	-.14	-.09	.28	.06	-.22	.03	.36	.57	.63	.37	.38		
Sb	-.21	-.30	-.33	-.26	-.39	.04	-.59	-.15	-.17	.02	-.05	-.34	
As	-.15	-.20	-.24	-.09	.40	.13	.15	-.56	-.20	.08	-.55	-.20	.04

*Correlation coefficients > .50 are illustrated in bold type

VI.7.1. Lower Mineralized Unit (Table VII B)

Within the LMU, Rh, Pt and Pd are strongly intercorrelated. TPGE positively correlates with Se and Cu but not S or Ni. Pt, Cu and Se are particularly strongly intercorrelated. Pt and Au, and Ni and Ir display a weak affiliation.

VI.7.2 Middle Mineralized Unit (Table VII C)

Within the MMU, Rh, Pt and Pd are moderately positively correlated and there is a consistent interdependence of Pt, Pd and Rh with Se, S, Cu. Pt and Au are moderately associated. Ni is moderately positively correlated with Ir, S and Se and is weakly correlated with Pt and Rh.

VI.7.3 Upper Mineralized Unit (Table VII D)

Within the UMU there is a notable lack of correlation between PGE and elements of BMS affiliation and among the PGE themselves. As previously described, sulphides in the UMU have been extensively replaced by mgn +/- py assemblages. Replacement of BMS by mgn +/- py assemblages results in redistribution of BMS elements (Cu, Ni, S) and possibly of PGE originally associated with BMS. This may partially explain the apparent lack of association between BMS elements and PGE concentrations. Cr, which negatively correlated with most elements in the other mineralized units, displays a positive relationship with S and Se.

PGE are associated with elements of BMS affinity in the LMU and MMU but not the UMU, demonstrating that the PGE have different chemical tendencies within the individual mineralized intervals. No association between PGE and elements of late magmatic or hydrothermal affinity (ie As, Te, Sb, Bi etc) or with Cr is evident from the correlation analyses. The correlation between PGE and Cu and Se in the LMU and MMU suggest that PGE may be associated with ccp. The correlation between TPGE and Ni strengthens if selected outlier points are rejected, suggesting there may also be a relationship between TPGE and pn.

VI.8 CHONDRITE NORMALIZED PROFILES¹ (CNP)

CNP reveal the overall distribution of PGE in the mineralized intervals and the relationship among the various PGE ratios. PGE deposits of the oxide/silicate affiliation have negative profiles; those of sulphide affiliation have positive profiles reflecting their relative depletion/enrichment of (Os, Ir and Ru) to (Rh, Pt and Pd) (Naldrett, 1981).

Chondrite normalized trends from the FRS have positive

¹CNP of the 89 mineralized samples were not recalculated to 100% sulphide as all three zones did not display a strong positive correlation with the distribution of BMS. Hence there is no basis for assuming that all the PGE crystallized in a sulphide fraction. Concurrently, petrographic studies indicate that original sulphide has been partially replaced by mgn +/- py assemblages indicating that S has been redistributed or removed from the system. If PGE were originally associated with sulphides this may not be the present affiliation as a result of alteration and recrystallization of primary sulphide assemblages.

slopes $[(Pt + Pd)/(Os + Ir + Ru) > 1]$ reflecting the low abundances of Os, Ir and Ru and the higher concentrations of Rh, Pt and Pd. Au distribution is erratic. Three samples (79, 114, and 112) from the basal LMU have flat CNP ($P/O < 5$). CNP for each of the LMU, MMU, and UMU display three distinct internal trends defined by variations in the $Pt/(Pt + Pd)^1$;

- (1) Positive Pd Profile [$Pt/(Pt + Pd) < 0.5$]
- (2) Plateau Pd Profile [$Pt/(Pt + Pd) = 0.5 - 0.7$]
- (3) Negative Pd Profile [$Pt/(Pt + Pd) > 0.7$]

These three trends all display a continuum of low to high PGE concentrations.

The trend of increasing $Pt/(Pt + Pd)$ with stratigraphic height is reflected in the CNP by an increasing proportion of Plateau and Negative Pd Profiles and decreasing proportion of Positive Pd profiles from the LMU to UMU. The range of Positive, Plateau and Negative Pd Profiles for the mineralized units intervals is illustrated in Fig. 15.

The LMU (Fig. 15A) is characterized by greater concentrations of Pd than Pt as indicated by the predominance of Positive Pd profiles (90%). Plateau (5%) and Negative (5%) profiles constitute a minor proportion of this mineralized interval.

¹CNP are referred to as "Pd enriched" when the slope between Pt and Pd is positive and "Pd depleted" if the slope between Pt and Pd is negative. The trends are viewed as Pd depletion rather than Pt enrichment as the change in slope between Rh and Pd remains relatively constant but the slope between Pt and Pd is variable.

FIGURE 15: Range of Chondrite Normalized Negative, Plateau and Positive Pd Profiles for the Lower, Middle and Upper Mineralized Units.

SYMBOLS: ○ = Range of Negative Pd Profile
 □ = Range of Plateau Pd Profile
 △ = Range of Positive Pd Profile

In the MMU (Fig. 15B) a strong overall trend of Pd depletion with increasing stratigraphic position is illustrated by the decreasing proportion of Positive Pd profiles (65%) relative to Plateau (23.5%) and Negative (11.5%) Pd profiles. The trend of increasing Pd depletion with increasing stratigraphic position continues in the UMU (Fig. 15C) where there is a further decrease in the proportion of Positive Pd profiles (35%) and a corresponding increase in Plateau (41%) and Negative (24%) Profiles. The shift in CNP relative to the mineralized units and rock type is graphically presented in Fig. 16. Peridotite and pyroxenite exhibit Positive and Plateau profiles ($Pt/Pt+Pd < 0.7$); gabbroic rocks typically exhibit Negative Pd profiles ($Pt/Pt+Pd > 0.7$), (Fig. 16A).

Barnes et al. (1985) used Pd/Ir ratios to characterize the slope of PGE CNP patterns. In the FRS Pd/Ir ratios are not reliable indicators of the overall slope of the PGE distribution pattern. It is evident from the trends of the three CNP patterns that Pd concentrations decrease with; (i) increasing stratigraphic position and (ii) more fractionated rock type. Positive Pd profiles are most prevalent in the LMU, and its proportion progressively decreases in the MMU and UMU as Plateau and Negative Pd profiles successively become more common (Fig. 16B). Positive Pd profiles are also most common in peridotite and pyroxenite. Pyroxenite has the greatest proportion of Plateau Pd profiles, and gabbroic rocks typically have Negative Pd profiles (Fig. 16A).

FIGURE 16.A: Distribution of Chondrite Normalized Profiles with Rock Type.

FIGURE 16.B: Distribution of Chondrite Normalized Profiles with Mineralized Unit.

Previous work on PGE in the FRS by Scoates and Eckstrand (1986) based on 12 PGE mineralized samples identified 2 populations of PGE CNP profiles (not normalized to 100% sulfide);

- 1) Steep profiles with high concentrations of Rh, Pt and Pd,
- 2) Shallow profiles with low concentrations of Rh, Pt and Pd.

Variations in the slope of CNP were attributed to be related to the thickness of cyclic units. Thinner cyclic units were relatively enriched in Rh, Pt and Pd and possessed steep CNP; thick cyclic units with lower tenors of Rh, Pt and Pd had shallow profiles. The relative enrichment of Rh, Pt and Pd in the thinner cyclic units was interpreted to be a product of more evolved residual magma already enriched in Rh, Pt and Pd. Upon S saturation, PGE crystallized with the sulphides.

From the more extensive database it appears that the "Steep" and "Shallow" profiles described by Scoates and Eckstrand (1986) represent a continuum of "Positive Pd Profiles" rather than two separate/distinct populations. No relationship between thickness of the cyclic unit and the slope of the CNP was established in this study; however, in the LMU and MMU elevated PGE concentrations were often associated with interlaminated strata.

VI.9 DISCUSSION & SUMMARY

The close association of PGE with sulphides, tellurides, selenides, arsenides, sulpharsenides, and antimonides is well established in the literature (Crocket 1979, 1981; Wright and Fleischer 1965; Mertie 1969; Naldrett 1981; Cabri 1981; Dillon-Leitch et al. 1988). The association of PGE with sulphides, notably po, pn, and ccp is the most common and has led many researchers to suggest that sulphide magmas behave as collectors of PGE (Naldrett and Duke, 1980; Naldrett and Cabri, 1976; Hulbert et al., 1988). Vermaak and Hendrik (1976) found that the proportion of PGE unaccounted for by platinum-group minerals within the Merensky Reef was primarily contained by base metal sulphides (BMS). The mode of occurrence of PGE within the BMS was not determined although it was postulated that PGE occur in solid solutions. An alternative suggestion that BMS are host to submicroscopic but discrete PGE particles, termed "colloidal solid solution", was forwarded by Vermaak and Hendriks (1976). Kinloch (1982) also suggested that solid solution or lattice substitution of PGE in BMS accounted for the important latent fraction of PGE, notably Pd and Rh within pn. Solid solution between PGE and BMS has been confirmed by Cabri and Laflamme (1976).

Kinloch (1982) noted the complex mineralogical association of the PGE in rocks from the Merensky Reef with arsenides, sulpharsenides, tellurides, bismuthides, antimonides and Pt-Fe alloys as well as sulphides. The

varied mineralogical assemblages were a feature that led Boudreau and McCallum (1985), Ballhaus and Stumpfl (1985), Stumpfl and Ballhaus (1986), Stumpfl and Rucklidge (1982) and Johan and Watkinson (1985) to stress the role of late stage magmatic/hydrothermal fluids in the concentration of PGE. Late magmatic/hydrothermal fluids may concentrate PGE, As, Sb and S as complex ions followed by precipitation as discrete minerals, often in association with ccp, the youngest major sulphide in the paragenetic sequence (Crocket, 1969).

The behavior of the PGE in the FRS during crystallization of the three PGE-bearing units differs, as indicated by the variable and progressive shift in the of PGE ratios with stratigraphic position, and by the differing strengths of correlation coefficients in PGE among the three mineralized units. The generalized trend of increasing $Pt/(Pt + Pd)$ with increasing stratigraphic position in the FRS is similar to patterns observed in the Stillwater and Fiskenaesset complexes (Page et al., 1982).

The distribution and geochemical behavior of PGE in the FRS are summarized by the following points;

- (1) Concentrations of Pt and Pd are higher than those of Os, Ir and Ru; Rh concentrations are low.
- (2) Concentrations of Os, Ir and Ru are greatest in peridotite from the stratigraphically lowest mineralized intervals and those concentrations decrease with stratigraphic height and fractionated rock type.

- (3) Trends of PGE, Cu, S, Se, Ni and Cr abundances indicate that the distribution of PGE is similar to that of Cu, Se and S. The profiles suggest that anomalous abundances of PGE are hosted by sulphide-bearing rocks; however, not all sulphide-bearing rocks contain anomalous concentrations of PGE.
- (4) There is a progressive shift towards increasing Pt/(Pt + Pd) with both stratigraphic height and more fractionated rock type. This trend is echoed by Pt/(Pt + Pd) ratios within the MMU and UMU but within the LMU there is a weak trend towards Pt depletion/Pd enrichment.
- (5) The UMU, which represents the products of the most fractionated magma, contains the lowest P/OIR and Pd/Ir ratios and the highest Pt/(Pt + Pd) ratio
- (6) Sulphide-bearing pyroxenite contains the widest range and the greatest number of anomalously high values of PGE.
- (7) Total PGE concentrations (TPGE) are associated with base metal elements (notably Cu) in the LMU and MMU, but not the UMU. There is no correlation between PGE and elements of "late magmatic/hydrothermal" affinity (As, Te, Sb) or with Cr content.
- (8) CNP of the mineralized samples have positive slopes $[(Pt+Pd)/(Os+Ir+Ru) > 1]$.
- (9) Variations of Pt/(Pt + Pd) define three patterns of CNP; Positive (< 0.5), Plateau ($0.5 - 0.7$), and Negative (> 0.7).
- (10) CNP reflect the overall trend of Pd depletion with

increasing stratigraphic position. The proportion of Positive Pd profiles decreases relative to Plateau and Negative Pd profiles from the LMU through the MMU and UMU respectively.

(11) Pd/Ir ratios are not accurate indicators of the overall behaviour of Pt + Pd + Rh relative to Os + Ir + Ru for the FRS. This is indicated by the variability of Pd content displayed by the three types of identified CNP.

(12) The role of chromite distribution likely plays an important role in the fluctuation of PGE ratios. The association of Os + Ir + Ru with chromite has been documented by others (Gain, 1985, Kinloch, 1982, Vermaak, 1976, Cousins and Vermaak, 1976). A combination of the low Os, Ir and Ru abundances in the FRS, and incorporation of available Os, Ir and Ru as inclusions into chromite during crystallization may account for the erratic fluctuations in both P/OIR and Pd/Ir ratios.

CHAPTER VII: SULPHUR ISOTOPE STUDY

VII.1 INTRODUCTION

The S isotopic composition of sulphides was determined to help interpret the provenance of S in FRS sulphides. The S isotopic composition is expressed as a $\delta^{34}\text{S}$ value or per mil deviation of the $^{34}\text{S}/^{32}\text{S}$ of the sample relative to a standard where;

$$\delta^{34}\text{S}\text{‰} = \frac{(^{34}\text{S}/^{32}\text{S})_{\text{sample}} - (^{34}\text{S}/^{32}\text{S})_{\text{standard}}}{(^{34}\text{S}/^{32}\text{S})_{\text{standard}}} * 1000$$

Equation 1

The standard is the troilite phase of the Canon Diablo Meteorite $\delta = 0$, (Ohmoto, 1987). Isotope ratios are referred to as heavy ($\delta > 0$) or light ($\delta < 0$) if the sample is enriched or depleted in ^{34}S with respect to the standard. Igneous rocks with juvenile sulphur from partial melting of the mantle should have $\delta^{34}\text{S}$ values of $0 \pm 1\text{‰}$ (Shima et al., 1963). Ohmoto (1987) suggested that those with ^{34}S values outside the range of -3 to +3 must have a crustal S component.

VII.2 METHOD

Eleven samples were submitted to the Stable Isotope Laboratory of the Ottawa - Carleton Geoscience Centre for ^{34}S analyses. Samples were chosen on the basis of high PGE concentration, high S content, representative rock type and variable stratigraphic position within the rock succession. Peridotite and pyroxenite host fine grained (<1

mm) disseminated po, ccp, pn, cbn, mkw, and py; gabbro contains fine grained (<1 mm) gn, ccp, py, po as well as veinlets (up to 1 cm) of gn and bn.

In ten samples the total S was analyzed because the amount of sulphide was too small to prepare concentrations of individual sulphide minerals. A sulphide separate (gn) was obtained from one sample. Descriptions of samples are given in Appendix v). Results of the analyses are listed in Table VIII.

TABLE VIII: Sulphur Isotope Results					
SAMPLE	ROCK	STRAT.	PGE	S	$\delta^{34}\text{S}$
NUMBER	TYPE*	HEIGHT (M)	(ppb)	(ppm)	
5-7835	3	549.5	908	4545	+9.7
5-7931	5	~472	<34	massive galena	+11.0
1-7025	5	180	900	8187	+9.2
2-7491	1	200.5	81	3381	+10.1
2-7533	3	173	658	7618	+10.1
2-7545	4	165.5	538	18042	+10.5
1-7185	1	69	795	6375	+12.4
1-7200	3	56.5	678	12422	+12.3
1-7218	3	38.5	615	2034	+11.8
1-7267	1	-4	28	2647	+17.4
1-7268	1	-5	668	2744	+16.6
*1 = peridotite; 3 = olivine clinopyroxenite; 4 = interlayered pyroxenite and gabbro; 5 = gabbro					

VII.3 DISCUSSION

All $\delta^{34}\text{S}$ values lie well outside the mantle range (+1‰, Shima et al., 1963; -3 to +3, Ohmoto and Rye, 1987), ranging from +9.2 to +17.4. The two samples with the heaviest ^{34}S signature are from the LCLZ. Generally the ^{34}S progressively decreases with increasing stratigraphic height, (Fig. 17). The gn separate from a gabbro relatively high in the succession has a ^{34}S signature that is similar to the total sulphur values (refer to Table VIII).

Many mafic to ultramafic igneous rocks such as the Duluth Complex, the Noril'sk intrusion and the Muskox intrusion have sulphides with similar ^{34}S values, (Fig. 18). The Duluth intrusion has ^{34}S values which range from 0 to +18 (Mainwaring and Naldrett, 1977; Ripley, 1981). Sulphides (po, ccp, cbn, and pn) are irregularly concentrated near the base of the complex where it intrudes metasediments. Sulphur in sulphide minerals from these country rocks range from +0.2 to +25.8. The occurrence of metasedimentary xenoliths and the heavy S isotopic values led Mainwaring and Naldrett (1977) and Ripley (1981) to suggest that S in the intrusion had been contaminated by S from surrounding country rocks. C isotopes from graphite in the Water Hen intrusion are also compatible with the process of assimilation of surrounding crustal rocks, (Mainwaring, P.R.; pers. comm., 1988).

FIGURE 17: Sulphur Isotope Distribution with Stratigraphic Position.

FIGURE 18: Range of Sulphur Isotopes within the Fox River Sill and other mafic-ultramafic intrusions.

The Noril'sk intrusion hosts sulphides (po, ccp and cbn) which have ^{34}S which ranges from +6.6 to + 17.6 (Godlevskii and Grinenko, 1963). It intrudes metasediments which contain anhydrite and have average ^{34}S values of +16.4. From the similar values, Gorbachev and Grinenko (1973) concluded that the source of S in the intrusion was from sulphate in the country rocks.

In the Muskox Intrusion, ^{34}S values range from +2 to +17 (Sasaki, 1969). Sulphides in the metasedimentary and metavolcanic country rocks range from -4 to +30. Sasaki (1969) considered two possibilities for the heavy isotopic values of sulphides from the Muskox Intrusion;

- (1) The S in the Muskox Intrusion is isotopically representative of mantle S at the time the Muskox magma was formed or,
- (2) That the "magmatic" mantle isotopic values of S was not preserved in Muskox sulphides as a result of either isotopic fractionation or, crustal S contamination from country rocks during ascent of magmas which formed the Muskox Intrusion.

The mafic metavolcanics and metasediments which the FRS intruded are sulphide-bearing. Po is the most common sulphide, with minor ccp and py as common though not abundant constituents of the mafic metavolcanics and intercalated carbonaceous shales (Scoates, 1981). There is no macroscopic evidence such as the presence of xenoliths,

that might imply assimilation of crustal material into the Fox River Sill magmas. However, altered and recrystallized gabbros within the UCLZ contain concentrations of galena and chalcocite as veinlets and as fine grained (<1 mm) disseminations that are unusual for a layered intrusion. Precise Pb isotope ratios from galena and chalcocite yield ages essentially coeval to the formation of the Fox River Sill but which have high $^{207}\text{Pb}/^{204}\text{Pb}$ values relative to the lead considered to be directly derived from the mantle, (Thorpe, R.; pers. comm., 1989).

VII.4 SUMMARY

A more comprehensive S isotope study which would include samples of the country rocks, and rocks of the Marginal and Hybrid Series of the Fox River Sill is necessary to provide a sufficient framework for determining the provenance of S. Data is too limited at this time to hypothesize on the origin and significance of S for the entire intrusion or on the relationship between S in the intrusion with S in the country rocks. However, the presence of consistent, anomalously heavy ^{34}S values in the Fox River samples places constraints on the provenance of S in the FRS. All ^{34}S analyses lie well outside the mantle range and values for the FRS are similar to those of Noril'sk, Duluth and Muskox where contamination of the magma by crustal S has been documented to have occurred. This suggests that the FRS magma has also been contaminated by

crustal S. Processes by which the magma may have become contaminated with heavy ^{34}S include (i) bulk assimilation of crustal S, with inherent heavy ^{34}S , during intrusion of numerous magma pulses and (ii) reaction of the FRS magma with a ^{34}S -enriched fluid phase.

Although there are no macroscopic features or, as yet, any corroborative heavy S isotope data from the surrounding country rocks, one indication that bulk crustal assimilation may have occurred during intrusion of the FRS is the unusually high concentration of galena in the gabbros of the FRS. High $^{207}\text{Pb}/^{204}\text{Pb}$ suggest that the FRS magma contained a major component of crustal lead that has evolved for a significant period of time within the upper crust of the earth. This is consistent with assimilation of galena-bearing crustal rocks during intrusion of the parental magmas of the FRS (Thorpe, R.; pers. comm., 1989). In the second process of contamination, a ^{34}S -enriched fluid phase may be generated by the conversion of py to po + sulphur species, in the crustal rocks (equation II). Grinenko and Thode (1970) have shown that in a closed gas system ^{34}S is preferentially fractionated into the SO_2 gas phase, and ^{32}S into the H_2S phase.

Equation II

This reaction and process has been demonstrated to have occurred during formation of the silver-sulpharsenide vein deposits in Cobalt, Ontario (Goodz et al., 1986). Mainwaring (1975) also noted the importance of such a reaction in the metasedimentary footwall rocks of the Water Hen Intrusion, Duluth, and mused on its influence on the heavy ^{34}S values of the intrusion. The predominance of po rather than py in the metasediments and metavolcanics of the Fox River Belt suggest that this process may have occurred, possibly as a result of contact metamorphism during intrusion of the FRS magmas. The ^{34}S -enriched fluid phase produced from such a reaction may subsequently have interacted with the FRS magma.

The anomalously heavy ^{34}S of the LCLZ, although spatially located only 55 m from an UCLZ sample with noticeably lighter ^{34}S , implies an abrupt change in the source of S in the UCLZ compared to that of the LCLZ. The trend from heavy ^{34}S values toward slightly lighter values with increasing stratigraphic height (Fig. 17) has also been observed in the Muskox, Bushveld, and Duluth Intrusions, (Sasaki 1969; Liebenberg 1970; Mainwaring and Naldrett 1976).

The heavier ^{34}S content of the LCLZ compared to the UCLZ may be attributed to a combination of the following factors:

- 1) a decrease in the amount of crustal S component in successive magma pulses. The larger volumes of magma pulses

which produced the thick cyclic units in the LCLZ had a longer period of time to assimilate crustal S, thereby increasing the amount that was incorporated. Crustal and juvenile S was thoroughly homogenized in the magma. As the volume of successive magma pulses decreased and the periodicity of intrusion increased, as interpreted from the thinner cyclic units of the UCLZ, crustal assimilation of S became less important and heavy S was successively diluted by juvenile S.

2) During fractionation, ^{34}S was preferentially incorporated into the crystallizing sulphides of the LCLZ, enriching the residual magma in ^{32}S (Ohmoto and Rye, 1979).

Crystallization of later formed sulphides in rocks from the UCLZ would have been enriched in the lighter ^{32}S relative to early formed sulphides.

3) Interaction of the FRS magma with a less ^{34}S -enriched fluid phase during formation of the UCLZ than during formation of the LCLZ.

Contamination of the FRS magma by either bulk crustal assimilation or by interaction with a ^{34}S -enriched fluid phase is possible. In order to generate such consistently, anomalously heavy ^{34}S requires an homogeneous S source as well as a sufficient supply of heavy S. From these constraints the process of bulk assimilation of crustal S seems a more significant method of contamination of the FRS magma. Large volumes of sulphide-bearing crustal material

could be assimilated into the magma and be thoroughly mixed by convection processes to provide a homogeneous, heavy ^{34}S signature. While this mixing process may also occur between ^{34}S -enriched fluids and the FRS magma, it seems unlikely that isotopic fractionation by itself could provide such a heavy ^{34}S signature (Ohmoto, 1987).

The process of "sulphidization" proposed by Cheney and Lange (1967), where crustal S is introduced into a magma by assimilation of surrounding country rocks, is the most plausible method for producing the observed heavy ^{34}S isotopic ratios observed in the FRS although interaction of the FRS magma with a ^{34}S -enriched fluid phase may contribute to the heavy S signature. High $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of FRS sulphides also suggest bulk contamination of the mafic FRS magma by crustal assimilation. Lighter ^{34}S signatures in the UCLZ suggest that crustal contamination of the FRS magma during crystallization of UCLZ rocks was not as significant as during crystallization of LCLZ rocks.

CHAPTER IX: SUMMARY AND CONCLUSIONS

In the PGE-bearing Merensky Reef of the Bushveld Complex, and the JM Reef of the Stillwater Complex, detailed work on the composition of platinum-group minerals, textural relationships of minerals and fluid inclusion studies has defined the importance of a late magmatic fluid phase (volatile-rich intercumulus material) in the genesis of stratiform PGE concentrations, (Boudreau et al. 1985, Schiffries 1982; Watkinson and Dunning 1979; Talkington and Watkinson 1984; Johan and Watkinson 1985). Alternatively, Barnes and Campbell (1988), suggest that the evidence supporting a late magmatic/hydrothermal origin of PGE deposits are the result of postcumulus processes which have been superimposed on previously formed magmatic stratiform PGE concentrations and that stratiform PGE deposits are the result of magma mixing events as summarized by Campbell et al. (1983) and Naldrett et al. (1987).

A model explaining the distribution of PGE in the Fox River Sill must incorporate the following observations:

- 1) The Fox River Sill is a major, layered ultramafic - mafic intrusion. Drill core from Fox 1 represents rocks which have crystallized from the most magnesian magmas; those from Fox 5 have crystallized from more fractionated magmas. The Lower Central Layered Zone/Upper Central Layered Zone contact marks a change from predominantly thick, ultramafic rock sequences in the Lower Central Layered Zone to thinner, ultramafic-mafic rock sequences in the Upper

Central Layered Zone. In this context, the Upper Central Layered Zone is located at a similar position as the Merensky Reef-bearing Critical Zone of the Bushveld Complex, and the JM-Reef bearing Banded Zone of the Stillwater Complex, as was pointed out by Scoates and Eckstrand (1986). While the PGE-bearing JM and Merensky Reefs have been spatially associated with mixing zones between magmas with two distinct compositions (Irvine et al. 1983, Irvine and Sharpe 1986), it is beyond the scope of this thesis to speculate on any similar association between PGE-bearing intervals in the Fox River Sill and the Lower Central Layered Zone/Upper Central Layered Zone contact.

2) Layers are modally, grain-size, and texturally graded and are variably laminated. Layer contacts are both phase - and modal-defined.

3) Thirty-two cyclic units (generally incompletely developed) were recognized, based on the systematic rhythmic succession of rock types composed of olivine, clinopyroxene and plagioclase cumulates. A complete cyclic unit is composed of dunite/peridotite -> olivine clinopyroxenite --> olivine gabbro. This likely represents a minimum number as thick dunite/peridotite sequences were grouped as one macrorhythmic cyclic unit. Variation in whole rock Ni content suggests that such sequences may represent the products of several influxes of magma. Periodic injections of new magma interrupted the olivine, clinopyroxene, plagioclase crystallization sequence, and displaced

fractionated magma to produce the numerous cyclic units observed.

4) Hydrous alteration of the primary silicate assemblages (serpentinization, uralitization, saussuritization) is pervasive. Pyroxenite is not as completely altered and recrystallized as the peridotite and gabbro. Many PGE-bearing pyroxenite intervals are coarse-grained to pegmatitic with original pyroxene grains partially altered to amphibole.

5) Major and trace element analyses indicate that individual rock types evolved toward a less mafic composition with increasing stratigraphic height and that ilmenomagnetite - bearing gabbros have crystallized from the most fractionated magmas.

6) Disseminated sulphides (<3 volume %) occur throughout the stratigraphic succession. Pyrrhotite, pentlandite, chalcopyrite, cubanite, mackinawite and pyrite are the dominant sulphide minerals. They occur as polymineralic and monomineralic grains molded around cumulus silicates. Bornite, sphalerite and galena are minor sulphide phases.

7) Sulphide assemblages range from Ni-rich in peridotite to more Cu-rich in pyroxenite and gabbro. This is supported by whole rock geochemical analyses.

8) Primary sulphides have been replaced and redistributed by silicate, oxide and second generation Cu-rich sulphide assemblages. Loss of sulphur is documented by magnetite +/- pyrite replacement of primary sulphide assemblages.

9) PGE concentrations are preferentially host by magmatic sulphide-bearing, medium to pegmatitic olivine clinopyroxenite. Pyroxenite is the least altered rock type, and contains the most anomalous and widest range of PGE, Cu, Ni, S and Se. This suggests a relationship between formation of the host lithology, associated sulphides and PGE mineralization. The coarse-grained to pegmatitic nature of the host sulphide-bearing pyroxenite and the recrystallization of some pyroxene to amphibole suggest the presence of a volatile phase.

10) PGE concentrations are richer in (Pt + Pd + Rh) than (Os + Ir + Ru). During crystallization of a magma PGE will strongly partition into a sulphide liquid phase (Naldrett and Duke 1980). Barnes et al. (1985) proposed that if sulphur saturation has not occurred, PGE concentration in the silicate liquid increases until either the solubility of the PGE metal or PGE sulphide phase is exceeded. Os, Ir and Ru have lower solubilities than Pt, Pd and Rh and may form Os-Ir alloys or sulphides such as laurite (RuS_2) which subsequently precipitate from the magma. Pt, Pd and Rh have higher solubilities and will be concentrated in the remaining magma until sulphur saturation occurs at which time Pt, Pd and Rh are incorporated into the sulphide liquid. Barnes et al. (1985) noted the importance of the timing of sulphur saturation as if it is delayed, there will be a greater opportunity for separation of the PGE into the (Os + Ir + Ru) and (Pt + Pd + Rh) groups. Scoates and

Eckstrand (1986), also advocate a combination of advanced fractionation of new magma pulses and late sulphide saturation of this melt as a means of concentrating Pt, Pd and Rh in the Fox River Sill. The predominance of (Pt + Pd + Rh) over (Os + Ir + Ru) in Fox River Sill rocks suggests that partitioning of the PGE occurred. The lack of PGE mineralization in thick, dunite intervals suggest Pt, Pd and Rh were concentrated in the more fractionated melt.

11) Pt/(Pt + Pd) ratios and chondrite normalized profiles indicate that with increasing stratigraphic height, Pd is depleted relative to Pt. This trend is also seen within individual cyclic units, especially in the Upper Mineralized Unit. The generalized trend of increasing Pt/(Pt + Pd) with increasing stratigraphic position in the Fox River Sill is similar to patterns observed in the Stillwater and Fiskenaesset complexes, (Page et al. 1982). Cousins and Vermaak (1976) suggest that Pt enrichment, relative to Pd, with increasing stratigraphic height is related to Fe enrichment in silicate minerals during fractionation processes and emphasized the siderophile tendency of Pt relative to Pd. Pd/Ir and Pt + Pd/(Os + Ir + Ru) ratios are erratic.

12) Trends of PGE, Ni, Cu, S, Se and Cr abundances with stratigraphic height indicate that the distribution of PGE is similar to that of Cu, Se and S. Anomalous PGE abundances are contained in sulphide-bearing rocks; however, not all sulphide-bearing rocks contain anomalous

concentrations of PGE.

13) Correlation coefficients indicate that PGE are moderately correlated with elements of base metal sulphide affinity (notably Cu) in the Lower and Middle Mineralized Units. In the Upper Mineralized Unit, PGE concentrations are not correlative with any of the base metal elements. Poor correlation among base metal elements and PGE may be a result of remobilization/recrystallization of sulphides during deuteric or metamorphic processes, especially where magnetite +/- pyrite replace sulphide assemblages. In the Middle Mineralized Unit where sulphide assemblages are not as extensively replaced by magnetite +/- pyrite, the correlation between PGE and base metal sulphide elements is stronger, suggesting that during the processes related to sulphur loss there is a separation between PGE and elements of base metal sulphide affiliation. There is no correlation between PGE and As, Te, Sb or Cr in the Lower, Middle or Upper Mineralized Units.

14) Sulphur isotopes are notably heavy (+9.2 -->+17.4) indicating that sulphur in the magma has a strong crustal component. The consistently heavy sulphur isotope signature suggests that the contaminated magma was thoroughly homogenized so that upon sulphur saturation all sulphides had anomalously heavy sulphur. The Lower Central Layered Zone sulphur isotopic signature is distinctly heavier than that of the Upper Central Layered Zone suggesting a change or modification in the sulphur source from the Lower Central

Layered Zone to the Upper Central Layered Zone. The most likely explanation is that as the amount of crustal component in successive magma pulses decreased, and the periodicity of intrusion of new magma increased, as interpreted from the thinner cyclic units of the Upper Central Layered Zone, heavy sulphur was successively diluted by juvenile sulphur. An alternative possibility is related to the Lower Central Layered Zone/Upper Central Layered Zone contact as possibly marking the site of mixing of two distinct magma compositions. A basic magma with a juvenile sulphur signature mixed with residual melt from the ultrabasic magma, which had partially crystallized to form Lower Central Layered Zone rocks, and had a heavy sulphur signature. The resulting sulphur isotopic signature of Upper Central Layered Zone rocks would be intermediate between the two.

A model for platinum-group element distribution in the Fox River Sill is proposed:

Fox River Sill magmas, which had assimilated crustal sulphur, were emplaced into the Fox River Belt. Sulphur saturation was not immediately attained, and heavy sulphur from the crust was thoroughly homogenized with juvenile sulphur in the magma chamber. During crystallization of the magma, Os, Ir and Ru may have formed alloys, whereas Pt, Pd and Rh were concentrated in the evolved liquid phase of the magma. Upon sulphur saturation, Pt, Pd and Rh were

dissolved into the sulphide liquid which upon cooling precipitated monosulphide solid solution. On further cooling, pyrrhotite, pentlandite and chalcopyrite exsolved from the monosulphide solid solution to form primary sulphide assemblages commonly observed as polymineralic grains. Periodic injections of new magma displaced and mixed with fractionated magma to form the numerous cyclic units observed. Compaction of the cumulate pile resulted in migration of volatile-rich, PGE-bearing intercumulus material. High PGE abundances in coarse-grained to pegmatitic sulphide and amphibole-bearing pyroxenite suggests that pyroxenite preferentially acted as sinks for the migrating deuteritic fluids and PGE abundances in the pyroxenite were subsequently upgraded. Local mobilization and redistribution of sulphides, as seen by the sulphide-silicate replacement and recrystallization textures, may have resulted in a geochemical separation of PGE and base metal sulphide elements. This is reflected by only moderate correlation among these elements.

From the above observations exploration targets for PGE concentrations in the Fox River Sill are contained in thin, more highly differentiated cyclic units of the Upper Central Layered Zone, as suggested by Scoates and Eckstrand (1986). More specifically, elevated PGE abundances are preferentially associated with coarse-grained, copper and sulphide-bearing intervals that exhibit evidence of deuteritic

alteration. The low tenor of PGE in dunite and in zones of fault breccia preclude these intervals as targets of PGE concentration.

Macdonald (1987) notes that where sulphur saturation has been attained as a result of assimilation of crustal sulphur, resultant PGE concentrations tend to be located at the contact between the intrusion and the country rocks (Sudbury, Noril'sk). Watkinson and Dahl (1988) have suggested that fluids released from assimilated country rock xenoliths mobilize Cu, Ag, Pb, Pt and Rh from the intruded rocks. These elements precipitate when the fluid reacts with pyrrhotite and magnetite. These observations suggest that another exploration target for PGE concentration in the Fox River Sill would be in sulphide and oxide-bearing rocks of the Marginal Series where the Fox River Sill is in contact with the country rocks, particularly where there is evidence of direct assimilation of the country rocks.

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Q1		1	3	5	7	9	11	13	15	17
DEPTH (cm)		101.5	102.5	103	105.5	108.5	106.5	200.5	429.5	546.5
SAMPLE NO.		1-7021	1-7019	2-7517	2-7513	2-7509	2-7497	2-7491	5-7976	5-7837
ELEMENT										
SiO2		46.30	44.30	45.70	44.80	45.60	42.20	41.30	45.40	49.50
Al2O3		0.19	0.16	0.18	0.21	0.25	0.13	0.14	0.18	0.25
Fe2O3		4.40	4.50	3.20	3.90	4.60	3.30	3.00	11.70	3.10
Cr2O3		0.25	0.16	0.42	0.30	0.34	0.33	0.34	0.14	0.50
Fe2O3i		7.30	10.70	9.90	11.70	11.10	10.20	12.10	6.30	6.50
Fe2O3		1.70	3.30	3.00	2.90	2.80	2.60	4.20	0.20	1.00
FeO		6.20	6.60	6.20	7.90	7.40	6.80	7.10	5.10	5.00
MnO		0.14	0.14	0.16	0.17	0.17	0.14	0.13	0.11	0.12
MgO		22.42	23.70	24.02	22.18	22.19	31.05	30.26	15.45	19.75
CaO		12.74	10.37	11.39	11.23	10.99	3.47	4.17	16.54	16.55
Na2O		0.00	0.00	0.00	0.10	0.30	0.00	0.00	0.00	0.00
K2O		0.07	0.05	0.00	0.06	0.04	0.00	0.04	0.05	0.07
LOI						0.04				
H2O1		4.40	6.10	5.40	5.20	5.00	9.60	9.50	4.50	2.20
LOI1		0.00	0.10	0.00	0.00	0.10	0.10	0.10	0.00	0.30
P2O5		0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00
S		0.01	0.47	0.24	0.82	0.45	0.20	0.36	0.00	0.18
Ba		32.00	34.00	28.00	16.00	72.00	11.00	15.00	19.00	40.00
Nb		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr		20.00	6.00	0.00	0.00	0.00	0.00	7.00	73.00	30.00
V		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Co		0.00	11.00	0.00	9.00	22.00	14.00	16.00	10.00	0.00
TOTAL		100.00	100.00	99.90	99.70	100.20	100.00	100.70	99.50	98.50

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APPENDICES

APPENDIX 1
SAMPLE PREPARATION AND ANALYTICAL PROCEDURES

1) Major and minor elements

Major and minor element analyses were done at the Geological Survey of Canada (G.S.C.) Laboratories in 1987 by x-ray fluorescence wavelength dispersive methods on fused disks. Detection limits given by the G.S.C. Laboratory are stated in Table i. One g of sample was mixed with 5 g of $\text{Li}_2\text{B}_4\text{O}_7$ and 0.3g of LiF, and fused to a glass disc within a platinum crucible. Major elements were measured on the disc using the wavelength dispersive method, with readings of 20 min/disc. Matrix effects resulting from absorption and enhancement caused by excitation of other elements within the specimen were corrected by theoretically determined alpha coefficients. Minor elements were measured on the powdered sample in a mylar floored holder using the energy-dispersive method.

Volatile fractions (H_2O_t , CO_2 , S) were determined by mixing the 0.5 g sample with vanadium pentoxide (V_2O_5) in nickel combustion boats, decomposing them at 950°C in a nitrogen atmosphere, and measuring evolved gases by non-dispersive infra-red absorptionometry (Bouvier and Abbey, 1980). FeO was determined by titration. Fe_2O_3 was calculated by ;

(Total Fe as Fe_2O_3 , T by XRF) - 1.1134 FeO (volumetric)

2) Trace elements

Trace elements Ba, Be, Co, Cr, Cu, La, Ni, V, Yb and Zn were analyzed by ICP. Pb was analyzed by Atomic Absorption. Co, Cr, Cu, Ni, V and Zn were prepared by both total dissolution and acid soluble dissolution methods. Acid soluble dissolution analyses are denoted by AS following the element name. The following description of the sample preparation is summarized from P Belanger of the G.S.C. Laboratories, (pers. comm. 1988).

i) Total dissolution. One g of sample is digested by a succession of acids (HNO_3 , HF, HCl, and HClO_4) and taken to dryness. The sample is taken up in dilute HCl and the solution is filtered. The residue is fused with 0.5 g of lithium metaborate and dissolved in the original filtrate to which has been added 5 ml of 0.8% EDTA to retain Ba in solution. The solution is diluted to 100 ml for a final concentration of 10% in HCl

ii) Acid soluble. Acid solubles are dissolved in 8 ml of reverse aqua regia ($\text{HCl}:\text{HNO}_3 = 1:3$ - Lefort mixture) at 90°C . The dry residue is then dissolved in HCl and water to obtain a final solution in 10% HCl. EDTA and Li-metaborate are then added to make this solution the same as the final solution for trace determination by ICP.

iii) F, Cl, S, As, Sb, Se and Te

Trace elements F, Cl and S were determined simultaneously by pyrohydrolysis and chromatography using a method devised and described by Hall et al., (1986). Trace elements As, Sb, Se and Te were determined by flameless atomic absorption spectrometry as described by Aslin (1976).

3) PRECIOUS METAL ANALYSES

Analyses of PGE (Os, Ir, Ru, Rh, Pt, Pd) and Au were done at the Nuclear Activation Services Ltd. Laboratories in Hamilton, Ontario (McMaster University). Twenty to fifty grams of sample, (crushed to -200 mesh fraction) was analyzed by extraction using a nickel sulphide fire assay followed by neutron activation. Detection limits as quoted by Nuclear Activation Services Laboratory are as follows:

TABLE i: Detection limits of chemical analyses

Table ia: XRF ANALYSES

ELEMENT	DETECTION LIMIT (WT%)
SiO ₂	0.40.
TiO ₂	0.02
Al ₂ O ₃	0.40
Cr ₂ O ₃	0.02
Fe ₂ O ₃	0.10
FeO	0.20
MnO	0.01
MgO	0.10
CaO	0.10
Na ₂ O	0.50
K ₂ O	0.05
H ₂ O _t	0.10
CO ₂ _t	0.05
P ₂ O ₅	0.02
S	0.04
Ba	.002
Rb	.003
Sr	.002
Y	.003
Zr	.002

Table ib: ICP ANALYSES

ELEMENT	DETECTION LIMIT (ppm)
Ba	20
Be	0.5
Co	5
Cr	10
Cu	10
La	10
Ni	10
Pb	20
V	5
Yb	0.5
Zn	5
F	50
Cl	100
S	50
As	0.5
Sb	0.5
Se	0.01
Te	0.5

Table ic: PGE ANALYSES

ELEMENT	DETECTION LIMIT (ppb)
Au	1.0
Os	3.0
Ir	0.1
Ru	5.0
Rh	1.0
Pt	5.0
Pd	5.0
Re	5.0

APPENDIX 11: MAJOR AND MINOR ELEMENT CHEMISTRY

RT#		1	1	1	1	1	1	1	1
STRATIGRAPHIC		-15	-7.5	-6	04.5	05.5	54.5	61.5	64
HEIGHT									
SAMPLE NO.		1-7281	1-7269	1-7266	1-7255	1-7254	1-7202	1-7194	1-7191
ELEMENT									
SiO ₂	36.40	35.80	36.20	37.70	39.20	36.30	36.80	36.90	37.60
TiO ₂	0.09	0.10	0.11	0.12	0.19	0.11	0.19	0.12	0.00
Al ₂ O ₃	1.30	1.90	2.00	2.20	3.40	0.31	2.50	2.60	2.50
Cr ₂ O ₃	0.84	1.51	0.97	0.92	0.21	0.34	0.35	0.48	0.25
Fe ₂ O _{3T}	11.00	10.10	10.10	8.30	6.00	11.40	9.40	10.10	10.60
Fe ₂ O ₃	6.80	5.80	6.00	1.20	1.50	5.70	4.60	5.40	10.60
FeO	3.70	3.90	3.70	4.60	4.10	5.10	4.40	4.20	
MnO	0.11	0.13	0.14	0.13	0.14	0.11	0.09	0.10	0.09
MgO	37.28	37.17	37.13	37.95	34.83	36.12	36.36	36.66	33.69
CaO	0.33	0.07	0.10	0.11	2.63	0.17	0.11	0.08	2.20
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.18	0.05	0.25	0.05	0.06	0.11	0.10	0.15	0.08
LOI									11.90
Si	12.10	12.70	12.70	13.40	12.30	12.30	12.60	12.80	
Al ₂ O ₃	0.30	0.20	0.10	0.20	0.20	0.20	0.10	0.30	0.20
Cr ₂ O ₃	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S	0.23	0.29	0.29	0.56	0.28	0.44	0.49	0.30	1.20
Ba	28.00	59.00	55.00	35.00	45.00	36.00	39.00	0.00	22.00
Nb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rb	0.00	0.00	13.00	0.00	0.00	0.00	0.00	0.00	0.00
Er	0.00	27.00	29.00	69.00	71.00	24.00	37.00	32.00	1.00
Y	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pr	0.00	5.00	16.00	0.00	24.00	13.00	10.00	26.00	23.00
TOTAL	99.70	99.70	99.70	99.20	99.10	100.20	98.70	100.00	88.60

*IN ALL APPENDICES RT 1 = PERIDOTITE; RT 2 = PERIDOTITE/PYROXENITE; RT 3 = PYROXENITE; RT 4 = PYROXENITE/GABBRO; RT 5 = GABBRO

RI	1	1	1	1	1	1	1	1	1
SIRKUNIGRAFMIL									
WEIGHT	68	65	69	90.5	111	116	137	194.5	315
SAMPLE NO.	1-7176	1-7170	1-7165	1-7164	1-7134	1-7115	1-7081	2-7500	2-7335
ELEMENT									
SiO2	38.00	34.50	34.10	36.40	35.00	35.50	37.70	40.10	36.70
TiO2	0.15	0.08	0.12	0.10	0.10	0.13	0.11	0.15	0.15
Al2O3	2.40	2.20	1.80	1.10	1.40	1.70	1.90	3.20	2.40
Cr2O3	0.35	0.59	0.82	0.86	1.10	0.94	0.61	0.58	0.67
Fe2O3	6.50	10.80	12.80	10.30	10.50	10.50	15.10	12.40	11.80
Fe2O3	3.80	4.50	5.70	4.70	6.20	5.20	8.80	7.10	6.60
FeO	4.00	5.70	6.40	5.10	3.70	4.80	5.70	4.80	4.70
MnO	0.13	0.12	0.11	0.09	0.07	0.07	0.07	0.14	0.12
MgO	36.22	35.00	34.70	37.02	37.52	36.73	34.61	31.48	35.49
CaO	1.48	0.82	0.08	0.07	0.08	0.09	0.12	3.32	0.26
Na2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.08	0.05	0.08	0.08	0.10	0.09	0.03	0.00	0.05
LOI									
H2O1	12.10	12.00	12.20	12.10	13.90	13.00	10.40	9.60	12.50
CO2	0.30	0.70	0.10	0.10	0.40	0.40	0.10	0.00	0.30
F2O5	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.03
S	0.25	0.81	0.69	0.58	0.26	0.67	0.58	0.11	0.39
Ba	56.00	40.00	54.00	54.00	33.00	43.00	68.00	31.00	77.00
Nc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Re	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	13.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Y	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.00	24.00
LOI	29.50	46.50	97.10	98.40	99.40	99.30	100.70	109.40	100.50

Wt		1	1	1	1	1	1	2	2	2
SINKHILLGRAPHS		551.5	482.5	522.5	545			50.5	58	27
HEIGHT		2-7285	5-7919	5-7859	5-7841	1-7257	2-7425	1-7253	1-7251	1-7210
SAMPLE NO.										
ELEMENT										
	SiO ₂	37.80	39.30	36.50	37.80	35.70	37.90	43.00	42.00	38.30
	TiO ₂	0.17	0.13	0.27	0.08	0.14	0.13	0.20	0.22	0.17
	Al ₂ O ₃	2.50	2.00	3.40	2.00	1.60	2.80	2.80	3.90	2.80
	Cr ₂ O ₃	0.61	0.51	0.59	0.62	1.35	0.80	0.23	0.20	0.29
	Fe ₂ O ₃	10.50	8.80	11.80	12.20	11.00	13.50	1.50	7.40	9.40
	Fe ₂ O ₃	5.60	5.40	6.20	5.80	6.50	7.50	1.10	1.70	9.40
	FeO	4.40	3.10	5.10	5.70	4.00	5.20	5.60	5.10	
	MnO	0.11	0.08	0.14	0.11	0.12	0.16	0.13	0.10	0.11
	MgO	35.12	37.24	35.41	34.45	37.02	34.60	29.74	29.95	30.87
	CaO	0.44	0.15	0.08	0.14	0.29	0.11	7.54	6.84	4.46
	Mg ₂ SiO ₄	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	K ₂ O	0.05	0.12	0.20	0.09	0.21	0.04	0.13	0.18	0.10
	Li ₂ O									12.50
	H ₂ SiO ₃	12.00	12.10	12.00	12.50	12.70	10.90	8.60	9.20	
	Li ₂ SiO ₃	0.40	0.10	0.10	0.20	0.40	0.10	0.20	0.30	0.40
	P ₂ O ₅	0.02	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.12
	S	0.12	0.12	0.44	0.26	0.27	0.11	0.34	0.19	1.15
	Ba	72.00	85.00	59.00	44.00	64.00	55.00	52.00	52.00	0.00
	Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	K	0.00	0.00	0.00	0.00	7.00	0.00	9.00	0.00	0.00
	Cl	14.00	13.00	0.00	24.00	17.00	0.00	37.00	52.00	15.00
	F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Br	0.00	0.00	73.00	57.00	0.00	0.00	22.00	29.00	17.00
	Sum	99.20	100.40	100.20	99.80	100.40	100.80	99.70	99.90	88.20

PT		1	2	3	4	5	6	7	8	9
STRATIGRAPHIC										
HEIGHT		47.5	53.5	55.5	57	74	146	208	27	12
SAMPLE NO.		1-7209	1-7203	1-7201	1-7199	1-7180	2-7494	2-7484	1-7252	1-7247
ELEMENT										
SiO ₂		59.00	58.40	59.20	40.20	39.20	42.70	41.80	45.20	48.10
Al ₂ O ₃		0.14	0.28	0.23	0.22	0.15	0.17	0.16	0.21	0.24
Fe ₂ O ₃		2.80	3.40	3.40	3.80	2.50	3.30	3.50	2.90	3.10
Cr ₂ O ₃		0.32	0.34	0.48	0.45	0.25	0.35	0.38	0.22	0.22
Fe ₂ SiO ₄		10.50	8.70	10.00	8.80	7.80	10.40	11.20	8.90	7.50
Fe ₂ SiO ₃		4.80	3.00	3.00	4.20	3.80	3.20	4.20	1.20	1.50
FeO		5.10	4.50	6.30	4.20	3.80	6.50	6.30	7.00	5.80
MnO		0.12	0.11	0.11	0.13	0.11	0.15	0.15	0.13	0.12
HgO		31.31	31.85	28.50	27.80	35.26	29.18	27.15	24.70	23.42
CaO		5.52	4.78	6.86	9.10	2.26	5.75	6.45	12.02	13.53
Na ₂ O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ₂ O		0.39	0.11	0.15	0.14	0.12	0.06	0.04	0.14	0.14
CO ₂				9.80						
H ₂ SiO ₃		10.80	10.50	8.80	9.00	12.10	8.80	8.00	5.20	3.90
CO ₂		0.20	0.19	0.10	0.20	0.20	0.20	0.90	0.00	0.10
H ₂ SiO ₄		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
S		0.35	0.47	0.81	0.42	0.46	0.25	0.57	0.45	0.39
Ca		1.00	12.00	29.30	21.00	41.00	7.00	28.00	12.00	0.00
H ₂		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe		0.00	0.00	0.00	12.00	2.00	0.00	0.00	2.00	3.00
Sr		10.00	47.00	1.00	19.00	39.00	17.00	0.00	16.00	68.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Li		13.00	15.00	17.00	21.00	24.00	12.00	7.00	18.00	10.00
CO ₂		100.20	98.20	98.00	99.50	100.00	100.80	99.30	99.30	99.90

R1		3	3	3	3	3	3	3	3
SITE/LOCATION		15	15.5	32	35.5	35.5	42.5	43	44
HEIGHT		1-7243	1-7253	1-7225	1-7221	1-7213	1-7215	1-7213	1-7212
SAMPLE NO.		1-7243	1-7253	1-7225	1-7221	1-7213	1-7215	1-7213	1-7212
ELEMENT									
SiO2		46.90	43.20	44.00	47.00	46.40	42.60	40.80	39.60
TiO2		0.22	0.19	0.17	0.20	0.20	0.17	0.17	0.17
Al2O3		3.10	2.50	3.30	3.70	3.50	3.30	3.10	2.90
Cr2O3		0.23	0.21	0.29	0.34	0.35	0.28	0.29	0.29
Fe2O3		7.40	7.70	7.90	7.20	7.60	8.40	8.60	9.70
FeO		1.80	2.40	2.60	1.40	1.60	3.50	5.10	3.50
MnO		5.10	4.80	4.80	5.20	5.20	4.40	4.20	5.60
MgO		0.13	0.11	0.12	0.13	0.13	0.12	0.10	0.10
P2O5		23.90	27.23	24.78	25.34	25.11	28.12	27.91	28.69
CaO		12.98	9.36	12.45	14.28	14.17	8.99	8.94	8.62
Na2O		0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O		0.09	0.07	0.05	0.13	0.16	0.12	0.10	0.09
LOI								11.20	
H2O		4.71	7.80	6.40	4.20	4.40	7.70	9.00	8.70
CO2		0.00	0.10	0.10	0.00	0.10	0.10	0.10	0.10
F2O5		0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00
S		0.12	0.16	0.13	0.15	0.19	0.21	0.37	0.71
Ba		35.00	32.00	41.00	59.00	16.00	36.00	25.00	41.00
Nb		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rb		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr		5.00	50.00	0.00	54.00	52.00	0.00	15.00	7.00
Zr		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LOI		18.00	0.00	10.00	10.00	24.00	0.00	12.00	6.00
TOTAL		99.40	99.10	99.20	100.10	99.60	99.70	100.10	99.10

RT	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC HEIGHT	51	51.5	53	56.5	68	67	121	141	151
SAMPLE NO.	1-7206	1-7205	1-7204	1-7200	1-7186	1-7185	1-7093	1-7056	1-7037
ELEMENT									
SiO ₂	41.20	40.30	40.70	42.00	40.40	39.10	42.00	47.50	45.20
TiO ₂	0.16	0.18	0.20	0.24	0.17	0.18	0.18	0.23	0.27
Al ₂ O ₃	3.40	2.90	2.80	3.20	2.70	2.90	2.50	3.10	10.80
Cr ₂ O ₃	0.32	0.31	0.35	0.39	0.31	0.29	0.34	0.43	0.09
Fe ₂ O ₃	6.50	7.00	9.50	9.10	8.70	10.60	831.00	9.20	7.40
Fe ₂ O ₃	2.60	3.10	9.50	9.10	4.50	5.50	4.20	9.20	1.00
FeO	5.70	5.30			3.80	4.60	3.50	0.00	5.80
MnO	0.11	0.11	0.10	0.12	0.08	0.08	0.10	0.13	0.11
MgO	28.05	27.96	27.22	25.14	31.16	30.95	31.18	19.63	17.55
CaO	8.54	8.30	8.47	11.35	6.05	5.00	6.88	15.27	13.34
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.30
K ₂ O	0.12	0.11	0.12	0.03	0.08	0.11	0.06	0.07	0.08
LOI		9.60	9.60	3.40					
H ₂ O	3.40	8.90			9.90	9.90	9.20		5.00
CO ₂	0.10	0.20	0.00	0.10	0.40	0.20	0.10	0.10	0.10
P ₂ O ₅	0.00	0.13	0.00	0.01	0.00	0.00	0.00	0.01	0.02
S	0.56	0.74	1.13	1.26	0.43	0.60	0.22	1.11	0.01
Ba	25.00	36.00	1.00	53.00	12.00	15.00	65.00	39.00	42.00
NO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Re	19.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Br	0.00	2.00	0.00	0.00	21.00	13.00	0.00	0.00	55.00
r	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Li	4.00	27.00	14.00	13.00	29.00	23.00	0.00	4.00	12.00
TOTAL	72.90	98.50	90.80	93.00	100.00	99.40	100.30	97.50	99.70

ELEMENT	SAMPLE NO.	1	2	3	3	5	5	5	5	5
		100	101	102	103	104.5	105	105.5	106	109.5
		2-7553	2-7552	2-7551	2-7549	2-7547	2-7546	2-7545	2-7544	2-7543
SiO ₂		45.20	45.70	45.20	42.80	41.30	43.00	43.40	45.00	45.00
TiO ₂		0.21	0.20	0.27	0.22	0.17	0.23	0.21	0.28	0.25
Al ₂ O ₃		3.60	3.60	3.70	3.10	2.90	3.50	3.50	10.00	6.80
Fe ₂ O ₃		0.24	0.24	0.25	0.19	0.14	0.19	0.16	0.13	0.16
Fe ₂ SiO ₄		9.41	9.30	9.00	10.50	14.20	12.00	12.90	7.70	9.00
Fe ₂ SiO ₃		2.30	2.00	1.80	10.50	14.20	12.00	12.90	1.20	2.10
FeO		6.40	6.60	6.50					5.90	6.70
MgO		0.13	0.13	0.13	0.11	0.11	0.12	0.12	0.14	0.13
Mg ₂		25.76	23.90	24.33	26.49	25.62	24.52	23.01	15.38	19.26
CaO		10.41	11.52	10.59	8.45	7.85	7.92	10.25	17.70	13.36
Na ₂ O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10
K ₂ O		0.05	0.05	0.04	0.06	0.06	0.06	0.05	0.04	0.14
Li ₂					7.50	7.50	6.90	6.10		
H ₂ O ₁		6.30	5.70	6.00					3.50	4.60
Li ₂ Si		0.10	0.00	0.10	0.20	0.00	0.20	0.00	0.10	0.00
P ₂ O ₅		0.00	0.13	0.02	0.00	0.00	0.00	0.12	0.13	0.02
S		0.11	0.10	0.15	1.02	2.09	1.76	1.77	0.36	0.76
Ba		55.77	42.00	72.00	29.00	49.00	6.00	14.00	11.00	81.00
Ni		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Co		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr		11.00	10.00	0.00	9.00	0.00	0.00	0.00	60.00	58.00
Zn		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
As		12.00	17.00	19.00	14.00	15.00	14.00	18.00	43.00	24.00
total		100.10	100.20	99.10	93.10	94.50	95.50	95.50	99.90	99.50

RT		1	2	3	4	5	6	7	8	9
STENOGRAPHIC										
HEIGHT		171	171.5	172.5	173	175.5	178	179	179.5	180
SAMPLE NO.		2-7536	2-7535	2-7534	2-7533	2-7532	2-7526	1-7029	1-7027	1-7025
ELEMENT										
SiO2		46.90	46.00	47.40	46.10	46.10	45.30	44.30	45.50	44.50
TiO2		0.22	0.20	0.22	0.21	0.20	0.16	0.23	0.22	0.24
Al2O3		3.80	2.80	3.10	2.80	3.20	3.00	4.10	3.80	3.90
Cr2O3		0.24	0.24	0.25	0.24	0.27	0.27	0.24	0.21	0.21
Fe2O3		10.50	11.40	9.90	10.50	9.50	10.00	9.50	10.70	10.50
Fe2O3		10.50	11.40	2.40	2.50	2.00	2.70	3.40	4.40	3.30
FeO				6.80	7.20	6.70	6.60	5.30	5.70	6.50
MnO		0.14	0.18	0.18	0.15	0.16	0.16	0.13	0.13	0.14
MgO		20.25	21.89	21.23	22.85	24.19	25.82	24.75	25.07	22.44
CaO		13.66	12.70	13.83	12.01	11.29	9.73	10.58	9.43	11.68
Na2O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O		0.05	0.06	0.07	0.05	0.05	0.04	0.04	0.07	0.08
Li2O		3.70	4.70							
H2O				3.90	4.90	5.50	6.20	6.00	6.30	5.20
CO2		0.10	0.00	0.00	0.10	0.10	0.00	0.00	0.00	0.10
P2O5		0.00	0.00	0.00	0.00	0.13	0.13	0.01	0.02	0.02
S		1.32	1.22	0.77	0.73	0.24	0.11	0.16	0.89	0.65
Ba		46.00	0.00	0.00	0.00	25.00	19.00	48.00	48.00	35.00
NC		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr		0.00	0.00	0.00	0.00	21.00	11.00	0.00	0.00	0.00
Zr		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr		17.00	17.00	18.00	13.00	19.00	14.00	15.00	10.00	17.00
TOTAL		97.00	96.70	100.10	99.90	100.20	100.10	99.30	99.70	99.10

RT	1	2	3	3	3	4	4	4	4
STRATIGRAPHIC									
HEIGHT	547.5	549.5				158.5	181	184.1	187
SAMPLE NO	5-7838	5-7835	2-7461	2-7441	1-7232	2-7554	2-7522	1-7018	1-7013
ELEMENT									
SiO2	48.20	46.30	44.60	43.80	47.80	46.20	45.40	44.90	46.00
TiO2	0.18	0.14	0.33	0.22	0.24	0.30	0.17	0.17	0.22
Al2O3	3.90	5.20	5.20	3.50	3.20	8.60	3.00	5.10	5.90
Cr2O3	0.49		0.28	0.33	0.27	0.22	0.31	0.15	0.14
Fe2O3	6.40	7.89	8.90	10.00	6.80	7.90	10.30	9.90	9.40
Fe2O3	0.90	2.00	2.10	2.90	1.00	1.40	2.80	2.70	2.80
FeO	5.00	5.10	6.10	6.40	5.20	5.80	6.90	6.50	5.90
MnO	0.10	0.11	0.14	0.12	0.11	0.14	0.15	0.16	0.13
MgO	21.25	22.50	24.15	26.99	23.20	17.15	24.89	22.83	20.52
CaO	14.81	13.70	9.69	7.62	13.51	15.04	10.29	11.55	12.61
Na2O	0.00	0.25	0.00	0.00	0.20	0.30	0.00	0.00	0.20
K2O	0.07	0.11	0.00	0.00	0.17	0.20	0.04	0.03	0.10
LOI									
H2O	3.90	4.30	6.80	7.50	3.90	3.70	6.20	5.30	4.60
CO2	0.40	0.10	0.20	0.20	0.00	0.10	0.20	0.10	0.00
F2O3	0.14	0.01	0.02	0.01	0.01	0.13	0.00	0.01	0.02
S	0.13		0.07	0.10	0.98	0.05	0.21	0.31	0.58
Ca	15.00	14.00	53.00	73.00	52.00	25.00	29.00	37.00	62.00
%b	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	33.00		46.00	0.00	21.00	134.00	9.00	0.00	13.00
r	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
cr	0.00		26.00	0.00	0.00	37.00	13.00	14.00	9.00
TOTAL	99.50		99.60	99.70	99.80	99.40	100.30	99.70	99.80

		5	5	5	5	5	5	5	5
STEEL CHANNEL									
Material		100.5	146	190	190.5	191	204.2	267	307
SAMPLE NO.		1-7071	1-7049	1-7005	1-7003	2-7504	2-7488	2-7393	2-7380
ELEMENT									
SiO ₂	45.40	46.10	45.70	45.90	47.30	46.90	49.60	43.80	50.20
Al ₂ O ₃	0.30	0.15	0.18	0.18	0.54	0.52	2.42	1.14	0.44
Fe ₂ O ₃	5.20	14.70	7.80	9.50	5.40	5.20	13.50	10.20	6.70
Cr ₂ O ₃	0.47	0.17	0.10	0.10	0.30	0.30	0.00	0.02	0.48
MnO	6.50	5.00	6.20	5.50	9.60	6.50	15.90	9.40	8.00
Fe ₂ Si	1.70	0.70	1.10	0.90	1.80	1.00	1.90	1.30	1.00
FeO	6.10	0.90	5.50	6.00	7.40	7.00	12.80	7.20	8.30
MnO	0.14	0.11	0.10	0.14	0.13	0.19	0.23	0.47	0.14
MgO	1.10	10.49	11.11	10.67	18.49	15.72	4.56	7.90	16.92
CaO	11.60	15.36	11.33	14.73	14.78	13.47	7.86	23.54	13.80
Na ₂ O	0.20	0.20	0.10	0.10	0.10	0.10	3.70	0.00	0.80
K ₂ O	0.11	0.24	0.05	0.04	0.04	0.00	0.79	0.04	0.20
LOI									
SiO ₂	4.50	3.60	5.40	4.90	3.70	3.00	2.50	3.20	3.30
Al ₂ O ₃	0.30	0.40	0.60	0.10	0.10	0.10	0.10	0.30	0.00
Fe ₂ O ₃	0.10	0.00	0.00	1.00	0.00	0.04	0.10	0.18	0.03
S	0.02	0.01	0.00	0.11	0.12	0.00	0.03	0.04	0.04
Fe	62.00	107.00	62.00	97.00	41.00	52.00	118.00	81.00	74.00
NO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO	0.00	11.00	0.00	1.00	1.00	0.00	16.00	0.00	0.00
Cr	28.00	155.00	8.00	27.00	45.00	30.00	172.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	12.00	21.00	0.00
Cr	18.00	22.00	6.00	0.00	1.00	37.00	70.00	99.00	55.00
TOTAL	49.40	99.40	49.40	49.40	100.10	99.60	100.00	99.40	100.50

RT		5	5	5	5	5	5	5	5
STRATIGRAPHIC									
HEIGHT		402.5	403	404.5	411.5	431	432	432.5	469.5
SAMPLE NO.		5-9028	5-9027	5-9026	5-9012	5-7974	5-7972	5-7971	5-7905
ELEMENT									
SiO ₂	49.40	50.80	51.40	45.60	45.10	44.80	45.10	44.00	46.90
TiO ₂	0.44	0.44	0.48	0.12	0.22	0.15	0.16	0.08	0.14
Al ₂ O ₃	7.20	7.30	7.90	15.50	12.50	13.60	10.40	16.50	5.80
Cr ₂ O ₃	0.44	0.43	0.42	0.15	0.06	0.06	0.08	0.10	0.35
Fe ₂ O ₃	8.10	7.50	7.40	4.90	6.50	5.20	7.20	4.00	5.00
FeO	0.90	0.70	1.00	0.80	0.50	0.40	0.60	0.60	0.30
MnO	6.50	6.10	5.80	3.70	5.40	4.40	5.70	2.70	4.30
MgO	0.14	0.14	0.13	0.10	0.12	0.12	0.15	0.28	0.15
MgO	16.62	15.14	14.29	12.92	13.66	13.14	17.10	9.62	18.50
CaO	13.34	14.08	14.34	15.04	17.32	18.18	15.80	22.53	18.60
Na ₂ O	1.00	1.40	1.60	1.00	0.00	0.00	0.00	0.00	0.00
K ₂ O	0.24	0.30	0.34	0.30	0.03	0.03	0.03	0.04	0.03
LOI									
H ₂ O _T	3.20	2.40	2.20	4.20	4.50	4.40	4.60	3.10	3.50
CO ₂	0.10	0.10	0.00	0.20	0.10	0.10	0.10	0.10	0.10
F ₂ O ₅	0.14	0.14	0.14	0.00	0.01	0.01	0.00	0.00	0.00
S	0.00	0.00	0.04	0.01	0.04	0.00	0.05	0.01	0.04
Ca	71.00	41.00	35.00	75.00	56.00	58.00	0.00	30.00	0.00
Nb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ko	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	55.00	60.00	70.00	67.00	5.00	34.00	62.00	168.00	30.00
r	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr	48.00	48.00	61.00	0.00	18.00	14.00	10.00	7.00	0.00
TOTAL	99.70	99.60	100.10	99.70	99.50	99.50	99.70	100.10	99.70

		5	5	5	5	5	5	5	5
SIRM 1000000000									
M210-		487	488	545	550.5				
SAMPLE NO.		5-7910	5-7908	5-7838	5-7834	5-7881	2-7434	5-7804	2-7408
ELEMENT									
	SiO ₂	43.30	43.80	47.70	44.90	41.90	47.80	45.30	51.80
	Al ₂ O ₃	0.12	0.10	0.10	0.09	0.08	0.17	0.08	1.16
	Fe ₂ O ₃	11.10	14.50	2.70	15.70	17.30	15.30	17.60	14.50
	Cr ₂ O ₃	0.23	0.15	0.51	0.17	0.05	0.09	0.02	0.00
	Fe ₂ SiO ₄	4.10	4.30	7.50	4.00	4.60	4.40	3.70	12.20
	Fe ₂ O ₃	0.20	0.50	1.30	0.30	0.80	0.90	0.80	1.90
	FeO	1.70	3.40	5.10	3.30	3.80	3.20	2.80	9.30
	MnO	0.15	0.10	0.13	0.08	0.10	0.09	0.07	0.20
	MgO	10.1	11.50	23.20	13.65	11.80	12.05	11.10	5.22
	CaO	20.41	18.44	13.64	18.75	18.82	15.50	16.89	8.70
	Mg ₂ SiO ₄	0.00	8.44	0.00	0.00	0.00	1.10	0.40	3.90
	FeO	0.00	0.05	0.00	0.51	0.00	0.53	0.49	0.62
	SiO ₂		0.14						
	Mg ₂ SiO ₄	0.00	0.40	4.50	0.20	4.80	2.90	3.60	2.60
	SiO ₂	0.00	0.30	0.20	0.10	0.10	0.10	0.40	0.20
	Fe ₂ SiO ₄	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Si	0.00	0.04	0.12	0.13	0.01	0.00	0.10	0.00
	Si	10.00	0.00	0.00	22.00	67.00	101.00	74.00	125.00
	Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Si	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00
	Si	25.00	108.00	30.00	129.00	108.00	179.00	144.00	211.00
	Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	Si	0.00	0.00	5.00	0.00	0.00	0.00	0.00	67.00
	SiO ₂	10.00	99.00	99.90	99.40	99.40	99.80	99.50	100.00

RT	1	1	1	1	1	1	2	2	2
STRATISGMPPLC	351.5	431.5	522.5	543			5.5	8	7
HEIGHT									
SAMPLE NO	2-7225	5-7919	5-7650	5-7841	1-7267	1-7415	1-7251	1-7251	1-7210
ELEMENTS									
BE	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10
CO	110.00	140.00	120.00	150.00	110.00	120.00	99.00	79.00	150.00
CR	2,500.00	2,600.00	2,600.00	1,600.00	2,500.00	1,500.00	1,500.00	1,200.00	1,500.00
CU	28.00	8.00	120.00	130.00	12.00	8.00	340.00	200.00	310.00
CA	3.00	5.00	3.00	5.00	3.00	4.00	4.00	4.00	4.00
NI	920.00	1,500.00	1,800.00	1,700.00	1,700.00	1,700.00	760.00	530.00	2,000.00
PS	16.00	11.00	27.00	0.00	2.00	4.00	0.00	0.00	0.00
V	76.00	57.00	60.00	50.00	33.00	96.00	120.00	130.00	98.00
TE	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.20
ZN	110.00	52.00	190.00	27.00	97.00	83.00	44.00	41.00	46.00
CO-MS	100.00	140.00	120.00	150.00	120.00	71.00	100.00	77.00	160.00
CR-MS	720.00	760.00	640.00	620.00	520.00	620.00	680.00	720.00	1,000.00
CU-MS	23.00	7.00	110.00	140.00	12.00	3.00	370.00	140.00	890.00
NI-MS	850.00	1,500.00	1,800.00	1,600.00	1,600.00	1,100.00	850.00	600.00	2,300.00
V-MS	4.00	27.00	31.00	29.00	22.00	26.00	64.00	76.00	60.00
ZN-MS	23.00	21.00	35.00	19.00	50.00	9.00	15.00	11.00	20.00
FE	0.00	0.00	0.00	0.10	0.10	0.10	0.10	0.10	0.10
SS	0.25	0.20	0.50	0.40	0.10	0.20	0.10	0.10	0.10
SE	0.15	0.15	0.40	0.15	0.15	0.08	0.55	0.55	2.15
F	231.00	105.00	152.00	146.00	10.00	60.00	203.00	302.00	232.00
CL	1,011.00	895.00	775.00	1,003.00	4,440.00	109.00	1,191.00	1,385.00	2,145.00
S-L	1,351.00	1,310.00	4,095.00	2,104.00	2,647.00	1,148.00	3,417.00	2,165.00	12,445.00
FE	0.15	0.15	0.15						

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3

MICRO

RT	3	7	9	9	9	3	9	9	9
STANTISAPPHIL	15	19.5	32	35.5	18.5	42.5	45	44	46
HEIGHT									
SAMPLE NO	1-7240	1-7238	1-7225	1-7221	1-7218	1-7215	1-7213	1-7210	1-7211
ELEMENT									
BE	0.20	0.20	0.10	0.20	0.20	0.10	0.20	0.20	0.10
EO	79.00	88.00	60.00	62.00	72.00	88.00	130.00	140.00	150.00
ER	1,500.00	1,300.00	1,800.00	2,000.00	2,000.00	1,700.00	1,700.00	1,600.00	1,700.00
EU	300.00	330.00	180.00	310.00	650.00	160.00	790.00	770.00	640.00
EA	3.00	3.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00
NI	500.00	660.00	470.00	610.00	906.00	1,400.00	1,900.00	1,600.00	1,900.00
PA	0.00	1.00	6.00	6.00	7.00	3.00	0.00	0.00	0.00
J	130.00	110.00	110.00	130.00	120.00	93.00	92.00	94.00	95.00
IS	0.20	0.20	0.10	0.20	0.30	0.20	0.10	0.20	0.10
IN	38.00	88.00	31.00	42.00	50.00	38.00	38.00	43.00	52.00
IC-AS	71.00	89.00	52.00	58.00	71.00	87.00	150.00	150.00	170.00
CR-AS	140.00	400.00	620.00	500.00	440.00	550.00	1,100.00	990.00	1,100.00
CU-AS	320.00	380.00	160.00	350.00	730.00	170.00	890.00	830.00	940.00
NI-AS	500.00	720.00	440.00	670.00	1,060.00	1,500.00	2,200.00	1,800.00	2,200.00
A-AS	32.00	37.00	36.00	34.00	29.00	35.00	58.00	53.00	62.00
LN-AS	17.00	17.00	11.00	19.00	20.00	19.00	30.00	21.00	34.00
AS	0.25	0.10	0.10	0.10	0.10	0.25	0.10	0.10	0.10
SO	0.25	0.10	0.25	0.10	0.60	0.25	0.10	0.10	0.10
SE	1.13	0.52	0.50	0.53	0.52	1.12	1.17	1.60	1.34
F	94.00	170.00	181.00	52.00	10.00	25.00	95.00	57.00	111.00
CL	1,106.00	1,065.00	1,227.00	630.00	675.00	1,129.00	989.00	1,196.00	1,416.00
S-S	1,186.00	1,699.00	1,243.00	1,404.00	2,034.00	1,831.00	3,329.00	2,640.00	2,645.00
IS	0.25		0.15			0.25			

RT	3	7	9	9	9	3	9	9	9
STATISTICS	15	19.5	32	35.5	38.5	42.5	43	44	46
HEIGHT									
SAMPLE NO	1-7245	1-7238	1-7225	1-7221	1-7218	1-7215	1-7213	1-7212	1-7211
ELEMENT									
BE	0.29	0.20	0.10	0.20	0.20	0.10	0.20	0.20	0.10
CO	79.00	88.00	60.00	62.00	73.00	88.00	130.00	140.00	159.00
CR	1,500.00	1,300.00	1,800.00	2,000.00	2,000.00	1,700.00	1,700.00	1,800.00	1,710.00
CU	300.00	330.00	160.00	310.00	650.00	160.00	790.00	770.00	840.00
LF	3.00	3.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00
NI	500.00	660.00	470.00	610.00	900.00	1,400.00	1,900.00	1,600.00	1,900.00
PB	0.00	1.00	6.00	6.00	7.00	3.00	0.00	0.00	0.00
V	130.00	110.00	110.00	130.00	120.00	93.00	92.00	94.00	95.00
VB	0.20	0.20	0.10	0.30	0.30	0.20	0.10	0.20	0.10
IN	38.00	88.00	31.00	42.00	50.00	38.00	38.00	43.00	52.00
UL-45	71.00	89.00	52.00	58.00	71.00	87.00	150.00	150.00	170.00
CR-45	74.00	400.00	620.00	500.00	440.00	550.00	1,100.00	950.00	1,100.00
CU-45	320.00	360.00	160.00	350.00	730.00	170.00	890.00	830.00	940.00
NI-45	500.00	720.00	440.00	670.00	1,000.00	1,500.00	2,200.00	1,800.00	2,200.00
V-45	32.00	37.00	36.00	34.00	29.00	35.00	58.00	53.00	62.00
UL-45	17.00	17.00	11.00	19.00	20.00	19.00	30.00	21.00	34.00
MS	0.25	0.10	0.10	0.10	0.10	0.25	0.10	0.10	0.10
SB	0.25	0.10	0.25	0.10	0.60	0.25	0.10	0.10	0.10
SE	1.13	0.52	0.50	0.53	0.52	1.12	1.17	1.60	1.84
F	94.00	170.00	181.00	52.00	10.00	25.00	95.00	97.00	111.00
CL	1,106.00	1,065.00	1,227.00	630.00	675.00	1,127.00	989.00	1,196.00	1,416.00
U-0	1,136.00	1,699.00	1,243.00	1,404.00	2,034.00	1,831.00	3,829.00	2,640.00	2,645.00
LE	0.25		0.25			0.25			

RT	1	2	3	4	5	6	7	8	9
STANDARD GRAPHIC	51	51.5	52	52.5	53	54	55	56	57
HEIGHT									
SAMPLE NO	1-7206	1-7205	1-7204	1-7200	1-7186	1-7165	1-7093	1-7056	1-7007
ELEMENT									
9E	0.10	0.20	0.20	0.20	0.20	0.10	0.10	0.20	0.10
CO	190.00	140.00	180.00	150.00	150.00	170.00	68.00	84.00	55.00
CR	2,000.00	1,500.00	2,400.00	2,100.00	1,800.00	1,700.00	1,300.00	1,500.00	550.00
CU	450.00	710.00	760.00	1,000.00	290.00	430.00	99.00	530.00	26.00
LM	4.00	3.00	4.00	4.00	3.00	3.00	3.00	3.00	2.00
NI	1,000.00	2,300.00	3,300.00	2,900.00	2,900.00	3,700.00	790.00	440.00	490.00
FB	16.00	460.00	4.00	0.00	6.00	0.00	11.00	11.00	9.00
V	98.00	99.00	100.00	110.00	82.00	75.00	100.00	150.00	110.00
12	0.10	0.10	0.20	0.20	0.10	0.00	0.10	0.20	0.10
ZN	36.00	45.00	61.00	53.00	39.00	42.00	54.00	43.00	44.00
CO-AS	100.00	160.00	200.00	170.00	170.00	170.00	69.00	76.00	31.00
CR-AS	900.00	970.00	890.00	930.00	930.00	840.00	820.00	440.00	150.00
CU-AS	470.00	770.00	820.00	1,100.00	320.00	470.00	92.00	510.00	19.00
NI-AS	1,100.00	2,700.00	3,700.00	3,400.00	3,400.00	4,200.00	820.00	450.00	270.00
V-AS	42.00	57.00	47.00	49.00	44.00	44.00	53.00	31.00	23.00
ZN-AS	13.00	29.00	24.00	37.00	28.00	26.00	36.00	23.00	16.00
FE	0.25	0.10	0.10	0.10	0.00	0.10	0.25	0.60	0.60
SE	0.25	83.50	0.10	0.10	2.50	0.10	0.25	0.60	0.60
SE	0.65	1.60	2.77	2.61	1.65	2.17	0.24	0.92	0.65
F	102.00	117.00	72.00	193.00	104.00	164.00	185.00	25.00	64.00
CL	1,679.00	1,648.00	587.00	977.00	742.00	960.00	720.00	280.00	337.00
S-D	5,455.00	7,855.00	10,540.00	12,422.00	4,234.00	5,075.00	2,112.00	11,069.00	125.00
1E	0.25						0.25	0.25	0.25

R#	1	2	3	4	5	6	7	8	9
SIRAL:SPMPHIC	150	161	162	163	164.5	165	165.5	166	167.5
HEIGHT									
SAMPLE NO	2-7553	2-7552	2-7551	2-7549	2-7547	2-7546	2-7545	2-7544	2-7540
ELEMENT									
BE	0.30	0.20	0.20	0.20	0.10	0.20	0.20	0.30	0.20
CO	76.00	77.00	74.00	120.00	150.00	140.00	120.00	64.00	82.00
CR	1,400.00	1,400.00	1,200.00	1,200.00	860.00	1,200.00	990.00	790.00	920.00
CU	140.00	250.00	340.00	770.00	1,400.00	1,500.00	1,300.00	860.00	850.00
LA	4.00	4.00	3.00	3.00	3.00	3.00	4.00	4.00	3.00
NI	550.00	560.00	510.00	1,100.00	1,100.00	1,100.00	780.00	450.00	700.00
PB	0.00	0.00	4.00	0.00	0.00	7.00	0.00	3.00	5.00
V	150.00	170.00	150.00	130.00	120.00	150.00	140.00	120.00	140.00
VB	0.20	0.20	0.20	0.10	0.00	0.10	0.20	0.40	0.20
ZN	45.00	45.00	35.00	47.00	54.00	69.00	55.00	52.00	38.00
CO-AS	62.00	63.00	70.00	130.00	160.00	150.00	130.00	58.00	90.00
CR-AS	450.00	420.00	440.00	530.00	330.00	450.00	320.00	250.00	350.00
CU-AS	140.00	270.00	370.00	820.00	1,500.00	1,600.00	1,400.00	930.00	960.00
NI-AS	560.00	550.00	540.00	1,300.00	1,200.00	1,300.00	870.00	510.00	840.00
V-AS	51.00	56.00	63.00	56.00	47.00	58.00	49.00	29.00	45.00
ZN-AS	12.00	10.00	17.00	18.00	21.00	25.00	18.00	16.00	22.00
NO	0.10	0.10	0.25	0.10	0.10	0.10	0.10	0.10	0.25
SB	0.10	0.10	0.25	0.60	0.10	0.10	0.10	0.10	0.25
SE	0.26	0.36	0.32	2.27	3.36	2.68	2.67	1.05	1.18
F	63.00	65.00	134.00	142.00	10.00	122.00	71.00	162.00	110.00
CL	165.00	155.00	157.00	217.00	147.00	170.00	135.00	232.00	277.00
S-D	1,097.00	1,386.00	1,814.00	1,739.00	20,824.00	18,560.00	16,042.00	13,479.00	131.0
0									
TE			0.25						0.25

AT	2	3	3	3	3	3	3	3	3
STRATIGRAPHIC	171	171.5	172.5	173	175.5	176	179	179.5	180
HEIGHT									
SAMPLE NO	2-7536	2-7535	2-7534	2-7533	2-7530	2-7526	1-7019	1-7027	1-7025
ELEMENT									
BE	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
CD	96.00	100.00	79.00	85.00	78.00	78.00	84.00	140.00	110.00
CR	1,300.00	1,500.00	1,400.00	1,400.00	1,600.00	1,700.00	1,300.00	1,200.00	1,300.00
CU	960.00	1,200.00	1,000.00	860.00	470.00	170.00	310.00	1,400.00	1,500.00
LA	2.00	4.00	3.00	4.00	5.00	4.00	3.00	3.00	3.00
NI	620.00	640.00	600.00	660.00	620.00	600.00	690.00	1,300.00	1,400.00
PB	0.00	22.00	5.00	1.00	4.00	0.00	5.00	12.00	3.00
V	160.00	150.00	160.00	150.00	130.00	120.00	140.00	150.00	150.00
YB	0.10	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10
ZN	62.00	61.00	64.00	61.00	45.00	48.00	42.00	55.00	51.00
CO-AS	94.00	99.00	73.00	81.00	69.00	65.00	76.00	140.00	110.00
CR-AS	310.00	320.00	320.00	380.00	440.00	340.00	360.00	460.00	340.00
CU-AS	1,000.00	1,300.00	1,100.00	920.00	490.00	170.00	350.00	1,500.00	1,600.00
NI-AS	700.00	730.00	650.00	710.00	640.00	600.00	700.00	1,400.00	1,500.00
V-AS	32.00	36.00	35.00	43.00	36.00	29.00	41.00	53.00	45.00
ZN-AS	18.00	28.00	24.00	21.00	15.00	11.00	18.00	31.00	31.00
AS	0.50	0.10	0.10	0.10	0.10	0.10	0.50	0.25	0.25
SB	0.10	0.10	0.10	0.10	0.10	0.10	0.50	0.50	1.70
SE	2.18	1.78	1.77	1.49	0.70	0.25	0.27	2.07	2.33
F	53.00	10.00	10.00	10.00	121.00	10.00	25.00	25.00	25.00
CL	335.00	248.00	235.00	214.00	238.00	194.00	224.00	176.00	186.00
S-D	13,567.00	13,145.00	8,301.00	7,618.00	3,034.00	1,010.00	1,261.00	9,640.00	8,187.00
TE							0.25	0.25	0.25

	1	2	3	4	5	6	7	8
STATIONING	191.5	192.5	193	195.5	198.5	198.5	200.5	202.5
HEIGHT								
SAMPLE NO.	1-7512	1-7519	1-7517	1-7513	2-7509	2-7497	2-7491	3-7476
ELEMENT								
BE	0.30	0.20	0.20	0.20	0.20	0.10	0.10	0.30
CG	30.00	37.00	80.00	96.00	83.00	100.00	86.00	49.00
CF	1,400.00	1,600.00	2,100.00	1,400.00	1,700.00	1,700.00	1,800.00	830.00
CL	130.00	700.00	89.00	750.00	130.00	43.00	54.00	81.00
LM	4.00	4.00	3.00	3.00	3.00	3.00	4.00	4.00
NI	710.00	370.00	600.00	1,000.00	430.00	1,000.00	720.00	280.00
PB	0.00	0.00	3.00	0.00	4.00	7.00	0.00	3.00
P	170.00	120.00	110.00	130.00	120.00	77.00	88.00	110.00
PB	0.20	0.10	0.10	0.10	0.20	0.00	0.00	0.20
7N	44.00	46.00	44.00	53.00	60.00	50.00	94.00	40.00
CO-45	58.00	69.00	73.00	100.00	77.00	110.00	75.00	27.00
CR-45	260.00	250.00	450.00	390.00	460.00	1,200.00	580.00	150.00
CU-45	400.00	720.00	91.00	800.00	200.00	43.00	47.00	79.00
NI-45	730.00	910.00	690.00	1,200.00	450.00	1,100.00	700.00	180.00
V-45	32.00	32.00	29.00	35.00	38.00	42.00	35.00	20.00
CH-45	14.00	23.00	13.00	21.00	24.00	18.00	15.00	12.00
HE	0.10	0.10	0.25	0.25	0.25	0.25	0.50	1.00
SB	0.10	0.30	0.25	0.25	0.25	0.25	0.50	0.70
SE	1.00	1.40	0.25	1.20	1.40	0.25	0.50	0.25
F	11.00	10.00	25.00	25.00	82.00	192.00	73.00	10.00
CL	151.00	184.00	149.00	238.00	240.00	210.00	156.00	178.00
SUB	3,181.00	4,925.00	1,242.00	3,884.00	4,250.00	2,037.00	2,381.00	1,819.00
TE			0.25	0.25	0.25	0.25		

RT	2	3	3	3	3	4	4	4	4
STRATIGRAPHIC	547.5	549.5				158.5	181	184.5	187
HEIGHT									
SAMPLE NO	5-7836	5-7835	2-7461	2-7441	1-7232	2-7554	2-7522	1-7016	1-7013
ELEMENT									
BE	0.50	0.20	0.20	0.20	0.20	0.30	0.20	0.20	0.20
CO	53.00	55.00	73.00	84.00	71.00	55.00	79.00	84.00	92.00
CR	3,900.00	2,200.00	1,700.00	1,900.00	1,700.00	1,300.00	1,700.00	910.00	850.00
CU	140.00	230.00	57.00	42.00	170.00	120.00	220.00	530.00	540.00
EW	5.00	4.00	5.00	5.00	3.00	3.00	4.00	3.00	3.00
NI	590.00	920.00	700.00	880.00	450.00	350.00	620.00	610.00	830.00
PB	0.00	5.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00
V	150.00	110.00	130.00	120.00	130.00	150.00	120.00	120.00	140.00
YB	0.50	0.10	0.40	0.20	0.20	0.40	0.10	0.00	0.10
ZN	34.00	53.00	45.00	40.00	37.00	58.00	60.00	47.00	76.00
CG-MS	42.00	87.00	55.00	63.00	57.00	36.00	69.00	75.00	82.00
CR-MS	340.00	500.00	590.00	610.00	340.00	290.00	530.00	200.00	210.00
CU-MS	150.00	250.00	45.00	29.00	180.00	120.00	230.00	600.00	580.00
NI-MS	590.00	1,000.00	610.00	720.00	410.00	280.00	640.00	610.00	860.00
P-MS	36.00	70.00	46.00	47.00	25.00	28.00	38.00	30.00	40.00
ZN-MS	2.00	43.00	18.00	10.00	11.00	10.00	20.00	22.00	15.00
MS	0.11	0.52	0.45	0.50	0.10	1.40	0.10	0.25	0.25
SS	0.90	0.00	1.31	0.54	0.25	1.70	0.10	0.25	0.90
SE	0.46	0.67	0.13	0.22	0.17	0.20	0.46	0.75	1.18
F	164.00	104.00	123.00	85.00	77.00	10.00	65.00	25.00	25.00
CL	279.00	485.00	223.00	225.00	849.00	266.00	165.00	180.00	305.00
S-D	1,547.00	4,545.00	630.00	910.00	952.00	595.00	1,840.00	989.00	5,781.00
TE					0.25			0.25	0.25

RT	1	5	1	5	5	5	5	5	5
STRATIGRAPHIC	402.5	405	404.5	411.5	431	431	431.5	469.5	485
HEIGHT									
SAMPLE NO	5-9028	5-9027	5-9026	5-9011	5-7974	5-7972	5-7971	5-7935	5-7913
BE	0.40	0.40	0.40	0.20	0.30	0.20	0.30	0.30	0.30
CO	49.00	46.00	42.00	42.00	51.00	41.00	53.00	24.00	50.00
CR	2,700.00	2,600.00	2,500.00	950.00	340.00	340.00	500.00	500.00	2,200.00
CU	67.00	110.00	170.00	14.00	320.00	16.00	33.00	19.00	320.00
LA	5.00	4.00	5.00	1.00	3.00	2.00	4.00	1.00	4.00
NI	330.00	310.00	290.00	270.00	270.00	160.00	230.00	150.00	410.00
PD	0.00	0.00	11.00	10.00	0.00	3.00	0.00	600.00	100.00
V	190.00	200.00	210.00	82.00	120.00	93.00	110.00	66.00	120.00
VB	0.80	0.80	0.90	0.60	0.30	0.10	0.20	0.00	0.20
ZN	75.00	78.00	64.00	45.00	60.00	37.00	54.00	54.00	180.00
CO-AS	22.00	17.00	16.00	19.00	39.00	23.00	33.00	11.00	22.00
CR-AS	680.00	580.00	610.00	190.00	120.00	100.00	120.00	180.00	370.00
CU-AS	55.00	110.00	190.00	5.00	340.00	16.00	27.00	9.00	200.00
NI-AS	170.00	160.00	150.00	140.00	240.00	98.00	170.00	64.00	220.00
V-AS	29.00	26.00	30.00	14.00	27.00	16.00	17.00	12.00	18.00
ZN-AS	14.00	9.00	7.00	15.00	46.00	18.00	26.00	24.00	63.00
AS	1.70	2.00	2.00	0.70	5.00	0.25	1.20	0.60	1.40
SB	0.10	0.11	0.20	1.70	7.20	0.50	1.10	0.25	0.10
SE	0.12	0.31	0.09	0.00	0.15	0.02	0.02	0.31	0.35
F	67.00	72.00	77.00	25.00	25.00	25.00	52.00	85.00	124.00
CL	436.00	531.00	525.00	349.00	184.00	148.00	195.00	232.00	194.00
S-D	144.00	194.00	169.00	108.00	258.00	25.00	95.00	182.00	523.00
TE				0.25	0.25	0.25		0.25	

APPENDIX 1: PLATINUM-GROUP ELEMENT CHEMISTRY

RI	1	1	1	1	1	1	1	1	1	
STRATIGRAPHIC	-15.00	-7.50	-6.00	4.50	5.50		54.50	61.50		64.00
HEIGHT										69.50
SAMPLE NO.	1-7201	1-7269	1-7260	1-7255	1-7254	1-721	1-7194	1-7191	1-7184	
ELEMENT										
Hg		1.00	8.00	2.00	9.00	6.00	1.00	1.00	18.00	
Os		1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50	
Ir		1.50	4.00	2.00	1.50	3.00	2.00	2.00	2.00	
Ru		3.00	18.00	7.00	8.00	2.50	2.50	15.00	4.00	
Rh		2.00	14.00	1.00	3.00	9.00	4.00	4.00	2.00	
Pt		19.00	140.00	21.00	73.00	220.00	110.00	120.00	150.00	
Re		38.00	490.00	5.50	210.00	230.00	19.00	480.00	240.00	
Se		2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	
totrue		65.00	667.00	36.5	301.00	466.00	310.30	622.50	405.10	
Pt ratio		0.03	0.22	0.18	0.26	0.49	0.37	0.20	0.38	
S	2,168.50	183.0	2,744.2	6,655.0	3,485.0	4,526.0	5,146.0	3,572.0	12,575.0	
SE-SRAI	232.21	59.12	218.36	81.14	200.97	277.66	355.62	360.64	241.75	
CU-NIKAI	0.00	0.01	0.01	0.02	0.21	0.15	0.07	0.06	0.20	
RI	1	1	1	1	1	1	1	1	1	
STRATIGRAPHIC	6.00	65.00	69.00	9.50	111.00	115.00	167.00	194.50	135.00	
HEIGHT										
SAMPLE NO.	1-7175	1-7170	1-7165	1-7164	1-7154	1-7115	1-7081	1-7500	1-7335	
ELEMENT										
Hg		17.00	1.00	4.00				8.00		
Os		1.50	1.50	4.00				1.50		
Ir		2.00	1.00	2.00				1.00		
Ru		2.50	2.50	30.00				2.50		
Rh		4.00	3.00	2.00				2.00		
Pt		30.00	23.00	24.00				83.00		
Re		2.50	170.00	50.00				220.00		
Se		2.50	2.50	2.50				2.50		
totrue		43.40	201.00	112.00				310.30		
Pt ratio		0.02	0.12	0.32				0.27		
S-D	2,356.00	194.0	8,955.0	5,994.0	2,339.0	6,377.0	5,869.0	619.0	3,632.0	
SE-SRAI	93.38	109.94	146.22	116.45	153.91	167.74	69.86	170.74	44.05	
CU-NIKAI	0.08	0.16	0.10	0.05	0.03	0.02	0.16	0.02	0.05	

APPENDIX 1: PLATINUM-GROUP ELEMENT COMPOSITION

RT STRATIGRAPHIC HEIGHT	1	1	1	1	1	1	1	1	1
SAMPLE NO.	1-7201	1-7209	1-7208	1-7255	1-7254	1-721	1-7194	1-7191	1-7184
ELEMENT									
Mo		1.00	0.00	2.00	9.00	0.00	1.00	2.00	10.00
Os		1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50
Ir		1.50	4.00	2.00	1.50	3.00	2.50	2.00	2.00
Ru		3.00	10.00	7.00	0.50	2.50	2.50	15.00	9.00
Rh		2.00	14.00	1.00	2.00	9.00	4.00	4.00	2.00
Pt		19.00	140.00	21.00	73.00	220.00	110.00	120.00	150.00
Pd		30.00	490.00	5.50	210.00	230.00	19.00	400.00	240.00
Re		2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
100ppb		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pt/100		0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.03
S		2,000.00	100.00	2,744.00	0,055.00	3,005.00	4,510.00	5,140.00	3,572.00
SE-GRAN		232.21	59.12	218.30	81.14	200.97	277.60	355.62	500.64
CU-NIKKI		0.00	0.01	0.01	0.00	0.01	0.15	0.07	0.00
RT STRATIGRAPHIC HEIGHT	1	1	1	1	1	1	1	1	1
SAMPLE NO.	1-7170	1-7170	1-7105	1-7104	1-7104	1-7115	1-7001	1-7500	1-7335
ELEMENT									
Mo		17.00	1.00	4.00				8.00	
Os		1.50	2.50	4.00				1.50	
Ir		2.90	1.00	2.70				1.30	
Ru		2.50	2.50	30.00				2.50	
Rh		4.00	3.00	2.00				2.00	
Pt		30.00	23.00	24.00				03.00	
Pd		2.50	170.00	50.00				220.00	
Re		2.50	2.50	2.50				2.50	
100ppb		43.40	201.00	112.00				310.30	
Pt/100		0.02	0.02	0.02				0.02	
S-D		2,330.00	194.00	0,955.00	5,994.00	2,339.00	0,577.00	5,009.00	019.00
SE-GRAN		93.38	109.94	146.22	118.45	153.91	107.74	09.06	170.94
CU-NIKKI		0.08	0.10	0.10	0.05	0.03	0.02	0.10	0.05

RT	1	1	1	1	1	1	2	2	3
STEREOLITHOGRAPHIC	351.50	462.50	522.50	543.00			6.50	8.00	47.00
HEIGHT									
SAMPLE NO.	1-7265	5-7919	5-7850	5-7841	1-7267	2-7425	1-7253	1-7251	1-7210
ELEMENT									
Hu				2.00	1.00		11.00	9.00	7.00
Us				1.50	1.50		1.50	1.50	3.00
Ir				0.50	1.70		1.20	1.60	3.30
Pd				2.50	9.00		2.50	2.50	23.00
Rh				1.00	1.00		5.00	5.00	6.00
Pt				25.00	5.00		64.00	81.00	180.00
Re				16.00	10.00		120.00	110.00	120.00
He				2.50	2.50		2.50	2.50	2.50
totPb				46.50	28.20		194.30	201.60	435.30
Pt ratio				0.61	0.33		0.35	0.42	0.45
S-D	1,351.01	1,832.0	4,095.0	3,034.0	2,647.0	1,148.0	3,417.0	2,165.0	12,445.0
SE-SKAI	59.22	87.34	112.33	126.54	109.56	69.67	169.74	175.52	171.18
LU-NIRMI	0.01	0.00	0.06	0.07	0.01	0.00	0.30	0.29	0.28

RT	1	2	2	2	2	2	2	2	3
STEREOLITHOGRAPHIC	47.50	57.50	55.50	57.00	74.00	198.00	206.00	7.00	12.00
HEIGHT									
SAMPLE NO.	1-7204	1-7203	1-7201	1-7199	1-7180	2-7494	2-7484	1-7252	1-7247
ELEMENT									
Hu	10.00	0.00	16.00	5.00	3.00	4.00	56.00	9.00	13.00
Us	2.00	1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50
Ir	2.00	2.00	3.10	2.30	2.70	1.40	1.10	1.80	1.90
Pd	16.00	2.50	11.50	2.50	15.00	2.50	2.50	2.50	14.00
Rh	0.00	0.00	6.00	4.00	3.00	3.00	2.00	8.00	6.00
Pt	130.00	150.00	230.00	170.00	140.00	100.00	50.00	93.00	110.00
Re	140.00	140.00	210.00	170.00	320.00	20.00	2.50	210.00	130.00
He	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
totPb	296.00	303.00	461.10	352.80	484.20	128.40	59.50	516.80	263.40
Pt ratio	0.48	0.52	0.52	0.50	0.30	0.83	0.95	0.31	0.46
S-D	2,199.04	540.0	8,087.0	4,221.0	4,992.0	2,045.0	5,889.0	4,787.0	1,037.0
SE-SKAI	261.55	242.29	234.94	270.08	350.56	215.16	178.30	213.08	327.87
LU-NIRMI	0.28	0.22	0.23	0.20	0.09	0.10	0.13	0.25	0.34

RI	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC	15.00	19.50	22.00	35.50	38.50	42.50	43.00	44.00	46.00
HEIGHT									
SAMPLE NO.	1-7243	1-7238	1-7225	1-7221	1-7216	1-7215	1-7213	1-7212	1-7211
ELEMENT									
Al	17.00	12.00	13.00	12.00	40.00	11.00	12.00	5.00	5.00
Ca	1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50	1.50
Fe	1.80	1.90	1.80	1.90	2.90	2.50	3.80	3.10	3.00
Ru	2.50	4.00	51.00	4.00	14.00	51.00	4.50	15.00	4.00
Rh	6.00	6.00	5.00	4.00	7.00	5.00	6.00	4.00	5.00
Pt	97.00	110.00	64.00	120.00	180.00	180.00	210.00	180.00	180.00
Pd	170.00	130.00	150.00	180.00	410.00	97.00	270.00	170.00	200.00
Re	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	5.00
totPGE	276.80	253.40	254.50	311.40	615.40	337.00	495.60	373.60	393.50
Pt ratio	0.36	0.45	0.33	0.40	0.31	0.65	0.44	0.51	0.47
S-D	1,188.01	699.0	1,243.0	1,404.0	2,034.0	1,881.0	3,829.0	7,640.0	7,645.0
SE-SRAI	1,355.35	506.06	241.35	377.49	452.31	595.43	305.56	209.42	240.68
CU-NIRAI	0.39	0.33	0.27	0.34	0.42	0.10	0.29	0.32	0.30
RI	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC	51.00	51.00	51.00	56.50	68.00	69.00	121.00	141.00	157.00
HEIGHT									
SAMPLE NO.	1-7206	1-7205	1-7204	1-7200	1-7186	1-7185	1-7093	1-7056	1-7037
ELEMENT									
Al	17.00	7.00	5.00	17.00	2.00	3.00			
Ca	1.50	3.00	1.50	3.00	1.50	1.50			
Fe	2.40	3.50	3.00	4.20	2.20	2.60			
Ru	50.00	16.00	13.00	2.50	13.00	15.00			
Rh	5.00	7.00	8.00	7.00	4.00	6.00			
Pt	180.00	170.00	170.00	300.00	120.00	240.00			
Pd	130.00	260.00	250.00	360.00	240.00	530.00			
Re	2.50	2.50	2.50	2.50	2.50	2.50			
totPGE	448.00	459.50	445.80	676.70	390.70	795.10			
Pt ratio	0.55	0.40	0.40	0.45	0.33	0.31			
S-D	5,455.07	656.0	13,643.0	12,422.0	4,234.0	6,375.0	2,112.0	11,069.0	125.0
SE-SRAI	155.82	207.68	200.10	210.11	384.98	371.76	113.64	83.12	400.99
CU-NIRAI	0.30	0.22	0.18	0.24	0.09	0.10	0.10	0.53	0.07

RT	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC	100	101	102	103	104.5	105	105.5	106	109.5
HEIGHT									
SAMPLE NO.	2-7553	2-7552	2-7551	2-7549	2-7547	2-7546	2-7545	2-7544	2-7540
ELEMENT									
Al	3.00		11.00	5.00	14.00	4.00	28.00	4.00	19.00
Os	1.50		1.50	1.50	1.50	1.50	1.50	1.50	1.50
Ir	1.00		1.60	2.80	2.70	3.10	1.90	0.50	1.50
Ru	11.00		19.00	32.00	4.00	8.00	5.00	9.00	2.50
Rh	4.00		1.00	12.00	13.00	13.00	10.00	3.00	2.00
Pt	35.00		78.00	130.00	150.00	160.00	120.00	39.00	98.00
Pd	45.00		150.00	400.00	440.00	410.00	400.00	71.00	210.00
Re	2.50		2.50	2.50	2.50	2.50	2.50	2.50	2.50
totPbE	147.50		251.10	578.50	611.20	595.60	538.40	124.00	315.50
Pt ratio	0.27		0.34	0.25	0.25	0.28	0.23	0.35	0.32
S-D	1,093.01,386.0	1,814.0	1,739.02,824.0	18,560.018,042.0	3,479.0	8,131.0			
SE-BRAI	237.88	259.74	176.41	193.37	161.35	155.17	147.99	301.81	145.12
CU-NIRAI	0.20	0.33	0.41	0.39	0.50	0.55	0.62	0.65	0.53

RT	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC	171.00	171.50	172.50	173.00	175.50	178.00	179.00	179.50	180.00
HEIGHT									
SAMPLE NO.	2-7536	2-7535	2-7534	2-7533	2-7530	2-7526	1-7029	1-7027	1-7025
ELEMENT									
Al	26.00	52.00	29.00	100.00	29.00	16.00	16.00	32.00	35.00
Os	1.50	1.50	1.50	3.00	1.50	1.50	1.50	1.50	1.50
Ir	1.20	3.30	3.30	5.40	1.20	1.20	1.80	2.70	3.60
Ru	3.50	19.00	2.50	2.50	3.00	2.50	2.50	2.50	2.50
Rh	7.00	9.00	11.00	7.00	2.00	3.00	6.00	11.00	18.00
Pt	140.00	210.00	190.00	420.00	110.00	90.00	97.00	120.00	180.00
Pd	180.00	240.00	310.00	220.00	51.00	53.00	170.00	390.00	690.00
Re			2.50	2.50	2.50	2.50	2.50	2.50	2.50
totPbE	334.20	482.80	518.30	657.90	168.70	151.20	278.80	527.70	895.60
Pt ratio	0.44	0.47	0.38	0.66	0.66	0.63	0.36	0.24	0.21
S-D	13,567.013,145.08,301.0	7,618.0	3,034.0	1,010.0	1,261.0	9,040.0	8,187.0		
SE-BRAI	160.66	135.41	165.04	195.59	230.72	247.52	214.12	228.98	284.60
CU-NIRAI	0.59	0.64	0.63	0.56	0.43	0.22	0.33	0.52	0.52

RT	3	3	3	3	3	3	3	3	3
STRATIGRAPHIC	181.50	182.50	183.00	185.50	186.50	196.50	200.50	429.50	546.50
HEIGHT									
SAMPLE NO.	1-7021	1-7019	2-7517	2-7513	2-7509	2-7497	2-7491	5-7976	5-7837
ELEMENT									
Au	15.00	18.00	9.00	10.00	6.00	5.00	3.00	3.00	5.00
Os	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Ir	3.00	3.20	1.20	1.10	0.80	0.90	0.80	2.20	1.10
Ru	2.50	2.50	14.00	9.00	10.00	2.50	3.50	6.00	2.50
Rh	14.00	14.00	5.00	2.00	2.00	5.00	2.00	10.00	3.00
Pt	140.00	160.00	90.00	86.00	61.00	65.00	53.00	82.00	33.00
Pd	350.00	480.00	2.50	49.00	43.00	2.50	20.00	120.00	62.00
Re	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
totPGE	551.00	661.20	114.20	148.60	118.30	77.40	80.90	223.70	103.10
Pt ratio	0.26	0.25	0.97	0.64	0.59	0.96	0.73	0.41	0.35
S-D	3,161.04	9,280.0	2,242.0	8,884.0	4,260.0	2,037.0	3,381.0	150.0	1,819.0
SE-SRM1	341.66	288.15	115.97	137.33	107.98	127.64	150.84	533.33	153.93
CU-NIRMI	0.35	0.44	0.12	0.42	0.31	0.04	0.06	0.31	0.25

RT	3	3	3	3	3	4	4	4	4
STRATIGRAPHIC	547.50	549.50				156.50	161.00	184.50	187.00
HEIGHT									
SAMPLE NO.	5-7838	5-7835	2-7461	2-7441	1-7232	2-7554	2-7522	1-7016	1-7013
ELEMENT									
Au	4.00	16.00			4.00	2.00	9.00	13.00	13.00
Os	4.00	8.00			1.50	1.50	1.50	1.50	1.50
Ir	2.50	14.00			1.60	0.50	1.00	1.20	1.40
Ru	16.00	27.00			2.50	20.00	14.00	15.00	14.00
Rh	14.00	19.00			5.00	1.00	2.00	5.00	6.00
Pt	110.00	530.00			53.00	17.00	96.00	60.00	57.00
Pd	97.00	310.00			75.00	45.00	72.00	170.00	190.00
Re	2.50	2.50			2.50	2.50	2.50	2.50	2.50
totPGE	249.30	908.00			145.60	85.00	186.50	252.70	269.90
Pt ratio	0.53	0.63			0.44	0.27	0.57	0.26	0.23
S-D	1,547.04	5,545.0	630.0	910.0	853.0	595.0	1,840.0	3,089.0	5,781.0
SE-SRM1	297.35	147.41	206.35	241.76	199.30	336.13	250.00	242.80	204.12
CU-NIRMI	0.20	0.20	0.07	0.04	0.31	0.30	0.26	0.50	0.40

RI	5	5	5	5	5	5	5	5	5
STRATIGRAPHIC	130.50	148.00	190.00	190.50	191.00	204.50	287.00	307.00	402.00
HEIGHT									
SAMPLE NO.	1-7001	1-7049	1-7005	1-7003	2-7504	2-7488	2-7393	2-7380	5-9029
ELEMENT									
Au			14.00	5.00	21.00				5.00
Os			1.50	1.50	1.50				1.50
Ir			1.00	1.20	0.70				0.60
Ru			2.50	2.50	8.00				2.50
Rh			5.00	5.00	4.00				6.00
Pt			58.00	54.00	68.00				31.00
Fd			160.00	130.00	42.00				140.00
Re			2.50	2.50	2.50				2.50
totPGE			248.00	194.20	122.20				181.60
Pt ratio			0.24	0.29	0.62				0.18
S-D	254.0	93.0	566.0	770.0	1,205.0	56.0	347.0	441.0	175.0
SE-SMAT	19.69	53.76	300.35	324.68	165.98	89.29	14.41	839.00	628.57
CU-NIRAI	0.11	0.08	0.30	0.42	0.44	0.01	0.75	0.84	0.30

RI	5	5	5	5	5	5	5	5	5
STRATIGRAPHIC	402.50	405.00	404.50	411.50	431.00	432.00	432.50	469.50	486.00
HEIGHT									
SAMPLE NO.	5-7925	5-7927	5-7928	5-7912	5-7974	5-7972	5-7971	5-7935	5-7913
ELEMENT									
Au	8.00	8.00	8.00		2.00	1.00	4.00		24.00
Os	1.50	1.50	1.50		1.50	1.50	1.50		1.50
Ir	0.80	0.70	0.50		0.70	2.00	2.40		0.80
Ru	3.00	4.00	2.50		2.50	2.50	2.50		2.50
Rh	2.00	3.00	2.00		1.00	3.00	8.00		1.00
Pt	50.00	62.00	49.00		59.00	88.00	200.00		54.00
Fd	11.00	33.00	10.50		130.00	60.00	110.00		33.00
Re	2.50	2.50	2.50		2.50	2.50	2.50		2.50
totPGE	128.50	104.40	86.00		194.90	157.20	322.40		92.80
Pt ratio	0.41	0.65	0.82		0.31	0.59	0.65		0.62
S-D	144.0	194.0	189.0	108.0	258.0	25.0	95.0	182.0	523.0
SE-SMAT	833.33	1,597.94	476.19	46.30	581.40	800.00	210.53	1,758.24	669.22
CU-NIRAI	0.23	0.41	0.58	0.03	0.59	0.14	0.14	0.10	0.48

RT	5	5	5	5	5	5	5	5
STRATIGRAPHIC	487	488	545	550.5				
HEIGHT								
SAMPLE NO.	5-7910	5-7906	5-7838	5-7834	5-7881	2-7434	5-7804	2-7406
ELEMENT								
Hu	19.00	10.00	2.00	16.00				
Os	1.50	1.50	1.50	1.50				
Ir	0.80	0.60	0.70	0.60				
Ru	3.00	2.50	7.00	2.50				
Rh	1.00	7.00	3.00	1.00				
Pt	72.00	60.00	57.00	49.00				
Pd	12.50	2.50	70.00	2.50				
Re	2.50	2.50	2.50	2.50				
TotPGE	90.60	74.10	139.20	57.10				
Pt ratio	0.85	0.96	0.45	0.95				
S-D	351.0	76.0	1,219.0	1,077.0	73.0	145.0	1,066.0	52.0
SE-SRWT	2,327.37	263.16	164.07	148.56	547.95	482.76	131.33	96.15
CU-NIRWI	0.49	0.15	0.17	0.30	0.19	0.54	0.64	0.25

APPENDIX 1: DESCRIPTION OF δ ISOTOPE SAMPLES

SAMPLE	$\delta^{34}\text{S}$	STRAW HEIGHT	PGE (ppb)	S (ppm)	Ni (ppm)	Cu	DESCRIPTION
5-7635	+9.7	550.5	908	4545	1000	250	Medium-grained (1-2mm) pl-bearing olivine clinopyroxenite with pegmatoidal (1 cm) pl-bearing pyroxenite phase. Intercumulus sulphides (Fo, Lcp) range from sparsely disseminated 1-2mm grains in medium grained pyroxenite to 3-5mm intercumulus "blebs" in pegmatoidal phase.
5-7931	+11.0	492	<34	massive	125	7	Highly altered gabbro consisting of mineral assemblage hydrogrossular, epidote, diopside, chlorite, and vesuvianite. Sulphide (6n) occurs as 4 gr (<1mm) disseminations and as massive (1 cm) veinlets.
5-7491	+10.1	220.5	31	3381	720	54	Interlaminated olivine clinopyroxenite and peridotite. Sulphide (fo) is concentrated as patches of poorly developed net textured sulphide in the peridotite and at its contact with the pyroxenite. Sulphide is finely disseminated (<12) throughout the pyroxenite and peridotite away from the lithologic contacts.
7533	+10.1	19.5	653	7618	600	800	Sulphide-bearing (3-5%) pl-bearing olivine clinopyroxenite.
7545	+10.5	165.5	538	18042	780	1300	Medium-grained (1-2mm) pl-bearing olivine pyroxenite - pyroxenite. Sulphides (3-4%) are intercumulus.
7185	+12.4	67	795	6375	3700	430	Sulphide-bearing (1-3%) olivine clinopyroxenite.
7200	+12.3	50.5	678	12422	2900	1000	Sulphide-bearing (1-2%) olivine clinopyroxenite.
7218	+11.8	38.5	615	2034	900	650	Sulphide-bearing olivine clinopyroxenite.
7025	+9.2	30.5	900	8187	1400	1500	Sulphide-bearing, coarse-grained (1-2mm) pl-bearing olivine clinopyroxenite.
7267	+17.4	-4	28	2647	1700	12	LCLZ Dunite - ol-rich oikocrystic peridotite.
7268	+16.8	-5	663	2744	2400	20	LCLZ Oikocrystic peridotite with disseminated, blebby (1mm) intercumulus sulphide.

A

LEGEND

- LCLZ DUNITE
- PERIDOTITE
- OLIVINE CLINOPYROXENITE
- GABBRO
- ILMENOMAGNETITE-BEARING GABBRO
- FAULT BRECCIA
- OVERBURDEN
- C.U. CYCLIC UNIT

VERTICAL SCALE 1:500

STRATIGRAPHIC SECTION OF 462W SECTION, FOX RIVER SILL

END

1|8.0|2.90

FIN