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Rocks, Chromite, and the Shebandowan Ni-Cu Mine, Shebandowan, Northwestern Ontario

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ARCHEAN VOLCANIC STRATIGRAPHY, AND PETROLOGY
AND CHEMISTRY OF MAFIC AND ULTRAMAFIC ROCKS,
CHROMITE, AND THE SHEBANDOWAN Ni-Cu MINE,
SHEBANDOWAN, NORTHWESTERN ONTARIO

by

© Penelope Morton

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

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Ottawa, Ontario.

April, 1982

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Chromite is ubiquitous throughout the ultramafic bodies, making up 1-2% of each body. It is zoned with fresh cores, ferritchromit rims and irregular magnetite overgrowths. Ferritchromit is always lower in MgO, usually lower in Al_2O_3 and Cr_2O_3 and higher in Fe_2O_3 and FeO relative to fresh cores. Stratigraphic compositional changes in chromite have been documented; there is an overall increase in Fe, decrease in Cr/R^3 and increase in Fe^3/Fe^3+Cr up section.

On the basis of TiO_2 , Al_2O_3 , and Fe_2O_3 contents of chromite, the ultramafic bodies are divided into two groups: one with TiO_2 - Fe_2O_3 -rich, Al_2O_3 -poor chromite, and one with TiO_2 - Fe_2O_3 -poor, Al_2O_3 -rich chromite. These divisions correspond respectively to the extrusive and intrusive ultramafic rocks.

Ultramafic flows and sills are compositionally similar. MgO averages 32% and SiO_2 44% in both; using a MgO-CaO- Al_2O_3 diagram, both show an olivine-orthopyroxene differentiation trend. Cluster and principal components analysis of whole rock analyses have been used to group the rocks by chemical similarity. This technique has shown that flows and sills differ only in their Ni, Cu, Co, and S contents. Sills are interpreted to be both synvolcanic with (when small and undifferentiated) and possibly reservoirs for (when large and layered) the flows that lie stratigraphically above them.

The Shebandowan Ni-Cu ore deposit is composed of pentlandite, pyrrhotite, chalcopyrite, pyrite, magnetite, with minor millerite, sphalerite and PGE. It is massive, with no net-textured ore. Breccia sulphide is common, stringer ore less so and disseminated ore almost absent. Overall Cu/Cu+Ni is 0.36 and Pt/Pt+Pd is 0.22. It lies at the top of one of the large ultramafic sills.

The overall mass ratio (R) of ultramafic rock to sulphide is 42. The ore is interpreted to have separated from an ultramafic magma, and the Cu/Cu+Ni ratio is explained by at least a 15 fold loss of Ni. This probably occurred during metamorphic differentiation as well as through CO₂ and H₂O alteration. The ore was emplaced into its present position, possibly by faulting and folding.

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Sheila Crawford, Ron Morton and J. Baker acted as able field assistants. Peter Goetz adapted the principal components analysis and cluster analysis programs to the Carleton computer. Dave Lefebure wrote and adapted a plotting program which I employed (Molerat). George Patterson spent a few days hauling canoes in the field to check a few outcrops. Some of the structural data comes from G. Stott.

The major bulk of the thesis was typed by Mary Ankarlo. I'd like to thank my mother, Joan Cane, for typing the tables in the appendices. Lesley Whitmore drafted some original diagrams and C. Grant drafted the geology map and mine plans. The trace element data were provided by the Geological Survey of Canada, through J. Franklin. R. Taylor and R. Conlon made thin and polished sections. Mr. and Mrs. G. Watkinson kindly allowed S. Crawford and me to stay in their cottage for 6 weeks in 1976.

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CHAPTER I: INTRODUCTION

1. General Statement

Shebandowan Mine, owned by Inco Metals, Ltd., is a Ni-Cu sulphide deposit associated with a metasomatized ultramafic sill within volcanic rocks of the Shebandowan-Wawa Subprovince of the Superior Province of northwestern Ontario. The mine is the only known economic Ni-Cu deposit in the Shebandowan Belt. There is a large amount of ultramafic rock within the belt, providing areas for possible Ni-Cu ore, but no other deposit has been found.

The initial purposes of this thesis were to 1) map and sample the ultramafic body associated with the ore deposit and to study the ore itself, 2) study the mineralogy, chemistry, and in particular the metamorphism and metasomatism of the mine ultramafic body and 3) map the enclosing volcanic rocks and other ultramafic rocks in the area. It was hoped that this information would yield data pertinent to the genesis of Shebandowan deposit, add to the knowledge of the metamorphism of ultramafic rocks and lastly investigate the possible relationship between alteration and Ni-Cu mineralization within the mine ultramafic body.

As with most research projects, not all initial goals were realized, but they were added to and amended along the way. As all rocks within the mapped area were of lower greenschist facies, very little new information relevant to metamorphism of ultramafic rocks was recorded. Because these ultramafic rocks are serpentized, chemistry of primary minerals cannot be used to define crystallization sequences of the ultramafic rocks. The only useful relict mineral is chromite.

Detailed sampling of the ore deposit itself proved impossible because sampling was limited by underground access and lack of ore

samples within drill holes selected to study the ore mineralogy and chemistry along strike and at depth. These samples were proposed for study by INCO, but had been used previously for a mill test and were no longer available.

Two distinct types of ultramafic rocks were identified within the map area and are concluded to be flows and sills. These were identified in the field through their rock associations; they are petrographically similar but can be chemically distinguished by cluster analysis. They can also be distinguished on the basis of chromite chemistry.

Because the most detailed work and what the author feels to be the most important work is based on the ultramafic bodies in the area, and not just the mine ultramafic body itself, the thesis is subdivided into 6 chapters. The first and last are respectively introduction and conclusions. Chapter 2 describes the geology and chemistry of the volcanic and volcanoclastic rocks, including that of the mine; chapters 3, 4, and 5 deal with the geology, mineral chemistry and petrochemistry of the ultramafic bodies.

2. Location and Access

Shebandowan Ni-Cu Mine is located on the southwestern edge of Lower Lake Shebandowan (Fig. I-1), some 70 km northwest of Thunder Bay, Ontario at 48°35' latitude and 90°15' longitude. The study area encompasses parts of Hagey, Lamport, Haines and Begin Townships. Access to the study area is via highway 11 and a paved mine road constructed by Inco in 1969. Access within the mine property itself was facilitated by the use of motor vehicles on gravel roads and by canoe.

FIGURE I-1: Location Map: Study area is Shebandowan Mine Area

3. Methods of Study

About 32 square kilometres (Fig. I-1) were mapped during the summers of 1976 and 1977 at a scale of 1:4800 except close to the mine where lines were spaced 200 feet apart (1:2400). When cut line was visible, it was used in preference to compass lines. Traverse lines trend 017° because all base maps (supplied by Inco), diamond drill hole locations and underground mapping are plotted with respect to 017° .

Also over much of the area, 017° was perpendicular to the strike of the rocks except around Zero, Maria and Peewatai Lakes, and there traverses trend 125° because the strike of the rocks ranged from 025° to 055° .

Because of the large amount of serpentized ultramafic rock and iron formation in the area, the sun and time were used as a guide to direction.

4. History of the Mine Area

Nickel in rocks from Discovery Point, Lake Shebandowan was first discovered by Brenner in 1913. In 1914 Cross discovered more nickel further west of Discovery Point (Cross, 1920). In 1936, the Ni-Cu property was acquired from Cross by International Nickel Co. Ltd. (now Inco Metals). In early 1965 diamond drilling was resumed and mining began in the early 1970's. The mine is still in production.

The area was first mapped by Cross (1920) but more detailed work was done by Watson (1928) and Tanton (1938). In the last twenty years, the area has been mapped by various Ontario Dept. of Mines geologists: Hodgkinson, 1968; Morin, 1973; and Srivastava and Fenwick, 1973. Unfortunately the Shebandowan Mine is very close to the junc-

tion of 4 townships and correlation among maps is not easy.

The Shebandowan mine area also lies within the Geotraverse Area (Goodwin, 1973) and is the subject of a structural thesis at the University of Toronto (Stott and Schwerdtner, 1981; Schwerdtner et al, 1979). Shegelski (1980) studied volcanoclastic and pyroclastic rocks in the vicinity of Shebandowan Mine.

A preliminary study of ultramafic rocks within the Shebandowan area was done by Watkinson and Irvine, 1964. Merenskyite was reported in the Shebandowan ore (Watkinson et al., 1978) and the chromitite horizon is included in a regional study of chromite in Ontario (Watkinson and Mainwaring, 1979).

CHAPTER II: GEOLOGY OF THE
SHEBANDOWAN MINE AREA

A. REGIONAL GEOLOGY

1. Introduction

Shebandowan Ni-Cu mine lies within the Shebandowan-Wawa Subprovince of the southern part of the Superior Province, northwestern Ontario. This subprovince is the most southerly of five east-west trending Archean superbelt whose boundaries are defined by regional changes in principal lithologies (Ayres et al., 1971). Shebandowan-Wawa Subprovince is bounded on the north by the Quetico Belt and to the south by Proterozoic and Paleozoic cover. The northerly contact is in part fault controlled but is mainly lithological.

Shebandowan-Wawa Subprovince is composed of granitic bodies and gneisses in the south and mafic to felsic metavolcanic and metasedimentary rocks in the north. It is these metavolcanic and meta-sedimentary rocks, herein called the Shebandowan Greenstone Belt, that are in part, the subject of this thesis. The general geology of a representative part of this greenstone belt is shown in Figure II-1.

For purposes of simplicity, the prefix meta will be omitted from all rock names in this thesis. Terms such as serpentinite, talc-carbonate schist and sericite schist are used where the original rock type is not evident. For definition and classification of rocks described, please refer to Appendix I.

2. Shebandowan Greenstone Belt

Shebandowan Greenstone Belt extends from the Canada-U.S. border (northeasterly) toward Thunder Bay, Ontario and its extension is interpreted to be exposed east of Lake Superior at Wawa and further east to the Kapuskasing Fault Zone. East of this zone, the belt is known as the Abitibi Volcanic Belt.

In the vicinity of Shebandowan Ni-Cu Mine, the greenstone belt is about 16 km wide (Fig. II-1) and is composed predominantly of mafic-volcanic and volcanoclastic rocks, with minor amounts of rhyolitic and sedimentary rocks. All rocks generally strike east-west and are steeply dipping. Age relationships among basaltic, felsic, and sedimentary rocks within the belt are generally not known.

Shebandowan Greenstone Belt is bounded on the north by the Kashabowie Group (Hodgkinson, 1968), of the Quetico Belt. Kashabowie-Group rocks are composed of fine-grained feldspathic greywacke with local arkose bands, which are now quartz-biotite schist. Bedding is distinct, striking 050° to 085° and dipping steeply. Metamorphic grade is generally middle amphibolite facies. Within the map-area (Fig. II-1), Kashabowie-Group rocks vary from 1-8 km in thickness which may or may not represent true thicknesses because of folding. In part, this group of sedimentary rocks is separated from the volcanic rocks by faults, such as the Postans Fault north of Upper Lake Shebandowan; elsewhere in the area the nature of the contact may simply be lithologically controlled.

On the southern side of the Shebandowan Greenstone Belt is the Perching-Gull-Northern Light Lakes Granitoid Complex, (Schwerdtner et al., 1978). It is composed of gneissic volcanic rocks as well as gneissic or massive tonalite, granodiorite and granite.

Geology of the Shebandowan Greenstone Belt depicted in Figure II-1 is representative of most of the belt. The following description of the geology is condensed from O.D.M. compilation map 2065

FIGURE II-1: Regional Geology of the
Shebandowan Greenstone Belt

Regional geology of the Shebandowan Greenstone Belt after Pye and Fenwick, 1964.

(Pye and Fenwick, 1964) and detailed work by Giblin, 1964; Hodgkinson, 1968; Morin, 1973; Srivastava and Fenwick, 1973a,b; Stott and Schwerdtner, 1981; and this study.

3. Mafic Volcanic Rocks

Basaltic flows, flow breccias and tuffs constitute most of the greenstone belt depicted in Figure II-1. In the west, around Burchell Lake, mafic volcanic rocks are exposed both north and south of rhyolite and rhyolitic breccias. According to Giblin (1964), these mafic rocks are composed of amphibolite schist and subordinate amounts of pillow lava, agglomerate tuff, chlorite schist and coarse-grained gabbroic phases. No andesite was recognized.

These mafic rocks are now composed of chlorite, hornblende, tremolite-actinolite, carbonate, albite, epidote and quartz. Banded iron formation was observed only in the southern half of the southern belt of mafic volcanic rocks. It is composed of fine-grained magnetite, quartz and amphibole, with minor carbonate and epidote. Exposures do not exceed 100 m in length or 20 m in width.

In the central part (Figure II-1) mafic volcanic rocks are exposed between Greenwater and Upper Middle Shebandowan Lakes as well as north of the Shebandowan Lakes. They consist of amphibolite schist with subordinate chlorite schist, tuff, agglomerate and porphyritic and pillow lavas (Hodgkinson, 1968). Banded iron formation up to 30 m wide and 1000 m long was recognized throughout the whole area.

In the east, mafic volcanic rocks have been mapped both north and south of Lower Shebandowan Lake. Morin (1973) reported that

both basaltic and andesitic volcanic rocks are present, but chemical analyses of the intermediate flows and flow breccia (Table AII-III) indicate that these rocks are mostly basalt. The mafic volcanic rocks are represented by pillowed lava, aquagene breccia, and fine-grained bedded tuff. Iron formation is recognized south of Lower Lake Shebandowan.

4. Felsic Volcanic Rocks

Most of the felsic volcanic rocks in the area are exposed in a 2-3 km wide band around Burchell Lake. These rocks consist of rhyolite, rhyolite breccia and tuff. According to Giblin (1964), rhyolite is aphanitic, composed of quartz, white mica, chlorite and carbonate. Rhyolite and dacite were recognized north of Upper Shebandowan Lake (Hodgkinson, 1968) and may be an extension of the Burchell Lake rhyolite.

5. Sedimentary Rocks

Sedimentary rocks occur in two thin east-west trending belts, one directly south of Lower Lake Shebandowan and the other 4 km south of Lower Lake Shebandowan (this study). The former is less than 1 km thick and composed predominantly of unsorted immature polymictic conglomerate consisting of volcanic detritus, minor shale and greywacke. Clasts consist of volcanic rocks that are poorly sorted and subangular; and the unit is thought to be coeval with the mafic volcanic succession. The southern exposure of sedimentary rocks extends eastward from the Tinto Lake Fault to the edge of the map-area. There, rocks vary from well-bedded greywacke-iron formation through greywacke-conglomerate to fine-grained mafic siltstone.

Clasts are well sorted and well rounded; graded beds and cross-bedding is common. These rocks appear to be unrelated to the sedimentary rocks to the north.

6. Mafic and Ultramafic Intrusive Rocks

Stocks and sills of diorite, gabbro, and peridotite are intrusive within the mafic volcanic succession. The majority of these are exposed in the central area, east of Greenwater Lake. Gabbro and diorite consist of hornblende, epidote, and saussuritized plagioclase. Peridotite is now serpentinite and talc-carbonate schist.

7. Granitoid Intrusions

There are two types of granitoid intrusions within the Shebandowan Greenstone Belt; foliated gneissic granodiorite to granite and massive to porphyritic granite to quartz monzonite and syenite. The largest of these plutons are exposed at Burchell Lake, Greenwater Lake, Middle and Lower Shebandowan Lakes and Peewatai Lake.

8. Younger Mafic Intrusive Rocks

Small dykes of basaltic composition cut both the granitic and volcanic rocks in the Shebandowan Greenstone Belt. These dykes are easily recognizable in the granitic rocks and where they cut the volcanic strata at a high angle. However, where they conform to strata they are not easily recognized.

9. Metamorphism

Metamorphic grade varies from lower amphibolite facies around Upper Shebandowan Lake to lower greenschist facies south of Lower Shebandowan Lake. Garnets occur in pillowed basalts west of Upper

Shebandowan Lake, but according to Hodgkinson (1968), hornblende-plagioclase is the usual assemblage in mafic rocks in the west and chlorite-quartz-albite (epidote) in the east (Morin, 1973).

10. Structure

According to Schwerdtner et al. (1979), two periods of tectonic deformation may be recognized in the Archean of northwestern Ontario: an early period of vertical-motion tectonics and large scale diapirism which resulted in isoclinal folding of the greenstone belts, and a later period of horizontal-motion tectonics which resulted in major strike-slip faulting. Isoclinal folding is recognized throughout the Shebandowan Mine area where younging directions are available and where marker horizons can be followed. Major strike-slip faults have been mapped and correlated within the Shebandowan Greenstone Belt; for example, the Postans Fault forms much of the northern boundary of the belt. Movement on this fault is not known. The Crayfish Creek Fault has 2 km of dextral movement near Upper Shebandowan Lake (Hodgkinson, 1968). Both these faults are subparallel to stratigraphy. Numerous cross faults, trending northeast-southwest, are present throughout the area, but movements on them have not been documented. Hodgkinson (1968) noted that metamorphic grade changes significantly across the Tinto Lake Fault; rocks southeast of the fault are higher grade than those north of the fault.

11. Economic Geology

To date only two economic mineral deposits have been found in the area: Burchell Lake Mine (North Coldstream Mines Ltd.) and Shebandowan Mine (Inco Metals, Ltd.). Burchell Lake Mine, a small

massive-sulphide deposit produced Cu-Au-Ag valued over 19 million dollars from 1958 to 1964 (Hodgkinson, 1968). It was associated with a small chert horizon found at the contact between mafic and felsic volcanic rocks (Giblin, 1964). Shebandowan Mine has been operating since the early seventies and has been producing Cu-Ni and platinum-group elements (PGE).

B. DETAILED GEOLOGY OF THE SHEBANDOWAN MINE AREA

1. Volcanic Stratigraphy

a. Introduction

The geology of the Shebandowan Mine area is depicted in Figure II-2 (in pocket). The map was condensed from 1:2400 and 1:4800 scale field maps, and where outcrop was sparse, mapping and interpretation were facilitated by access to Inco's drill core and magnetometer maps. Figure II-3 is an example of a magnetic profile map condensed from Inco's data.

Approximately 135 thin section descriptions of volcanic and volcanoclastic rocks and 200 of ultramafic rocks serve as a basis for the petrography. These descriptions are located in a data file available at Carleton University.

Two cycles of tholeiitic basaltic volcanism are recognized. The older cycle is characterized by basaltic tuff interlayered with massive basalt flows which grade upward into porphyritic pillowed basalt. These rocks appear to be coeval with a volcanoclastic suite exposed southeast of the Tinto Lake Fault, around Maria, Zéro, and Peewatai Lakes (Fig. II-2).

FIGURE II-3: Magnetic profile map of part of the Shebandowan Mine Area - (lines are spaced 400 feet apart)

The younger volcanic unit grades upward from thinly layered high-Mg basalt and intercalated tuff into pale green amygdaloidal pillowed and autobrecciated basalt. Within the Shebandowan Mine area, the top of the older cycle is marked by a thick (200-300 m) andesitic submarine ash or debris flow. This unit appears conformable within the map area and serves as a good marker horizon. It is chemically distinct from basaltic rocks and is accidental to the mafic volcanic successions.

Volcanic rocks trend east-west and are vertically dipping, except those rocks exposed southeast of the Tinto Lake Fault. There rocks strike northeast-southwest and dip about 70° to the northwest.

b. Older Succession

1. Basalts (Unit 1)

The older basalt succession has an apparent thickness of 1800 m in the western part of the Shebandowan Mine area, around Loch McLean, and thins to about 300 m just south of #2 mine shaft. East of Castor Island, older basalts are covered by thick glacial overburden, and their thicknesses cannot be estimated. A synformal axis is interpreted to lie within this succession of rocks (see Figures II-6, II-8), and therefore true maximum stratigraphic thickness is about 800-900 m. A cross-section (herein called the ramp section (Figure II-7) through the thinnest portion of these rocks is provided by an underground ore pass that has been constructed from the mine (400 level, #2 shaft) to the mill site.

In general, the older succession is composed of about 15-30% basaltic tuff and tuffaceous sedimentary rock and 55% massive basalt

flows that grade upward into pillowed (20%) basalt flows. The percentage of tuff is greatest just east of Loch McLean and is least in the ramp section.

The massive flows are fine-grained and dark green with usually 5-10% (0.5 mm) plagioclase phenocrysts. In places, these flows are intensely sheared and foliated, and are mapped as chlorite schists. Mineralogy of unsheared basalt is plagioclase (with sericite alteration), epidote, chlorite, carbonate and quartz. Amygdules (5%), where present, are filled with quartz and chlorite. Quartz and carbonate veining is common.

Toward the top of this succession, basalt is pillowed and even where highly sheared, pillow selvages are evident. These pillowed lavas are light green on weathered surface, contain few amygdules, and have been intensely carbonatized. Pyrite cubes are ubiquitous.

In places the pillowed basalt contains at least 20% large plagioclase phenocrysts. Plagioclase has since been altered to chlorite and epidote (Plates A-I, II). These feldspar-phyric flows are exposed at the mill, in the ramp section, 500-600 m south of #1 shaft and at the junction of the mine road and the road to #2 shaft.

At the mill site, a variolitic lava about 17 m thick is exposed. Chemically it is a high-Mg basalt (sample 76-PM-317, Table AII-3) and it appears to be younger than the feldspar-phyric unit exposed behind the mill. Whether it belongs to the older episode of volcanism or is correlative with the younger high-Mg basalts is not known. In thin section, white varioles (1-30 mm in diameter) are aphanitic and opaque, and the pale green, fine-grained matrix is likewise opaque (Plate A-III, IV).

PLATE A

1. Pillowed feldspar-phyric flows. Unit 1. Mill.
2. Altered feldspar phenocrysts in a pillowed lava flow. Sample 76-PM-315. Unit 1.
3. Variolitic lava, Mill. Unit 1.
4. Photomicrograph of contact between ocelli and matrix, variolitic lava, Mill. Scale of Photo 5.9 mm. Unit 1.
5. Altered ultramafic rock: now quartz-ankerite-pyrite and fuchsite. Unit 6c.
6. Altered ultramafic rock west of SW Bay. Rock is situated underneath quartz-ankerite rock shown in 5. Unit 6.
7. Same as 6.
8. Cross-bedding in siltstone, Maria Lake. Unit 2.

Basaltic tuff and tuffaceous sedimentary rock vary from ash to lapilli tuff with minor bedded sedimentary units such as shale. Ash tuff is rare, but where present is less than a metre in thickness, finely banded and composed of quartz, feldspar, chlorite, and epidote. Crystal tuff is also laminated and composed of broken crystals (0.5 mm) of plagioclase set in a fine-grained matrix of brown epidote, chlorite and quartz. Lapilli tuff consists of about 30% pink, subangular to subround fragments set in a medium-grained matrix of 50% epidote, 25% actinolite and 25% quartz and feldspar. Pink fragments are composed of broken plagioclase crystals enclosed in a matrix of quartz and epidote. Pink coloration is due to hematite staining. Pyrite is an accessory mineral.

Distinct ferruginous carbonate horizons occur within the older succession (Unit 6c, Figure 11-2). These are composed of quartz, ankerite, pyrite, and fuchsite and are easily traced because of their unique mineralogy and resistance to erosion (Plate A-5). The thickest of these units (60 m) is exposed southwest of Southwest Bay and on an island in the bay itself. Highly altered ultramafic rock (talc-carbonate schist) is in direct contact with this horizon (Plate A-6,7) and the quartz-ankerite-pyrite rock is thought to be an altered equivalent of the ultramafic rock.

Outcrops of rocks of similar compositions are also exposed near Loch McLean and on the peninsula between Discovery and Southwest Bays. Their outcrop is sporadic, thickness less than 10 m and no ultramafic rocks were found in association with these quartz-ankerite-pyrite rocks.

ii. Volcaniclastic rocks (unit 2)

Coeval with the older cycle of volcanism is a group of sedimentary rocks that is exposed southeast of the Tinto Lake Fault around Maria, Zero and Peewatai Lakes. These rocks strike $N70^{\circ}E$ and dip $70^{\circ}NW$ and have a true thickness of 600 m. Graded bedding, cross-bedding, channel scours and rip-ups serve as good indicators of younging directions. Rocks grade upward from bedded magnetite-chert-greywacke iron formation through greywacke-conglomerate to finely banded, fine-grained mafic siltstone. Contacts are gradational and it is not unusual to find greywacke, conglomerate and siltstone beds in the same outcrop. Iron formation, on the other hand, is only found with greywacke.

The iron formation is best exposed on the shore of Zero Lake and at the contact with the Peewatai Lake Stock (see Fig. II-2). Iron formation beds vary from 1 cm to 3 m in thickness, generally averaging about 10 cm. They are composed of magnetite and chert. Interbedded with the iron formation are thin greywacke beds that vary in thickness from 0.2 to 20 cm. They are generally composed of 60% feldspathic and 40% mafic minerals. In thin section, greywacke is banded and composed of blue-green amphibole, quartz, feldspar, and carbonate. Quartz is recrystallized to a mosaic.

Conglomerate is well exposed on the eastern shore of Zero Lake. Beds are about 6 m thick, composed of 40-50% cobble-sized clasts of white, porphyritic quartz-monzonite and granite (about 50%), feldspar-phyric basalt (30%), hornblende-porphyritic basalt (10%) and shale (10%). Clasts are well rounded and are elongated vertically.

Matrix consists of sand-sized clasts of plagioclase-bearing basalt, hornblende, quartz and feldspar. Elsewhere within the unit, conglomerate is usually pebble conglomerate and beds are usually less than 15 cm thick.

Greywacke is composed of 60-70% angular to subangular feldspar and quartz grains (>0.5 mm <1mm) set in a matrix of fine-grained chlorite. Beds vary from 0.5 to 4 cm thick. Greywacke weathers pink but on fresh surface is light grey.

Siltstone is finely laminated (0.5 mm), dark grey to black on fresh surface and light grey on weathered surface. It is composed of green actinolite, fine-grained untwinned feldspar, with minor quartz. Feldspar exhibits alteration to sericite and saussurite. Banding is defined by the actinolite/feldspar ratio, which causes alternating dark and light bands. Cross-bedding (less than a metre in amplitude) is very common in the siltstone (Plate A-8). Toward the top, siltstone is more mafic and on fresh surfaces appears massive but on weathered surfaces cross-bedding is evident.

Throughout this volcanoclastic succession are occasional beds of mafic, lapilli and crystal tuff that are now composed of actinolite. Some of the fragments weather high (Plate B-1), showing that these are indeed tuffs and not basalt flows or mafic dykes. Toward the very top of the siltstone, fine-grained mafic tuff is very common, and siltstone and tuff are not easily distinguished in the field.

c. Younger Succession (units 4 and 5)

Rocks of the younger basaltic cycle are exposed over about 60% of the Shebandowan Mine area. They are divided into two distinct

PLATE B

1. Mafic tuff, Zero Lake. Unit 2.
2. Flows and banded, epidote-rich intercalated tuffs, Discovery Point. Unit 4.
3. Thin section of flow breccia, Maria and Zero Lakes. Unit 4. Scale of photo: 4 cm.
4. Vesicular pillowed basalt, Tailings Dam. Unit 5.
5. Same as 4.
6. Glomeroporphyritic basalt, sample 76-PM-312. Unit 5. Scale of photo: 2.1 mm.
7. Pillow breccia south of Southwest Bay. Unit 5.
8. Flow-top breccia south of Southwest Bay. Unit 5.

types based on texture, mineralogy and chemistry. The earliest and least abundant (unit 4) are high Mg-basalt (8-16% MgO) with intercalated fine-grained mafic tuff. They compose 15% of the younger cycle, and are exposed on Discovery Point, in underground workings and northwest of the previously described volcanoclastic succession. Their maximum exposed thickness is about 500 m.

On Discovery Point, basalt flows are massive or pillowed and individual flows are generally less than 10 m thick. Pillows are flattened (Plate E-1) and in places, pillow selvages give the rock a highly banded appearance (Plate B-2). Basalts are composed of actinolite, epidote, and chlorite with accessory white mica and magnetite. In two thin sections, microlites of plagioclase remain. Interbedded tuffs are less than 20 cm thick, are pale green and are composed of actinolite and epidote with minor (5%) quartz grains (Plate E-2).

Intercalated with these basalts are thin (0.5 to 3.3 m), black, coarse-grained, magnetic flows that in thin section show relict textures indicating olivine accumulations. Chemically they are picrites (samples 76-PM-19, 20, Table AII-III, 20% MgO). They consist of brown hornblende, actinolite, chlorite, and talc with accessory magnetite and chromite.

Basaltic rock exposed northwest of the volcanoclastic succession (Fig. II-2) consists of banded mafic tuff (10-11% MgO), mafic flow breccia and black fine-grained mafic flows. Tuffs are more numerous and more banded toward the Tinto Lake Fault. There, a few black and white magnetite-chert iron formations are interlayered with the tuff.

Chemically these rocks are similar to basalts and tuffs on Discovery Point, but differ in the degree of shearing, thickness of flows and the type of phenocrysts. Basalts on Discovery Point are sheared, and obviously folded and kink banded; those southeast of Tinto Lake Fault have been folded but show relatively little penetrative deformation. Flows on Discovery Point seldom exceed 10 m in thickness whereas the flow breccia southeast of the Tinto Lake Fault is about 80 m thick. Also this same breccia has augite phenocrysts, (now actinolite [Plate B-3] in both fragments and matrix); no augite phenocrysts were recognized on Discovery Point.

The rest of the younger volcanic cycle is characterized by pale green, amygdaloidal pillowed basalt, massive basalt, pillow breccia, and hyaloclastite with minor amounts of ash tuff, black-white magnetite-chert iron formation, jasper-magnetite iron formation, and pyrite-bearing graphitic shale. These rocks compose 50% of the Shebandowan mine area.

These rocks are depicted in hand specimen and in thin section, in Plates B-4 and C-3. They are composed of chlorite, quartz, plagioclase and epidote, but in some cases the rocks are relatively fresh, with original plagioclase and augite crystals.

The best exposures of amygdalar pillowed basalt are found southwest of the tailings dam. There a large area has been bulldozed, exposing many outcrops of well-formed pillows (Plate B-4). Pillows vary in size from less than 0.3 to 2 m in length. Amygdules are plentiful and are generally 1 cm to 3 cm long, and they coalesce toward the top of the pillow. These amygdules are now

filled with mixtures of chlorite, epidote, quartz, and carbonate. Basalt is now composed of brown hornblende phenocrysts and micro-lites of plagioclase set in a matrix of plagioclase, actinolite, quartz, chlorite, and carbonate. In some cases, small plagioclases are glomeroporphyritic (Plate B-6).

Pillowed and massive flows as well as autoclastic flow breccia, pillow breccia (Plate B-7,8) and hyaloclastite are exposed south of the mine road between Southwest Bay and the mill, and on the mine road around mile 1 and mile 3. In hyaloclastite, shattered glass fragments have devitrified to fine-grained opaque masses of chlorite and epidote (Plate C-1,2,3). Quartz, chlorite and carbonate are also common, both in the matrix and in the shards. Fragments vary in size from 1-100 mm and are plate-like or blocky with sharply defined edges and corners.

Ash tuff is rare, and where present is less than 2-3 m thick. It is finely banded, weathers white and in thin section is composed of small angular crystals of quartz, plagioclase and chlorite set in an extremely fine-grained brown matrix of epidote minerals.

Iron formation is relatively common in this succession of rocks. Two types are recognized: thick (20-40 m) black and white banded magnetite-chert horizons (Plate C-4) and thinly banded, thin (1-3 m) red-black jasper-magnetite horizons (Plate C-5). The best exposure of the former is south of Hoestrom Lake. These iron formations are easily traceable using magnetometer maps, as shown in Figure II-3.

Thin graphitic shales are also present throughout the area but generally weather low so that they have only been identified in drill hole and as conductors on geophysical surveys.

PLATE C

1. Hyaloclastite. Unit 5.
2. Hyaloclastite. Unit 5.
3. Photomicrograph of hyaloclastite. Unit 5.
Scale of photo: 5.9 mm.
4. Banded, folded, black and white magnetite-chert iron formation. Unit 5.
5. Banded, highly contorted jasper-magnetite iron formation associated with basalts. Unit 5.
6. Photomicrograph of black/white iron formation showing graded bedding. This specimen came from iron formation that wraps around the ultramafic rock near Southwest Bay.
Scale of photo: 4 cm. Unit 5.
7. Cross-cutting mafic dyke. Host rocks are unit 1. Ramp.
8. Mafic dyke cross-cutting Peewatai Lake Stock.

d. Mafic and Ultramafic Intrusions and Ultramafic Flows (units 6a, 6b, 6d, and 8)

i. Gabbros (unit 6a)

The older and younger volcanic successions both contain stocks, sills and dykes of gabbro. These are medium grained, white to light grey on weathered surface and dark green on fresh surface. Sills are less than 300 m thick; stocks are 300-400 m in diameter and the largest dyke appears to be at least 1200 m long and 300 m wide. Relict ophitic textures indicate that they were composed of about 50% plagioclase and 50% pyroxene. In some thin sections, fresh clinopyroxene is present and orthopyroxene is altered along fractures to tremolite and serpentine. These bodies are present in both older and younger successions, but are much more prevalent in the latter.

ii. Shonkonite (unit 8)

Southeast of the Tinto Lake Fault, within the succession of volcanoclastic rocks and high Mg-basalt is a 400 m diameter stock of shonkonite. It varies from light to dark grey on weathered surface and is black on fresh surface. Grain size varies from less than 1 mm to 1 cm, depending on whether it is an equigranular or porphyritic phase. Phenocrysts (up to 20%) consist of well-formed euhedral crystals of augite that in some places have altered to chlorite and hornblende. Equigranular phases consist of 60-70% blue-green hornblende, 20-25% augite, 4% opaques, 2% apatite, and accessory carbonate, biotite and muscovite. No potassium feldspar was identified but chemical analyses indicate about 20% orthoclase in the norm (sample 77-77, Table AII-III, IV). This alkalic intru-

sion is unrelated texturally, mineralogically, and chemically to either of the tholeiitic cycles of volcanism.

iii. Ultramafic rocks (units 6b and c)

Two groups of lens-like conformable ultramafic bodies are present throughout the Shebandowan mine area. They are both harzburgites to lherzolites (with minor olivine-websterite and gabbro), but they may be distinguished by rock association. One group is always associated with black and white chert-magnetite iron formation and basaltic hyaloclastite, whereas the other group has no distinct rock association. The former group is only found within the younger volcanic succession, the latter most commonly in the older succession.

In the case of the former group, younging indicators such as pillowed basalts, flow breccias, and graded bedding in iron formation (Plate C-6) all indicate that iron formation lies above the ultramafic rock. At one outcrop, between the mine road and Hoestrom Lake, a fragment of ultramafic rock (now tremolite schist, sample 76-PM-253) was recognized within the associated iron formation, which indicates that the ultramafic rock is older than the iron formation. Therefore, these ultramafic rocks may well have been in contact with seawater, and are tentatively identified as flows. As there is no evidence to the contrary, ultramafic rocks without iron formation and hyaloclastites are assumed to be sills.

The geology, petrography and chemistry of these groups of ultramafic rocks are discussed in detail in chapters 3 and 5.

iv. Small mafic dykes (unit 10)

Small (0.2 - 1 m) mafic dykes are present throughout the older succession of basalt and volcanoclastic rock and the high Mg-basalt.

They are decidedly lacking throughout the rest of the volcanic pile. They vary from black aphanitic to porphyritic diabase dykes and sills (Plate C-7). In the vicinity of the mine they show deformation due to folding and faulting, and kink banding is common. Within volcanoclastic rocks they are dark green, coarse-grained and composed of actinolite and altered plagioclase. They, too, are folded with the strata.

Some mafic dykes cross-cut the Peewatai Lake stock (Plate C-8) and show no deformation or folding and it is assumed that mafic volcanism continued after both older and younger cycles of basaltic volcanism and after the folding events. No age determination has been made in the area and all mafic and ultramafic rocks are considered to be of Archean age.

e. Felsic Pyroclastic Rocks (unit 3)

Toward the top of the older cycle of basaltic volcanism is a thick (300 m) andesitic ash or debris flow which strikes east-west, dips vertically and is repeated within the volcanic pile by folding (Fig. II-2). It is chemically unrelated to the two cycles of volcanism (see page 67). In outcrop the rock is composed of subangular to subround green fragments in a red feldspar-rich matrix, or red feldspar-hornblende-rich fragments in a green chloritic matrix (Plate D-1). The northern limb of the unit is more pervasively red-green in colour, whereas the southern limb is white to light grey, except southwest of Southwest Bay, where pink fragments are found in a green chloritic matrix.

Fragment size varies from 1 cm in diameter to greater than 1 m. Fragments are composed of small rock fragments of carbonate, sericite

and quartz set in a matrix of chlorite, saussurite and recrystallized quartz (Plate D-2,3). Fresher samples contain both alkali feldspar and black acicular hornblende. Pyrite is ubiquitous and magnetite common.

Toward the top of the unit graded beds are common. They are fine-grained bedded ash tuffs. On the shore of the small lake southwest of Southwest Bay, bedded sandstone and conglomerate lie on top of this ash or debris flow (Plate D-4). This small exposure is thought to be a local proximal facies of the pyroclastic rock.

Close to the Crayfish Creek Fault this unit shows tremendous strain in the form of shearing (Plate E-4) and kink banding (Plate E-5). The fragments are sheared and flattened into pancake shapes south of Discovery Point. Because of this, geologists at the mine have called the unit agglomerate and this name occurs on all their plans and sections.

Shegelski (1980) studied this rock type to the east of this map-area. He concluded that these pyroclastic rocks as well as some polymictic conglomerates and arenites were the result of sub-aerial volcanism and associated fluvial deposition. He bases his conclusions on "the absence of pillows in the extrusive andesites in combination with stratification and grading of the pyroclastic tuff-breccias" (p. 342, Shegelski, 1980). Within the sedimentary rocks he recognized structures typical of fluvial deposition, including planar bedding, large-scale cross-bedding, mud chips, and asymmetrical ripple marks. Within the Shebandowan mine area, where good control of mapping was maintained, the basalts both below and on top of the unit are pillowed, very little sedimentary

PLATE D

1. Felsic pyroclastic rock. Unit 3. Mine road, approximately 6 miles east of mine.
2. Photomicrograph of thin section of fragment in felsic pyroclastic rock. Unit 3. Sample from outcrop north of Southwest Bay. Scale of photo: 2.1 mm.
3. Photomicrograph of matrix in above. Note broken feldspars, crossed polars, 2.1 mm.
4. White conglomerate and sandstone. Proximal facies to Unit 3. Outcrop located on small lake southwest of Southwest Bay.
5. Felsic dyke which cross-cuts basalts on Discovery Point. Note later movement along cleavage.
6. Fold in greywacke-siltstone, south end of Zero Lake. Unit 2.
7. Fold in interbedded greywacke-iron formation east side of Zero Lake. Unit 2.
8. Magnetite-chert iron formation--cross-cutting cleavage. Scale in cm. Unit 5.

rock is present, and where present has none of the above sedimentary features. Therefore, within the Shebandowan mine area, the author cannot designate this rock type as subaerial.

f. Granitoid Intrusions

Within the Shebandowan mine area are two plutons of granitic composition: the Shebandowan Lake Stock (10 by 2.5 km) and the Peewatai Lake Stock (4 km in diameter). The former is a foliated gneissic granodiorite to granite, the latter a porphyritic quartz monzonite to syenite. Numerous quartz-feldspar porphyritic dykes are associated with each intrusion.

i. Shebandowan Lake Stock (unit 7a)

In the Shebandowan Mine area, Shebandowan Lake Stock is exposed on Discovery Point, west to Loch McLean and in underground workings and diamond drill core east of Discovery Point. In outcrop it is pink to light grey in colour, medium-grained (3-4 mm) and composed of varying amounts of quartz, alkali-feldspar, plagioclase, and chlorite. In thin section, all feldspars are altered and quartz is recrystallized to mosaics. The stock is foliated in an east-west direction, parallel to the general strike of strata and foliation. Jointing in a predominantly north-south direction is common. The stock varies from quartz monzonite and granite to granodiorite.

ii. Peewatai Lake Stock (unit 9)

Peewatai Lake Stock intrudes volcanoclastic rocks southeast of the Tinto Lake Fault. The stock is circular in plan, is porphyritic quartz monzonite, except close to its western margin,

PLATE E

1. Stretched pillowed basalts, Discovery Point.
Unit 4.
2. Thin section of tuff interlayered with
Mg-rich basalts, Discovery Point. Unit 4.
Scale of photo: 6 mm X 4 mm.
3. 6" graphite seam (fault gouge), Ramp.
4. Stretched fragments in 3 dimensions.
Unit 3.
5. Kinking of unit 3, close to the Crayfish
Creek Fault, Ramp.

1.

where it is granitic, and in the northwest corner which is syenitic. The rock is bright pink in outcrop, is very fresh and shows no penetrative fabric. It is composed of 25% orthoclase phenocrysts up to 1 cm in diameter set in a matrix of medium-grained (3 mm) alkali-feldspar, quartz, orthoclase and actinolite. At the northwest margin of the pluton, there is intrusion breccia consisting of fragments of basalt, ultramafic rock and iron formation in a monzonitic matrix. Xenoliths are up to 25 cm in diameter.

iii. Felsic dykes

In the high Mg-basalt on Discovery Point, dykes and sills of quartz-feldspar porphyry and feldspar porphyry are common (Plate D-5). They are infolded into basalts and basaltic tuffs. These intrusive rocks are also found in the northern and southern mine ultramafic bodies (see Figure II-2), and are interpreted to be apophyses of the Shebandowan Lake Stock.

Felsic dykes in the younger succession are rare and only two or three have been recognized.

The shonkonite exposed southeast of the Tinto Lake Fault has numerous cross-cutting granitic and syenitic dykes. These are not folded and show no preferred orientation and as such, may be apophyses of the Peewatai Lake Stock.

g. Position of the Shebandowan Ni-Cu Mine

Shebandowan Ni-Cu Mine lies at the contact of the northern mine ultramafic sill and the high Mg-basalts that are exposed on Discovery Point (Morton, 1979). The orebody is composed of massive and breccia ore: pyrrhotite, pentlandite, chalcopyrite, pyrite,

magnetite with minor platinoid minerals. There is little or no disseminated ore. According to younging directions in the northern and southern mine ultramafic bodies, ore lies at the top of the northern mine ultramafic body (see Chapter IV).

h. Summary of Stratigraphy

Shebandowan mine area is underlain by two successions of tholeiitic basalt and related volcanoclastic rock. They are divided into a younger and older succession. The older succession is composed of pillowed basalt, mafic pyroclastic rock and plagioclase-phyric flows. Accidental to this cycle is an andesitic ash or debris flow which appears to be conformable within the map-area. The younger succession is subdivided into older high Mg-basalt and picrite and the younger pale green subaqueous pillowed basalt, pillow breccia and hyaloclastite. The size, nature, and distribution of amygdules suggest that this cycle of volcanism was formed in shallow water (Moore et al., 1973).

Associated with each succession of volcanism is a distinct ultramafic group: harzburgite-lherzolite sills in the older succession and harzburgite-lherzolite flows in the younger succession. The Shebandowan Ni-Cu mine is spatially related to an ultramafic sill that intrudes close to the contact between the older and younger series, directly underneath the high Mg-basalt. The ore occurs on top of the ultramafic body.

Figure II-4 shows the temporal evolution of the Shebandowan mine area.

FIGURE II-4: Temporal Evolution of the Shebandowan Mine Area
(For numbers, see Legend, Figure II-2)

2. Structure of the Shebandowan Mine Area

a. Introduction

Schwerdtner et al. (1979) recognized only two periods of tectonic deformation in the Archean rocks of northwestern Ontario (isoclinal folding, followed by major strike-slip faulting), whereas Stott and Schwerdtner (1981) report at least 3 periods of folding deformation (2 isoclinal and 1 kink) within the Shebandowan mine area. From this study it also appears that three folding events occurred in the area as well as major strike-slip and cross faulting.

The first folding event resulted in isoclinal nappes which were then continuously refolded along an east-west trending axis. The next period of folding was along a north-south axis, resulting in gentle warping of the isoclinally folded strata. Strike-slip faulting occurred during and after these folding events, whereas cross faulting appears to have occurred only after the folding events.

b. Isoclinal folding

The best evidence in outcrop for isoclinal folding in the Shebandowan mine area is seen southeast of the Tinto Lake Fault in volcanoclastic rocks. There, bedding is easily measurable; there are many top facing indicators (graded bedding, cross-bedding, channel scours) and also many measurable minor folds (Plate D-6,7). The rocks are not well lineated and foliation is generally parallel to bedding.

Bedding strikes between 035° and 060° and dips 70°NW (Fig. II-5). Within the sedimentary package, younging directions are northwest on the west side of Zero Lake and southeast on the east

FIGURE II-5: Structural Data from the Shebandowan Mine Area

- A. Poles to bedding, all volcanoclastic rocks around Maria, Zero and Peewatai Lakes, 107 points.
- B. Poles to bedding, greywacke-iron formation unit, Maria and Zero Lakes, 56 points.
- C. Mineral lineations - Dakota, Zero, and Maria Lakes, 24 points.
- D. Mineral lineations - Younger volcanic succession, 42 points.
- E. Mineral lineations - Cleavage intensive rocks, Discovery Point area and unit 3, south of Crayfish Creek Fault, 18 points.

Data for A and B, this thesis; data for C, D and E from G. Scott, University of Toronto.

A

B

C

D

E

FIGURE II-5

side of Zero Lake. Mineral lineations in the area plunge 65° to 75° to the northeast (Fig. II-5) and minor folds as well as cleavage-bedding intersections at the south end of Zero Lake indicate that the fold closes just south of the lake. Younging indicators consistently show that rocks young away from Zero Lake, which means that this synformal structure is really an anticline.

The same kinds of structures on a smaller scale are seen in the younger volcanic succession, south of Southwest Bay. There an iron formation wraps around a thick ultramafic flow (Fig. II-2). Bedding and foliation trend east-west and younging indicators (pillowed basalt, flow top breccia and graded bedding in iron formation) suggest that rocks face away from the centre of the ultramafic rock. Minor folds in the iron formation plunge 55° southwest and the fold appears to close to the east. This fold is a synform but facing directions again show this to be an anticline (Fig. II-6a, 6b, in pocket).

Within the ramp section (Fig. II-6c, 7) the andesitic debris flow (unit 3) is repeated within the section. Top directions show that the southern limb of the unit faces to the south, and it is inferred that the northern limb tops to the north (the ultramafic rock directly north of the northern limb of unit 3 does young to the north). W-folds in quartz veins in the feldspar-phyrlic flows of the central part of the mine ramp plunge to the east at 50° . This also is a synformal structure that is in reality an anticline.

The fold axes within the Shebandowan mine area are depicted in Figure II-8. (in pocket).

FIGURE II-7:
RAMP SECTION

Figure II-9 is a regional cumulative strain pattern for the Shebandowan Lake Area (Stott and Schwerdtner, 1981). Initially Stott (personal communication) interpreted the oppositely plunging strain fields as large scale anticlines plunging west and synclines plunging east. Their later interpretation does not say this and in fact, one of their anticlines passes across the strain boundary. They interpret these domains as D_1 -isoclinal folding and D_2 as secondary isoclinal folding that penetrates only the more ductile components (e.g. sedimentary and felsic volcanic rocks). They suggest a model of sequential development of strain domains in which a deformation is superimposed upon an earlier regional deformation and produces strain domain patterns with coherent (non-dislocated) boundaries. They do not speculate on a mechanism for this model.

c. Interpretation of the Isoclinal Folding

Figure II-10 illustrates a large scale nappe formation and with continued shortening, its refolding. If the nappe is shortened to an extreme (more isoclinal folds), the axial plane cleavage of the first nappe (S_1) will parallel the axial plane cleavage of the second series of folds (S_2) and as such, they will be indistinguishable in outcrop. Also a section drawn through M will result in synforms that are synclines whereas a section through N will result in synforms that are anticlines (see Fig. II-10). The latter is what is seen in the Shebandowan mine area: one major foliation and synforms that are anticlines. In other words, the best explanation of the isoclinal structures seen in the Shebandowan

FIGURE II-9: Structural Map of the Shebandowan Mine Area after Stott and Schwerdtner, 1981

FIGURE II-10: Result of refolding a nappe structure

mine area is that the rocks were first overturned (S_1) and continuously shortened along an east-west axis (S_2). We are then, now looking at the bottom of a nappe-like structure. This is interpreted to be two folding events, but could conceivably be continued deformation. In support of this idea are minor structures in iron formation that show refolded folds and merging foliations as shown in Figure II-10 (Plate C-4 and Figure II-11).

d. Open Folding

South of Hoestrom Lake, within the younger succession is a domal structure 400 m in length and 200 m wide. It is outlined by a thick (20-40 m) black and white banded iron-formation and plunges gently to the west on its western side and gently to the east on its eastern side. A north-south cross-cutting cleavage is present in the iron formation (Plate D-8) and it is thought to be related to gentle folding along a north-south axis. Canoe-shaped structures within iron formation elsewhere in the volcanic pile also suggest folding along a north-south axis. Within basalts, no secondary cross-cutting cleavage was measured.

e. Faulting

Major faults within the Shebandowan mine area are shown in Figure II-12. The two most prominent are the Crayfish Creek and the Tinto Lake Faults. These faults can be seen as strong lineaments on air photographs and the faults have been mapped by Hodgkinson (1968), west and south of the Shebandowan mine area. The Crayfish Creek Fault is one of the major strike-slip faults that is reported by Schwerdtner et al. (1979). Apparent movement on this fault measured west of the Shebandowan mine area is about

HIDOR FOLDING IN IRON FORMATIONS SOUTH OF THE HILL COMPLEX

FIGURE II-11: Sketches showing types of folds present in iron formation in Shebandowan Mine Area

FIGURE II-12: Major faults in the Shebandowan Mine Area (numbers refer to fault blocks)

3 km in a dextral sense (Hodgkinson, 1968). Movements on other faults in the area have not been documented.

i. Crayfish Creek Fault

Within the Shebandowan mine area, the Crayfish Creek Fault is marked by intense shearing, mylonitization and kink-banding. Close to the fault, unit 3 becomes sheared and sericitized, the fragments flattened like pancakes (Plate E-3). Within the ramp section, kink-banding of this unit is seen (Plate E-4). From diamond drilling and underground workings, it appears that the Crayfish Creek Fault dips steeply south (Fig. II-25), is parallel to bedding from Loch McLean to 0.5 km east of #2 shaft where the strike changes direction and cross-cuts strata at a low angle (Fig. II-2). Apparent movement on the fault is about 300 m in a dextral sense.

ii. Tinto Lake Fault

Tinto Lake Fault strikes 060° and is delineated by a major escarpment just west of Maria and Zero Lakes. The fault abuts against the Crayfish Creek Fault east of the tailings dam. No extension north of the Crayfish Creek Fault has been found, in outcrop or on air photographs. On the north contact of Peewatai Lake Stock, a fault strikes 055° and dips 60° SE and it appears either to be the Tinto Lake Fault or a splay of that fault. Metamorphic grade of rocks is epidote amphibolite facies southeast of the Tinto Lake Fault and lower greenschist facies on the northwest side.

iii. Cross Faults

Two other northeast-southwest trending faults occur in the vicinity of Southwest Bay and just east of the mill complex. Apparent movement on the former is 650 m and on the latter 250 m, both in a sinistral sense. Both either abut against or splay into the Crayfish Creek Fault.

A small normal fault, just west of ventilation island, within the mine (Fig. II-12) strikes 020° and dips 50° east and shows normal displacement of 90 m. Apparent strike-slip movement of this fault is dextral (Fig. II-2).

iv. Other Faults

Within the ramp section (Fig. II-7) a steep north-dipping fault, which separates south-facing rocks in the north from north-facing rocks in the south, is marked by fault gouge and 25 cm of graphite (Plate E-5). The dashed line (A) in Figure II-12 represents an electrical conductive zone in the area that separates south-facing rocks in the north from north-facing rocks in the south. It is interpreted to be an extension of the graphite bearing fault in the ramp and to be an old fault that was active toward the end of isoclinal folding. It is definitely offset by 650 m on the cross fault near Southwest Bay. To explain reversal of younging directions across this fault, younger rocks underneath must have been moved up relative to the older succession, by approximately 800 m (see Fig. II-6a,b,c).

The area has been separated into 7 major fault blocks (Fig. II-12) which show different average strikes and dips of the major foliation and/or bedding. Strike varies from 110° in block 6 through 100° in 1, 080° in 2, 090° in 3, 075° in 4, 055° in 5, and back to

100° in 7. This change in strike might well be due to rotation, as well as strike-slip and/or normal displacement on these faults.

v. Relative Ages of Faulting

The earliest fault in the area appears to be fault A, depicted by a dashed line (Fig. II-12). No rotation of strike is found across this fault. Because all northeast-southwest trending cross-faults seem to abut against or splay into the Crayfish Creek Fault, it is inferred that both crossfaults and the Crayfish Creek Fault are of the same relative age. No extensions of the crossfaults have been found on the northern side of the Crayfish Creek Fault. This might equally be due to lack of outcrop and the amount of glacial overburden in the northeast.

f. Summary of Structural Geology

Figures II-8 and II-6 are respectively structural and cross-sectional figures of Shebandowan mine area that show that the area has undergone at least three periods of folding. The first resulted in a nappe that was then refolded along the same axis to yield overturned strata in the Shebandowan area. Later, cross folding in a north-south direction is documented by gentle warping of the isoclinal strata.

Two stages of faulting are interpreted to have occurred in the area, one early stage which probably was associated with isoclinal folding that caused younging reversals. The second stage broke the area into 7 major fault blocks, causing movement in both dextral and sinistral senses and probable rotation on fault surfaces.

3. Metamorphism in the Shebandowan Mine Area

Metamorphic grade varies from lower greenschist to upper greenschist facies. Mafic rocks at low grade are characterized by chlorite-quartz-carbonate-plagioclase ($<An_{30}$); chlorite-quartz-carbonate-epidote-plagioclase ($<An_{30}$); chlorite-quartz-carbonate-epidote; chlorite-quartz-carbonate-epidote-actinolite; and chlorite-quartz-epidote-actinolite. Epidote and actinolite + quartz are characteristic of the upper greenschist facies.

Rocks north of the Crayfish Creek Fault on Discovery Point are composed of actinolite-epidote-quartz; actinolite-epidote; or fine-grained actinolite and microlites of plagioclase and in general are indicative of the upper greenschist facies. South of the Crayfish Creek Fault to the southern limit of the map-area and east to the Tinto Lake Fault, rocks are either fresh (plagioclase and relatively unaltered augite) or lower greenschist facies. The latter is more prevalent. Mafic rocks are composed of chlorite-quartz-carbonate with minor epidote, relict augite and plagioclase microlites. Volcanic textures have not been destroyed. Feldspar phenocrysts have been altered to epidote and some chlorite in most instances.

Southeast of the Tinto Lake Fault, metasedimentary rocks are composed of quartz-actinolite-plagioclase, whereas mafic tuffs and flows are either entirely actinolite or mixtures of actinolite with minor plagioclase. These are the highest grade rocks in the area.

Xenoliths of mafic rock in the Peewatai Lake Stock are composed entirely of blue-green actinolite. It could be interpreted that the higher grade of metamorphism in rocks southeast of the Tinto Lake Fault is due to contact metamorphism, caused by the

intrusion of the Peewatai Lake Stock, but further south and west, metamorphic grade is higher in rocks from the southeast side of the Tinto Lake Fault (Hodgkinson, 1968) relative to the northwest side. It is therefore assumed that rocks southeast of the Tinto Lake Fault have undergone a higher temperature and pressure gradient than rocks northwest of the fault.

Rocks north of the Crayfish Creek Fault are very close to the Shebandowan Lake Stock, and because rocks away from the stock (and north of the Crayfish Creek Fault--3 km east of the mill) are lower greenschist facies, it is assumed that rocks on Discovery Point have undergone contact metamorphism.

4. Chemistry of Mafic and Felsic Volcanic and Intrusive Rocks

a. Introduction

Chemical analyses were made of 95 rock specimens from the Shebandowan mine area, 39 of which were of ultramafic rocks. This latter group is discussed in detail in Chapter V. Analyses of samples, normative mineralogy, and descriptions of analytical techniques employed in this thesis are reported in Appendix II. Figure II-13 is the legend for all figures in this thesis illustrating chemical relationships.

Metamorphic facies concepts (Turner, 1981) show that all igneous rocks are metastable with respect to surface conditions (P, T, μ) and therefore any subsequent mineralogical readjustment due to sea-floor alteration, or, burial metamorphism will result in low grade mineral assemblages of chlorite, epidote, sericite, carbonate, and albite. Low-grade metamorphism of ultramafic rocks will result in serpentine, chlorite, carbonate, talc and oxides.

FIGURE II-13: LEGEND FOR CHEMICAL DIAGRAMS

Ultramafic Rocks

- Harzburgite and lherzolite: Body B
- Olivine gabbro and olivine websterite: Body B
- ▲ Harzburgite: Body A
- ◻ Olivine gabbro: Body A
- Ultramafic rocks from ultramafic bodies with associated iron formation
- Mg-rich basalt north of Body A (unit 4)

Mafic and Felsic Rocks

- × Younger tholeiitic basalt: unit 5
- + Older tholeiitic basalt: Unit 1
- Δ Dyke rocks, gabbro: unit 6a
- ⊕ Tuffaceous basaltic rock: unit 1
- ◻ Felsic pyroclastic rock: unit 3
- S Shebandowan Lake Stock and apophyses: Unit 7a,b
- P Peewatai Lake Stock: unit 9

This readjustment involves mobilization of major oxides, in particular K_2O , Na_2O , Fe_2O_3 , H_2O and MgO . If there is no large-scale mass transport involved with this "metamorphism," then chemical analyses of greenschist rocks should yield good estimates of their original composition. Unfortunately, we cannot always say whether metasomatism was involved or not, because we do not know the original composition.

Analyses are plotted on a K_2O+Na_2O versus K_2O/K_2O+Na_2O diagram (Hughes, 1972), to check for sea-water alteration effects, either during or after volcanism. The majority of samples lies within the igneous spectrum (between the dashed lines on Fig. II-14). Four samples lie markedly below the igneous spectrum; these are either rich in MgO and low in alkalis, or as in the case of sample 77-95, composed of actinolite and considered to have undergone K_2O+SiO_2 enrichment during metamorphism. The four samples (2 dykes and 2 mafic tuffs in unit 4) that lie close to the dashed line, although still below the igneous spectrum are least altered. Analyses of Hawaiian basalts (for example C87, C71, C90, C76; MacDonald and Katsura, 1964) all project below the igneous spectrum as defined by Hughes. Samples that lie well within the spilite field are G9 and 45110-880. The former belongs to the older series; the latter is a basalt that separates the northern mine ultramafic body from the southern mine ultramafic body (older series) and has a very high Na_2O content relative to other basalts in the Shebandowan mine area. It is proposed that G9 and 45110-880 may have undergone spilitization. All other samples in the spilite field are felsic rocks, lie very close to the line, and are either altered or project in those positions because of analytical error (see Appendix II).

FIGURE II-14: Diagram showing 'igneous spectrum' (between dashed lines) as defined by Hughes, 1972

All the volcanic rocks have been classified according to Irvine and Baragar (1971) as subalkaline (Fig. II-16) with the exception of 45110-880, which plots in the alkalic field and is thought to be a spilite. In general, all mafic rocks, intrusive and extrusive of the older and younger successions, show a tholeiitic iron enrichment trend on an AEM diagram (Fig. II-15). Felsic intrusive and extrusive rocks, on the other hand, appear to have calc-alkaline affinities (Fig. II-15).

b. Chemistry of Mafic Rocks

1. Classification

Basalts of both older and younger rocks (flows and tuffs) plot in the subalkaline field of MacDonald and Katsura (1964) (Fig. II-16). All the younger succession are classified as tholeiitic basalts; samples from the high Mg-basalts (unit 4) are all olivine normative except tuff which is quartz normative, whereas the subaqueous hyaloclastites and pillowed basalts are half quartz and half olivine normative (Irvine and Baragar, 1971).

In the older succession, four samples are classified as calc-alkaline and the rest are quartz or olivine tholeiites. These calc-alkaline rocks are feldspar-phyric basalts (G10 and 76-PM-269) and two samples of bedded tuff that are close to the break between the older and younger succession.

According to Pearce and Cann (1973) analyses of modern basalts project into 3 areas on a $Ti/100 - Sr/2 - Zr$ diagram. These are representative of ocean floor basalts, low-K tholeiites and calc-alkaline island arc basalts. On this $Ti/100-Sr/2-Zr$ diagram, analyses of Shebandowan mafic rocks scatter across all three divi-

FIGURE II-15: A.F.M. diagram showing all analyses of Shebandowan Mine rocks. Dashed line from Irvine and Baragar, 1971, separates tholeiitic from calc-alkaline trends. A=total alkalis
F=FeO
M=MgO

FIGURE II-16: Plot of analyses of basaltic and felsic rocks in Shebandowan Mine Area
 Line from Macdonald and Katsura, 1964, separates alkaline (top) from
 tholeiitic (bottom) rocks

sions. Condie (1981) notes that average values of analyses of basalts from Archean greenstone belts usually fall within the modern oceanic ridge basalts (MORB) or calc-alkaline fields. He says that caution must be exercised in using this diagram to deduce tectonic settings in the Archean.

Davies et al. (1978) provide refined trace element discriminant diagrams to distinguish between calc-alkaline and tholeiitic rocks in the Archean but they employ Y analyses which are not available in this study.

On Miyashiro's (1975) diagram of SiO_2 versus FeO/MgO [total Fe as FeO], most basaltic rocks from Shebandowan plot in the tholeiitic field, with the exception of G10, 77-8 (unit 2), 77-80 (unit 4) and 2 dyke rocks (which lie close to the line (see Fig. II-17)). The first two samples were classified as calc-alkaline by Irvine and Baragar's (1971) method but 77-80 was a quartz tholeiite; also 76-PM-269 and 76-PM-208 were both classified calc-alkaline by Irvine and Baragar's method but plot in the tholeiitic field of Miyashiro.

In summary, most basaltic tuffs and flows would be classified as tholeiitic. The older succession is calc-alkaline toward the top, for example the phyrlic flows. The base of the younger volcanic succession is marked by extrusion of high Mg-basalts (picrites) which change upward into quartz- and olivine-normative subaqueous pillowed basalts and auto-brecciated flows.

2. Major element variation.

Chemical variation diagrams, for example FeO/FeO+MgO versus MgO and CaO contents, were drawn for all major elements. These are not presented here because there appeared to be no difference in

FIGURE II-17: FeO/MgO versus SiO_2 for analyses of basalt from Shebandowan Mine Area, after Miyashiro, 1975

chemical variation between older and younger basaltic successions; when plotted together they form one trend on all diagrams.

Mafic dykes have lower SiO_2 , FeO , and TiO_2 and higher MgO and CaO contents relative to basaltic rocks in both successions (see Table II-1 and AII-III). These dykes thus may have originated from less fractionated magmas than either the older or younger successions and are probably feeder systems for the basalts.

3. Rare Earth Elements

Smith (1978) analysed basalt, felsic pyroclastic rock and granite in the Shebandowan Belt for whole, trace, and rare-earth elements. Several samples analyzed are from the Shebandowan mine area, in particular analyses of Shebandowan Lake Stock and basalt exposed in the road cut at mile 1 on Inco's mine road (younger succession). According to Smith, basalts are tholeiitic, have moderate to high Ni (25-125 ppm), Cr, and V (250-300) contents and chondrite normalized rare earth element (REE) patterns are unfractionated (Fig. 1, p. 186, Smith, 1978).

Condie and Baragar (1974) report relatively flat, unfractionated REE patterns from basalt from the Abitibi region as well. The difference between the two areas is the presence of small Eu anomalies in basalt from Abitibi. None exists in Shebandowan basalts. These flat unfractionated patterns can be produced by partial melting of mantle in which neither garnet nor amphibole remain in the residue (Condie, 1980).

4. Trace Element Variation

Mean concentrations of Ni, Cr, V, Co, Ba, and Sr are tabulated in Table II-2 for each of the rock units in Figure II-2, as well as

Table II-1: Average Chemical Composition of Mafic Rocks.

	<u>Unit 1*</u>	<u>Unit 4</u>	<u>Unit 5</u>	<u>Units 6a, 10</u>
SiO ₂	49.1	48.5	49.9	46.9
TiO ₂	1.13	0.75	1.29	0.82
Al ₂ O ₃	14.1	12.1	12.8	12.8
FeO	11.6	11.7	13.5	10.6
MgO	5.30	11.4	6.06	8.91
MnO	0.19	0.19	0.22	0.18
CaO	9.12	9.84	8.64	11.5
K ₂ O	0.32	0.86	0.35	0.82
Na ₂ O	2.32	1.38	2.40	1.74
L.O.I.	4.56	1.46	2.22	3.98
TOTAL	97.74	98.18	97.38	98.25
FeO/MgO	2.19	1.13	2.23	1.22

* Unit 1: 76-PM-208, 269, 316, 317; 77-PM-8, 10, 24; G68008, 10

Unit 4: 76-PM-4, 10, 19, 20, 185; 77-PM-80, 134

Unit 5: 76-PM-283, 286, 303, 330, 331; 77-PM-71

Units 6a, 10: 77-PM-95, 111; 76-PM-332, 336, 284, R7

Table II-2: Average Trace Element Abundances of all rock units in the Shebandowan Mine Area

Basalts:	<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>V</u>	<u>Ba</u>	<u>Sr</u>
unit 1 (9*)	188	241	63	151	140	288
unit 4 (7)	401	835	102	214	116	108
unit 5 (6)	208	113	81	215	77	123
Volcaniclastic Rocks:						
unit 2 (4)	98	272	28	107	535	383
Pyroclastic Rocks:						
unit 3 (6)	98	124	38	107	493	614
Intrusive Rocks:						
mafic dykes (6a & 10) (6)	168	419	65	212	630	705
Shebandowan Lake Stock (3)	173	45	53	88	397	540
Peewatai Lake Stock (3)	58	20	22	66	1355	656
Shonkinite (3)	192	861	40	241	597	615
Average Basalt ¹	150	200	48	250	250	465
Average Granite ¹	0.5	4	1	20	600	285
Sturgeon Lake; Wabigoon (70) ^{2*}	124	279	66	237	54	-
Archean Tholeiitic Basalt ³	162	256	38	385	99	149

*number of analyses

¹from Krauskopf, 1967

²from Breaks and Bond, 1977

³from Goodwin, 1977

average abundances for basalt and granite (Krauskopf, 1967), basalt from Sturgeon Lake area (Breaks and Bond, 1977), and average Archean tholeiitic basalt (Goodwin, 1977). Ni, Cr and Co contents in unit 4 (high Mg-basalt) are much higher than those of an average basalt, Archean tholeiite or a tholeiite from Sturgeon Lake. Ni, Cr, and Co contents of unit 1 (older basalts and tuffs) and Ni and Co contents of unit 5 are similar to tholeiitic averages, whereas the Cr value for unit 5 is somewhat lower than tholeiitic averages, 113 ppm vs. 200-276. Values for Ba and Sr in units 1, 4, and 5 are similar to those of an average Archean tholeiite.

5. Comparison of Shebandowan Mine Area Basalts with the Ely Greenstone, Vermilion District, Minnesota

The Vermilion District is located in northeastern Minnesota and its extension into Canada in a northeasterly direction is the Shebandowan Greenstone Belt. The district is divided into three formations: the Ely, the Knife Lake, and Vermilion Lake Groups and the Newton Lake Formation. The Ely Greenstone is divided into three members: the lowest member is composed of massive and pillowed basalt and andesite flows to intermediate felsic tuffs and breccias. Chemically both tholeiitic and calc-alkaline rocks are present with calc-alkaline rocks appearing toward the top. The top of this member is marked by the deposition of the Soudan Iron Formation. The upper member consists of 90% pillowed to massive basalt flows which are all tholeiitic. Thin banded iron formation is common in this upper member. Rocks of the Ely Greenstone are decidedly similar to the older and younger succession of the Shebandowan mine area, but are lacking in ultramafic intrusive and extru-

sive rocks. For purposes of comparison the lithology and chemistry of the basaltic rocks of the Ely Greenstone are listed in Table II-3 (from Schulz, 1978). Analyses of basalts from the Ely Greenstone published by Sims (1972) range from picrites to quartz tholeiites but they have not been divided into Upper and Lower members. TiO_2 content is always less than 1.5% and in 67% of the analyses, they contain less than 1% TiO_2 .

c. Chemistry of Felsic Volcanic and Intrusive Rocks

1. Submarine ash or debris flow (unit 3)

Seven analyses of the submarine ash or debris flow that occurs close to the break between the older and younger successions are presented in Table AII-III. Only six analyses are plotted on diagrams because the analysis of 77-132 totals only 90%. SiO_2 content (dry weight) varies from 58.2 to 67.5%, K_2O from 0.63 to 2.87%, and Na_2O from 2.9 to 4.94%. Samples are classified as calc-alkaline andesites or dacites according to Irvine and Baragar, 1971 (Fig. II-15). A sample from mile five on the mine road, one mile east of the map-area, consists of fragments that are slightly more siliceous but less aluminous than the matrix. Total alkali content is the same in each (5.3%).

Ni, Cr, V, and Co contents are considerably lower than Shebandowan mine area basalts (see Table II-II) whereas Ba and Sr are very much higher than those of basalts. According to Smith (1978), REE show fractionation of light relative to heavy REE (70:10), with very small Eu anomalies. This is indicative of magmas formed from melting of crustal rocks.

Table II-3: Stratigraphy and Chemistry of the Ely Greenstone,
Vermilion District, Minnesota

Ely Greenstone:

Upper Member	Mafic lava, mainly pillowed Intermediate-mafic pyroclastic rocks Diabasic gabbro Iron formation	3,600 m
Soudan Iron-Formation Member	Iron formation Intermediate-mafic pyroclastic rocks	150 m
Lower Member	Mafic to intermediate amygdaloidal, dominantly pillowed lava Diabasic gabbro Mafic to felsic pyroclastic rocks	3,000 m

	Lower Ely		Upper Ely	
	Basalt	Andesite	Low Ti Basalt	High Ti Basalt
SiO ₂	48.49	58.76	50.11	50.84
Al ₂ O ₃	16.00	15.50	15.69	14.53
FeO	11.84	6.18	11.32	12.65
MgO	7.63	5.44	6.63	5.34
CaO	11.37	8.50	12.16	11.67
Na ₂ O	2.66	4.37	2.38	2.61
K ₂ O	0.77	0.33	0.36	0.33
TiO ₂	0.80	0.59	0.89	1.50
P ₂ O ₅	0.02	0.11	0.05	0.10
MnO	0.21	0.12	0.21	0.21
Mg value	0.57	0.65	0.55	0.47
Al ₂ O ₃ /TiO ₂	20.0	26.3	17.6	9.7
CaO/Al ₂ O ₃	0.71	0.55	0.77	0.80
Cr	370	249	314	108
Ni	177	161	125	47
Y	9.6	16	20	34
Zr	24	136	50	94
Rb/Sr	0.109	0.037	0.093	0.048
K/Rb	438	489	321	559
(La/Sm)FF		2.56	0.83	0.65
(Sm/Yb)EF		2.19	1.10	1.23

(from Schulz, 1978)

2. Granitoid Intrusions

Two analyses of Shebandowan Lake Stock and two of quartz-feldspar porphyry dykes which are comagmatic with the stock are presented in Table AII-III. They are granodiorite in composition and lie on the calc-alkaline trend (Fig. II-5). They have abnormally high Ni and V contents for granitic rocks and slightly low Ba and slightly high Sr (see Table II-2). These Ba and Sr levels reflect the calcic nature of the Shebandowan Lake Stock relative to a normal granite. High Ni and V contents might well be due to assimilation of ultramafic rock and/or high Mg-basalt, or by metamorphic distribution of Ni from the Ni-Cu ore body. REE data compiled by Smith (1978) show very strong fractionation of light relative to heavy REE (50:1), as well as a small positive Eu anomaly.

Stott and Schwerdtner (1981) suggest that the Shebandowan Lake Stock is "structurally an acceptable candidate as the sub-volcanic equivalent of the late "Timiskaming" calc-alkaline volcanic suite (Shegelski, 1980) to the south and east." In terms of this thesis, they suggest that the Shebandowan Lake Stock is the subvolcanic equivalent of unit 3. Because the REE patterns for each are different, it is concluded that they are not intrusive and extrusive equivalents of one another (Smith, 1978).

Three analyses of the Peewatai Lake Stock are tabulated in Table AII-III. They range from syenite to granite in composition. Sample 77-113 is representative of most of the stock and is a quartz-monzonite. SiO_2 content (dry weight) varies from 62 to 73%. Ni content is less than the Shebandowan Lake Stock (58 versus 173 ppm) but is still higher than average granite (<1 ppm) (Table II-2).

Ba and Sr contents are much higher in the Peewatai Lake Stock than the Shebandowan Lake Stock and the high Ba is related to the former's higher K_2O content. The high Sr content is not consistent with the lower CaO content of Peewatai Lake Stock compared to that of the Shebandowan Lake Stock.

d. Summary of the Chemistry of the Shebandowan Mine Area

Shebandowan basaltic rocks are characterized by two series of tholeiitic rocks. They cannot be chemically distinguished, except that the top of the older succession is composed of pillowed feldspar-phyric basalts and interbedded tuffs that are calc-alkaline. Toward the very top of this older succession, a calc-alkaline submarine ash or debris flow was formed. From geological mapping and petrography, it is interpreted to be accidental to the basaltic volcanic piles. Chemically, its REE pattern shows that it was derived from crustal rocks, whereas basalts have formed from the mantle.

The younger succession is marked by the presence of MgO rich picrites, high in Ni and Cr, and interbedded mafic tuffs that become quartz and olivine tholeiites higher up the pile (unit 5). REE data of the tholeiitic rocks are unfractionated, and the absolute REE contents are directly correlated to the amount of iron in the rock (Smith, 1978).

Mafic dykes are richer in MgO and CaO and have lower SiO_2 , TiO_2 and FeO contents than the basalts they intrude. They are probably derived from a more primitive magma than the basalts, or represent the more mafic fraction of the basaltic pile (i.e. the

feeder system). Because ultramafic rocks form an integral part of the volcanic cycle, magma genesis is discussed at the end of chapter 5.

Basalts and mafic rocks have been intruded by the Shebandowan Lake Stock, a granodiorite, and the Peewatai Lake Stock, a quartz-monzonite. These plutons are rich in Ni and V relative to average granitic rocks, and the Shebandowan Lake Stock has a strong enrichment of light REE relative to heavy REE. These REE patterns are consistent with their derivation by crustal anatexis of sedimentary rocks (Chou et al., 1977).

C. GEOLOGY OF THE SHEBANDOWAN Ni-Cu MINE

1. Introduction

The geology of the Shebandowan Ni-Cu Mine is condensed from Inco's 100 scale (1200:1) plans and sections. All data were reduced to 200 scale (2400:1) and reinterpreted by the writer. Samples of rock, ore and inclusions in the ore were collected in the summers of 1976, 1977, and 1978 and by D. H. Watkinson in 1975. All electron microprobe analyses of sulphide minerals were performed at Carleton University by the writer.

All sections, plans, ore and rock samples are located according to a mine grid which is based on 017° as north (Fig. II-18). Generally ore lies at the contact of the mine ultramafic body and the Mg-basalt (unit 4). Detailed petrography of the ultramafic rocks in contact (or close to the contact) with the ore body is discussed in Chapter III.

FIGURE II-18:
SHEBANDOWAN MINE GRID

2. Geology of the host rocks

a. Introduction

Within the mine itself, Inco geologists have distinguished seven rock types. The relationship between Inco's mappable units and those in this thesis are as follows:

granite -	refers to Shebandowan Lake Stock and apophyses (7a, 7b)
banded greenstone -	epidote rich, pillowed basalts and tuffs of unit 4
breccia sulphide -	ore zone
massive sulphide -	
peridotite -	usually harzburgite or lherzolite
hornblendite -	peridotite, olivine gabbro, or olivine websterite; now tremolite and serpentine (6b)
greenstone -	includes all basalts and tuffs that are not banded, including feldspar-phyric flow rocks (units 2 and 4)
agglomerate -	intermediate volcanic - usually unit 3 - not present in mine but located 100-300 m south of the ore zone

Contacts between these units are sharp, and in many cases are fault controlled. Faults are recognized by chlorite and serpentine slickensides, and in places fault gouge and rubble. Chlorite commonly occurs within granitic intrusive rocks, along joints and fractures, such that in places in the mine, granitic rocks are dark green and are indistinguishable from basalt.

b. Shape of the ore body

Figure II-19 (in pocket) is a series of schematic plans of Shebandowan Mine's 400 through 2000 levels. Because most of the

2

data on Figure II-19 is from Inco's mapping and drill hole logging, all basaltic rocks are mapped as one unit, although in fact, may be made up of units 2 and 4.

On the 400, 600, and 800 levels (Figs. II-19, 21, 22b), ore is more or less continuous from 20,000E to 23,000E. The ore lies between banded high Mg-basalt and tuff (unit 4) to the north and a mixture of ultramafic rock, granitic intrusion and basalt to the south. The northern mine ultramafic body in this area, as depicted in Figure II-19, is highly disjointed. In section (Fig. II-20), the northern mine ultramafic body is more continuous with depth. Between 22,000E and 23,000E (Fig. II-22), ore is downfaulted by a small normal fault, trending 020° and dipping 50°E. A comparison of the 800 and 1000 levels (Fig. II-19) shows the disappearance of ore in the west on the 1000L and its reappearance farther east at the 24500 section, which is the approximate position of the #2 mine shaft. Ore is relatively continuous with depth from the 1000 to 1800 levels. In projection (Fig. II-22), ore plunges east at 050° and pinches out at depth.

On the 1000, 1400, and 1800 levels, ore lies at the contact between basalts on the north and ultramafic rock on the south. On the 1200 and 1600 levels, ultramafic rock forms both the hanging wall and footwall.

From 23,000E to 24,000E, 1000L and below, the ore body and enclosing rocks are intruded by a large apophysis of the Shebandowan Lake Stock (Fig. II-22a,b). The position of the intrusion corresponds to the normal fault and lack of ore, east of 23,000E above 1000L.

FIGURE II-20: Three cross-sections of the
Shebandowan Mine (vertical
scale in thousands of feet)

For legend see Figure II-2

FIGURE II-22a: PLAN VIEW OF CONTACT BETWEEN THE SHEBANDOWAN LAKE STOCK AND THE MINE SERIES VOLCANIC ROCKS (stock on north side)

FIGURE II-22b: PROJECTION OF THE SHEBANDOWAN ORE BODY ONTO THE 10,000N SURFACE (looking north)

East of 26,500E, sulphide mineralization is sub-economic, and usually consists of disseminated sulphides in granite, basalt, and ultramafic rock or as small discontinuous pods of massive sulphide. At 28,400E, this mineralization is totally enclosed in the Shebandowan Lake Stock (Fig. II-20).

c. Shape and size of the mine ultramafic bodies

The northern and southern mine ultramafic bodies are separated from one another by a thin layer of basalt and/or granitic intrusive rock, about 10-50 m thick. The ore is always associated with the northern mine ultramafic body, whereas a thin (0.15 to 3 m thick) disseminated to massive chromite horizon occurs at the south side of the southern mine ultramafic body.

The two ultramafic bodies are clearly defined in levels 2000 through 1200 and, perhaps the 1000L, but on the 800, 600 and 400 levels, the northern mine ultramafic body is composed of a series of fault wedges of ultramafic rock, enclosed within basalt, granite, and ore. The southern mine ultramafic body, on the other hand, reaches its maximum thickness (200 m) at the 24,500E section at surface and on levels 400 and 600. At all levels below 600L, the southern mine ultramafic body does not exceed 50 m in thickness and is usually less than 25 m (Fig. II-19).

Ultramafic rock has been encountered in drill holes as far east as Castor Island, and there only one ultramafic body has been found. It is chromite bearing, which suggests that it is the southern mine ultramafic body.

d. Effects of folding and faulting on the Ni-Cu deposit

The Crayfish Creek Fault (Fig. II-23) is located at the contact between the southern mine ultramafic body and unit 3 from 16,000E to 26,000E, where it changes strike and cross-cuts strata at a low angle (Fig. II-2, 12). It dips approximately 78° to the south.

From 26,000E, fault B (Fig II-12) marked by mylonitization, occurs along the contact between the southern mine ultramafic body and unit 3. The chromite horizon is located along the Crayfish Creek and B faults.

These major faults are at least 100 m south of the ore zone (compare Figs. II-21 and II-23). But numerous faults, probably splay faults related to the Crayfish Creek Fault system cross-cut and parallel mine strata. Where rocks are not faulted, they are highly jointed. Major jointing directions in each of the following: northern mine ultramafic body, granite, basalt, and ore, are shown in Figure II-24. The ore and northern mine ultramafic body have similar jointing patterns, 107° and vertical; basalts have 2 directions: 107° vertical and 77° and vertical, whereas granitic rocks show fairly consistent joint patterns perpendicular to other rocks in the mine: 017° vertical and a set that is almost horizontal.

3. Mineralogy of the Ore Deposit

a. Introduction

Shebandowan Ni-Cu mine is a massive Ni-Cu ore deposit composed of Po-Pn-Cp-Py-Mt with minor Sp, Mi and Merenskyite. The overall Cu/Cu+Ni ratio is 0.36 (N.L. Anderson, pers. comm.) and the Pt/Pt+Pd ratio is 0.22 (Eckstrand et al., 1981).

FIGURE II-23: Trace of the Crayfish Creek Fault in Shebandowan Mine

FIGURE II-24: Poles to joints in Shebandowan Mine
 A Northern Mine Ultramafic Body - 180 points
 B High Mg-basalts - 171 points
 C Granitoid Rocks - 220 points
 D Ore - 60 points

There are basically two types of ore: 1) massive sulphide (M) and 2) breccia sulphide (BxS) and stringer (S). The first makes up the bulk of the ore. No net-textured disseminated ore has been seen in the mine (Inco geologists) but pyrite rich disseminated ore (15-20% sulphides) occurs in one small area of the mine (800L, 248E, 100 & 104N). Samples of all types of ore, inclusions in ore (in breccia sulphide and in massive ore) have been collected and studied. Descriptions of thin sections are tabulated in a petrographic file at Carleton University and modal sulphide minerals are reported in Table II-4. Location and a short description of ore and mineralogy of each sample analyzed are compiled in Table AIII-I.

b. Ore Types

Typical massive ore is composed of Po-Pn-Cp-Py-Mt. Po grains form polygonal mosaics; Pn occurs at Po grain boundaries and as large (5 mm) Pn "eyes" throughout massive ore (Plate F-1). Pn shows little or no alteration to violarite; Cp occurs in stringers and inclusions in Po and at Po-Po and Po-Pn grain boundaries. Euhedral Mt (less than 1 mm in diameter) makes up to 10% of the ore in places (Plate F-1). The amount of pyrite varies: in some samples it forms less than 3% of the ore (e.g. Sh 54) whereas in other samples (e.g. 1000L, 245 section) pyrite makes up 25% of the ore. In the former, Py grains are less than 0.1 mm in diameter, have ragged edges and occur at Po-Po and Po-Pn boundaries. Where Py occurs in significant proportions, it forms large euhedral grains (3-4 mm) that are fractured and healed by Cp (Plate F-2).

Table II-4: Modal proportions of sulphide and oxide minerals

<u>Sample #</u>	<u>Po</u>	<u>Py</u>	<u>Cp</u>	<u>Pn</u>	<u>Mi</u>	<u>Sp</u>	<u>Mt</u>	<u>Total % Sulphides</u>	<u>Ore Type</u>
Sh-9	40	0	50	5	-	-	5	100	BxS
Sh-6	60	tr	30	5	-	-	5	100	BxS
Sh-3	70	5	5	20	-	-	tr	100	M
Sh-54	77	4	5	10	-	-	4	100	M
Sh-50	20	50	20	7	-	-	3	75	S
Sh-14	1	3	90	1	-	-	5	28	S
Sh-52	10	45	25	5	-	15	-	80	M
Sh-55	15	75	5	5	-	-	-	60	I
1000L-2490	35	35	8	20	-	-	2	100	M
I-10B	30	10	40	15	-	-	5	50	BxS
45171-50	50	8	8	25	-	-	2	100	M
I-15A	30	30	14	22	-	-	4	50	BxS
38941-10	8	70	20	2	-	-	-	8	S
38921-0	35	5	50	10	-	-	-	30	BxS
36513-160	60	5	5	25	-	-	5	95	M
30468-1050	10	20	58	10	-	-	2	5	S
36514-200	-	65	15	-	20	-	-	10	S
30431-1040	-	80	15	-	5	-	-	5	S
SH-1000B	50	tr	4	30	-	-	15	100	M
SH-1012	tr	92	4	2	-	-	tr	85	BxS
800L-248E	-	30	50	15	3	-	-	20	Diss.

PLATE F

1. Pentlandite eyes in pyrrhotite with euhedral magnetite, massive ore. SH 1000B.
Scale: 2.1 mm.
2. Pyrite fractured and healed by chalcopyrite.
Scale: 0.53 mm.
3. Pyrite-pyrrhotite-chalcopyrite-sphalerite, SH-2. Scale: 0.53 mm.
4. Chalcopyrite-pyrite symplectite, SH-55.
Scale: 2.1 mm.
5. Grain of merenskyite in pyrrhotite, SH-9.
Scale: 0.21 mm.
6. Disseminated ore: chalcopyrite-millerite 800L-248E-100N. Scale: 0.53 mm.
7. Quench-textured pyroxene(?) now tremolite and serpentine. Sample from d.d.h. 36584, just below iron formation. Scale: 2.1 mm.
8. Polygonal jointed, ultramafic rock, located south of Southwest Bay. Unit 6d.

Corrugated and granulated edges are not uncommon. Chalcopyrite is concentrated with the pyrite in these samples. Sp has been identified and analyzed in one sample of Py rich ore (Plate F-3). It is associated with Cp and Po, concentrated with large Py grains.

Cp usually occurs with the Py, either as fracture fillings or at Py-Po or Py-Pn grain boundaries. Cp and Py also form symplectites (Plate F-4). Cp is also concentrated around the edges of inclusions in the ore.

Breccia sulphide ore is composed of fragments of peridotite, basalt, and granite set in a matrix of sulphide minerals. Fragment size varies from less than 1 cm to greater than 1 m, and fragments are subround to subangular. Sulphide minerals make up 30-80% of the rock. Ore minerals are Po-Cp-Pn-Py: Po varies from 30-60%, Cp from 14-50%, Pn from 5-24%, and Py from 0-30%. Sulphides have the same habits as in massive ore except that Pn has small flecks of Vi throughout.

Merenskyite (Watkinson et al., 1978) has been identified and analyzed in two samples (Sh-6, Sh-9, Plate F-5) of chalcopyrite-rich breccia sulphide ore. These samples come from an area in the mine that has a local grade of 28% Cu, 2% Ni and small (5-40 μ) rounded grains of merenskyite are readily visible in polished section. They generally occur in Cp or Po or at Cp-Po grain boundaries.

Stringer ore, where present, is composed predominantly of Cp and Py with minor Po and Pn (Table II-4). Millerite has been identified in three samples of stringer ore in peridotite. It forms massive grains with Py, Py and Pn or with Cp. Violarite and Po are not seen in those samples:

Disseminated ore is present in one area of the mine; 800L, 248 section, 100-104N. Ore is composed of 20% 5 mm sized spots of sulphide mottled throughout tremolite rich rock (Plate F-6). Sulphides are composed of Cp-Py-Pn-Mi. Pyrite is white, euhedral, and has Cp inclusions; Ph occurs with Py. Mi is massive, occurring with Cp, Py, and Pn. Mt is present only as skeletal pseudomorphs of olivine.

c. Mineral Zoning

No systematic studies of mineral zoning in the ore body have been undertaken; however, Inco geologists at Shebandowan Mine report that Ni grade increases eastward, as does the amount of pyrite. Cp is richest in stringer and breccia-sulphide ore, and PGE values vary in direct relation to the amount of chalcopyrite.

d. Inclusions

Table II-5 is a compilation of various types of inclusions in the Shebandowan ore body (this study). Thin section studies reveal that most of the inclusions are composed of varying amounts of tremolite, chlorite and serpentine. Using ideal compositions for these minerals and a $\text{FeO}/\text{FeO}+\text{MgO}$ ratio of 0.2 (see chemical analyses), the composition of the inclusions vary from olivine gabbro (20% MgO) to peridotite (I-6). Textures are mostly destroyed; only I-6 and I-16 can be identified as originally peridotite. All these inclusions would be called hornblendite by Inco mine geologists.

Sulphide mineralogy within these inclusions consists of Cp with minor Po-Pn-Py. Mt is secondary after olivine and/or chromite.

Table II-5: Composition of inclusions in Shebandowan Mine

<u>Sample Number</u>	<u>Location</u>	<u>Rock-type</u>	<u>% opaque</u>	<u>Opaque Mineralogy</u>
I-1	600L, 2030 stope 20400 section	82 tr; 10 ch; 5 hbl	3	Cp(Mt)
I-2	"	55 tr; 40 ch; 3 hbl	2	Cp(Py-Po-Pn)
I-3	"	65 tr; 30 ch; 4hbl	1	Il-Mt(Py)
I-5	600L, 2130 stope 20950 section	40 tr; 55 ch; 3 hbl	2	Chr-Il
I-6	"	20 tr; 25 ch; 53 serp	2	Chr-Mt(Cp-Po)
I-7	600L, 2130 stope 21150 section	60 tr; 24 ch; 8 hbl	8	Cp-Py(Pn-Po)
I-10A	"	serp-ch-trem	50	Cp-Po-Pn-Py-Mt
I-10B	"	60 tr; 40 ch	50	Cp-Po-Pn-Py-Mt
I-14	800L, 2347 stope	Basalt	2	Cp-Il(Py-Mt)
I-15a	"	Granodiorite	50	Po-Py(Pn-Cp-Mt)
I-15B	"	Basalt	1	Il(Cp)
I-16	800L, 2485 stope	60 tr; 20 ch; 10 tc	10	Po-Cp-Pn-Py(Vi)
I-17	1000L, 2490 stope	trem-ch	2	Po(Pn-Cp-Chr-Mt)

4. Mineral Composition

a. Composition of ore

Analyses of Po, Py, Pn, Cp, and Sp are included in Table AIII-II. Average trace element contents of Py, Po, Pn are tabulated in Table II-6 for each sample. Analyses of merenskyite are reported by Watkinson et al. (1978).

Po composition varies from $\text{Fe}_{.87}\text{S}$ to $\text{Fe}_{.89}\text{S}$, with minor Co and Ni contents (see Table II-6). The $\text{Ni}/(\text{Ni}+\text{Co}+\text{Fe}^{+2})$ ratio in Pn varies from 0.523 to 0.544; Co content varies from 0 to 0.16 moles per 8S. The Co rich grains correspond to the lower Ni values. Cp is stoichiometric. Py varies from being stoichiometric FeS_2 to having 1.5% Co (by weight) in its structure. Pure white euhedral pyrite is generally Co rich (Sh 54, Sh 3), whereas yellowish Py that has symplectic intergrowths with Cp is Co poor. Merenskyite varies from $(\text{Pd}_{.63}\text{Fe}_{.07}\text{Ni}_{.34})(\text{Sb}_{.02}\text{Bi}_{.03}\text{Te}_{1.89})$ to $(\text{Pd}_{.7}\text{Fe}_{.07}\text{Ni}_{.21})(\text{Bi}_{.11}\text{Te}_{1.81})$ (Watkinson et al., 1978).

Minerals analyzed in the ore are of the same general composition, with the exception of sulphides in Sh 55. Sh 55 is a peridotite inclusion in massive ore (Sh 54), which contains approximately 60% sulphide (Table II-4). Both Pn and Py in this sample are deficient in Co and Pn is Ni-rich (Table II-6).

b. Geothermometry and geobarometry

Malik (1974) studied the partitioning of Ni and Co between Po and Pn (200 to 500°C) and found that the relationship between temperature and Ni-Co distribution in co-existing Po-Pn pairs is as follows:

Table II-6: Average trace element contents of Py, Po and Pn (in weight %)

<u>Sample Number</u>	<u>Ore Type</u>	<u>Co in Py</u>	<u>Co in Po</u>	<u>Ni in Po</u>	<u>Co in Pn</u>
SH-50	Stringer	0.80	0.05	0.53	0.06
SH-52	Massive	1.02	0.14	0.53	1.18
SH-54	Massive	1.52	0.12	0.36	1.02
SH-3	Massive	1.66	--	0.39	0.78
SH-55	Inclusion in Massive Ore	0.23	--	0.21	--
SH-14	Stringer (Cp rich)	1.18	not analyzed	not analyzed	0.80
SH-6	Breccia-Sulphide	not analyzed	0.09	0.55	0.93
SH-9A	Breccia-Sulphide	not analyzed	0.12	0.35	1.15

$$T (^{\circ}\text{C}) = 589.81 - 578.38X + 360.62X^2 - 82.08X^3$$

$$\text{where } X = \frac{K_{\text{Co}}^{\text{Pn-Po}} - 1.3}{K_{\text{Ni}}^{\text{Pn-Po}} - 1}$$

Using this relationship, the temperature of Po-Pn equilibrium in massive ore is 546°C. Co-existing Po-Pn in an inclusion in Py (Sh 50) yields a temperature of 583°C. Both these temperatures are beyond the measured limits of the equation (500°C), so may have a large error inherent in them.

Scott (1973) calibrated a geobarometer involving Sp in equilibrium with Py and hexagonal Po. Sp becomes progressively less FeS rich with increasing pressure. Average mole percent FeS in Sp in Shebandowan Mine is 9.88%. Using Figure 2, p. 4-69 (Scott, 1973), this value plots above the 7.5 kb isobar, close to the estimated 10kb isobar. This value seems inordinately high, because grade of metamorphism is only greenschist. It is probably safe to assume that sphalerite re-equilibrated at lower temperatures, and therefore lost some of its FeS component, and hence yields anomalous results.

5. Conclusions

Besson et al. (1979) classified Shebandowan Mine as a synvolcanic deposit, associated with komatiites, but its paragenesis is uncertain because it was in a "tectonically reworked terrane."

The ore deposit is typical of magmatic Ni-Cu ores associated with ultramafic lenses except for the following:

1. Overall Cu/Cu+Ni ratio (0.36) is much higher than that of ores associated with magmas whose MgO

content is greater than 30%.

2. There is no net-textured or disseminated ore.
3. Ore lies at the top of the ultramafic body, not toward the bottom.

There are ultramafic flows within the volcanic succession (see Chapters 3, 4, and 5), and the Shebandowan Ni-Cu ore body, appears to be related to an ultramafic sill. The ore's genesis and the genesis of the ultramafic rocks are discussed at length at the end of Chapter 5.

CHAPTER III: GEOLOGY OF
ULTRAMAFIC BODIES WITHIN THE
SHEBANDOWAN MINE AREA

1. Introduction

Two distinct ultramafic rock associations have been mapped within the Shebandowan mine area. They are briefly mentioned in Chapter II, but are discussed in detail in the next three chapters. Detailed geology and petrography of the ultramafic rocks are discussed in this chapter, whereas chromite composition and whole rock composition are discussed in chapters IV and V respectively.

All ultramafic bodies mapped within the Shebandowan mine area are shown in Figure III-1. Most contacts have been drawn on the bases of outcrop pattern, diamond drill holes and magnetic anomalies. A few small ultramafic bodies have been intersected only by drill holes and their extensions are interpreted from magnetic data. Those ultramafic bodies studied in detail are labelled A to F. Detailed sampling was undertaken from diamond drill hole samples kept in storage by Inco at Sudbury and from underground sampling in the mine and in the ramp.

A and B are, respectively, the northern and southern mine ultramafic bodies. Simplified petrography of samples from these bodies is tabulated in Tables AI-IV, AI-V and AI-VI. General geology and sample locations are depicted in Figures III-2-3. Descriptions of samples from C, D, E-1, E-2, and F are tabulated in Tables III-1, 2, and 3 but mineral assemblages as determined by x-ray are reported in Table AI-VI. Corresponding drill hole numbers and ultramafic bodies are as follows:

C: 30414

D: 26399

E₁: 30401

E₂: 36584

F: Hed #1

FIGURE III-1: Distribution of ultramafic rocks in the Shebandowan Mine Area

E_1 and E_2 are interpreted to be faulted extensions of the same ultramafic lens (Fig. II-2).

2. Geological Setting of Ultramafic Rocks

a. Introduction

On the basis of field criteria, ultramafic rocks have been divided into two groups: a) those with iron formation and basaltic hyaloclastite, and b) those without iron formation or any specific rock association. Bodies E and F belong to the former, A, B, C, and D to the latter. Of those ultramafic lenses shown in Figure III-1, those associated with iron formation are only found within the younger volcanic succession whereas those with no specific rock association are found predominantly in the older succession with only a few in the younger.

b. Ultramafic Rocks with Iron Formation

Lens-like bodies of ultramafic rock, varying from harzburgite to lherzolite with minor olivine gabbro are exposed within the younger volcanic succession. They vary from 10-150 m thick up to 3 km long. They are conformable with bedding, strike east and dip vertically. They are invariably associated with black and white, magnetite-chert iron formations (1-8 m thick) and dark green iron-rich (76-PM-331, Table AII-III) basaltic hyaloclastite (up to 10 m thick).

The exact association is ultramafic rock in contact with iron formation, which is in contact with hyaloclastite. A fragment of ultramafic rock has been found in the iron formation associated with the ultramafic body south of Southwest Bay (sample 76-PM-253),

indicating that the iron formation is younger. Pillowed basalts associated with hyaloclastite in two areas, as well as flow-top breccia (Plate B-8) also indicate that the iron formation is on top of the ultramafic rock. Oriented thin sections of iron formation were examined and graded bedding (Plate C-6) indicated that the iron formation is on top of the ultramafic rock.

There is no contact metamorphism of the iron formation or other intrusive characteristics, and the iron formation is a submarine chemical sedimentary rock, and thus formed at the seawater-bedrock interface; which means that the ultramafic rock must have been a flow. No typical quenched textures have been recognized in the field although a few quenched pseudo-pyroxenes (now talc-carbonate and serpentine) have been recognized in thin section (Plate F-7).

c. Ultramafic Rocks without Iron Formation

Approximately half of the ultramafic bodies in the Shebandowan mine area have no associated iron formation. These too are harzburgite to lherzolite in composition with a variable amount of olivine gabbro, are conformable with bedding, vary from a few metres to 250 m thick and are up to 6 km long. In most cases contact relations have not been observed, but body B is in fault contact with the andesitic pyroclastic flow to the south. Most of the other ultramafic bodies within this group have only been encountered in drill holes or in isolated outcrop. It is assumed, for want of better evidence, that these ultramafic rocks are sills.

3. Petrography and Field Characteristics of the Ultramafic Rocks

a. Ultramafic Rocks with Iron Formation

Two ultramafic lenses, E and F, were sampled and studied, at 6.1 m intervals (E) and 3.05 m intervals (F). Body E is 71-99 m thick with iron formation varying from 3 to 12 m thick whereas body F is 15 m thick with a 1 m thick iron formation. No fresh minerals were found in body F but relict orthopyroxene, clinopyroxene and olivine are present in parts of body E. Modal mineralogy of samples from each lens is presented in Tables III-1 and 2.

The iron formation varies from thin (1-2 mm) to thicker (0.5-2 cm) alternating bands of white quartz and magnetite. In thin section, quartz is granoblastic with tiny needles and local rosettes of green actinolite. Epidote is present in magnetite layers with or without actinolite. Graded bedding caused by grain size variation in magnetite and quartz is present on both the thin section (Plate C-6) and hand specimen scale.

In outcrop, ultramafic rock is blue-black on fresh surface, rusty-brown on weathered surface. Polygonal jointing is visible on weathered surfaces (Plate F-8). Harzburgite is generally fine-grained with small rounded pseudo-olivines up to 1 mm in diameter. Lherzolite exhibits large (0.5-1 cm) pseudo- and fresh pyroxenes that poikilitically enclose small round to euhedral olivine grains. Where shearing is present, these textures are lacking.

Within body E, harzburgite occurs toward the bottom of the ultramafic lens and is composed of more than 60% small euhedral pseudo-olivine grains (0.1 to 3 mm, average 1 mm) which are now serpentine, set in a pale green matrix of chlorite and serpentine.

Table III-1: Modal Mineralogy of Samples from Body E (DDH's 30401, 36584)

Sample	Ch	Serp	Brown Hbl	Tr	Tc	Cb	Op	
30401-580 IF								
570	40		3-4	24	3-4	-	1	
560	12	8	-	35	3-5	40	1	
540	10	40	3	35	10	-	1-2	No fresh px, textures destroyed
520	10	43	8	13% altera- tion of opx	-	-	1	25% cpx
500	10	48	8	4	8	-	1-2	20% cpx
480	15	42	1	alteration of opx	-	-	2	15% cpx
460	10	57	-	-	4	-	4	25% opx now tc/serp/cb ?
440	10	60	3	-	2	-	3	8% cpx 17% altered opx and cpx tc/serp/cb
420	8	51	8	4	4	-	3	5% cpx 18% altered px
400	5	62	tr	4	4	-	4	22% px - mostly cpx. cpx poik. Encloses Fresh opx
380	5	62	-	tr	tr	-	3	14% cpx, 11% altered opx
360	5	73	-	10	-	-	2	15% opx now tc/serp 5% cpx
340	5	60	-	10	-	-	5	10% cpx
320	12	50	tr	-	10	-	3	8% cpx 12% opx tc/tr
300	10	50	tr	6	-	-	4	15% cpx 10% opx
280	5	65	-	tr	-	-	3	5% ol, 13% opx, 12% cpx
260	5	65	tr	-	-	-	5	20% cpx 7% opx Ch/tr/serp
240	10	65	3	9	tr	-	6	12% cpx - fresh 13% opx Ch/tr/serp
220	15	20	tr	35	-	tr	-	Chromite layer 1/2 mm wide. 7% augite 5% augite; 25% rounded grains of tr/serp
36584-340 IF								
360	30	-		48	20		1-2	Quenched pyroxenes
380	30	10	8	50	-		1-2	
400	40	-	6	48	6		1-2	
420	30	50	2	5	10	3	3	
440	35	45	2	10	5		tr	
450	33	45	2	10	10		tr	
480	27	55	1	10	-	5	2-3	
500	30	45	1	7	10	5	2	
520	35	40	tr	10	12		2-3	
540	15	48	3	-	20	10	3	cb is dol trace opx
560	15	50	6	5	20	1-2	<1	cb is cc
590	5	75	3	5	10	-	2	trace bi
600	10	60	3	5	10	2	3	trace bi, cpx, opx
620	10	-	-	-	-	65	1	cb is cc; 25% bi
660	15	50	2	-	10	-	.5	8% ol; 5% cpx, 5% opx
680	15	65	1	3	-	-	1	15% cpx
700	15	70	tr	-	-	-	2	10% cpx trace bi
720	12	64	tr	-	-	-	4	8% cpx 2% opx
740	20	60	-	-	-	-	2	12% cpx 6% opx
760	20	60	-	-	-	-	2	12% cpx 6% opx
780	20	64	2	-	-	-	1-2	10% cpx 2% opx
800	20	62	1	-	-	-	tr	2% cpx 15% opx
820		basalt						
850		gabbro						

Magnetite outlines the pseudo-olivine grains (Plates G-1,2). Talc and tremolite are minor, and carbonate is rare. Small euhedral chromite grains (<0.1 mm) make up 5% of the rock. Clinopyroxene, where present, is generally fresh, whereas orthopyroxene has usually altered to mixtures of chlorite, serpentine and talc. Texturally the olivine appears to be cumulate, where the pyroxenes are intercumulus.

Lherzolite is more prevalent toward the top of the body and makes up 60-75% of the lens. It is now composed of 40-55% small pseudo-olivines (1-3 mm) poikilitically enclosed by large (up to 1 cm) pyroxenes. Clinopyroxene is usually fresh; orthopyroxene has usually altered to mixtures of talc and tremolite. Again the olivine appears to be mostly cumulate, pyroxenes are intercumulus. Brown hornblende is not uncommon, and where present, poikilitically encloses small round olivines. Relict olivine (Fe_{81}) cores are seen in 3 samples from body E (Plate G-2,3).

In general the percentage of serpentine is about 55-70% throughout body E, except in the top 20 m (Table III-1) where it is less than 40% and the amount of tremolite increases from trace and minor amounts to 33-50% of the rock. This is probably a reflection of an increased Ca content toward the top of the ultramafic flow.

Small euhedral chromites (~0.1 mm) are present throughout the body (1-3%). They are zoned from chromite to ferritchromite to magnetite. Magnetite and ferritchromite rims probably formed during serpentinization.

Body F, however, is considerably smaller than body E and has no fresh minerals. Its modal and normative mineralogy (Table III-2)

Table III-2: Normative¹ and Modal Mineralogy of Samples from Body F².

NORMATIVE

<u>Footage</u>	<u>Ol</u>	<u>Opx</u>	<u>Cpx</u>	<u>An</u>
150	57	25	1	13
165	55	26	5	11
175	53	38	-	6
195	71	13	3	9
205	54	23	11	9
218	67	26	-	2

MODAL³

<u>Footage</u>	<u>Tr</u>	<u>Ch</u>	<u>Serp</u>	<u>Tc</u>	<u>Hbl</u>	<u>Cb</u>	<u>(Dol)</u>	<u>Cc</u>
150	20	-	40	30	8	-		
165	5	-	20	25	-	50	✓	✓
195	-	-	35	50	-	15	✓	
205	-	-	50	30	-	20	✓	✓
218	-	5	60	30	-	5		

¹ From Appendix Table AII-IV.

² For location see Figure II-2. Hole was drilled by Sherritt-Gordon Mines on the Hedley Option, 1600' NW of Whitmore Lake at -45° directly S.

³ Modal analysis is visual.

PLATE G

1. Magnetite outlining pseudo-olivine, now serpentine. 36584-480, 2.1 mm, plane polarized light.
2. Magnetite outlining relict olivine. Olivine is the mineral with high relief, separated from the magnetite (white) by a zone of serpentine. 30401-300, 0.53 mm, reflected light.
3. Relict olivine cores, with magnetite outlines. 36584-660, 2.1 mm, plane polarized light.
4. Pseudo-orthopyroxene poikilitically enclosing pseudo-olivine. H150, 5.9 mm, crossed polars.
5. Blades of pseudo-olivine, 26399-650a, 2.1 mm, plain polarized light.
6. Serpentine after olivine, R230, 5.9 mm, crossed polars.
7. Tremolite after pyroxene and plagioclase, R20, 2.1 mm, plane polarized light.
8. Magnesite and magnetite after olivine, 36577-2010, 2.1 mm, crossed polars.

indicate that it is primarily harzburgite in composition, rather than lherzolite. The rock is made up of more than 50% small euhedral pseudo-olivines, now talc and carbonate, set in a matrix of serpentine. Texturally, the olivines are cumulate. Chlorite is rare and tremolite and hornblende are only present in the uppermost sample. Primary euhedral chromite (<0.1 mm) with secondary ferrit-chromit and magnetite rims and secondary magnetite after olivine make up less than 2% of each of the samples studied. Pseudo-pyroxene where present, poikilitically encloses pseudo-olivine (Plate G-4), and is interpreted to be intercumulus.

b. Ultramafic Rocks without Iron Formation

Of four ultramafic bodies without iron formation, two are the northern and southern ultramafic bodies of the Shebandowan Mine. These have been studied both across and along strike. The others, bodies C and D, are located just south of the mine ultramafic bodies (Fig. III-1). These latter lenses were intersected in drill holes and their extent interpreted from magnetic data. Due to the differences in the amount of information available for each lens, each is discussed separately.

1. Body C

Body C extends from 20,500E to 24,800E (1.3 km) (Fig. III-1), and is on average 21 m thick. Its thickness was sampled at 6.1 m (20 ft) intervals. Modal mineralogy is tabulated in Table III-3. No fresh silicate minerals occur, although relict igneous textures are common. Small euhedral zoned chromites (0.05-0.07 mm) are ubiquitous. In thin section they are light brown with black rims (now magnetite).

Table III-3: Modal¹ Mineralogy of Bodies C & D.

30414* (Body C)

<u>Footage</u>	<u>Tr</u>	<u>Ch</u>	<u>Serp</u>	<u>Tc</u>	<u>Op</u>	<u>Cb</u>	(Cb from x-ray)
220	-	10	-	60	<1	30	M (Dol)
240	-	15	-	15	5	65	Dol (M)
260	-	-	67	20	3	10	
280	-	-	60	25	<1	15	Dol
300	tr	10	50	30	5	5	
320	tr	-	60	20	5	15	Dol
340	-	-	25	10	5	60	Dol

26399* (Body D)

<u>Footage</u>	<u>Tr</u>	<u>Serp</u>	<u>Tc</u>	<u>Ch</u>	<u>Cc</u>	<u>Opx</u>	<u>Cpx</u>	<u>Hbl</u>	<u>Op</u>
420	-	60	15	10	-	1-2	5-8	4	2
460	5	50	15	15	-	-	2-3	10	2
510	-	55	25	tr	19	-	-	-	1
650a	-	40	43	tr	15	-	-	-	2

¹ Modal analysis is visual.

* For location, see Figure II-2 or Table AI-III.

Sixty to eighty percent small round pseudo-olivines (0.5-2 mm, average 0.8 mm) rimmed by magnetite are set in a matrix of carbonate and/or serpentine. Olivines are now serpentine, carbonate, talc or mixtures of them all. Chlorite is a minor constituent throughout the body, whereas tremolite is rare, and only found in trace amounts at 300' and 320'. Very little poikilitic pseudopyroxene is seen. Serpentine, talc and dolomite (some magnesite) are the major constituents. Carbonate is more abundant toward the margins of the ultramafic body, increasing from 5-10% in the centre to 60% toward the margins.

11. Body D

Body D intersected in diamond drill hole 26399 is about 700 m long and consists of two ultramafic lenses, 50 and 30 m thick, separated by 12 m of basalt and graphitic shale. Shearing is very prevalent, with 0.3 m of fault gouge at the most southerly contact and numerous slips and shears as well as brecciation throughout each lens.

The southerly lens is composed of serpentine, talc and chlorite with some fresh orthopyroxene, clinopyroxene and brown hornblende. The rock was originally composed of 22-25% pyroxene with approximately 10% clinopyroxene and is therefore called a herzolite. Olivines vary from small round grains (<0.1 mm) enclosed in pyroxene to euhedral grains up to 2.5 mm large set in a serpentine-chlorite matrix.

The more northerly lens is composed of serpentine-talc-calcite with no relict pyroxene or hornblende. It was composed of 60% euhedral cumulate olivine 1-1.5 mm large (now talc-calcite *).

serpentine) set in a matrix of serpentine and minor chlorite. Texturally this rock resembles harzburgite in the area but it has a high calcite content.

Of particular interest in this ultramafic body is a sample from the northerly contact (650a, Table III-III). Long blades (4 mm x .1 mm) of pseudo-olivine, now serpentine and magnetite (Plate G-5) occur at this contact indicating some quenching, which in turn may indicate intrusion into cold or cold, wet rock. The host rock is basalt now composed of actinolite and epidote with minor quartz. This is one of the few places where an intact contact that did not show faulting and/or brecciation could be sampled.

iii. Body A

All data for the northern mine ultramafic body come from diamond drill holes. Descriptions of samples collected within the mine on a grid system (Fig. III-2) are tabulated in Table AI-V. Other holes that were sampled in detail are 30468 and 36551 (see Table AI-III for location).

The shape and extent of body A parallels that of the ore body (see Chapter II, pages 73-79). It extends from approximately 16000E where it is exposed at surface and plunges eastward to approximately 27500E, where differences between bodies A and B become rather indistinct. From 19000E to 22500E, body A is disjointed and consists of blocks and slices (15 m wide) suspended in a matrix of ore, basalt (unit 4), and granitic rock. East of 22500E, it is more continuous, especially with depth. At the 1000 level (L) and below, it is distinct from the body B and varies

from approximately 67 m on the 1200L to less than 20 m wide on the 2000L and along strike from 22500E to 27500E.

At 22400E, within hole 36551, body A is 94 m thick. Samples were collected every 30 m. From normative mineralogy (Table AII-IV) it appears that the ultramafic rock varies from a dunite in the south, through harzburgite to an olivine websterite or gabbro (17% normative plagioclase, see Chapter V), in the north. Ore is spatially associated with the less mafic fraction.

Diamond drill hole 30468 (Fig. III-3,4) intersects 15 m of body A at the 24500E section. There body A is composed of harzburgite with approximately 25% pseudo-orthopyroxene enclosing round pseudo-olivines (1 mm). The rock is now composed of calcite, dolomite and talc. Sample 1050, toward the top, is composed of tremolite, chlorite and talc and very little relict texture remains. Chemically it is a lherzolite.

Sampling of body A was undertaken at 1000 foot (304.8 m) intervals from 16000E to 27000E at each level in the mine, surface to 2000L. Where body A and ore were intersected by a diamond drill hole, the sample closest to the ore zone was collected. A compilation of the resulting mineral assemblages and their location with respect to the ore body is presented in Figure III-2.

The most common mineral association is talc-carbonate $\pm$ serpentine. Minor chlorite is ubiquitous. X-ray data indicate that the carbonate is usually calcite and/or dolomite. The zones delineated on Figure III-2 are defined in Figure III-6, and discussed under the heading 'distribution of secondary metamorphic minerals.'

iv. Body B

The southern mine ultramafic body (B) extends from at least 18000E to 34000E just east of Castor Island (Fig. II-2). It reaches its maximum thickness at 24500E section where it is 150 m thick and thins to less than 60 m toward the east. Diamond drill holes sampled and studied are tabulated in Table III-4. Detailed petrographic studies were made of the ramp, drill holes 36577, 36575, 41041 and 41057, which cover 24500 to 34400E, a distance of 3 km. Good exposures of this ultramafic body are found just south of the #2 shaft, and on ventilation island.

In outcrop it is black, fine-grained, and very magnetic. In hand specimen, small euhedral pseudo-olivine grains are set in a soft black matrix, or pseudo-olivines are enclosed by coarse-grained (up to 1 cm) pseudo-pyroxenes. Faults and shear zones are common and marked by chlorite and/or serpentine slickensides. Carbonate veins are common.

Sample numbers, normative and modal mineralogy of rocks from the ramp section are depicted in Figures III-3, 4. Through this very thick section of body B, there appear to be at least four discrete zones marked by either an abrupt change in mineralogy, a zone of xenoliths or a thin (15 cm) band of magnetite. The breaks occur at 90', 285', and 400' (see Fig. III-2). The rock types in each zone are as follows:

Z	0-90	50% hz	50% ol-gb
Y	90-285	100% hz	
	285-300	zone of xenoliths	
X	300-400	50% hz	50% ol-gb and ol-websterite
W	400-460	50% lh	17% hz 33% ol-gb

Table III-4: Diamond Drill Holes sampled through Body B. (from west to east)

DDH	N	E	Thickness (m)	Chromite sample number
35480-1000L	10480	19400	61	
9448	9300	21800	55	
9445	9465	22600	128	390'
30468	9998	24500	146	
Ramp		24500	140	R-16
45110-1000L	11178	25000	30.5	1030'
30436	10151	26600	3	243'
36577	13090	28400	104	
36575	13450	30000	49	
30442	12070	31200	55	1400'
41041	14800	32800	61	
41057	15350	34400	79*	

*includes gabbro

FIGURE III-3: Legend for Ramp (Bodies A and B) and sample locations.

FIGURE III-4: Normative and Modal Mineralogy and composition of chromite within the Ramp

Overall through the ramp, body B is composed of 67.5% harzburgite, 25.8% olivine gabbro and websterite, and 6.7% lherzolite.

Relict textures in the harzburgite and lherzolite are very similar to those that have been described in bodies E, F, C, and D (see pages 98-105). Grain sizes are also similar, 0.1 to 3 mm for olivine, up to 1 cm for pyroxene, and chromites are less than 0.1 mm.

Secondary mineral assemblages vary with the zone (Z, Y, X, or W). Within Z, harzburgite at the southern contact is marked by a 15 cm chromite horizon, which gives way to a dolomite-talc rock (1 m away) and then to serpentine-talc as the dominant mineral assemblage. However, in zone Y serpentine (mostly antigorite) is most abundant and generally makes up more than 80% of the rock (Plate G-6). Dolomite is minor, talc and chlorite rare and tremolite nearly absent. Within W and X, harzburgite is composed of serpentine, talc and chlorite with minor dolomite and tremolite. Lherzolite within X and Y is generally composed of tremolite-chlorite with minor dolomite. Talc is rare.

Olivine gabbro, however, is altered mostly to tremolite (>45%) and chlorite (>25%) with minor talc and hornblende. Normative plagioclase increases to 35-40% and the percentage of normative olivine drops to 25% (see Fig. III-3). Most igneous textures within the olivine gabbro have been destroyed by secondary minerals (Plate G-7).

Body B (and possibly body A) is intersected in diamond drill hole 36577 at the 28400E section, which is 1.2 km east of the ramp. There, the ultramafic body is about 100 m thick and samples were

taken where available. The northern contact is marked by the Shebandowan Lake Stock and the southern by sheared and kinked, fragmented mylonite (unit 3). No ore was seen within ultramafic rock although disseminated and stringer sulphide are present in the stock.

Texturally the rock resembles olivine cumulate; very little poikilitic pseudo-pyroxene is recognized in the samples. The ultramafic rocks are composed of dolomite-magnesite-talc with 5% opaques (chromite and magnetite) (Plate G-8). The amount of carbonate increases toward the stock.

Diamond drill holes 36575, 41041, and 41057 were sampled every 3.05 m (10 feet) by Inco and their thin sections were made available. In all cases the northern contact is Shebandowan Lake Stock. The southern contact is with sheared felsic volcanic rock (unit 3). No ore is present but chromite occurs toward the south contact; therefore this is assumed to be body B. Modal mineralogy of samples from these drill holes is reported in Table AI-IV.

Drill hole 36575 is located 1/2 km east of 36577, and intersects ultramafic rock at depth. There body B is approximately 49 m thick with 15 m in the central portion where there were no samples, and hence no information. Relict textures are not well preserved, Shearing and cataclastic textures are evident. Close to the Shebandowan Lake Stock, the ultramafic rock is now composed of 85% Mg-carbonate, 10% talc, and 5% disseminated opaques. The Mg-carbonate was identified by stain only, and hence may be magnesite and/or iron-free dolomite.

Magnetite forms net texture, indicating olivines were approximately 3 mm in diameter. Carbonate decreases systematically to 30%

15 m away from the stock, and talc and chlorite increase to 30% each. No tremolite or serpentine are present. From 1970-2050, no information is available, but from 2060-2100, the ultramafic rock is composed of mixtures of talc, serpentine, and Mg-carbonate. At the south contact, Mg-carbonate increases to 60%, whereas within the central part of this section (2060-2100), serpentine is dominant. Of particular interest in this drill hole is the systematic increase in carbonate toward the stock and the overall lack of tremolite.

Diamond drill hole 41041 is located at 32800E, 0.85 km east of 36575. There the ultramafic lens is intersected at depth (~460 m) and is 61 m thick. It is composed of harzburgite and olivine gabbro or possibly pyroxenite. The northern half of the ultramafic body was composed of more than 60% olivine grains, now serpentine with minor talc. Carbonate is minor except at the contact with the Shebandowan Lake Stock where dolomite composes 50% of the rock. The southern half appears to have been olivine gabbro, or pyroxenite now composed of talc, chlorite, and calcite. This is in fault contact with sheared and kinked felsic pyroclastic rock (unit 3).

At 34400E, 0.5 km east of 41041, body B is intersected at depth in 41057 (~460 m) and is 80 m thick, including a 26 m section of gabbro and 32 m of mafic tuff (see Table AI-IV). The true thickness of the ultramafic body is 16 m in the north and 6 m in the south. The northern ultramafic zone is faulted against the gabbro, which in turn appears to be faulted against the southern ultramafic section.

Generally the mineral assemblage is talc-Fe carbonate (probably ankerite) + chlorite. Serpentine is absent from all samples in this hole. Gabbro is now composed of calcite, tremolite, saussurite, with occasional talc and chlorite. Carbonate content does not increase toward the contact as it does in previously described sections through body B.

In summary, the four discrete zones mapped in the ramp cannot be traced along strike of body B. In the ramp, B is composed of 67% harzburgite, 7% lherzolite, and 26% olivine-gabbro and olivine-websterite. To the east, B appears to be composed of dominantly harzburgite with minor olivine gabbro, and farthest east, gabbro. Secondary minerals in the ramp consist predominantly of serpentine, with lesser amounts of talc and chlorite, with tremolite present in the olivine-gabbro. Toward the east, there is a decided lack of tremolite and serpentine, and Mg- or Fe-carbonate are the dominant minerals with lesser amounts of talc and chlorite. Serpentine is present in large amounts only in 41041, where dolomite is present only in the contact zone with the Shebandowan Lake Stock. Pyroxenitic rock in this hole is now calcite, chlorite, and talc.

4. Chemical Composition of Primary Minerals

a. Distribution

All ultramafic bodies within the Shebandowan mine area have undergone some degree of H_2O and CO_2 metasomatism. Primary minerals olivine, orthopyroxene, and clinopyroxene are found only in bodies D and E, and in several outcrops of ultramafic rock southwest of Southwest Bay. Small zoned chromites, however, are ubiquitous and

compose from less than 1 to 5% of each ultramafic body studied. The zoning results from alteration of chromite to ferritchromit and magnetite.

Within body E, relict pyroxene occurs in the lower 61 m of drill hole 36584 and 91 m of drill hole 30401, whereas relict olivine has been identified in only one sample from each hole (Table III-I). They are located in the lower central part of the body.

b. Mineral Compositions and Geothermometry

Analyses of olivine from 30401-300 and pyroxenes from 30401-300, 500 are reported in Table AIII-III. Only three grains of olivine were analyzed; each was Fo_{81} with minor amounts of Mn (~ 0.3 wt%). Ni was recognized in a wavelength scan but was not analyzed. Coexisting orthopyroxene is En_{84} and clinopyroxene is diopsidic augite $\text{Ca}_{0.4}\text{Fe}_{0.1}\text{Mg}_{0.5}\text{SiO}_3$ (see Fig. III-5). Clinopyroxene from 30401-500 is the same composition as that in 30401-300. Brown hornblende within 30401-500 was also analyzed and is plotted on Figure III-5 for purposes of comparison.

The equilibrium temperature of crystallization as determined by the two pyroxene geothermometer is 1121°C (Wood and Banno, 1973) or 1098°C (Wells, 1977) using pyroxene grains that are in contact with one another. The average compositions of clino- and orthopyroxene from 30401-300 yield 1137°C (Wood and Banno, 1973) or 1131°C (Wells, 1977). Co-existing chromite-olivine from the same rock gives a temperature of 1204°C (Jackson, 1969) or 1012°C (Fabriès, 1979). If much re-equilibration of Fe and Mg between chromite and secondary alteration minerals had taken place, the

FIGURE III-5: Projection of composition of pyroxene and amphibole in Body E

equilibrium temperature determined by the olivine-chromite geothermometer should be much lower (Roeder et al., 1979). But it yields about the same temperature as the two pyroxene geothermometer, thus supporting the hypothesis (see Chapter IV) that the cores of the chromites are unaltered.

5. Distribution of Secondary Metamorphic Minerals

Of the secondary or metamorphic ultramafic mineral assemblages identified, all are compatible with greenschist facies metamorphic conditions. No pseudo-secondary olivine, diopside, or enstatite were recognized, which means that both texturally and mineralogically the highest grade of metamorphism was greenschist facies (Turner, 1981). The minerals found in thin section and by x-ray analysis are antigorite, lizardite, tremolite, dolomite, calcite, magnesite, chlorite, and talc. With the exception of chlorite, all minerals can be represented in the system $\text{MgO-CaO-SiO}_2\text{-H}_2\text{O-CO}_2$.

Even though all mineral assemblages are indicative of greenschist facies, there appears to be a change in mineral assemblage which is interpreted to be a function of changes in CO_2 and H_2O fugacities. Tromsdorff and Evans (1977) have shown that changes ophicalcite to ophidolomite to ophimagnesite represent an increase in the proportion of CO_2 in the pore fluid.

Critical mineral assemblages, among the above-mentioned mineral phases are plotted on a $\log \text{CO}_2\text{-log H}_2\text{O}$ diagram (Fig. III-6). Divariant zones have been numbered II through VI. The breakdown of antigorite to talc and magnesite is also shown (zone I); its position was taken from Tromsdorff and Evans (1977). Both antigorite and lizardite are present in Shebandowan rocks, but from x-ray

analysis, antigorite is the dominant serpentine phase. In terms of the invariant point [Di, Fo] (Fig. III-6), the slopes of the univariant curves are only dependent upon the stoichiometry of CO_2 and H_2O given off or consumed in each reaction, and thus the slopes of the univariant lines remain the same, regardless of pressure and temperature. Because of this, Figure III-6 is assumed to a reasonable approximation to the system.

The $P_{\text{CO}_2} + P_{\text{H}_2\text{O}} = 2000\text{b}$ curve does not intersect the invariant point [Di, Fo] or three of the curves surrounding that point, and therefore is not present on a $T-X_{\text{CO}_2}$ diagram at 2000 bars (Skippen and Tromsdorff, 1975). This might well mean that these mineral assemblages are not stable until higher pressures, or in fact that they are metastable. Figure III-6 is useful nevertheless, because the mineral assemblages do give a sense of $f_{\text{H}_2\text{O}}$ and f_{CO_2} , even if it is only relative. It can be seen that the assemblage tc-cc-serp (zone VI) represents a higher $f_{\text{H}_2\text{O}}$ than tc-dol-cc (zone III).

Using this diagram, ultramafic mineral assemblages in the Shebandowan mine area have been assigned to one of the zones and the zone numbers are plotted on Figure III-7. Contacts have been drawn between zones. Generally, the distribution of the zones is consistent with Figure III-6. In other words, rocks from zone IV are not in contact with rocks of zone III. In the case of body F, an assemblage indicative of the invariant point [Di, Fo] separates IV from III.

Some generalizations are drawn from Figure III-7. There is an overall increase in f_{CO_2} toward the Shebandowan Lake Stock for any section. For example, at 30000E there is a gradation from IV, V to

FIGURE III-7: Distribution of mineral assemblages in ultramafic rocks in Shebandowan Mine Area

V to II, III to I, which involves both an increase in f_{CO_2} and a probably decrease in $f_{\text{H}_2\text{O}}$ over a distance of 1 km. At 25000E the same gradation exists, with the exception of zone I, but the relative thickness (50 m) is much less than at 30000E. Because of the absence of zone I, overall lower f_{CO_2} than at 30000E can be inferred, but $f_{\text{H}_2\text{O}}$ is still high because both zonal gradations are above the invariant point (Fig. III-6).

Within the northern mine ultramafic body (A) (Fig. III-2), from 20000 to 23000E, assemblages in the ultramafic body are within zones VI and III, indicating a relatively high $f_{\text{H}_2\text{O}}$. f_{CO_2} increases eastward (zones III and I) and then decreases toward 26000E. There are two assemblages indicative on zone II (23000E, 800 level and 25000E, 400 level) which means at these points there was a drop in $f_{\text{H}_2\text{O}}$.

It is interesting to note that the areas of Zone I are close to an apophysis of the Shebandowan Lake Stock. Likewise, east of 27000E (Fig. III-7) where zone I is wide, the ultramafic body is in direct contact with the stock. In the west, a zone of banded basalts separates the stock from body A, and except near the small apophysis, no zone I exists.

Within body F, mineral assemblages are indicative of an increase in f_{CO_2} from the top of the ultramafic body to the bottom, with a slight increase in $f_{\text{H}_2\text{O}}$. Samples related to zones are as follows:

	footage	zone
top	150	IV, V
	165	[Di, Fo]
	195	II, III
	205	III-VI
bottom	218	II, III or IV.

This change is abrupt and over 20 m. Samples from body E (112 m) are all in zones IV, V.

Body C, on the other hand, has assemblages that indicate the same fH_2O from the top to bottom (II to I) with an increase in fCO_2 . Compared to C, bodies E and F have assemblages indicative of higher fH_2O than those of body C, and lower fCO_2 .

6. Relationship of Disseminated Sulphide Minerals To Alteration Minerals

Eckstrand (1975) demonstrated that certain disseminated Ni-sulphide mineral assemblages are spatially associated with certain types of ultramafic alteration, in particular serpentinization and talc-carbonate (tc-cb) alteration. He found that in the Dumont body, Quebec, sulphur-poor Ni-sulphides occur with serpentinite whereas sulphur-rich Ni minerals such as millerite occur with tc-cb rocks.

All known sulphide-silicate mineral assemblages in ultramafic rocks from the Shebandowan mine area are tabulated in Table III-5. No consistent relationship between silicate and sulphide minerals is ascertained. However, bodies E and F, which have silicate assemblages indicative of a higher fH_2O and lower fCO_2 than those of body C, do not have any millerite present, whereas body C does have assemblages containing millerite. But within body C, where there is an increase in fCO_2 from 340' to 220', there is a corresponding decrease in fS_2 (see Table III-5). Thus, within bodies E and F, there appears to be a decrease in fS_2 corresponding to an increased fH_2O , whereas within body C, a decrease in fS_2 corresponds to an increase in fCO_2 . This has not been explained.

Table III-5: Compilation of Silicate, Sulphide and Oxide Assemblages

Sample Number	Silicate Assemblage	Zone	Opagues
Body A			
30468-1010	serp-tc-cc	VI	py-cp-mt
-1030	serp-tc-dol	II, III	py-cp-mt
-1050	trem-ch		py-po-pn-cp
35431-10	serp-tc-trem-cc	V-VI	po-cp-mt
36514-200	tc-trem-q		py-mi-cp
36678-20	serp-tc-cc	V	cp-mt
38921-0, 10	serp-tc-dol-cc	V-III	py-po-pn-cp-mt
43322-180	serp-dol-cc	V, VI	py-mi-cp
45171-50, 80	tc-trem-dol-cc	II-III	py-po-pn-cp-mt
30431-440	tc-dol-M-ch	I	py-cp
-1040	tc-trem-cb-ch		py-mi-cp
44816-80, 90	tc-trem-ch		cp-mt
30424-430	trem-dol	IV, II	mt
44806-460	serp-tc-trem-cc	V-VI	py-po-cp-mt
Body B			
R17	serp-tc-trem-cb		py-cp-mt
R18	serp-trem	IV, V	py-mi-mt
R19	serp-tc-trem	IV, V	py-po-cp-mt
R20	serp-tc-trem	IV, V	py-cp-mt-hem
R90	serp-tc-cc-dol	VI-III	py-cp-mt
R140	serp-dol		py-mi-mt
R22	serp-dol-M		py-mi-cp-mt
R23	serp-dol-M		py-mi-cp-mt
R230	serp-cb		py-mi-cp-mt
R24	serp-dol		py-mi-mt
R280	serp-cb		py-mi-mt
R28	serp-trem	IV, V	py-mi-mt
R29	trem		cp
R350	serp-trem	IV, V	py-cp-mt
R360	serp-tc-cb		py-mi-cp-mt
R400	trem		py-cp-mt
R420	trem-cb		py-cp-mt
R430	serp-trem	IV, V	py-mi-mt
Body C			
30414-220	tc-M-ch	I	py-po-pn-cp-mt
-240	tc-dol-M-ch	I	py-pn-mt
-260	serp-tc-cb	II, III	py-cp-mt
-280	serp-tc-dol	"	py-cp-mt
-300	serp-tc-cb-ch	"	py-mi-cp-mt
320	serp-tc-dol	"	py-mi-vi-mt
-340	serp-tc-dol	"	py-mi-mt
Body E			
30401-240	serp-trem-ch	IV, V	py-mt-il
-280	serp-trem-ch	IV, V	py-mt
-300	serp-trem-ch	IV, V	py-cp-mt
-500	serp-trem-tc-ch	IV, V	py-cp-mt
36584-660	serp-tc-ch		py-mt
-680	serp-ch		py-cp-mt
Body F			
H150	serp-tc-trem	IV, V	py-mt
H165	serp-tc-trem-dol-cc	(Di, Fo)	py-mt
H195	serp-tc-dol	II, III	py-pn-cp-mt
H205	serp-tc-dol-cc	III-VI	py-mt
H218	serp-tc		py-pn-mt

Within bodies A and B, there appears to be no consistent relationship between $f\text{CO}_2$ and $f\text{H}_2\text{O}$ and $f\text{S}_2$. Millerite occurs with silicate assemblages indicative of high $f\text{H}_2\text{O}$ and low $f\text{CO}_2$ as well as the reverse. This well may be a function of the bodies' close proximity to the Shebandowan ore body. The large amount of sulphide may well buffer the assemblages of sulphide minerals close to the ore body.

CHAPTER IV: COMPOSITION OF CHROMITE
WITHIN SELECTED ULTRAMAFIC BODIES
IN THE SHEBANDOWAN MINE AREA

1. Introduction

Chromite is an accessory mineral found in all types of ultramafic rocks. Even though it occurs in only minor amounts (1-2%), Irvine (1965) recognized that it would be an important indication of the physiochemical conditions under which its host rocks formed. Because of its varied compositional range in both di- and trivalent elements, it would be sensitive to chemical and thermal conditions of formation.

Indeed, Cameron (1977) has found that the composition of chromite can be correlated with stratigraphic height within the lower critical zone of the Bushveld Complex. Also, Johan (1980) has shown that chromites that have precipitated from a silicate magma that may have been in equilibrium with a sulphide melt, are of a different composition than those chromites that may have precipitated from a "barren" silicate melt. He has used this to predict or explain barren ultramafic and gabbroic bodies. Because of these successes, it was hoped that the chemical composition of disseminated chromite within Shebandowan mine area ultramafic rocks might yield pertinent data to aid in the interpretation of their formation.

Disseminated chromite is ubiquitous throughout the ultramafic rocks in the Shebandowan mine area. It occurs as small grains (<.02 mm) included in pseudomorphs after olivine or orthopyroxene or as larger (.04-.1 mm) grains throughout the matrix; the latter may be cumulate or adcumulate. Almost without exception, in each polished thin section fresh chromite grains were available for study. See Plates H and I for a variety of habits. Because of this,

analyses of chromites were performed to aid in top determinations (Cameron, 1977; Hill and Roeder, 1974). As it was not known if the Shebandowan Ni-Cu ore body lies at the top or the bottom of the ultramafic rocks, this might be a means for establishing its position. Secondly, it was hoped that the composition of the primary chromite might prove useful in separating out prospective ore bearing ultramafic bodies from barren ones (Johan, 1980). Thirdly, it was hoped that a study of the chromites might establish some relationship between the chromitite horizon and disseminated chromite in body B.

All chromite analyses are reported in Table AIII-IV. In total 47 samples were analyzed, usually 4-10 grains in each sample. Where variation from grain to grain was small, the analyses were averaged; but in general, marked variations were found, so individual analyses are reported and plotted separately.

2. Use of Chromite Compositions to Establish Younging Directions

a. Theory

Irvine (1965, 1967) first suggested that chromite might prove to be a sensitive geothermometer and since then, co-existing chromite-olivine pairs have been used as geothermometers with limited success (Jackson, 1969; Evans and Frost, 1975; Roeder et al., 1979; Fabriès, 1979). Because of this compositional change of the chromite with temperature (at constant O_2 fugacity and pressure), in an intrusion or a thick lava flow where fractional crystallization could take place, consistent changes in the composition of chromite might be related to stratigraphic height. Cameron (1977) has

indeed found that chromite in both chromitites and silicate-rich rocks of the Lower Critical Zone of the Bushveld Complex show an increase in total iron, Al/R^{+3} and Fe^{+3}/R^{+3} and a sympathetic decrease in Cr/Fe , $Mg/Fe+Mg$ and Cr/R^{+3} up section. Because of this it was hoped that chromite in the Shebandowan mine area ultramafic bodies would show the same types of variation, and hence yield • younging directions within the ultramafic bodies.

There are two drawbacks to this that need to be discussed:

- 1 - the possible subsolidus redistribution of Fe and Mg between chromite and silicates, in particular with olivine and pyroxene (Roeder et al., 1979) and
- 2 - the effect of serpentinization (Bliss and Maclean, 1975; Groves et al., 1979) and metamorphism (Evans and Frost, 1975).

Roeder et al. (1979) have shown by experiments on natural samples (chromite and host rock) that Fe^{+2} and Mg re-equilibrate with ease at temperatures in excess of $1200^{\circ}C$, and suggest that this may well continue at temperatures as low as $800^{\circ}C$. Cameron (1975, 1977) has argued the reverse for rocks from the Lower Critical Zone of the Bushveld. He stated (1977, page 1090),

"In any given chromitite, chromite is in places poikilitic in plagioclase, in other places poikilitic in bronzite. If subsolidus equilibrium has taken place, chromite in bronzite should have a lower Mg/Fe ratio than chromite surrounded by plagioclase (Irvine, 1967). Analyses show that this is not the case; hence the composition of chromite was fixed not later than the end of the postcumulus state of crystallization, ..."

In Shebandowan rocks, where co-existing olivine and chromite were analyzed, the equilibrium temperature determined was $1204^{\circ}C$ (Jackson, 1969) or $1012^{\circ}C$ (Fabries, 1979), temperatures consistent

with those from the 2 pyroxene geothermometer (page 117). If re-equilibrium had taken place, determined temperatures should be much lower than these.

The effect of serpentization and regional metamorphism cannot be dismissed so easily. Bliss and Maclean (1975) have shown that during serpentization, magnetite rims form on chromite, but during greenschist and epidote-amphibolite metamorphism, ferritchromit forms from the original magmatic chromite.

Within Shebandowan mine area rocks, three kinds of alteration are recognized: 1. irregular magnetite overgrowths, 2. concentric ferritchromit rims that occur between a dark grey chromite core and bright magnetite rim (Plates H and I) and 3. hematite lamellae in chromite (Plate I-4). Occasionally the ferritchromit-magnetite contact is marked by a zone of silicate inclusions (Plate H-1,2,8), which is indicative of the size of the original magmatic chromite. In some samples, no visible ferritchromit rim was visible (Plate H-3,4,5) and the chromite has a simple magnetite overgrowth. Where alteration to ferritchromit occurs, chromite cores are usually round (Plates H-6, I-5) with a concentric zone of ferritchromit and irregular zone of magnetite. Contacts are sharp.

The ferritchromit rim is always lower in MgO , usually lower in Al_2O_3 , slightly lower in Cr_2O_3 and higher in Fe_2O_3 and FeO relative to the chromite core. For purposes of comparison, average values of ferritchromit rims from 4 samples are plotted in Figure IV-8, along with their respective core values.

Analyses from core to edge of one grain from sample Cr-3 (Plate I-6) in the ramp are reproduced in Table IV-1, showing the chemical changes from core to ferritchromit rim.

PLATE H

1. Chromite with small ferritchromit rim and magnetite overgrowth. Zone of inclusions separates ferritchromit from magnetite. H205, 0.21 mm.
2. Chromite, ferritchromit, and magnetite similar to above, H218, 0.21 mm.
3. Chromite with magnetite overgrowth, 30401-300, 0.21 mm.
4. Chromite (no ferritchromit or magnetite) in relict olivine, 30401-300, 0.53 mm.
5. Chromite and magnetite, 30401-300, 0.21 mm.
6. Chromite with magnetite and pyrite (white) overgrowth, 30414-340, 0.21 mm.
7. Chromite, diffuse ferritchromit and magnetite, I10A, 0.21 mm.
8. Ferritchromit and magnetite separated by zone of inclusions, 77-PM-57, 0.21 mm.

PLATE I

1. Chromite with ferritchromit and small magnetite overgrowth. Chromitite horizon: note fracturing of grain after period of alteration. 45110-1030, scale: 0.21 mm.
2. Chromite, ferritchromit and magnetite, chromitite horizon. 30442-1400, scale: 0.21 mm.
3. Chromite, ferritchromit rim and magnetite overgrowth, R280. Scale: 0.21 mm.
4. Chromite with hematite lamellae, thick ferritchromit rim and small magnetite overgrowth, R360. Scale: 0.21 mm.
5. Chromite, small ferritchromit rim and large magnetite overgrowth, R23. Scale: 0.21 mm.
6. Chromite from 3 feet above chromite horizon (disseminated zone). Note magnetite overgrowth appears to have broken away. Oil spots note positions of microprobe analyses, Cr-3, grain 10. Scale: 0.21 mm.
7. Chromite, very small ferritchromit rim and their irregular magnetite overgrowth. 30414-300. Scale: 0.21 mm.
8. Chromitite horizon. Note start of development of ferritchromit rim, 9445-390. Scale: 0.21 mm.

Table IV-1: Chemical analyses across a chromite grain from Cr-3 (from rim to rdm).
(Analyses are 30 μ apart; see Plate I-6).

	A	B	C	D	E	F	G
TiO ₂	1.1	1.09	1.12	1.04	1.08	1.05	.55
Al ₂ O ₃	17.21	18.8	18.4	18.1	18.1	18.01	16.01
Cr ₂ O ₃	32.31	33.4	33.2	33.5	33.4	33.2	29.3
Fe ₂ O ₃	16.48	15.9	15.91	16.2	15.8	16.7	32.4
FeO	22.45	18.4	18.2	18.1	18.2	21.5	31.2
MgO	7.83	10.9	10.9	10.8	10.6	8.95	.99
MnO	.45	.18	.16	.22	.15	.16	.3
Fe ³ /Fe ³ +Fe ²	.397	.438	.446	.446	.438	.411	.483
Mg/Mg+Fe	.384	.513	.516	.515	.509	.425	.005

Hematite lamellae were identified in only 8 samples. In all cases, ferritchromit and magnetite rims were present as well as hematite lamellae. This lattice network (Plate I-4) is caused by the oxidation of Fe^{+2} to Fe^{+3} , and expressed by the development of fine hematite lamellae along {111} planes. According to Haggerty (1976) this partitioning of Fe^{+3} enriches the core spinel in Mg, Al, and Cr.

Under reflected light, cores and rims could be easily distinguished, but once carbon coated colour variation in chromite grains was occasionally obscured. Consequently MgO and Cr_2O_3 were analyzed together, and the most $\text{MgO-Cr}_2\text{O}_3$ rich part of the grain was analyzed. Where variation among grains was extreme, either because of re-equilibration with melt (Cameron, 1979) or presence of altered or oxidized grains, the most MgO and Cr_2O_3 rich grain (or group of grains if homogeneous) was chosen to compare one sample to the next. With this method it was hoped that some of the problems caused by the ferritchromit rims could be avoided.

Analyses of chromites from ultramafic bodies (A,F,C,F) were performed at regular intervals of stratigraphic height and their composition compared. Grains with hematite lamellae were avoided, except in some sections where hematite was identified in all chromites (R360, R22, 38921-0). In general, these grains were intermediate between chromite and ferritchromit in composition. They were low in MgO , high in FeO but similar in Al_2O_3 and Cr_2O_3 content to fresh chromite.

b. Results

1. Body F

From field relations (Chapters II and III) the stratigraphic facing in ultramafic bodies E and F was known (or any ultramafic body associated with iron formation). Body F was chosen to study because it was thinner than body E (15 m vs. 100 m).

In general, chromite grains in body F are euhedral, have very thin ferritchromite rims (0.001-0.008 mm) which can only be recognized by the presence of a zone of silicate inclusions (Plate H-1,2). Magnetite rims, however, vary from .002 mm to .02 mm thick. This is a reflection of both the variable extent of magnetite growth and the section cut through the grain. There were no other visible signs of chromite alteration (i.e. hematite or ilmenite lamellae). However, upon analysis, average MgO contents varied from .41 wt% in H205 to 5.15 wt% in H218. Individual analyses of the most MgO rich grain in each sample are as follows:

150 - 3.88%
165 - 5.00%
195 - 4.12%
205 - 0.34%
218 - 8.75%

which are low for magmatic chromite (Haggerty, 1976b). Because of this, analyses of chromite from body E, which contain fresh olivine and pyroxene, were performed. There the most MgO rich grain in the 4 sections analyzed were: 10.5% MgO in 30401-240; 6.83% in 280; 7.93% in 300; and 7.09% in 500.

The analyses from body F were slightly lower in MgO relative to those of body E, but other chemical parameters were not consist-

ent with alteration to ferritchromit. The Al_2O_3 and Cr_2O_3 contents were high, indicating no alteration. Therefore, it was decided to use the analyses.

The TiO_2 content was high (see page 147), and this is consistent with re-equilibration with magma (Haggarty, 1976a), or rapid quenching (see page 169). Individual and average analyses of samples are tabulated in Table AIII-IV, pages 327 - 329. Average Fe_2O_3 and Cr_2O_3 contents for each section in body F are plotted on Figure IV-1. There is an increase in Fe_2O_3 and decrease in Cr_2O_3 up section. When all R^{+3} elements are considered (Fig. IV-2), there is a systematic increase in Fe_2O_3 relative to Cr_2O_3 up section and a slight decrease in Al_2O_3 relative to Fe_2O_3 . The $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ ratio remains about the same. Pertinent ratios (e.g. Cr/R^{+3}) are represented in Table IV-2 for the most MgO rich grain in each section. They follow the same trend up section of overall increase in Fe , decrease in Cr/R^{+3} and increase in $\text{Fe}^3/\text{Fe}^3+\text{Cr}$.

If these changes of ratios were a result of serpentinization and/or metamorphism, silicate assemblages should show increase $f\text{O}_2$ up section. However, the reverse trend is observed. Silicate assemblages are consistent with increased $f\text{CO}_2$ down the ultramafic body (see page 123) and usually CO_2 -rich fluids are highly oxidizing (Eckstrand, 1975).

11. Body C

Chromite grains vary from 0.03 to 0.05 mm in diameter, are euhedral and make up ~3.5% of each sample. They usually have very thin ferritchromite rims (<0.001 mm) and thin (0.002 mm) to thick (0.01 mm) magnetite overgrowths. These magnetite overgrowths are

HED DDH 1

FIGURE IV-1: Average Fe_2O_3 and Cr_2O_3 contents of chromite from Body F

FIGURE IY-2: Average R^{+3} contents of chromite from samples in Body F

Table IV-2: Compositional variations of the most Mg-rich chromite grain present in samples from Body F.

<u>Sample</u>	<u>$\text{Fe}^{+2}/\text{Fe}^{+2}+\text{Mg}$</u>	<u>Fe^3/R^3</u>	<u>Cr/R^3</u>	<u>Al/R^{+3}</u>	<u>$\text{Cr}/\text{Cr}+\text{Al}$</u>	<u>$\text{Fe}^{+3}/\text{Fe}^{+3}+\text{Cr}$</u>
H150	.81	.26	.50	.24	.68	.34
H165	.76	.31	.47	.22	.67	.38
H195	.79	.21	.55	.24	.69	.27
H218	.57	.18	.54	.28	.65	.25
H205	.98	.32	.49	.19	.72	.40

irregular when thin (Plate I-7) but are subhedral when thick (Plate H-6). Note that in Plate H-6 the thick magnetite rim has overgrown pyrite as well as chromite. Analyses of grains from samples in diamond drill hole 30414 (body C) are tabulated in Table AIII-IV.

The Cr_2O_3 and Fe_2O_3 contents for the most MgO-rich grain from each slide are plotted on Fig. IV-3. Fe_2O_3 increases as Cr_2O_3 decreases from 220 to 320. Analyses of 340 appear to be the same as 220.

Part of the Al_2O_3 - Cr_2O_3 - Fe_2O_3 triangle is represented in Figure IV-4. The increase in Fe_2O_3 is again shown in this diagram. The absolute Al_2O_3 content appears to remain the same from sample to sample. Pertinent chemical ratios are reported in Table IV-3 for the most MgO-rich grain in each slide. There is an increase in Fe^3/R^3 and Al/R^3 from 220 to 320 and a sympathetic decrease in Cr/R^3 . Overall iron content increases from 220 to 320. If the stratigraphic chemical parameters are correct (Cameron, 1979) then the top of this ultramafic body appears to be at 340, or in other words south facing (see Fig. II-2).

Of particular note is the similarity in composition of chromites in 220 and 340. Because both these samples come from the margins of the ultramafic body, their similar compositions are expected if both margins chilled at the same time. This would occur if this body were injected as a sill.

iii. Bodies A and B - ramp section

The ramp section (Figs. III-3,4) comprises 198 m of harzburgite, lherzolite, olivine gabbro, granitic dykes and basalt. The chromite

FIGURE IV-3: Cr_2O_3 and Fe_2O_3 contents of the most MgO-rich grain in each sample from Body C

FIGURE IV-4: Part of the Al_2O_3 - Cr_2O_3 - Fe_2O_3 triangle.

Most MgO rich grain from each sample in Body C

Table IV-3: Chemical ratios from the most MgO-rich grain in samples from Body C.

<u>Sample</u>	<u>Mg/Fe+Mg</u>	<u>Fe³/R³</u>	<u>Cr³/R³</u>	<u>Al/R³</u>	<u>Cr/Cr+Al</u>	<u>Fe³/Fe³+Cr</u>
220	.493	.131	.629	.240	.724	.173
240	.525	.142	.603	.255	.703	.191
260	.474	.151	.591	.259	.696	.203
280	.507	.153	.577	.270	.681	.210
300	.477	.174	.575	.252	.696	.232
320	.455	.191	.555	.254	.701	.256
340	.505	.131	.597	.267	.691	.185

grains from samples R16, Cr3, R17, R18, R19, R140, R22, R23, R230, R24, R280, R28, R350, R360, R420, R430, 30468-1010, 1030, 1050 have been analyzed and reported in Table AIII-IV.

Chromites are ubiquitous throughout the harzburgite, lherzolite, and some pyroxenite, but are absent in olivine gabbro, granitic rocks and intermixed basalt. Where present they make up from 60% (chromitite horizon - R16) to less than 1%. Generally they average 1-2%. They are typically small (0.02-0.08 mm), have thin ferrite-chromite rims (~ 0.004 mm), and have thin to thick magnetite overgrowths (Plate I). Hematite laths and needles have been identified in most grains in R360, R22, and in some grains in R430, 30468-1010, 1030, and R18.

The Cr/R^{+3} , $\text{Cr}/\text{Cr}+\text{Al}$, $\text{Fe}^{+3}/\text{Fe}^{+3}+\text{Cr}$ and $\text{Mg}/\text{Fe}+\text{Mg}$ ratios for the most MgO-rich grain in each sample have been plotted in Figure III-4. Although the chemical trends are not as pronounced as they are in bodies F and C, there does seem to be a characteristic decrease in Cr/R^{+3} and $\text{Cr}/\text{Cr}+\text{Al}$ and sympathetic increase in $\text{Fe}^{+3}/\text{Fe}^{+3}+\text{Cr}$ toward the north for each of the 5 zones of ultramafic rock present in the ramp (see Chapter III). Each of the numbers plotted in Figure III-4 is reproduced in Table IV-4, along with $\text{Fe}^{+3}/\text{R}^{+3}$ and Al/R^{+3} ratios.

c. Summary

Although chemical analysis of chromite is a slow, expensive method for attaining younging directions, the method does seem to work in the Shebandowan mine area. It was successful in bodies F and C, and apparently successful in the ramp. This cryptic zoning of chromite in body C and the ramp has been used to determine

Table IV-4: Chemical ratios from the most MgO-rich grain in samples from bodies A and B.

<u>Sample</u>	<u>Mg/Fe+Mg</u>	<u>Fe³/R³</u>	<u>Cr³/R³</u>	<u>Al/R³</u>	<u>Cr/Cr+Al</u>	<u>Fe³/Fe³+Cr</u>
R16	.560	.147	.491	.363	.575	.232
Cr3	.516	.200	.439	.361	.548	.314
R17	.308	.141	.36	.499	.423	.279
R18	.251	.160	.47	.370	.565	.25
R19	.224	.196	.22	.604	.273	.471
140	.348	.108	.535	.357	.600	.161
R22	.112	.166	.517	.317	.620	.243
R23	.583	.136	.490	.374	.566	.217
230	.485	.123	.517	.36	.589	.193
R24	.390	.123	.52	.357	.593	.191
280	.344	.114	.52	.366	.583	.181
R28	.206	.178	.446	.576	.555	.280
350	.468	.179	.454	.367	.553	.282
360	.364	.176	.426	.398	.513	.285
420	.100	.207	.390	.403	.492	.346
430	.177	.169	.402	.429	.483	.297
1010	.268	.121	.460	.419	.524	.208
1030	.251	.218	.454	.417	.467	.225
1050	.2	.114	.530	.361	.591	.178

tops in two areas, and together with top directions from an outcrop of pillowed basalt and structural considerations, indicate that the Ni-Cu ore body is now on top of the ultramafic body.

3. Relationship of Chromite Composition to Individual Ultramafic Bodies

a. Introduction

With the abundance of data collected from the analyses of chromite, it is evident that chromites from bodies F, C, and A and B are chemically distinct. Because cores and rims of many grains were analyzed, there is new information to add to the literature concerning the alteration of chromite during low-grade metamorphism. Along with these data, and data from chromites in body E, the chromitite horizon and other samples of body A and inclusions in the ore body (Table AIII-IV), a comparison and discussion of the chemical traits of the ultramafic bodies follows.

1. TiO_2 , MnO, and ferric iron contents

The TiO_2 content of chromites analyzed varies from below detection to 10.2 weight %. Within any single body the variation is not large (Table IV-5), but among bodies there are substantial differences in average TiO_2 contents of chromite grains. In particular, chromite in bodies E and F have contents that average 4 wt%, whereas chromite in body A is 0.5 wt%, B is 0.8 wt%, C is 1.9 wt%. The variation in TiO_2 content in bodies A (s.d. = 0.4) and B (s.d. = .07) is much less than bodies E (s.d. = 2.8) and F (s.d. = 2.1). Variation in body C is intermediate (s.d. = 1.8).

Within body C, there is a bimodal distribution of TiO_2 -rich and TiO_2 -poor chromite. In sample 30414-320, there are 6 high-Ti

Table IV-5: Average TiO_2 , MnO , and $\text{Fe}^{+3}/\text{R}^3$ contents for each ultramafic body (numbers in brackets are standard deviations).

<u>Body</u>	<u># samples</u>	<u># analyses</u>	<u>TiO_2</u>	<u>MnO</u>	<u>$\text{Fe}^{+3}/\text{R}^3$</u>
A	8	33	0.5 (0.4)	1.1 (.5)	.182 (.050)
B	14	78	0.8 (.07)	1.3 (.7)	.183 (.080)
B-chromitite	6	33	0.6 (0.5)	0.4 (.4)	.165 (.059)
C	7	50	1.9 (1.8)	1.1 (1.0)	.185 (.044)
E-1	4	24	4.0 (2.8)	1.7* (1.5)	.332 (.110)
F	5	31	3.9 (2.1)	1.7 (.7)	.349 (.100)

*11 samples analyzed for MnO

chromite grains (avg. 5.01 wt% TiO_2). If these are deleted, the average TiO_2 content of C drops to 1.46% from 1.9% and the s.d. drops from 1.8 to 1.4. The upper 95% confidence limit of the TiO_2 -poor chromite would then be 4.23 wt% TiO_2 , well below the average of the TiO_2 -rich grains. Therefore we can say they are bimodally distributed. The same distribution is found in one sample from body D.

Within body E, chromite contains from 0.61 to 10.2 wt% TiO_2 , and has a continuous, not bimodal distribution. Also, in body F, TiO_2 varies continuously from 0.54 to 7.75 wt% TiO_2 . Chromites with the highest TiO_2 values in E and F are associated with hornblende (analyses 5,6 H150; 5,6 30401-240; Table AIII-IV).

There are similar distributions of MnO and $\text{Fe}^{+3}/\text{R}^{+3}$. The MnO contents of chromites in bodies E and F are slightly higher than those of the chromitite horizon. The $\text{Fe}^{+3}/\text{R}^{+3}$ ratios of chromite in bodies E and F are much higher than those of A, B, and C and chromitite, which probably represents originally higher O_2 fugacity in bodies E and F (Irvine, 1965).

To check the effects of ferritchromite alteration, the average TiO_2 , MnO, and $\text{Fe}^{+3}/\text{R}^{+3}$ contents of cores and rims for several samples are tabulated in Table IV-6. It can be seen that there is a consistent decrease in the amount of TiO_2 in the rim relative to the core, but an increase in the MnO content and $\text{Fe}^{+3}/\text{Fe}^{2+}+\text{Fe}^{3+}$ ratio. Although not tabulated, there is an overall increase in iron from core to rim. It is interesting to note that the TiO_2 content is lower in ferritchromite, compared to unaltered cores, and thus it is concluded that the TiO_2 contents of chromite grains are not related

Table IV-6: Average TiO_2 , MnO , and $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ contents of cores and rims.

Sample	TiO_2^*		MnO		$\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$	
	<u>core</u>	<u>rim</u>	<u>core</u>	<u>rim</u>	<u>core</u>	<u>rim</u>
38921-0	.21	.22	.66	1.03	.295	.517
44806-460	.29	.12	1.03	1.61	.335	.550
9445-390**	.24	.20	.32	.58	.357	.254
30442-1400	.28	0	.36	.28	.406	.556
30491-440	.11	.03	.31	.23	.297	.505
R16	.6	.36	.84	.77	.340	.368
H165**	2.79	2.39	1.17	2.23	.420	.389
R350***	.2	.58	.5	1.49	.404	.432
Cr3	1.1	.55	.16	.3	.440	.483
R18	2.89	.78	1.29	2.50	.278	.518
R280	.88	.11	1.34	1.73	.256	.438
R17	.62	.52	.78	1.36	.292	.483
I10	.56	.38	1.29	1.82	.248	.514

*in wt %.

** Al_2O_3 about the same; rims caused by oxidation to hematite; enriched in FeO and low $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$.

***Not a rim but a cracked altered grain vs. unaltered center

to their alteration to ferritchromit, but are rather related to their original formation.

ii. Al_2O_3 , Cr_2O_3 , and MgO contents

Another obvious difference in chromite composition among ultramafic bodies is the Al_2O_3 content. Weight percent Al_2O_3 vs. $\text{Fe}/\text{Fe}+\text{Mg}$ ratio is plotted in Figure IV-5. It can be seen that bodies E and F (Hed & 30401) have the lowest Al_2O_3 content (average ~8 wt%), body C (30414) intermediate with ~12 wt% Al_2O_3 content, and bodies A and B considerably higher at 18-20 wt% Al_2O_3 . Body A chromites usually have higher Al_2O_3 contents than those of B.

Within bodies E (31 analyses) and F (24 analyses), there is a negative correlation of $\text{Fe}/\text{Fe}+\text{Mg}$ and Al_2O_3 content (correlation coefficients are -.87 and -.90 respectively). This trend is not present in bodies A, B, C, and the chromitite horizon.

Al_2O_3 - Cr_2O_3 - Fe_2O_3 contents for each ultramafic body are plotted in Figure IV-6. In terms of these three components, spinels with the highest chrome content come from a picrite flow in the high-Mg basalts (unit 4), north of the ore body. Samples from body C are the next highest, whereas the chrome content of bodies A, B, E, and F are very similar. A trend to Fe_2O_3 enrichment is seen in samples from bodies E and F; it is not evident in samples from the other ultramafic bodies.

The relationship between Al and Mg content is shown in Figure IV-7. Al vs. Mg atomic proportions (per 32 oxygens) are plotted against one another. For the same Al^{+3} content, body C has the highest Mg content (3-4 atoms) (note that it also had high Cr content, Fig. IV-6). Body A is very high in Al content but notably low

FIGURE IV-5: Al_2O_3 content versus $\text{Fe}^{+2}/\text{Fe}^{+2} + \text{Mg}$ for all chromite grains analysed, Shebandowan Mine Area

FIGURE IV-6: Fe_2O_3 - Al_2O_3 - Cr_2O_3 contents
of chromite from the Shebandowan
Mine Area

FIGURE IV-7: Atoms of Al and Mg for 32 oxygens
of chromite from the Shebandowan
Mine Area

in Mg content. The chromitite horizon has an Mg content similar to body C (3 to 4 atoms Mg), but the Al content is much higher (5 to 6 vs. 3 to 4 atoms in C).

Within bodies E and F there is a good positive correlation between Mg and Al contents. Least squares fit to their distribution yield a slope of 0.67 for F (31 analyses), 0.94 for E (24 analyses), with correlation coefficients of 0.87 and 0.82 respectively. No such correlation exists for the other ultramafic bodies or the chromitite horizon.

Cr/Cr+Al vs. Fe/Fe+Mg ratios are plotted in Figure IV-8, and a compilation of analyses from all bodies is plotted in Figure IV-9. Chromites from bodies A, B, and C have a relatively constant Cr/Cr+Al ratio (for each body), regardless of the Fe/Fe+Mg ratio, whereas Cr/Cr+Al ratios of chromite from the chromitite horizon decrease, with increasing Fe/Fe+Mg ratios (see Figure IV-8). Cr/Cr+Al ratios of chromites from bodies E and F increase with increasing Fe/Fe+Mg ratios. Because there exists a negative correlation of Al_2O_3 with Fe/Fe+Mg, this may not represent an increase in Cr with Fe/Fe+Mg, but rather a decrease in Al with an increase in Fe/Fe+Mg.

As a group Cr/Cr+Al values are bimodal. Bodies C, E, and F vary from 0.62 to 0.75 and bodies A and B and the chromitite horizon vary from 0.48 to 0.62, for a complete range in $Fe^{+2}/Fe^{+2}+Mg$ ratios. There is very little overlap (see Fig. IV-9). A summary of these observations is compiled in Table IV-7.

FIGURE IV-8: Cr/Cr + Al versus $\text{Fe}^{+2}/\text{Fe}^{+2} + \text{Mg}$
ratios of chromite from Shebandowan
Mine Area

FIGURE IV-9: Compilation of data from the Shebandowan Mine Area, $Cr/Cr+Al$ vs $Fe/Fe+Mg$

Table IV-7: Summary of Observations.

- Bodies E and F
- high TiO_2 , MnO , $\text{Fe}^{+3}/\text{R}^3$
 - high $\text{Cr}/\text{Cr}+\text{Al}$
 - negative correlation of Al_2O_3 and $\text{Fe}/\text{Fe}+\text{Mg}$
 - positive Al^{+3} and Mg^{+2} correlation
 - Fe_2O_3 enrichment trend.
- Body C
- highest in Cr^{+3} and Mg^{+2} content
 - highest in $\text{Cr}/\text{Cr}+\text{Al}$
 - analyses are very clustered on all plots; little variation
 - bimodal distribution of TiO_2 -rich grains in 30414-320.
- Chromitite horizon
- lowest in MnO content
 - lowest in $\text{Fe}^{+3}/\text{R}^{+3}$
 - similar TiO_2 to chromites from bodies A, B, and C
 - decrease in $\text{Cr}/\text{Cr}+\text{Al}$ with increase in $\text{Fe}/\text{Fe}+\text{Mg}$.

b. Oxidation State of the Ultramafic Bodies
as Determined from Chromite Analyses.

Chromite contains both ferrous and ferric iron in its structure. At similar pressures and temperatures and in rocks of similar composition, $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ ratios of spinels should yield relative estimates of oxygen fugacity at the time of precipitation. For example, chrome spinels found in lunar rocks contain no ferric iron (Haggarty, 1972) because of crystallization under reducing conditions.

$\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ ratios of bodies A, B, E, and F have been compiled and plotted versus $\text{Mg}/\text{Mg}+\text{Fe}^{+2}$ in Figure IV-10. It can be seen that the $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ ratio within body B is highly variable and overlaps with bodies E, F, and A. However, body A is distinct from bodies E and F; it has a much lower $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ ratio for the same MgO content than either E or F. There is very little overlap.

Irvine (1965) calculated theoretical oxygen fugacity isobars for Al-free and Cr-free spinel solid solutions in equilibrium, with both olivine and orthopyroxene, at constant temperature and pressure. The numbers +2, 0, -2, etc., on the isobars when added to a constant, yield $\log f_{\text{O}_2}$ in atmospheres. Absolute O_2 fugacities cannot be calculated because of the paucity of thermodynamic data, but Figure IV-11 can be used in a relative sense.

Analyses of chromites from bodies A, B, C, E, and F are plotted in Figures 12a, 12b, as well as a compilation of chromite analyses from the literature (Irvine, 1967, 1973). Analyses from body B have been separated into two groups--one from the central portion of the ramp corresponding to zone Y (harzburgite), the

FIGURE IV-10: Compilation of $\text{Fe}^{+3}/\text{Fe}^{+2} + \text{Fe}^{+3}$ and $\text{Mg}/\text{Mg} + \text{Fe}^{+2}$ ratios of chromite from the Shebandowan Mine Area

3

FIGURE IV -11: Isobars for $\log O_2$ fugacity for Cr free (Al) and Al free (Cr) spinels at constant T and P (from Irvine, 1965)

FIGURE IV-12a, 12b: $\text{Fe}^{+3}/\text{R}^3$ versus $\text{Fe}/\text{Fe} + \text{Mg}$
ratios for chromites from the
Shebandowan Mine Area

(see Figure IV-8 for legend)

second from zones Z, X, and W (mostly lherzolite, olivine websterite, olivine gabbro, and minor harzburgite). This separation is based on the compositional differences between the two groups of rocks. Because all chromites analyzed (not including ferritchromite) contain Al, when projected onto this plane $[\text{MgFe}_2\text{O}_4\text{-Fe}_3\text{O}_4\text{-Mg(AlCr)}_2\text{O}_4]$ from within the spinel prism, an analysis located on the +2 isobar within the prism will plot below the +2 Cr-free isobar (see Fig. 12, Irvine, 1965), but above the +2 isobar of the Al-free chromite. The greater the amount of Al, the farther above the +2 Al-free isobar the analyses will plot. This fact must be remembered when comparing analyses of differing Al_2O_3 contents. Using Figure 12a,b and remembering the variation in Al_2O_3 content (see Fig. IV-5):

A	18-19% Al_2O_3	
B central	18%	"
edges	15-16%	"
C	12%	"
F	6-7%	"
E	8-9%	"

A relative estimate of $\log f\text{O}_2$ is as follows:

A:	from -2 to a probable maximum of 0.
B central:	from 0 to 2
zones W,X,Z:	0-2
B-chromitite:	2 to 4
C:	2 (except TiO_2 -rich grains)
F:	0-2
E:	2-4

Composition of chromite from E and F should plot close to the Cr-free isobar, whereas A, B, and perhaps C should be intermediate between the Cr-free and Al-free isobars. It is interesting to note that even though the $\text{Fe}^{+3}/\text{R}^{+3}$ for zones X, Z, W of B are higher than for zone Y, all are formed at the same O_2 fugacity. Only their chemical compositions are slightly different.

Most disseminated chromites have formed at approximately the same O_2 fugacity: $\sim +2$. A notable difference is the $f\text{O}_2$ of chromites in body A and in inclusions in the ore (also body A); they formed at slightly low $f\text{O}_2$, around -2 . Another interesting point is that the high- TiO_2 chromites in body C appear to have crystallized at a lower $f\text{O}_2$ than other grains in body C. This might be the case, or because the presence of TiO_2 is not taken into account when calculating these isobars, perhaps this diagram is not applicable for TiO_2 -bearing chromites. This might well be the case because if there is Ti^{+4} in the chromite structure, Fe^{+2} (not Fe^{+3}) is required for charge balance and hence $\text{Fe}^{+3}/\text{Fe}^{+2} + \text{Fe}^{+3}$ is low. If this is the case, O_2 fugacities for E and F are also too low.

c. Discussion

1. Similarities and differences

On the basis of TiO_2 , Al_2O_3 , and Fe_2O_3 contents of chromite, the ultramafic bodies can be divided into two groups: one with TiO_2 -rich, Fe_2O_3 -rich, Al_2O_3 -poor chromites and one with TiO_2 -poor, Fe_2O_3 -poor, and Al_2O_3 -rich chromites. Interestingly, this division

corresponds to the two types of ultramafic rock recognized in the field--the former one with, the latter one without iron formation.

High ferrian, TiO_2 -rich (Al_2O_3 -variable) chromites have been reported from numerous suites, including the "replacement" pegmatite in the critical zone of the Bushveld (Cameron and Glover, 1973), from basalts: East Molokai, Hawaii (Beeson, 1976), Snake River Basalt (Thompson, 1973), Makaopuhi Lava Lake, Hawaii (Evans and Moore, 1968; Evans and Wright, 1972), and from spinels in kimberlites (Mitchell and Clarke, 1976). Furthermore, high- TiO_2 - Al_2O_3 chromian spinels have been described in lunar rocks (Haggerty, 1972) but these have no ferric iron. Chromites from bodies E and F (with iron formation) are very similar, both to the above-mentioned terrestrial chromites and to the ferrian counterpart to the lunar chromites.

There are two ways that high- TiO_2 chromites might form: (1) through late-stage reaction with residual magma (Ridley, 1977; Haggerty, 1976) or (2) by initial precipitation from a melt at high $f\text{O}_2$ and rapid quenching (Thompson, 1973; Evans and Wright, 1972). According to Hill and Roeder (1974) complete solid solution exists between chromite and titaniferous magnetite, at temperatures of 1100-1300°C; however, they found that at oxygen fugacities below 10^{-8} atm, the precipitation of chromite is interrupted by the precipitation of clinopyroxene, and at lower temperatures, titaniferous magnetite precipitates together with pyroxene. They also found that at higher oxygen fugacities ($>10^{-8}$ atm) there is no gap in the crystallization of spinel because the increased ferric iron plays an important role in stabilizing the spinel.

Within bodies C and D, where the chromites appear to be bimodally distributed, it is probable that the TiO_2 -rich chromites were formed by late-stage reaction with magma. Chromite grains that were enclosed in olivine or pyroxene could not have reacted with magma, whereas those present as phenocrysts could have reacted with residual magma. Interestingly, within body C, no TiO_2 -rich chromite was found in samples 30414-220 and 340 or close to the bottom of the sill (240'). Most are present in 320, just below the top of the sill (75% of the grains are TiO_2 -rich) and it is likely that if any type of fractional crystallization by crystal settling took place, the samples that represent the highest amount of residual magma would be toward the top, and hence the most likely samples to have high TiO_2 values in their chromites. This is indeed the case in body C.

The chromites in bodies E and F do not show this bimodal distribution of TiO_2 , but have a continuous distribution of TiO_2 contents. From their experimental work, Hill and Roeder (1974) found that at high $f\text{O}_2$ ($>10^{-8}$ atm), there was no miscibility gap between chrome spinel and titanomagnetite. Using the relative $\log f\text{O}_2$ values determined using Irvine's (1965) calculated isobars, it was shown that chromites in E and F formed at higher $f\text{O}_2$ than those of other bodies in the area. Thus, the simplest explanation for their low to high TiO_2 contents is that the $f\text{O}_2$ was high enough to stabilize spinel, and the miscibility gap between chrome spinel and titanomagnetite was not encountered, allowing for a continuous variation in TiO_2 contents.

With the exception of one grain in R420 (4.95% TiO_2) and two in R19 (2.32 and 2.38 wt% TiO_2), all grains analyzed in bodies A and B are similar to E and F, but chromites are definitely different. Analyses of chromites from A and B (not including chromitite horizon) imply log O_2 fugacities from -2 to 2, whereas those from E and F from 0 to +4, and those latter numbers may appear low because of the high TiO_2 content (see page 147). Chromites from E and F thus precipitated from a magma of higher O_2 fugacity than A or B. This accounts for the differences in their compositions.

ii. Chromitite horizon

Although analyses from samples from the chromitite horizon are plotted in Figures IV-5 to 12 and tabulated in the previous tables, for ease of discussion a summary of their compositional characteristics follows. The average oxide contents for all grains from the chromitite horizon are listed in Table IV-8 and compared to values for an average stratiform chromite deposit (Dickey and Yoder, 1972).

The oxide composition of Shebandowan chromitite falls well within the minimum and maximum values reported by Dickey and Yoder (1972) but, in general, Shebandowan chromitite is lower in Cr_2O_3 and MgO and higher in Al_2O_3 , Fe_2O_3 , and FeO than an average stratiform deposit. There seems to be a considerable change in composition along strike of the chromitite horizon. A sample collected from near the #1 shaft (19000E) has much higher MgO and Cr_2O_3 contents than samples collected at 22600, 24500, and 31200E. A systematic sampling at 500 to 1000 feet intervals should be undertaken to document these changes along strike.

Table IV-8: Average oxide contents of chromites from the chromitite horizon, compared to those of an average stratiform deposit.

	<u>Shebandowan chromitite</u>		<u>Average stratiform*</u>	
			Max.	Min.
TiO ₂	.6	.6	1.8	.2
Al ₂ O ₃	19.2	16.6	21.6	11.8
Cr ₂ O ₃	37.0	46.2	58.1	34.9
Fe ₂ O ₃	12.6	-	-	-
FeO	19.7	25.0**	38.7	11.6
MgO	9.8	11.1	16.9	6.0
MnO	.4	.3	.4	.2

*From Dickey and Yoder, 1972: average of 45 analyses from 3 bodies.

**All Fe as FeO.

The chromitite horizon, if compared to disseminated chromite in body B, has similar Al_2O_3 and $\text{Cr}/\text{Cr}+\text{Al}$ contents, lower $\text{Fe}^{+3}/\text{R}^{+3}$, but higher MgO contents. One noticeable difference is its position on Figure 12a ($\text{Fe}^{+3}/\text{R}^{+3}$ vs. $\text{Fe}/\text{Fe}+\text{Mg}$). It plots at a relatively higher $f\text{O}_2$ than the other samples from body B, and this possibly implies that an increase in $f\text{O}_2$ may have caused precipitation of the chromitite horizon. In support of this idea, Snethlage and Klemm, (1978) from oxygen fugacity measurements on chromites from the Bushveld complex, also found that chromites from massive parts of the layers are in equilibrium with higher oxygen fugacities than those chromites of the host rocks.

4. Compatibility of Chromite with the Formation of the Sulphide Ore Body.

a. Theory

The segregation of a sulphur-rich liquid from a silicate melt occurs when the activity of each component is the same in both liquids and when sulphur has reached its saturation limit in the silicate melt. Sulphur dissolves in an ultramafic melt by replacing O linked to Fe^{+2} (Maclean, 1969; Haughton et al., 1974; Shima and Naldrett, 1975). The sulphur content at sulphide saturation (SCSS, i.e. where a sulphide liquid separates from a silicate melt) decreases with increasing $f\text{O}_2$ (Haughton et al., 1974) or contrary to this, increases with $f\text{O}_2$ if oxygen fugacities are initially very low (Shima and Naldrett, 1975). In other words, Shima and Naldrett (1975) maintain that the SCSS only decreases with increasing $f\text{O}_2$ when this results in significant increase in the $\text{Fe}^{+3}/\text{Fe}^{+2}+\text{Fe}^{+3}$ ratio, and when this does not occur (as in the case at very low

oxygen fugacities), it is possible that an increase in fO_2 may actually cause an increase in SCSS. The way to study this phenomenon is to look at the early spinels that have precipitated from the silicate melt, and that were presumably in equilibrium with that melt.

Johan (1980), using theoretical considerations based on chromite stoichiometry, devised a diagram that allows the distinction of chromites that precipitated from a silicate magma that may have equilibrated with a sulphide melt, from those chromites that are likely to be "barren" of sulphide. The diagram is reproduced in Figure IV-13a. The curve that separates area A from area B (Fig. IV-13a) is the projection of intersection of two surfaces, relating the composition of chromite that can co-exist with metallic iron, and the oxidation limit. Numerically the curve is:

$$g = \frac{0.711 - 1.111x}{1-x} = \frac{Cr^{+3}(Al^{+3} + Fe^{+2})}{Fe^{+2} \cdot Al^{+3}}$$

where x is $Mg/Mg+Fe^{+2}$. For further explanation, see Johan (1980).

When $\frac{Cr^{+3}(Al^{+3} + Fe^{+2})}{Fe^{+2} \cdot Al^{+3}}$ of the chromite is $> g$ (area A, Fig. IV-13a),

then the silicate melt was not likely to have been in equilibrium with a sulphide melt, and hence the resulting rock is barren.

If $\frac{Cr^{+3}(Al^{+3} + Fe^{+2})}{Fe^{+2} \cdot Al^{+3}}$ is $< g$ (area B, Fig. IV-13a), then a sulphide

liquid may have coexisted with this silicate melt. Analyses of chromites from silicate rocks with no Ni-Cu sulphide ore deposits are plotted in IV-13b and those from the rocks hosting Ni-Cu ores are plotted in IV-13c. There seems to be a reasonable accord between

FIGURE IV-13: A. Theoretical function relating $\frac{\text{Cr}^{+3}(\text{Al} + \text{Fe}^{+2})}{\text{Fe}^{+2} \cdot \text{Al}}$ (G) to $\text{Mg}/\text{Mg} + \text{Fe}$ (x),
 Zone A represents barren rocks; zone B, mineralized rocks, (Cu-Ni)
 B. Chromites from barren rocks
 C. Chromites from mineralized (Cu-Ni) deposits

(from Johan, 1980)

the theory and the practice. Notable exceptions are analyses of chromite from Kambalda, which ~~is~~ found in komatiites. There most chromites associated with ultramafic rock that is not barren plot in zone A rather than B. This is attributed to quenching of the chromite and its inability to re-equilibrate completely with melt (Johan, 1980).

b. Results from Shebandowan Rocks

Analyses of Shebandowan chromites have been plotted on g vs. x diagrams (Fig. IV-14). Within body F, the majority of analyses lie in the B field--those compatible with equilibration with sulphide melts, whereas body E straddles both A and B zones. In body C, most analyses fall in the "barren" zone, whereas analyses from body B straddle the mineralized and barren zones.

Once analyses from B are separated into zones W, X, Y, and Z, we find that chromites from zone Y fall in the barren zone, whereas those from W, X, and Z fall within the mineralized zone (Fig. IV-15a vs. IV-15b). Analyses from chromites from body A and from inclusions in the ore fall within the mineralized zone.

From these results, some sulphide ore might be present in bodies A, parts of B, and body F. Ore is found with A, but not B and F.

Johan (1980) is careful to point out that his diagram is not infallible, and generally tries to present only analyses that fit the theory. He states that zoning in chromite, effects of serpentinization, later reaction with melt, or possible quenching would produce disequilibrium, and hence analyses of such chromites would not plot into the prescribed areas on his diagram (Johan, 1980, p. 214-216). Therefore, analyses that straddle the "barren-

FIGURE IV-14: G versus x diagrams for chromites
from the Shebandowan Mine Area

mineralized" line can be ascribed to any of the above. But chrom-
ites from the northern mine ore body are compatible with formation
of a sulphide melt.

CHAPTER V: CHEMISTRY OF SELECTED ULTRAMAFIC BODIES
/ WITH REFERENCE TO THE VOLCANIC SUCCESSION
AND FORMATION OF THE SHEBANDOWAN NI-Cu MINE

1. Introduction

Forty-one samples of ultramafic rock from the Shebandowan mine area have been analyzed for major and trace elements. These are presented in Table AII-III and normative mineralogy in Table AII-IV. All Fe is presented as FeO and all data are considered on an anhydrous basis. Precision is discussed in Appendix II.

Sample 77-420 has 10.38% corundum in the norm, and has not been included in any of the diagrams or discussions, because this amount of corundum is indicative of alteration (see Appendix II).

Normative calculations of analyses yield plagioclase but no or very little clinopyroxene in the norm. Petrographic studies indicate that there are pseudomorphs after clinopyroxene in the rocks, but no pseudomorphs after plagioclase. Using the chemical analyses of fresh orthopyroxene, clinopyroxene, and chromite (Appendix II), and calculating the Al_2O_3 content in each to be .05, .1 and .4 moles respectively, the normative plagioclase content decreases and pyroxene contents increase. Some of the ultramafic rocks have brown hornblende (e.g. H150), which may be primary, but this mineral has not been taken into account in the norm calculations. Because of its CaO and Al_2O_3 contents (see Table AII-III), it is represented by plagioclase in normative mineralogy calculations.

Therefore, rocks are classified petrographically, and where textures have been destroyed, compositions have been used to establish rock type, by taking the Al_2O_3 contents of pyroxenes and chromite into account.

Discussions within this chapter will focus on (a) general trends of the ultramafic rocks, (b) comparison of these trends with known ultramafic chemical affinities, (c) distinguishing flows from sills on the basis of factor and cluster analysis, (d) genesis of the ultramafic rocks, and (e) the relationship of the ore body to the mine ultramafic bodies (A and B). The legend for most of the diagrams presented in Chapter V is represented in Figure V-1.

2. Chemistry of Shebandowan Mine Area Ultramafic Rocks

a. General Chemical Trends

Of the ultramafic and mafic rocks analysed from the Shebandowan mine area, most are harzburgite (>40% olivine, <10% plagioclase, <5% clinopyroxene) or two-pyroxene olivine gabbro. There is minor olivine websterite and lherzolite. The harzburgite and lherzolite are now serpentinite or talc-carbonate schist, whereas the olivine gabbro and olivine websterite are tremolite-talc-carbonate schist with little or no serpentine and carbonate. Relict textures indicate that olivine is a cumulate phase in the harzburgite and lherzolite, with pyroxene poikilitically enclosing olivine. The relict textures in olivine gabbro and olivine websterite are not well preserved. Ophitic intergrowth of plagioclase (now saussurite) and pyroxene (now tremolite) is seen in some olivine gabbro, whereas in olivine websterite most if not all relict textures have been destroyed. These rocks have been described in Chapter 3.

Compositionally, harzburgite contains from 39 to 44% SiO_2 and 30 to 41% MgO. The most MgO-rich, SiO_2 -poor rocks are almost

FIGURE V-1: LEGEND FOR CHEMICAL DIAGRAMS

Ultramafic Rocks

- Harzburgite and lherzolite: Body B
- ◻ Olivine gabbro and olivine websterite: Body B
- ▲ Harzburgite: Body A
- ◻ Olivine gabbro: Body A
- Ultramafic rocks from ultramafic bodies with associated iron formation
- Mg-rich basalt north of Body A (unit 4)

Mafic and Felsic Rocks

- × Younger tholeiitic basalt: unit 5
- ⊕ Older tholeiitic basalt: Unit 1
- △ Dyke rocks, gabbro: unit 6a
- ⊙ Tuffaceous basaltic rock: unit 1
- ◻ Felsic pyroclastic rock: unit 3
- S Shebandowan Lake Stock and apophyses: Unit 7a,b
- P Peewatai Lake Stock: unit 9

dunite. The $\text{FeO}/\text{FeO}+\text{MgO}$ ratio (by weight) is 0.22 to 0.31, averaging 0.29 (see Fig. V-2). This average corresponds to a mole percent of about 0.2 ($\text{Fo}_{80}, \text{En}_{80}$ etc.). Olivine gabbro and olivine websterite, on the other hand, vary from 46 to 50% SiO_2 and 13.5-27.4% MgO , and their $\text{FeO}/\text{FeO}+\text{MgO}$ ratios are highly variable (0.2 to 0.5).

$\text{FeO}/\text{FeO}+\text{MgO}$ (by weight) is plotted against CaO in Figure V-2. All harzburgite and lherzolite have less than 4.6 wt% CaO , whereas all olivine gabbro and olivine websterite have CaO contents >7.5 wt% CaO . The only exception to this is sample 76-PM-328, which is pyroxenite. Analyses of basalts and dykes from the Shebandowan mine area are also plotted in Figure V-2; their CaO contents vary from ~6-14%, with $\text{FeO}/\text{FeO}+\text{MgO}$ ratios from 0.4 to 0.8.

Ni , TiO_2 , Cr_2O_3 contents and $\text{Cu}/\text{Cu}+\text{Ni}$ ratios for all ultramafic rocks are plotted against MgO on Figure V-3. There is a strongly positive correlation between Ni and MgO below about 32% MgO , above which Ni contents are highly variable. Cr_2O_3 , on the other hand, maintains a steady positive correlation from 13 to 40% MgO . TiO_2 contents generally decrease with an increase in MgO content, although below 30% MgO , there is considerable scatter in TiO_2 contents. The $\text{Cu}/\text{Cu}+\text{Ni}$ ratio is highly variable and there appears to be no correlation between it and the MgO content. It should be noted that most of the samples have $\text{Cu}/\text{Cu}+\text{Ni}$ ratios of less than 0.1, regardless of MgO content.

b. Detailed Composition of Bodies A and B (Sills)

Whole rock and trace element contents of bodies A and B, sampled from the ramp, are plotted on Figures V-4 and V-5 respectively.

FIGURE V-2: CaO versus FeO/FeO + MgO for ultramafic and basaltic rocks in Shebandowan Mine Area

FIGURE V-3: Ni, TiO₂, Cr contents and Cu/Cu + Ni ratios of Shebandowine ultramafic rocks

Within zone Z (0-90') there is a decrease in MgO , Cr_2O_3 , and a corresponding increase in SiO_2 , TiO_2 , CaO , and Al_2O_3 and $\text{FeO}/\text{FeO}+\text{MgO}$ up section. This corresponds petrographically from serpentinite (olivine cumulate) to tremolite-saussurite schist (two-pyroxene gabbro).

Zone Y, all harzburgite, is markedly consistent in composition, with high MgO , low TiO_2 , SiO_2 , CaO and Al_2O_3 . Cr_2O_3 increases toward the mid-section of Y; FeO content varies from 12.5 to 18% with no systematic change.

Within zone X, MgO and FeO decrease (but $\text{FeO}/\text{FeO}+\text{MgO}$ increases) whereas SiO_2 , CaO , and Al_2O_3 generally increase up section. Within zone W, there is no consistent change, probably due to lack of data. Sample 77-420 has been plotted but its data points are unreliable.

Within body A, there are only 2 analyses; SiO_2 , CaO , and Al_2O_3 increase up section.

S, Ni, Co, Ba, and Sr are plotted on Figure V-5. There is very good correlation among S, Ni, Co, and between Ba and Sr. Little else can be gained from this diagram, other than to show that trace elements seem to show the same chemical breaks that major elements do in body B.

The weighted average composition of body B, calculated using the volumes of different rock types found in the ramp is reported in Table V-1, with its normative mineralogy. Using the definitions of harzburgite and lherzolite reported in Appendix I, the overall composition is lherzolite, which plots close to the line that separates harzburgite from lherzolite.

FIGURE V-4: Major element content of Body B and part of A, Ramp section. (see Figure III-3 for legend)

FIGURE V-5: Trace element content of Body B and part of A, Ramp Section. (see Figure III-3 for legend)

Table V-1: Weighted compositional averages and norms of bodies B and F.

<u>Analyses</u>			<u>Norm</u>		
	<u>Body B</u>	<u>Body F.</u>		<u>Body B</u>	<u>Body F</u>
SiO ₂	43.59	43.22	ilmenite	.44	.63
TiO ₂	.23	.33	chromite	1.34	1.10
Al ₂ O ₃	4.84	4.06	orthoclase	.65	0
Cr ₂ O ₃	.60	.49	albite	1.35	.28
FeO*	13.86	16.21	anorthite	7.15	5.72
MnO	.17	.20	clinopyroxene	7.27 (Di ₈₁)	5.98 (Di ₇₉)
MgO	32.59	32.55	orthopyroxene	25.91 (En ₈₁)	30.54 (En ₇₉)
CaO	3.24	2.63	olivine	54.86 (Fo ₈₁)	55.57 (Fo ₇₉)
Na ₂ O	.16	.03			
K ₂ O	.11	-			

*All Fe as FeO both in analysis and norm

c. Detailed Composition of Body F

Body F has been interpreted to be a flow from field criteria (see Chapters 2 and 3). Using the average chemical composition (Table V-1), it is lherzolite with 5.98% clinopyroxene. It plots very close to the harzburgite-lherzolite line and to B.

Cr_2O_3 and TiO_2 contents and $\text{FeO}/\text{FeO}+\text{MgO}$ ratio are plotted on Figure V-6. There are systematic increases in TiO_2 and $\text{FeO}/\text{FeO}+\text{MgO}$ toward the top of the flow; Cr_2O_3 also shows a general increase up section, but it is not as consistent.

Major elements have not been plotted but it appears that Al_2O_3 increases and MgO decreases up section, whereas SiO_2 and CaO are somewhat erratic.

These trends are similar to those in body B with the exception of Cr_2O_3 , SiO_2 , and CaO . Cr_2O_3 decreases up section in B, whereas it increases in F; SiO_2 and CaO increase upward systematically in B (except zone Y), whereas they are irregularly distributed in F. These differences might well reflect difference in thickness (15 vs. 150 m) rather than inherent chemical difference between B and F.

3. Comparison of Shebandowan Mine Area Ultramafic Rocks with Known Ultramafic Chemical Affinities

a. Introduction

Over the last 12 years there has been a wealth of literature concerning Archean ultramafic flows and sills and related mafic rocks (Viljoen and Viljoen, 1969; Pyke et al., 1973; Arndt, 1977a; Arndt et al., 1979; Nesbitt et al., 1979; Anhaeusser, 1980). In

FIGURE V-6: Trace element content and $\text{FeO}/\text{FeO} + \text{MgO}$ ratios of samples from Body F.

these papers, the term komatiite (originally defined by Viljoen and Viljoen, 1969) has been used to include rocks formed from ultramafic liquid parental magma as well as associated basalts. In some areas these basaltic komatiites were distinguished from tholeiites (Arndt, 1977; Viljoen and Viljoen, 1969) by using various chemical parameters, but these chemical criteria really only have local applications (Arndt et al., 1977; Nesbitt et al., 1979) and were not useful in comparing one area to the next.

At the Penrose conference in 1979 (Arndt and Brooks, 1980), it was decided that the term komatiite be redefined as an ultramafic flow (Arndt and Brooks, 1980) so all ultramafic rocks with textures indicative of being deposited as a flow are called komatiites, regardless of chemical affinity or lineage.

From field criteria in the Shebandowan mine area, there are both ultramafic flows and sills. The flows are komatiites by the Penrose definition, and these occur only within the younger basaltic succession. The ultramafic sills occur in the older volcanic succession. Important questions in this area then become: are the flows related compositionally to the sills; that is, derived from the same mantle source, with the same or slightly different degrees of partial melting of 2 different source areas, or by drastically different amounts of partial melting of the same source rock? Are the sills magma chambers for the overlying flows? Also, has any crustal contamination caused the differences?

Unfortunately, there are no rare earth data for Shebandowan mine area ultramafic rocks and these questions cannot be answered fully. Comparing these rocks with komatiites and non-komatiites

from other areas is useful, because it allows the reader to compare the unknown (i.e. Shebandowan mine area rocks) with the known, but it by no means answers the fundamental questions. All chemical data for Shebandowan mine area ultramafic rocks are presented on standard plots in the following section and in the next section; mathematical techniques are used to distinguish the flows from the sills.

b. TiO_2 , SiO_2 , Al_2O_3 , and $\text{FeO}/\text{FeO}+\text{MgO}$ contents

Figures V-7, 8 are plots used by Arndt (1977) and Arndt et al. (1977) initially to separate komatiites from tholeiites. On the TiO_2 - SiO_2 diagram (Fig. V-7), komatiites from the Munro Township area plot below the line, tholeiites above the line. All analyses of ultramafic and basaltic rocks from Shebandowan mine area are plotted on Figure V-7, and it is obvious that all ultramafic rocks (both sills and flows) plot below the line within the komatiitic field, and basalts straddle the line. Of the basalts, most are thought to be tholeiitic (see Chapter II).

Figure V-8 is a representation of Al_2O_3 vs $\text{FeO}/\text{FeO}+\text{MgO}$; the line separates analyses of tholeiites from komatiites in Munro Township (Arndt et al., 1977). Komatiites plot above the line, tholeiites beneath the line. It is obvious that most Shebandowan mine area ultramafic rocks plot below the line, in the tholeiitic field contrary to their classification by Figure V-7. Basalts straddle the line as they do in Figure V-7, but not with the same consistency. According to Nesbitt et al. (1979) this diagram serves to separate the more 'evolved' rocks from the less so. In

FIGURE V-7: SiO_2 versus TiO_2 contents of all analyses of Shebandowan Mine Area rocks²

FIGURE V-8: Al_2O_3 versus $\text{FeO}/\text{FeO} + \text{MgO}$

this case both flows and sills seem to have evolved to the same degree.

Both younger and older basaltic successions appear to be more evolved than the dykes (open triangles) or the high Mg-basalts (closed squares) of unit 4.

c. CaO , Al_2O_3 , and MgO contents

Nesbitt et al. (1979) defined two types of komatiites; Type 1 has $\text{CaO}/\text{Al}_2\text{O}_3$ ratios of approximately 1.5 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of around 11, and Type 2 has $\text{CaO}/\text{Al}_2\text{O}_3$ ratios of ~ 1 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of ~ 20 . The first are Al-depleted and are representative of komatiites from Barberton Mountain Land and the latter are representative of ultramafic flows from Munro Township.

Average CaO/TiO_2 , $\text{Al}_2\text{O}_3/\text{TiO}_2$, and $\text{CaO}/\text{Al}_2\text{O}_3$ ratios from bodies A, B, F, picrites and the chondrite values are listed in Table V-II. The $\text{CaO}/\text{Al}_2\text{O}_3$ ratios in B and F are very similar ($\sim .65$), well below the higher $\text{CaO}/\text{Al}_2\text{O}_3$ values of known komatiites. $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 ratios for bodies A and B are remarkably similar to a chondrite, whereas those of body F are much less. This point is discussed in the section on genesis of ultramafic rocks.

The relationships between $\text{CaO}/\text{Al}_2\text{O}_3$ ratio and MgO content are depicted in Figures V-9, 10. The average MgO and $\text{CaO}/\text{Al}_2\text{O}_3$ contents for bodies B and F are the same, but the spread in values is markedly different. The range in MgO content of body F (open circles) is 30-32% MgO , whereas that of body B is 12-42% MgO . Likewise $\text{CaO}/\text{Al}_2\text{O}_3$ values vary from 0.1 to 1.3 for body F, but from 0.2 to 2.5 for body B. These differences are due to the differentiation of body B into

Table V-2: Average CaO/TiO_2 , $\text{Al}_2\text{O}_3/\text{TiO}_2$, and $\text{CaO}/\text{Al}_2\text{O}_3$ ratios of ultramafic rocks in the Shebandowan Mine Area.

	<u>CaO/TiO_2</u>	<u>$\text{Al}_2\text{O}_3/\text{TiO}_2$</u>	<u>$\text{CaO}/\text{Al}_2\text{O}_3$</u>
Body B	14.1	21.0	.67
Body A	18.7	20.8	.94
Body F	8.0	12.3	.65
High Mg-basalt (unit 4)	13.	16.	.81
Chondrite*	17.	20.4	.82
Archean Pyrolite**	18.5	19.5	.95

*Sun and Nesbitt (1977)

**Green (1975)

drastically different rock types, whereas body F is all harzburgite and lherzolite.

Analyses of both basalts and ultramafic rocks from Shebandowan mine area are plotted on Figure V-10a, a $\text{CaO-MgO-Al}_2\text{O}_3$ plot. As olivine and enstatite precipitate from a magma, the composition of the liquid moves away from the MgO corner. When clinopyroxene begins to precipitate, the line of descent moves away from the MgO-CaO line. This is well-illustrated by Theo's Flow (Fig. V-10b), that formed with clinopyroxene precipitation (Arndt, 1977) and picrites (Fig. V-10d), that show olivine and orthopyroxene precipitation. Analyses from stratiform ultramafic bodies are also plotted in Figure V-10c. Both Dundonald Sill and Pechanga show the clinopyroxene trend, whereas the Bushveld and Stillwater show the olivine-enstatite trend with a much later clinopyroxene trend.

Ultramafic rocks from Shebandowan mine area have the olivine-enstatite trend, whereas basalts and dykes show first the olivine-enstatite fractionated trend and then the clinopyroxene trend. This is born out by relict textures which do show cumulate olivine grains but orthopyroxene is usually poikilitic. Clinopyroxene, where evident, is always poikilitic.

d. Summary

By comparison of analyses of ultramafic rocks from Shebandowan mine area with ultramafic rocks from other areas, in particular Munro Township and Barberton Mountain Land, it is evident that intrusive and extrusive rocks from Shebandowan mine area cannot be distinguished from one another compositionally, by using standard.

FIGURE V-10: MgO-CaO-Al₂O₃ contents of ultramafic rocks from Shebandowan Mine Area compared to other areas.

For b, solid circle is cumulate peridotite, open square is hyaloclastite, open circle is cumulate clinopyroxenite, closed square is gabbro and closed triangle is aphanitic clinopyroxenite.

plots. If the Al_2O_3 vs. $FeO/FeO+MgO$ plot serves to separate the more evolved rocks from the less evolved rocks, then both intrusive and extrusive ultramafic rocks in the Shebandowan mine area have evolved to the same extent (Nesbitt and Sun, 1979). From the $CaO-MgO-Al_2O_3$ plot, it is evident that the ultramafic rocks have formed by olivine-enstatite fractionation.

It might be argued that flows and sills from the Shebandowan mine area may have formed from an ultramafic parental magma, or have been extruded and intruded respectively as a crystal-liquid mush of peridotitic composition which formed from a less ultramafic magma. The overall composition of bodies B and F is similar, with $MgO = 32\%$ and $SiO_2 = 44\%$. These values are very similar to those reported by Arndt et al. (1977) for ultramafic lava flows from Munro Township. Also there is very little clinopyroxene, and none as a cumulate phase, present within the Shebandowan area ultramafic bodies. Clinopyroxene as a cumulate phase is characteristic of Theo's Flow, layered peridotitic gabbro flow of tholeiitic parentage (Arndt et al., 1977). It is for these reasons that ultramafic flows and sills in the Shebandowan mine area may have formed from an ultramafic parental magma.

4. Distinguishing flows from sills

a. Introduction

Muir (1979) was able to distinguish extrusive from intrusive ultramafic rocks from the Shaw Dome area, Ontario, by using 6 discriminant triangular diagrams involving molar proportions of both major and trace elements and, as well, by statistically valid discriminant functions. He used the following six diagrams:

- i $\text{Fe}_2\text{O}_3 - 2\text{CaO} - \text{Al}_2\text{O}_3$
- ii $\frac{1}{2}\text{MgO} - 2\text{CaO} - \text{Al}_2\text{O}_3$
- iii $\frac{1}{2}\text{MgO} - \text{Fe}_2\text{O}_3 - \text{Al}_2\text{O}_3$
- iv $\text{Ni} - \text{Cr} - 20\text{Zn}$
- v $\text{Ni} - 20\text{Co} - 20\text{Zn}$
- vi $\text{Ni} - 20\text{Cu} - 20\text{Zn}$

and in each, a line could be drawn to successfully separate flows from sills. Muir attributed these differences in chemistry to different mineralogical compositions of flows and sills.

For the Shebandowan mine area rocks, the first two diagrams separated peridotite from olivine gabbro and olivine websterite, regardless of origin (flow or sill), whereas using the latter four, all analyses of ultramafic rocks from the Shebandowan mine area plot in the extrusive fields. What is of interest, though, is that using trace elements, analyses from the flows (Body F, 76-PM-301 and 76-PM-328 and 76-PM-19, 76-PM-20) all plot in discrete zones in these diagrams (for example, see Fig. V-11). In some cases lines separating flows from sills can be drawn.

Because these graphical discriminatory diagrams looked promising, some statistical analyses were applied to analyses of Shebandowan mine area ultramafic rocks.

b. Principal Components Analysis

1. Introduction

The first application of statistics to analyses of Shebandowan mine area ultramafic rocks involved a principal components analysis

FIGURE V-11; Ni-20Cu-20Zn discriminant diagram from Muir, 1979.
I= intrusive
E= extrusive

of the chemical data. The program, written by Davis (1973) was adapted to the Carleton computer by Peter Goetz. This type of analysis tries to interpret the structure of a variance-covariance matrix, by linearly transforming M original variables to M new variables, where each new variable is a linear combination of the old. The process is performed such that each new variable accounts for successively as much of the total variance as possible. The utility of this analysis is judged by its performance, and not by any theoretical considerations (Davis, 1973).

The problem with chemical analyses is that whole rock data consists of a closed data set, and spurious negative correlations are inevitable (Davis, 1973). Addition of trace element data (which is not a closed set) helps to lessen this problem. All data are standardized (Davis, 1973) to avoid weighting due to large differences in numbers (e.g. ppm vs. percent).

ii. Results

Using this program, 5 components were found that account for 82.3% of the data variance. They are:

			<u>% variance</u>
component 1	MgO, CaO, V		44.14
2	S, Cu, Co, Ni		16.12
3	FeO, MnO, Zn		10.80
4	Cr ₂ O ₃		6.21
5	SiO ₂ , Sr		5.03
TOTAL			<hr/> 82.3

These components can be explained by the following mineralogy:

1. Olivine and clinopyroxene
2. Ni-Cu-sulphide mineralization
3. Fe-bearing minerals such as olivine, orthopyroxene, clinopyroxene and chromite
4. Chromite
5. Olivine versus SiO_2 -rich minerals.

The fact that these components can be attributed to various minerals present in the rocks adds credibility to the analysis.

The other possible 13 components from an 18x18 data array account for only 17.7% of the data variance. Interpretation of this analysis does not aid in separating flows from sills, until some sort of clustering, or discriminatory functions, are applied. As there were not enough data to apply discriminant functions, cluster analysis was applied.

c. Cluster Analysis

1. Introduction

Within cluster analysis (Davis, 1973), objects (in this case chemical data) are grouped by similarity. Correlation co-efficients are used as the measure of similarity, and those with the highest similarities are linked first. Two objects can be connected only if they have mutually highest correlations, and after 2 objects are clustered, their correlation with other observations are averaged. What results is a diagram known as a dendrogram, separating a data set into some sort of similarity classification scheme.

ii. Results

Four dendrograms are presented in Figure V-12. Cluster analysis using 9 major and 9 minor elements is depicted in Figure V-12b. On this chemical basis, there are two groups, which are actually types of peridotite and olivine gabbro/olivine websterite. In other words, the clustering has separated the mafic from the ultramafic rocks. Samples which do not cluster into either group are lherzolite.

Because component 1 (Principal Components Analysis) accounted for about 45% of the variance, clustering was performed using CaO, MgO and V. Results are presented in Figure V-12b. This yields very similar results to Figure V-12a. Harzburgites have been clustered together, and olivine gabbro/olivine websterite together.

Clustering using component 2 is presented in Figure V-12c. Harzburgites are distinguished from the less ultramafic rocks, and are divided into two groups (flows and sills) strictly on their Co, S, Ni, and Cu contents. On combining components 1 and 2 (Fig. V-12d), analyses of harzburgite sills cluster together, whereas the analyses of the flows and less ultramafic rocks cluster in one large group. This latter group is divided into ultramafic flows (open circles) and olivine gabbro/olivine websterite sills (open squares). In other words, by using components 1 and 2, which account for 60% of the variance in the raw data, the analyses of ultramafic rocks can be divided into three groups: harzburgite sills, flows, and olivine gabbro/olivine websterite sills.

FIGURE V-12: Cluster analysis of analyses of Shebandowan Mine Area ultramafic rocks

- A. 9 major and 9 minor elements
- B. CaO-MgO-V, Component 1

FIGURE V-12 cont'd: Cluster Analysis

C. Co, Ni, S, Cu, Component 2

D. Components 1 and 2 combined

What is interesting about this analysis is that:

(1) clustering by similarity works, because it separated olivine-rich from olivine-poor rocks.

(2) in conjunction with principal components analysis, it can be used to separate flows from sills at a very primitive level, and

(3) the most pronounced difference between sills and flows is their Co, Ni, S, and Cu contents. Upon checking average analyses (Table V-3), it is evident that Cu, Ni, and S contents are much higher in bodies A and B compared to F, Co contents are similar, but the variance of Co is much higher in A and B than in F.

d. Summary

Using cluster and principal components analyses, it is possible to divide ultramafic rocks into various chemical groups, firstly into peridotite versus pyroxenite and olivine gabbro and with further analysis into flows and sills. This is primitive at best and must be considered tentative. In no dendrogram do flows cluster as a totally separate group, but rather as a sub-group within their sill counterparts, suggesting that they may be both chemically and genetically related.

5. Petrogenesis of Ultramafic Rocks in Shebandowan Mine Area

a. Theory

Green (1975) presented a model for ultramafic magma genesis caused by the upward movement of a peridotite diapir under adiabatic conditions. As the diapir ascends, the degree of partial melting increased, successively eliminating clinopyroxene, garnet, and orthopyroxene as residual phases in equilibrium with the liquid.

Table V-3: Arithmetic and Log Normal means of Co, Cu, Ni, S contents of ultramafic rocks in Shebandowan Mine Area (in ppm).

		<u>Co</u>	<u>Cu</u>	<u>Ni</u>	<u>S (%)</u>
Sill	Body A	148 ¹ (73) ³	424 (448)	2717 (1126)	.60 (.38)
		176 ² (.29) ⁴	208 (1.44)	2536 (.40)	.49 (.75)
	B	127 (49)	352 (462)	1966 (1012)	.32 (.41)
		118 (.38)	183 (1.13)	1619 (.64)	.14 (1.73)
Flow	Body F, 201 & 328	141 (12)	32 (19)	1133 (133)	.12 (.04)
		141 (.08)	27 (.68)	1125 (.14)	.11 (.28)
	High Mg- basalts - picrites (2)	120	85	640	n.d.

¹Arithmetic mean

²Natural log normal mean

³Standard derivation in ppm

⁴Standard derivation in ln units

Density differences in residual phases, garnet ~ 3.7 , olivine 3.3, enstatite 3.3, and liquid < 3 could cause differential settling of phases such that garnet could be removed and olivine and enstatite entrained. With this as the case the resulting magma would be depleted in Al_2O_3 and heavy REE (such as the case of komatiites from Barberton Mountain Land).

Naldrett and Turner (1977) and Arndt (1977b) argued that after 30-50% partial melting, the viscosity differences between melt and solids are so great, that some of the liquid separates from the solid residue and escapes to the surface to form basalts. Continued rising of the diapir (now much more mafic than Green's (1975) pyrolite) would cause more partial melting to occur and these liquids would be much more ultramafic than the first, and be extruded as komatiites, and high Mg-basalts.

Nesbitt et al. (1979) preferred a model whereby komatiitic liquids form by a one-stage partial melting event. In their simplest model, they maintained that in a series of basalt liquids, representing increasing amounts of melting, the $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 ratios increase until a plateau is reached which represents the complete release of all the Al and Ca into the melt. Further melting will alter absolute abundances but will not change ratios. And therefore, if one-stage melting took place, the CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios would be that of the source. From their analyses, they maintain that most komatiites (with the exception of those from Barberton Mountain Land) have ratios similar to a chondrite, and also Green's (1975) Archean pyrolite, indicating that they formed by a one-stage melting event. If a two-stage (or any) sequential

melting event took place, and Ti was incompatible, then most of the TiO_2 would be present in the first melt. But the weighted averages of the first and second melts and the residue should equal the original amount in the mantle.

In the case of Naldrett and Turner's (1977) two-stage model, a TiO_2 value of 0.39 wt% was calculated for the original mantle diapir which is double the value of Green's (1975a) Archean pyrolite (0.2 wt%), which Nesbitt et al. (1979) maintained unlikely. It is also interesting to note that all estimates of komatiitic liquid composition (Table II, Naldrett and Turner, 1977) have CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios similar to that of a chondrite, indicating that these might well be formed by a one-stage melting event, rather than two.

The author presents these melting models here, to show that at the present time, there are conflicting data and theories that have yet to be resolved.

Table V-4 is a compilation of all salient data from each of chapters III, IV, and V. Any model proposed for the petrogenesis of the Shebandowan mine area ultramafic rocks must explain most, if not all, of these data.

Table V-4: Summary of petrographic, mineralogical, and chemical data from Shebandowan Mine Area ultramafic rocks.

	Flows (E, F)		Sills A, B, C, D	
			width (m)	length
SIZE:	F = 18 m X 1 km		A 20-94	together,
	E = 115 m X 3 km		B 60-150	6 km
			C 37	1.25 km
			D 80	.8 km
ROCK TYPE: Petrographically:	F = harzburgite and lherzolite		A	harzburgite to olivine gabbro
	E = Minor harzburgite		B	harzburgite to olivine gabbro
	Lherzolite		C	harzburgite to lherzolite
	Olivine websterite		D	harzburgite to lherzolite
	Olivine gabbro			
Chemically:	F = overall lherzolite (see Table V-1)		B	overall lherzolite (see Table V-1)
			A	no good weighted average.
GEOLOGIC POSITION:	Younger basaltic succession			Older basaltic succession
SILICATE MINERALOGY	F = no fresh silicates			No fresh silicates
	E = Fo ₈₁	from lower central position		
	En ₈₄			

Table V-4 cont.

CHROMITE CHEMISTRY:

E and F: high in TiO_2 (4 wt%)

high in MnO (1.7 wt%)

 $\text{Fe}^{3+}/\text{R}^{3+}$ high (.34)low Al_2O_3 (8%)A low in TiO_2 .5%

B " " .4%

C bimodal in TiO_2 (1.9%)

A,B,C low in MnO 1.1%

A,B high in Al_2O_3 18-21%C intermediate in Al_2O_3 12%

Relative Oxygen Fugacity:

F = 0-2*

E = 2-4*

* probably low because of high TiO_2 content

A = -2 to 0

B = 0-2

C = -2

CHEMISTRY:

 $\frac{\text{Mg}}{\text{Fe} + \text{Mg}}$

F = .76 to .8 (average .78)

76-PM-301 = .79

A = .78 to .83

B = .69 to .86

Av .81

76-PM-328(E) = .66 (just below iron formation)

average CaO/TiO_2 : F = 8" $\text{Al}_2\text{O}_3/\text{TiO}_2$: 12

less than chondrite

B = 14 A = 18.7

21 21

similar to chondrite

b. Petrogenesis.

From the limited chemical data presented, the most reasonable explanation of Shebandowan mine area ultramafic rocks is that the flows and sills are related. Chemically they are very similar and from cluster analysis, it appears that the most noticeable difference is in their Ni, Cu, Co, and S contents. From chromite analyses, it was shown that those chromites formed in parts of body B and bodies A and F could have equilibrated with a sulphide melt, whereas those in zone Y of body B were less likely to have done so (see Chapter IV, page 176). If this is the case, then the separation of the flows and sills as performed by cluster analysis may well be interpreted simply by the fact that a sulphide melt equilibrated with some of the ultramafic rock and not with the other. This is discussed further in the last section of this chapter.

If it is maintained that the flows and sills are chemically related, is it plausible that the sills were reservoirs for the flows or simply synvolcanic sills? The complex structure due to folding and, in particular, faulting, make it impossible to map out any feeder system connecting flows and sills, but it is of interest to note that most of the data in Table V-4 can be explained using either hypothesis.

The sills are present in the older basaltic succession and the flows lie above them in the younger volcanic succession. Bodies A and B (sills) in particular intrude very close to the contact between older and younger basaltic cycles, but due to the amount of faulting the nature of this contact is not clear.

All sills are composed of lherzolite and harzburgite, and the thicker ones (A and B) have a small proportion of olivine gabbro and olivine websterite. Small flows (F) are harzburgite and lherzolite, whereas large flows (E) consist mostly of lherzolite and olivine websterite (harzburgite in body E is minor). The sills have slightly higher $Mg/Mg+Fe$ ratios and lower TiO_2 contents (see Table V-4) than flow F. Because of the different TiO_2 contents, the CaO/TiO_2 and Al_2O_3/TiO_2 are higher in the sills than flow F. The values for sills A and B are close to those of a chondrite; those of flow F are slightly lower (Tables V-2, 4).

If the sills acted as reservoirs for flows, and if some olivine (and perhaps orthopyroxene) had precipitated before the ultramafic magma was tapped, then we would expect lower $Mg/Mg+Fe$ ratios in the flows, and slightly higher Ti contents. One would also expect relative CaO and Al_2O_3 as well as Ti contents to increase, and there-

fore the CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios should be the same as the sills. This is not so.

If sills and flows are simply synvolcanic counterparts, then $\text{Mg}/\text{Mg}+\text{Fe}$ ratios and Ti contents should be the same in each. CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios in each should also be the same. This is not the case.

One drastic difference between the flows and the sills is in the chromite chemistry. Chromites from flows are high in TiO_2 , MnO and Fe^3/R^3 and low in Al_2O_3 compared to those in sills. The chromites from flows appear to have formed at a slightly higher $f\text{O}_2$ than the sills (see chapter IV).

The higher TiO_2 , MnO , and Fe^3/R^3 values can be explained by formation at high $f\text{O}_2$, above the titanomagnetite-chromite immiscibility gap (Hill and Roeder, 1974). Whereas within the sills $f\text{O}_2$ was lower, and hence the immiscibility gap was encountered and low TiO_2 chromites formed. The fact that chromites from sills are higher in Al_2O_3 content suggests that they may have formed at a higher pressure than their counterparts in the flows (Irvine, 1967). Therefore, the chromite chemistry is consistent with the fact that bodies A, B, C, and D are sills and E and F are flows. The fact that they are chemically distinct does not detract from the theory that the ultramafic rocks they are associated with are probably related.

The question can still be asked, are the sills reservoirs for the flows or are they synvolcanic? Some of the sills (body C, for example) are small, are not layered and it is doubtful if they acted as reservoirs for any of the flows. Body B, on the other hand, is

much larger, and has at least 4 different chemical and mineralogical zones, two of which are separated by a zone 10-20 m wide of xenoliths of gabbro, ultramafic rock and basalt which may mark part of the roof of the magma chamber. This particular body may well result from several different pulses of magma, and likewise may well have been tapped as a source for flows. The question is then answered: some may be reservoirs and some are probably not.

If the younger basalts (unit 5) were formed in a first melting of the mantle (Naldrett and Turner, 1977), most of the TiO_2 should be in these basalts, and there would be little TiO_2 available for the sequential melts; therefore it is concluded that this tholeiitic suite of basalts represents a different amount of partial melting of the mantle, and not part of the same melting event, as that of the ultramafic flows. The high Mg-basalts (unit 4) are volumetrically small, and may well represent the first melt of an ascending mantle diapir. They are reasonably low in TiO_2 (~0.75 wt%) and because their volume is small, the TiO_2 content of 0.3 wt% of the ultramafic flows is not precluded.

6. Relationship of the Shebandowan Ni-Cu Mine to Ultramafic Bodies A and B

a. Introduction

The spatial relationship between the mine ultramafic bodies and the Ni-Cu ore deposit is well-documented through underground work and diamond drilling (see Chapter II). Field mapping as well as cryptic compositional changes in chromite has indicated that the ore deposit lies on top of the ultramafic lenses, in particular body A. The question is: did the Ni-Cu ore separate from an ultramafic-

mafic magma as an immiscible sulphide melt, or was any other process involved? To help answer this question, pertinent metal ratios for the Shebandowan Ni-Cu mine are tabulated in Table V-5, and are compared to typical values for Kambalda-type ore deposits in western Australia, the Pipe ore deposit of the Thomson Belt, and Levack West of Sudbury.

b. Chemistry of the Ore

Throughout this thesis the northern mine ultramafic body (A) has been consistently distinguished from the southern mine ultramafic body (B), because ore is spatially associated with A and not B. By simple volume calculations using mine plans and sections the amount of ore at Shebanowan mine is too great to have separated from such a small amount of magma (in A). Using both bodies A and B, the R value (ratio of ultramafic rock to sulphide by weight) is only 42 (Table V-5). Values of 2500 are characteristic of Kambalda ores, and Sudbury is about 1000 (Naldrett, 1979). Therefore, it is concluded that if the ore initially separated from an ultramafic magma, it must have done so from both bodies A and B as well as some rock above or below the present erosion surface.

Campbell and Naldrett (1979) have shown that the amount of ultramafic rock that a sulphide melt separates from and equilibrates with (i.e. R value) determines the metal ratios in the sulphide melt. The equation they use is

$$y_1^{\text{sulphide}} = \frac{x_1^{\text{silicate}} D (R+1)}{R+D}$$

where x_1^{silicate} is the initial concentration of 1 in the silicate

Table V-5: Comparison of Shebandowan Ni-Cu ore with Levack West, Kambalda-type and Pipe ore bodies.

	<u>Shebandowan</u>	<u>Kambalda-type</u>	<u>Pipe</u>	<u>Levack⁵ West</u>
$\frac{\text{Cu}}{\text{Cu}+\text{Ni}}$	.36 ¹	.08 ³	.04 ³	.40
$\frac{\text{Ni}}{\text{Fe}+\text{Ni}}$	.07 ^{1,2}	.16 ⁴	.06 ⁴	.08
$\frac{\text{Co}}{\text{Ni}+\text{Co}}$	.03 ²	.02 ³	.04 ³	.02
$\frac{\text{Co}}{\text{Co}+\text{Cu}}$	.05 ²	.21 ³	.50 ³	.03
$\frac{\text{Pt}}{\text{Pt}+\text{Pd}}$	.22 ²	.34 ³	.31 ³	.48
R*	42 ¹	2500 ³	50 ³	1000 ⁴

* R = ratio of ultramafic-mafic rock/metal sulphide ore.

1. This study
2. Eckstrand et al. 1981
3. Naldrett et al. 1979, Campbell and Naldrett, 1979
4. Naldrett, 1979.
5. Hoffman et al., 1979.

magma, y_i^{sulphide} is the final concentration of i in sulphide melt, D is the partition coefficient of i between sulphide and silicate (wt% metal in sulphide melt/wt% metal in silicate magma) and R is the ratio of the mass of silicate magma to the mass of sulphide melt in equilibrium with the silicate magma. Using this equation, where there are large variations in R , but where D values are similar, absolute levels of metals in sulphide ore change, but metal ratios remain the same. Where D values are very different, however, (e.g. Pt = 1000, Ni = 100), the variation in R , causes changes in the metal ratios in the sulphide ore (Campbell and Naldrett, 1979). Some of these effects are compiled in Table V-6. For a sulphide melt that separates from an ultramafic magma with 27% MgO, Cu/Cu+Ni and Co/Co+Ni ratios stay about the same, whereas Co/Cu+Co increases and Ni/Ni+Fe and Pt/Pd+Pt decrease (from $R=2500$ to $R=42$).

If we compare Shebandowan ore with calculated values using $R=42$, then we see that the Cu/Cu+Ni ratio is very high in Shebandowan (0.36 vs. 0.05), Co/Co+Cu very low and the other 3 ratios are consistent with separation from an ultramafic magma. Superficially, the Shebandowan ore body has too much copper to have separated from an ultramafic magma containing 27% MgO. Using the Cu/Cu+Ni ratio alone, this sulphide melt apparently separated from a silicate magma containing ~10% MgO (Fig. 5, Rajamani and Naldrett, 1978).

If we compare ratios involving Pt, Pd, Cu, and Ni (Table V-7) of Shebandowan ore with magmatic sulphide ore with $R=42$, we find that the Pt/Pt+Pd and Pt/Pt+Cu ratios of Shebandowan are consistent with separating from a silicate magma with 27% MgO, but the Pt/Pt+Ni and Pd/Pd+Ni ratios are too large by a factor of 18-20. In order

Table V-6: Estimated metal ratios in magmatic Ni-Cu ore that separated from an ultramafic silicate magma.

Assumptions: MgO = 27%

	<u>Co</u> ¹	<u>Ni</u> ¹	<u>Cu</u> ¹	<u>Fe</u>	<u>Pt</u> ⁴	<u>Pd</u> ⁴
D [†]	40	100	250	5 ²	1000	1500
x*	65	1200	45	8.44 ³	.9	1.5

	<u>R = 2500</u>	<u>R = 42</u>	<u>Shebandowan</u>
$\frac{\text{Cu}}{\text{Cu}+\text{Ni}}$	.1	.05	.36
$\frac{\text{Co}}{\text{Co}+\text{Ni}}$	.02	.04	.03
$\frac{\text{Co}}{\text{Co}+\text{Cu}}$	.20	.41	.05
$\frac{\text{Ni}}{\text{Ni}+\text{Fe}}$	.16	.06	.07
$\frac{\text{Pt}}{\text{Pd}+\text{Pt}}$	.31 ⁴	.24	.22

† D=wt% metal in sulphide melt/wt% metal in silicate

* x is the value in ppm at R = ∞ ; Fe in % melt

1. Campbell and Naldrett (1979)

2. Rajamani and Naldrett (1978)

3. Naldrett and Turner (1977)

4. Naldrett et al. (1979)

Table V-7: Estimated platinum group ratios with R=42 compared to those ratios present in Shebandowan Ni-Cu ore.¹ (Assumptions the same as in Table V-6).

	<u>R = 42</u> ²	<u>Shebandowan</u>
$\frac{\text{Pt}^3}{\text{Pt}+\text{Pd}}$	.24	.22
$\frac{\text{Pt}}{\text{Pt}+\text{Cu}}$	.018	.027
$\frac{\text{Pt}}{\text{Pt}+\text{Ni}}$	.001	.018
$\frac{\text{Pd}}{\text{Pd}+\text{Cu}}$	.055	.09
$\frac{\text{Pd}}{\text{Pd}+\text{Ni}}$	.003	.06

1. Eckstrand et al. (1981): values may not be representative
2. Naldrett et al. (1979)
3. Pd and Pt values multiplied by 1000.

words, there appears to be too much Pd and Pt for the amount of Ni, but Pd and Pt correspond well with the amount of Cu. One way to equalize these ratios is to assume that Ni has been lost to the system by 15 to 20 fold. If this is done, then $Pt/Pt+Pd$, $Pt/Pt+Cu$, and $Pd/Pd+Cu$ remain the same, whereas $Pt/Pt+Ni$, $Pd/Pd+Ni$, as well as $Cu/Cu+Ni$ values are lowered considerably and become compatible with the ore having separated from a silicate magma with 27% MgO. For example, the $Cu/Cu+Ni$ ratio becomes 0.03-0.04. If we assume alternatively that we have added Cu to the system, then none of PGE to Cu and Ni ratios are compatible with separating from an ultramafic magma, whereas the $Pt/Pt+Pd$ ratio is.

If we argue that the ore separated from a gabbroic (MgO=10%) magma, then the $Pt/Pt+Pd$ ratio is considerably lower than that expected in an Ni-Cu sulphide ore with $Cu/Cu+Ni=0.36$ (Naldrett and Cabri, 1976).

c. Discussion

The most obvious explanation of the $Ni/Cu+Ni$ ratios is that the sulphide melt that formed the Shebandowan ore body may have separated from a gabbroic liquid (with 10% MgO). Outstanding arguments against this are (1) lack of any substantial amount of gabbro in the Shebandowan mine area, (2) the intimate association of ore with ultramafic rocks, and (3) the $Pt/Pt+Pd$ ratio. The ore has many inclusions but most of them are peridotite, pyroxenite, and inclusions derived from high Mg-basalt (unit 4) and the Shebandowan Lake Stock (unit 7). There are no gabbro inclusions.

Figure V-13 is a diagram compiled by Duke (1980), where he has plotted $Ni/Ni+Cu$ in sulphide vs. $Mg/Mg+Fe$ in olivine (or rock

FIGURE V-13: Ni/Ni + Cu versus Mg/Mg + Fe ratios of co-existing olivine for various Ni-Cu ore deposits, from Duke, 1980

if there is no fresh olivine) for various Ni-Cu mines. Using this plot it appears that the Ni/Ni+Cu ratio of Shebandowan ore correlates very well with an olivine composition of Fo_{81} , calculated from the weighted compositional average of body B. The olivine cumulate, however (for example, harzburgite in zone Y), has a calculated value of Fo_{85-86} . Green and Nicholls (1975) found that the olivine co-existing with an ultramafic liquid of Mg/Mg+Fe of 0.85 had a composition zoned from Fo_{94} to Fo_{89} . Therefore given that the bulk average of body B yields a good approximation to the initial magma composition, olivine co-existing with a liquid with Mg/Mg+Fe of 0.81, the forsterite composition will be higher, as calculated from the analyses of harzburgite. This being the case, Shebandowan olivine composition would plot considerably off the trend, and it would appear that for an olivine composition of Fo_{86} , the Ni/Ni+Cu ratio is anomalously low.

Therefore, if one assumes, and it is the contention of the author, that the ore separated from an MgO-rich liquid, then some other process must be envisioned to allow for the high Cu, Pt, and Pd contents (with respect to Ni). The reasons the author believes that the ore separated from an ultramafic magma are:

1. Spatial relationship with bodies A and B
2. Lack of gabbro both with the ore body and in the Shebandowan mine area.
3. Lack of gabbroic inclusions in ore, whereas there are abundant pyroxenite and peridotite inclusions
4. Ni/Ni+Fe, Co/Co+Ni and Pt/Pt+Pd are consistent with ore having separated out from an ultramafic magma (R=42)

position of chromites indicates that they formed from a magma that could have equilibrated with a sulphide melt.

Several facts that this contention does not explain are:

1. The high Cu/Cu+Ni ratio of the ore
2. High Pt and Pd contents, with respect to the amount of nickel
3. Lack of any net-textured ore in the deposit--it is either massive or breccia sulphide (sulphide with many silicate inclusions). Disseminated ore, where present (it is very minor) consists of mostly chalcopyrite and pyrite with millerite and minor pentlandite.
4. Its location on top of the ultramafic rocks, and
5. The large amount of ~~ore~~ with respect to the volume of host rock.

Additional processes must be postulated to explain these facts.

d. Genesis of Shebandowan Ni-Cu Ore

From the analyses of chromite, it was shown that chromite from zone Y, body B, did not precipitate from a magma that had equilibrated with a sulphide liquid, and the author would like to maintain that given a large magma reservoir of ultramafic liquid, somewhere at depth (under enough pressure to form aluminous chromite), a certain amount of olivine precipitated before sulphide became saturated and separated as an immiscible sulphide liquid.

Using the weighted bulk composition of body B, Ni and Cu values from sulphide-free ultramafic and gabbroic rock in body B, and assuming a total amount of olivine fractionation similar to that in zone Y (20-25%), then a new magma composition can be calculated. This is tabulated in Table V-8. It yields an MgO value of approximately 28%, Mg/Mg+Fe of 0.77 and a Cu/Cu+Ni ratio of 0.18. Pd and Pt would also be enriched in the silicate liquid.

Table V-8: Comparison of ultramafic magma before and after olivine and chromite fractionation.

	<u>1</u>	<u>2</u>
SiO ₂	43.85	45.4
TiO ₂	.23	.31
Al ₂ O ₃	4.37	6.23
Cr ₂ O ₃	.60	.27
FeO	13.95	15.1
MgO	32.79	27.9
CaO	3.26	4.33
Na ₂ O	.16	.21
K ₂ O	.11	.15
NiO	.17	.10
Cu-ppm	128	174

1. Weighted average of Body B. NiO and Cu contents determined from non-sulphide bearing samples.
2. After 25% olivine (Fo₉₀ with 0.4 wt% NiO) and 1% chromite fractionation.

At this stage an immiscible sulphide melt separated from the magma. There is still enough Ni in the remaining magma to form the deposit the size of Shebandowan, but there is only 60% of the amount of S necessary (assuming 0.45 wt% S at sulphur saturation, Shima and Naldrett, 1975) and 40% of the amount of Cu (if the initial Cu value was 128 ppm - see Table V-8). If a more reasonable Cu value of 30 ppm is used (Rajamani and Naldrett, 1978) as the initial Cu content of the ultramafic magma, then there is only 10% of the necessary Cu available in the remaining silicate magma.

After the sulphide melt separated from the magma, some of the remaining ultramafic liquid (with MgO = 27-28%) travelled to surface and extruded as flows. A certain amount of time must have separated these two episodes to allow for sulphides to separate and settle. They are certainly not entrained in the flows, as S, Ni and Cu contents are low in the flows.

Once a massive and disseminated sulphide body had formed, folding would tend to make the more plastic rock unit (in this case ore) move into areas of least stress. This would be a way of localizing ore into a massive deposit. Faulting (which has been intense in the mine rocks and surrounding area) might then cause ore to be localized still further. Because of the sulphide's ability to flow under stress, even at low temperatures, faulting might then cause the ore to flow, entraining fragments of host rock (Spry, 1969).

Faulting and folding is well-documented within the Shebandowan mine area and faulting within the mine is intensive. Metamorphism reached lower to mid-greenachist facies, and near the Shebandowan

Lake Stock, higher grade assemblages are recorded in silicate rocks. This succession of metamorphism and folding with some faulting, later strike-slip faulting, and then intrusion of the Shebandowan Lake Stock, might allow concentrating processes to occur within the ore. Barrett et al. (1977) recorded localized remobilization of Cu ($\pm$ Fe) relative to Ni in metamorphosed Western Australian volcanic associated Ni-Cu ore. The same kind of localization is present within the Shebandowan mine. It is not unusual to find extremely Cu-rich stringers of ore projecting into the basalts and Shebandowan Lake Stock which form the hanging wall of the deposit.

During H_2O and CO_2 metamorphism, a large amount of fluid must have moved through both the ultramafic and ore bodies. These fluids would be capable of causing widespread intergranular diffusion of S and perhaps Cu and Ni. If these processes took place on a large scale, at least fifteen times the amount of Ni in Shebandowan mine must have been removed from the initial sulphide deposit. Using this amount of Ni depletion, all pertinent metal ratios in the ore are compatible with forming from a sulphide melt that separated from an ultramafic magma. If this much Ni has been removed, a large amount of S must have also left the system to balance the amount of sulphide minerals. This being the case, there is a tremendous Ni, Cu and S shortage in the amount of ultramafic rock present in bodies A and B. Approximately 10 times this amount of ultramafic rock would be needed to form an ore deposit the size of Shebandowan mine.

It is not inconceivable that a large part of the ultramafic body has been eroded off, or there is more at depth. The same may

be true of the ore deposit. Perhaps some of the ultramafic rock and ore has been partly assimilated by the intrusion of the Shebandowan Lake Stock. Certainly it is not inconceivable that xenoliths and rafts of ultramafic rock (and perhaps Ni-rich ore) are present within the Shebandowan Lake Stock. The Ni content of samples analyzed of Shebandowan Lake Stock are much higher than normal granites and granodiorites (see Table II-2), so it might not be unreasonable to say some of the Ni diffused into the Shebandowan Lake Stock.

The following ideas are offered as alternatives.

It is also possible that contamination by Fe-rich and perhaps Cu-rich sulphides of the ultramafic magma took place. There are pyrite rich massive sulphides throughout the older basaltic succession so this may not be unexpected. There is one area within the Shebandowan ore body where sphalerite, in association with chalcopryrite, pyrite, and magnetite, is found. If a small Cu-Zn massive sulphide body had been assimilated, it is one way to increase Cu at the expense of Ni.

If a gabbroic melt were the source rock for the Shebandowan ore body, then the Cu/Cu+Ni ratios are correct, but the Pt/Pt+Pd are slightly low (Naldrett and Cabri, 1976). Also because of the lower S, Ni contents of gabbroic (or basaltic) melts at least 100 times the mass of the ultramafic rock present in bodies A and B is needed to make the Shebandowan ore body.

CHAPTER VI:
CONCLUSIONS

The conclusions of this thesis vary from geological field relationships, composition of chromite in ultramafic rocks, petrochemistry of the ultramafic rocks to the genesis of the Shebandowan Ni-Cu ore. Because of their diverse nature, they are presented here in point form.

1. Two series of tholeiitic basalt underlie the Shebandowan mine area. The older succession is composed of pillowed basalt, mafic pyroclastic rock and plagioclase-phyric flows. Coeval with this succession is a suite of volcanoclastic rocks varying from iron-formation to greywacke, conglomerate, and siltstone. These are exposed around Maria, Zero, and Peewatai Lakes. The younger volcanic succession is characterized by minor high Mg-basalt and mostly pale green subaqueous pillow basalt, pillow breccia, and hyaloclastite. The size, nature and distribution of amygdules, suggest that this cycle of volcanism was formed in shallow water (Moore et al., 1973). Accidental to these successions is an andesitic submarine ash or debris flow, which is conformable in the Shebandowan mine area, and acts as a marker horizon.

2. Two groups of ultramafic rocks are recognized within the Shebandowan mine area. These are flows with associated iron formation and hyaloclastite in the younger succession and sills of harzburgite-lherzolite composition in the older succession. The Shebandowan Ni-Cu mine is associated with an ultramafic sill that intrudes close to the contact between the older and younger volcanic series. From structural and stratigraphic considerations, the ore lies toward the top of the sill, at the contact with high Mg-basalt (unit 4) and in some cases older basalt (unit 1).

3. These basaltic successions (both younger and older) as well as ultramafic rocks have been intruded by the Shebandowan Lake Stock, a synkinematic granodiorite; and later by the Peewatai Lake Stock, a quartz monzonite to syenite.

4. The Shebandowan mine area has undergone two, perhaps three periods of folding. The first resulted in overturning of strata with continued shortening resulting in an east-west foliation. Within the area, this has resulted in tight isoclinal synforms that are really anticlines. This could be interpreted as two folding events, or could conceivably be the result of continued deformation. A later gentle warping of stratigraphy took place, which is shown by a north-south cleavage, and domal features throughout the area.

Strike-slip faulting occurred both during these folding events, and at a later time. Later cross-faults with at least 1/2 km of movement are documented in the Shebandowan mine area.

5. Ultramafic rocks, both flows and sills, are petrographically similar. They both have pseudomorphic textures indicative of olivine and orthopyroxene cumulate phases, and clinopyroxene as intercumulus. The smaller sills and flows are undifferentiated, whereas the larger ones (bodies B (sill) and E (flow)) are compositionally layered from harzburgite to olivine gabbro.

Geothermometry, using analyses of relict ortho- and clinopyroxenes in body E, yields an equilibrium temperature of crystallization of $\sim 1200^{\circ}\text{C}$.

6. Both flows and sills are now serpentinite or talc-carbonate schist. Secondary mineral assemblages are compatible with an overall high fH_2O and an increased fCO_2 toward the Shebandowan Lake Stock.

7. The only ubiquitous relict mineral within all of the Shebandowan ultramafic rocks is chromite. These chromites are zoned, with fresh cores, ferritchromit rims and irregular magnetite overgrowths. Ferritchromit is interpreted to have formed during upper greenschist metamorphism, whereas magnetite formed during serpentinization. Ferritchromit is always lower in MgO, usually lower in Al_2O_3 and Cr_2O_3 , and higher in Fe_2O_3 and FeO relative to fresh cores.

8. Compositional changes in chromites within body F (younging direction known) follow a trend of overall increase in Fe, decrease in Cr/R^3 and increase in Fe^3/Fe^3+Cr up section. These criteria, determined in body F, have been used to establish that body C is south-facing and body B north-facing. These facing directions are compatible with structural and stratigraphic considerations.

9. On the basis of TiO_2 , Al_2O_3 , and Fe_2O_3 contents of chromite, the ultramafic bodies can be divided into two groups: one with TiO_2 - Fe_2O_3 -rich, Al_2O_3 -poor chromites and one with TiO_2 -, Fe_2O_3 -poor and Al_2O_3 -rich chromites. This division corresponds to the two kinds of ultramafic rock recognized in the field, the former flows, the latter sills. These chemical differences can be explained on the bases of fO_2 and pressure differences. The TiO_2 -rich, Al_2O_3 -poor chromite was formed at low pressure and high fO_2 , whereas the TiO_2 -poor, Al_2O_3 -rich chromite was formed at higher pressure and lower fO_2 .

10. The composition of the Shebandowan chromitite falls well within the minimum and maximum bounds of an average stratiform chromite deposit (Dickey and Yoder, 1972), but in general Shebandowan

chromitite is lower in Cr_2O_3 and MgO and higher in Al_2O_3 , Fe_2O_3 , and FeO relative to an average stratiform deposit. From compositional changes between the disseminated chromite and the massive chromite in body B, it appears that the massive chromite formed at a slightly higher $f\text{O}_2$ than the disseminated, and it is postulated that a change in $f\text{O}_2$ resulted in the formation of the chromitite horizon.

11. Using a theoretical diagram developed by Johan (1980) it appears that chromite in bodies A, F, E, and part of B are compatible with forming from a silicate magma that may have been in equilibrium with a sulphide liquid.

12. If the Al_2O_3 vs. $\text{FeO}/\text{FeO}+\text{MgO}$ diagram developed by Arndt (1976) serves to separate more evolved rocks from less evolved rocks (Nesbitt et al., 1979), then ultramafic flows and sills in Shebandowan mine area have evolved to the same degree. The average compositions of bodies B (sill) and F (flow) are very similar with ~32% MgO and ~44% SiO_2 . On a $\text{CaO}-\text{MgO}-\text{Al}_2\text{O}_3$ plot, an olivine-orthopyroxene differentiation trend is shown.

13. Principal components analysis of whole rock analyses of ultramafic rock (both flows and sills) shows that five factors account for 82.3% of the data variance. These are: (1) $\text{MgO}, \text{CaO}, \text{V}$; (2) $\text{S}, \text{Cu}, \text{Ni}, \text{Co}$; (3) $\text{FeO}, \text{MnO}, \text{Zn}$; (4) Cr_2O_3 ; and (5) SiO_2, Sr . The first two account for 60.2% of the variance. These factors can be easily interpreted in terms of mineralogy:

- i. olivine and clinopyroxene
- ii. Ni-Cu sulphides
- iii. Fe-bearing minerals

iv. chromite

v. olivine versus SiO_2 -rich minerals.

14. Cluster analysis using major and trace element data divide the ultramafic rocks into olivine gabbro and olivine websterite versus harzburgite. The flows group as a sub-group within the harzburgite sills, except when clustering using component 2 - Ni-Cu-Co-S, and then harzburgite-lherzolite flows plot as a separate group.

This is interpreted to mean that the flows and sills are chemically and probably genetically related; the difference being in their sulphide content.

15. Sills are thought to be both synvolcanic with (when very small and undifferentiated, e.g. C) and possible reservoirs for (e.g. B - layered) the flows that lie stratigraphically above them in the younger volcanic succession.

16. The Shebandowan Ni-Cu Mine is composed of Pn, Po, Cp, Py, Mt, with minor Mi, Sp and PGE. It is massive with no net-textured ore. Breccia sulphide is common, stringer ore less so. Disseminated ore is almost absent. Overall Cu/Cu+Ni ratio is 0.36 (N.L. Anderson, pers. comm.) and the Pt/Pt+Pd ratio is 0.22 (Eckstrand et al., 1981). It lies on top of ultramafic bodies A and B - in particular A - and has many inclusions of peridotite and pyroxenite. The overall mass ratio of ultramafic rock to sulphide (R) is 42 (using both bodies A and B).

17. The ore is interpreted to have separated from an ultramafic parental magma, represented by the weighted composition of body B, less 25% olivine and 1% chromite fractionation (see

Table V-8). The Cu/Cu+Ni ratio is explained by at least a 15-fold loss of Ni, which corresponds to a 10-fold loss in ultramafic rock. Using these values, the PGE ratios are correct. This loss in Ni can be ascribed to metamorphic differentiation as well as loss through CO₂ and H₂O alteration. The ultramafic rock could have been faulted off, or rafts of it might be present in the Shebandowan Lake Stock. Certainly some xenoliths of ultramafic rock have been intersected in diamond drill holes through the stock, and the possibility remains that there might be many more.

The ore was emplaced into its present location, probably by faulting and folding.

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Appendix I.

Definitions and Petrography

Table AI-I

Mineral Abbreviations

act	actinolite	liz	lizardite
ab	albite	m	magnesite
alf	alkali-feldspar	mt	magnetite
amph	amphibole	ml	millerite
ank	ankerite	ms	muscovite
anth	anthophyllite	ol	olivine
ant	antigorite	op	opaque
ap	apatite	or	orthoclase
aug	augite	opx	orthopyroxene
bi	biotite	pen	penninite
cc	calcite	pn	pentlandite
cb	carbonate	pl	plagioclase
cp	chalcopyrite	Ksp	potassium feldspar
ch	chlorite	py	pyrite
chr	chromite	px	pyroxene
cpx	clinopyroxene	po	pyrrhotite
czo	clinozoisite	Q	quartz
di	diallage	saus	sausserite
dol	dolomite	ser	sericite
ep	epidote	serp	serpentine
fa	fayalite	sp	sphalerite
fo	forsterite	tc	talc
grun	grunnerite	tt	titanite
hem	hematite	trem	tremolite
hbl	hornblende	vi	violarite
hyp	hypersthene	zo	zoisite
il	ilmenite		

Table AI-II
ROCK ABBREVIATIONS

and	andesite
bs	basalt
cong	conglomerate
di	diorite
du	dunite
gb	gabbro
gn	granite
gdr	granodiorite
gwke	greywacke
hz	harzburgite
lh	lherzolite
ol-gb	olivine gabbro
pd	peridotite
pxte	pyroxenite
q-monz	quartz monzonite
spte	serpentinite
shte	shoshonite
tc-cb schist	talc-carbonate schist

CLASSIFICATION OF ULTRAMAFIC PLUTONIC ROCKS

FIGURE AI-1: Classification of ultramafic rocks used in this thesis, from Eckstrand, 1979.

Table AI-III: List of diamond drill holes logged and sampled.

Diamond Drill Hole	Mine Coordinate Location		Dip	Strike
	N	E		
9441	7720	21480	-43	360°
9445	9465	22600	-55	360°
9448	9300	21800	-67	360°
26399	9590	29830	-45	360°
30401	9600	32600	-50	180°
30414	9280	21800	-55	180°
30436	10151	26600	-55	360°
30442	12070	31200	-58	360°
30468	9998	24500	-54	360°
36551	9910	22400	-60	360°
36561	10000	28200	-50	360°
36575	13450	30000	-65	180°
36577	13090	28400	-60	180°
36584	6270	25400	-45	360°
41002	7800	23800	-45	360°
41041	14800	32800	-75	180°
41052	10600	7400	-50	360°
41057	15350	34400	-75	180°
36563	2550S	24800W	-50	360°
36581	5300S	24200W	-50	360°
<u>Underground</u>				
35480-1000L	10480	19400	0	180°
36640-1000L	10480	20400	-28	180°
38940-600L	10054	21800	0	360°
38941-600L	10043	21800	0	180°
45110-1000L	11178	25000	-8	180°
<u>Anomaly Holes</u>				
26391	See Figure II-2		-45	180°
26394	"	"	-45	180°
36563	"	"	-45	360°

Table AI-IV: Detailed petrography of rocks in three diamond drill holes drilled through the northern and southern mine ultramafic bodies in the eastern section of the Shebandowan mine area.

(Bodies A & B)

<u>Hole</u>	<u>Location</u>	<u>Azimuth</u>	<u>Dip</u>
36575	30000E, 13450N	180°	-65
41041	32800E, 14800N	180°	-75
41057	34400E, 15350N	180°	-75

All sections were stained for calcite/dolomite and for Fe (siderite-ankerite) using alizarin red S and K_3FeCN_6 . X-rays have been used in a few carbonate identifications, but for the most part, carbonate minerals are listed Fe, Mg, Cc and dolomite. Modal estimates are visual.

Diamond Drill
Hole and Footage

Notes

Mineralogy

carbonate

	tc	ch	q	plag	bl	lilz	Fe	Mg	cc	dol	ant	ser	zo	ep	trem	anth	op	di	
36575-1930	10							85									5		ol cumulate pd
1940	20	10						65									5		"
1950	40	12						40									8		no original texture. pd
1960	30	25	x	x				35						x			x		schistose
1970	30	30		7				30									3		foliated, kinked cataclastic rock
2060	60	40																	foliated - no opaques
2070	40	15						40									5		pd no relict textures
2080	20					65		10									5		pd - foliated
2090	20					60		18									2		ol cumulate pd
2100	35	x						60									x		pd - no relict textures
2150		20	25									25		30					banded lapilli tuff basaltic

x = present m = minor

Diamond Drill
Hole and Footage

Mineralogy

Notes

	tc	ch	q	plag	bi	liz	Fe	carbonate		dol	ant	ser	zo	ep	trem	anth	op	di	
41041-2230	30					10			50								10		dunitic pd
2240	75										25								" "
2250	m					x		x	x										ol cumulate pd
2270						80		x	x								8		"
2280		x				80	x										3		"
2300	25	25				25											3	22	"
2330						96		x									3		"
2340		x	x								x								tuff
2360		x									x								pd
2370	x	x	x						x				40				3		meta-gabbro or pxte
2380	15	7				10			45				20				3		"
2400	40					90			30										pd
2430	25	55							20										pxte
2440	30	35	5						30				5						"
2475		x	x						x										mylonite
2490	30	40	20																sheared and kinked Unit 3

x = present m = minor

**Diamond Drill
Hole and Footage**

Mineralogy

Notes

	tc	ch	q	plag	bi	li2	carbonate			Fe	Mg	cc	dol	ant	ser	zo	ep	trem	ath	saus	op	di	
41057-1790	50	5	10							30												5	Pd-q in veins
1800		30			20	15				35													basalt
1820	30	5								30											5		pd
1850		60	10	20										5	m	m							basalt plag-An40 dyke
1860	55	25	10										10										mylonite
1870	35	35	5										15		m								mylonite
1875		20																			80		basalt
1900		x											x			x							ophitic texture
1920	40	20											20					20					foliated gabbro
1950	m	10											25				m				60		gabbro
2000		m	m														50				40		gabbro
2070		x	x	x									x								x		basalt- quenched plag.
2090	5	30											40								20		mafic ash tuff
2130		x	x										40										crystal tuff
2160		25	25										25					20	5				???
2180	30	5								65													foliated catacl
2190	30	5								65													pd.
2200		15	65							18											2		hybrid xenolith
2210		x	x							x											x		tuff-wacke rock

x = present m = minor

Table AI-V:
Petrography and Location of Ultramafic Rocks
Sampled in Shebandowan Mine
(Modes are visual)

4

<u>Location</u>		<u>Sample Number</u>		<u>Mineralogy</u>				<u>Carbonate</u>	<u>Opaque</u>	<u>Rock Type</u>	<u>Notes</u>
East	Level	DDH	footage	serp	tc	trem	ch	cc	dol	M	Q
16,000	400	44872	400		20	50	10		mt-hem	pxte or bs	+ 20 hbl
17,000	400	26357	570						hem-py-il	banded mafic tuff	
	1200	9443	1468,1500							gb	
	2000	44818	2490		20	10	70	m		pd.	coarse-grain
18,000	400	26377	620						hem-mt	bs or gb	act-ep-q-cc
19,000	800	9436	880							um	no thin sec.
	1200	9436	1530,1540							um	"
	1600	37705	1070						5 py-chr	tuff	ch-cb-q
	2000	37730	1360	5	30			55	10	pd	ol cumulate
20,000	surface	26335	220,230	30	x				10	pd	ol cumulate
	400	35431	10			30	x	x	3 mt-po-cp	um	um
	800	35470	10		68		7	60% cb		pd	opx present
	1600	35440	1110				8	20		pd	no thin sec.
	2000	36606	1390							q-fd-porphyry	
21,000	surface	36514	200,210		25	50			15(ep) 10 cp-py-mt	pxte	
	400	36678	20	60	25		5	10	chr-mt-cp	pd	sheared pd.
	800	36659	10,20						cp-(po-py)	bs	90% act
22,000	surface	36513	160,170			50	30		10	pd	160 ore, 170 pd.
	400	38921	0,10	10	30			50% cb	10 (cp-po-pn-py)	pd	0 ore, 10 pd.
	800	38969	120						2	basalt	shows di-cular needles of plag.

<u>Location</u>		<u>Sample Number</u>		<u>Mineralogy</u>				<u>Opagues</u>			<u>Rock Type</u>		<u>Notes</u>
<u>East</u>	<u>Level</u>	<u>DDH</u>	<u>footage</u>	<u>serp</u>	<u>tc</u>	<u>trem</u>	<u>ch</u>	<u>cc</u>	<u>dol</u>	<u>M</u>	<u>Q</u>		
23,000	surface	9452	20, 180										20-ore, 130pd. ol cumulate 50-ore, 80 pd. sheared
	400	43322	180	70	m			10	10		10 mi-py-cp-chr	pd.	
	800	45171	50, 80		x	x	x	x	x				
	1600	40746	1350, 1360	5	30			-60%--			3	pd.	
	2000	40770	1810			x	x	x	x			q-fd-porphyr	
24,000	400	30431	440		15	10		--70%--			5% chr-cp-py	pd.	schistose opx's present
	800	"	1040, 1060		10	60	10	--15% cb--			5 mi-py-cp	gb or pxte	
	1600	30421	1740		30	10	10	-50%--				pd.	
25,000	surface	44816	80, 90, 100		20	50	25				chr-cp	pd.	+ hbl no relict tex. ol bearing- schistose
	400	30424	430		50			50			mt (trace)	?	
	2000	30433	2520	15	85							pd.	
26,000	400	44806	460	40	30	m		---20% cb--			10 mt-py-cp-po	pd	ol cumulate sheared
	1200	49545	940		x			x	x	x	60	ore	
27,000	800	36253	1000		33			m	60		7	pd.	no relict tex. minor pale green mica ol cumulate ol cumulate
	1200	52475	950, 960	35	25			30			10	pd.	
	1600	52455	950	85	m			m	12		10 (chr-po-cp-mt)	pd.	
	2000	58296	1310, 1320	70	25	m					5	pd.	

X = present m = minor

✓ Table AI-VI:

Mineral Assemblages
as Determined by
X-ray Diffraction

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
Chromite Horizon									
RL6	x					x			
Cr 6	x							x	
Cr 3	m	x				x		x	
9445-390				x		x		x	x
30442-1440		x		x		x			
30436-243				x	x			x	x
45110-1030		x		x		x			
Northern Mine U.M. Body									
36551-440		m	x	x					
36551-330	x				x	x			
36551-230	x					x	m		
36551-130	x					m	x		

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
36577-2010		x		m		x	x		
36577-2030		x		m		x			
36577-2050		x		x		x	x		
36577-2190		x				x	x		
36577-2240		x		x		x			
36561-320	x	x				x			
36561-390	x	x		x		x			
30468-1010	x	x		x	x				
30468-1030	x	x		x		x			
30468-1050			x	x					
RAMP SECTION									
G680011	x	x				x			
G680012	x	m		m					

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
G680013		x	x	x					
G680016	x	x				x			
R90	x	x		x	x	x			
R120	x	x		x		x			
R140	x					x			
G680017	x								
G680018	x					x	x		
G680019	x					x	x		
R230	x								
G680020	x					x			
R400			x	x					
R420			x	x				x	
G680028		x	x	x					

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
U.M. Bodies in Map Area									
36584-540	x	x				m			
36584-560	x	x	x		x				
36584-620				x	x				x
36584-820	x		m	x	x				
26399-610	x	m			x				
26399-650a	x	x			x				
30401-50				x	x			x	
30401-210			x			x			
30401-220	x		x	x					
30401-560		x	x	x	x				
30401-570		x	x	x					
30414-220	x(?)	x		x		m	x		

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
301414-240		x		x		x	m		
301414-280	x	x				x			
301414-320	x	x							
301414-340	x	x				x			
Hed-150	x	x	x	(?)	m				
-165		x		m	x	x			
-175	x	x				x			
-195	x	x				x			
-205	x	x			x	x			
-218	x	m							
26394-190		x		x		x			
26394-210	x	x		x		x			
26394-260		x		x		x	x		

Sample and Location	Serp	Tc	Trem	Ch	Cc	Dol	M	Q	Mica
76-PM-99				x		x		x	
76-PM-129						x		x	
77-PM-22						x		x	x (Cr)
77-PM-23		x		x		x			
77-PM-27B		x		x		x			
77-PM-30	x	x				x			
77-PM-32B	x	x							
77-PM-40			x	x					
Mine grid sampling									
26335-230	x	x		x	x	x			
30421-1740		x		x	x	x			
30431-440		x		x		x	x		
30431-1040			x	x					

Appendix II

Whole Rock Geochemistry

APPENDIX II: Whole Rock Geochemistry

Whole rock compositions of 95 rock samples were analyzed by Inco Metals company; rocks were analyzed under the guidance of R. A. Alcock. Samples were fused with lithium-tetraborate, ground, and then pressed into pellets and analyzed by X-ray fluorescence. Na_2O was not determined at this laboratory. Cu, Ni, Co and Zn analyses were performed by atomic absorption methods (HCl , HNO_3 , HClO_4 , HF digestion) in the Exploration Assay Laboratory in Copper Cliff (Inco Metals). Sulphur was determined by the conventional Leco combustion method.

Trace elements were analyzed by emission spectrochemical methods at the analytical chemistry section of the Geological Survey of Canada. Analyses are accurate to $\pm 15\%$ of the reported value. Samples with Na_2O values greater than 2 wt% were re-analyzed by XRF (fusion method) by Bondar Clegg Co Ltd. Results are tabulated in Table AII-III.

Total Fe is reported as FeO ; S in wt% is included in the totals. Co values marked with an asterisk were determined using emission spectroscopy where atomic absorption values were not available. Correlations between methods (Atomic absorption versus emission spectroscopy and emission spectroscopy versus XRF) for Cu, Ni, Co, TiO_2 and Cr_2O_3 are reported in Table AII-I. Generally there is good agreement between methods: emission spectroscopy yields slightly larger values of Cu and Co compared to atomic absorption.

All analyses of ultramafic rocks total between 98 and 102 wt% and the average is 99.7%. Basalt analyses on the other hand consistently have low totals (95.9 to 100.3; average 97.9%). Analyses of felsic rocks from the area total between 97.5 and 98.6; average is 98.1%. This may be attributed to low alkali values or a systematic error in either or both of the Laboratories (Bondar Clegg and Inco).

Table AII-I: Correlations between Analytical Methods

<u>Atomic Absorption</u>		<u>Emission Spectroscopy</u>		<u>XRF</u>	<u>Slope</u>	<u>Correlation</u>
Cu	vs	Cu			.949	.9670
Ni	vs	Ni			.992	.9943
Co	vs	Co			.937	.9658
		TiO ₂	vs	TiO ₂	1.07	.9873
		Cr ₂ O ₃	vs	Cr ₂ O ₃	1.01	.9875

A comparison of three of Inco's basalt analyses and three published analyses (Hodgkinson, 1968) from what are thought to be the same rocks in the Discovery Point area are shown in Table AII-II. There is good agreement between the samples for SiO_2 , Al_2O_3 , total Fe, CaO and MnO but MgO and K_2O values of Inco analyses are much higher than those of Hodgkinson whereas Na_2O , TiO_2 and LOI are much lower in the former. Unfortunately, Hodgkinson's analyses total low as well so no estimate of accuracy can be made.

	1	2	3	4	5	6
	S-62-3-6	76-PM-20	S-62-3-5	76-PM-10	S-62-3-7	77-PM-134
SiO ₂	44.6	46.2	48.5	46.8	46.5	48.4
Al ₂ O ₃	12.8	12.6	11.6	12.2	13.4	14.3
Fe ₂ O ₃	2.14	n.d.	2.23	n.d.	2.77	n.d.
FeO	11.9	11.2	9.72	12.1	10.1	11.7
MgO	10.1	13.7	9.88	9.39	7.85	7.91
CaO	8.83	9.45	9.88	9.39	11.1	10.7
Na ₂ O	1.67	1.01	1.77	0.93	2.19	1.91
K ₂ O	1.06	1.40	0.14	0.73	-	0.48
H ₂ O + CO ₂	2.86	2.11	2.61	2.03	1.96	1.06
TiO ₂	0.92	0.61	0.75	0.60	0.98	0.91
S	-	n.d.	0.52	n.d.	0.31	0.10
MnO	0.19	0.18	0.16	0.16	0.23	0.20
TOTAL	98.0	98.72	98.12	98.06	97.45	97.67

TABLE AII-II: Comparison of basalt analyses from the Discovery Point area. (1, 3 and 5 are from Hodgkinson, 1968 and 2, 4, and 6 are from this thesis)

Normative Mineralogy

Mineral norms were calculated using VULCID-Carleton University, modified after Irvine and Baragar, 1971. All analyses are recalculated to 100% before calculating normative mineralogy. Results are tabulated in Table AII-IV. 17 ultramafic rocks (harzburgite) and 5 felsic rocks have corundum in the norm. With the exception of G11, G12, 77-90, 77-420 and H218, all the corundum in the ultramafic rocks can be accounted for by the Al_2O_3 content of chromite and orthopyroxene. Analyzed chromites from these samples yield average $\text{Al}/(\text{Al} + \text{Cr})$ ratios of 0.4 and analyzed orthopyroxene has approximately 1% Al_2O_3 . These values yield 1% corundum in the norm (for an average harzburgite).

The five exceptions have probably suffered CaO loss during either carbonatization or serpentinization; only sample 77-420 seems inordinately high (10.39) and this analysis has been ignored in interpretation for the reason of alteration.

Of the felsic rocks, 30236-620, which is an andesitic tuff has 4.97% corundum in the norm. The chemical total is only 96.8 and either loss of Na_2O and K_2O during alteration or a poor analysis can account for this. 76-213, 76-270, 77-15 and 66-133 have less than 1.12% corundum and mobilization of Na_2O or K_2O probably accounts for this.

Two ultramafic samples of the northern mine ultramafic body have negative quartz in the norm. This is either indicative of SiO_2 loss or CaO , MgO gain. These two rocks have undergone extensive carbonatization, and the negative quartz is probably a reflection of this alteration.

Table AII-III:

Chemical Analyses
of
Shebandowan Rocks

Major elements in per cent,
minor elements in ppm.

Sample #	G 680 11	G 680 12	G 680 14	G 680 13	G 680 15	G 680 16	77-90	77-120
SiO ₂	38.3	38.1	44.1	43.5	47.1	37.2	36.4	40.1
TiO ₂	0.23	0.15	0.42	0.34	0.54	0.26	0.25	0.19
Al ₂ O ₃	6.78	4.80	12.7	8.05	13.0	3.01	2.79	3.81
Cr ₂ O ₃	0.40	0.53	0.17	0.42	0.17	0.40	0.44	0.40
FeO	12.3	12.9	11.5	11.4	10.1	13.8	16.3	11.9
MgO	29.8	31.9	14.2	21.3	12.8	32.5	30.8	30.5
MnO	0.16	0.15	0.20	0.15	0.18	0.17	0.14	0.11
NiO	0.19	0.17	0.41	0.09	0.04	0.15	0.40	0.16
CaO	2.22	1.09	7.38	7.60	8.75	0.98	0.65	1.98
K ₂ O	-	-	1.37	-	1.71	-	-	-
Na ₂ O	0.04	0.05	1.23	0.54	1.48	0.02	-	0.03
LOI	10.7	10.3	4.83	5.79	4.24	11.4	10.1	10.6
Sum	101.12	100.14	99.25	99.65	100.11	99.89	100.07	99.98
Ba	8	9	1.40	.9	130	9	5	5
Co	120	115	170	85	.55	85	265	95
Cu	160	90	810	55	75	155	1800	65
Ni	1800	1620	3870	910	385	1420	3880	1590
S (%)	.094	.104	.736	.469	.065	.092	1.8	0.2
Sr	53	21	130	36	110	47	10	51
V	48	52	170	146	180	37	28	36
Zn	90	90	140	75	70	50	70	65
Zr	59	72	99	110	91	58	20	20

Sample #	77-140	G 680 17	G 680 18	G 680 19	G 680 20	77-280	G 680 21	G 680 22
SiO ₂	37.5	36.5	36.1	37.1	36.5	39.2	28.3	36.0
TiO ₂	0.07	0.16	0.06	0.08	0.06	0.07	1.24	0.11
Al ₂ O ₃	2.08	1.76	1.61	1.84	1.47	1.54	19.1	2.97
Cr ₂ O ₃	0.53	1.40	0.75	0.69	0.63	0.75	0.05	0.48
FeO	11.1	15.3	12.1	10.8	14.9	11.3	12.8	13.5
MgO	36.4	32.9	35.4	36.7	33.3	35.9	25.6	28.9
MnO	0.10	0.25	0.11	0.11	0.13	0.09	0.43	0.10
NiO	0.20	0.31	0.35	0.22	0.37	0.22	0.01	0.37
CaO	0.86	0.33	0.53	0.46	1.00	0.30	0.66	3.79
K ₂ O	-	-	-	-	-	-	-	-
Na ₂ O	-	0.02	0.01	0.01	0.03	-	0.01	0.00
LOI	11.6	11.0	13.3	13.0	11.1	10.9	11.2	13.1
Sum	100.44	100.42	100.87	101.16	100.8	100.47	99.40	99.63
Ba	5	8	5	6	11	5	16	78
Co	125	150	170	135	200	135	40	210
Cu	45	1130	365	40	390	145	10	635
Ni	1980	2860	3290	2110	3480	2250	150	3540
S (%)	-	.493	.545	.151	.589	0.2	.022	.308
Sr	30	21	38	12	77	38	16	120
V	20	59	-	24	36	20	210	47
Zn	75	215	80	50	85	100	170	65
Zr	20	96	37	34	77	20	160	86

Sample #	Hed 150	Hed 165	Hed 175	Hed 195	Hed 205	Hed 218	76-PM-301	76-PM-328
SiO ₂	39.1	39.4	39.9	36.5	39.0	37.1	40.9	43.7
TiO ₂	0.37	0.34	0.29	0.26	0.27	0.25	0.31	0.63
Al ₂ O ₃	4.63	3.68	3.51	3.20	3.03	3.70	4.63	7.44
Cr ₂ O ₃	0.48	0.41	0.44	0.41	0.47	0.39	0.46	0.26
FeO	15.4	13.9	14.4	14.7	14.0	14.2	12.9	16.7
MgO	27.3	28.0	29.6	29.6	26.9	32.5	27.7	18.4
MnO	0.17	0.20	0.16	0.23	0.19	0.14	0.20	0.15
NiO	0.12	0.11	0.12	0.12	0.12	0.12	0.21	0.08
CaO	2.68	3.21	1.15	2.58	4.08	0.32	3.51	5.14
K ₂ O	-	-	-	-	-	-	-	-
Na ₂ O	0.13	0.01	0.01	0.01	0.01	0.01	0.26	0.55
LOI	8.53	10.6	9.67	12.1	11.3	10.7	7.93	4.93
Sum	98.91	99.86	99.25	99.71	99.37	99.43	99.01	97.98
Ba	6	5	5	5	5	5	17	32
Co	140	135	145	140	150	120	160 **	140 **
Cu	30	25	10	35	65	10	30	50
Ni	1220	1130	1190	1140	1220	1150	1200	815
S (%)	.1	.1	.1	.1	.1	.2		
Str	13	44	10	74	44	17	18	14
V	84	67	59	50	40	41	92	120
Zn	105	100	100	90	100	95	85	90
Zr	21	20	20	20	20	20	110	110

Sample #	Hed 150	Hed 165	Hed 175	Hed 195	Hed 205	Hed 218	76-PM-301	76-PM-328
SiO ₂	39.1	39.4	39.9	36.5	39.0	37.1	40.9	43.7
TiO ₂	0.37	0.34	0.29	0.26	0.27	0.25	0.31	0.63
Al ₂ O ₃	4.63	3.68	3.51	3.20	3.03	3.70	4.63	7.44
Cr ₂ O ₃	0.48	0.41	0.44	0.41	0.47	0.39	0.46	0.26
FeO	15.4	13.9	14.4	14.7	14.0	14.2	12.9	16.7
MgO	27.3	28.0	29.6	29.6	26.9	32.5	27.7	18.4
MnO	0.17	0.20	0.16	0.23	0.19	0.14	0.20	0.15
NiO	0.12	0.11	0.12	0.12	0.12	0.12	0.21	0.08
CaO	2.68	3.21	1.15	2.58	4.08	0.32	3.51	5.14
K ₂ O	-	-	-	-	-	-	-	-
Na ₂ O	0.13	0.01	0.01	0.01	0.01	0.01	0.26	0.55
LOI	8.53	10.6	9.67	12.1	11.3	10.7	7.93	4.93
Sum	98.91	99.86	99.25	99.71	99.37	99.43	99.01	97.98
Ba	6	5	5	5	5	5	17	32
Co	140	135	145	140	150	120	160 **	140 **
Cu	30	25	10	35	65	10	30	50
Ni	1220	1130	1190	1140	1220	1150	1200	815
S(%)	.1	.1	.1	.1	.1	.2		
Sr	13	44	10	74	44	17	18	14
V	84	67	59	50	40	41	92	120
Zn	105	100	100	90	100	95	85	90
Zr	21	20	20	20	20	20	110	110

Sample #	30468-1010	30468-1030	36551-130	36551-230	36551-330	36551-440	76-PM-19	76-PM-20
SiO ₂	37.9	37.4	31.0	28.3	35.4	44.2	45.9	46.2
TiO ₂	0.19	0.21	0.06	0.06	0.07	0.30	0.77	0.61
Al ₂ O ₃	4.38	4.27	1.09	1.21	1.68	5.64	7.08	12.6
Cr ₂ O ₃	0.41	0.40	0.57	0.58	1.24	0.45	0.23	0.20
FeO	15.4	13.9	12.7	11.1	14.3	11.1	13.0	11.2
MgO	29.7	27.8	35.7	30.5	34.8	24.0	18.5	13.7
MnO	0.13	0.16	0.17	0.19	0.15	0.13	0.19	0.18
NiO	0.19	0.33	0.30	0.20	0.46	0.16	0.07	0.06
CaO	1.38	1.94	0.88	2.88	0.58	7.40	9.25	9.45
K ₂ O	-	-	-	-	-	-	0.20	1.40
Na ₂ O	0.02	0.01	0.07	-	-	0.23	0.97	1.01
LOI	8.91	9.33	17.3	26.7	10.7	4.56	2.56	2.11
Sum	99.81	96.25	100.54	101.92	100.18	98.37	98.72	98.72
Ba	5	5	5	5	5	5	33	170
Co	210	205	195	150	225	105	100 **	140 **
Cu	85	910	1040	35	405	70	65	105
Ni	1860	3280	3030	1950	4560	1620	710	570
S (%)	1.2	0.5	0.7	0.2	0.8	0.2		
Sr	34	15	36	35	21	14	64	52
V	42	68	20	20	22	73	160	170
Zn	85	85	90	50	110	70	60	70
Zr	20	31	20	20	20	20	97	100

Sample #	76-PM-320	77-PM-75	77-PM-77	77-PM-95	77-PM-111	76-PM-332	76-PM-336	76-PM-284
SiO ₂	44.6	39.8	49.5	49.2	48.3	49.3	44.9	46.5
TiO ₂	0.34	1.56	0.85	1.00	0.77	0.52	0.93	0.78
Al ₂ O ₃	5.59	10.3	13.2	11.6	11.3	13.9	11.8	15.8
Cr ₂ O ₃	0.63	0.06	0.23	0.02	0.08	0.09	0.10	0.05
FeO	12.8	14.7	9.52	9.98	10.8	8.94	12.5	10.8
MgO	24.1	12.3	8.45	9.05	9.43	8.72	11.5	8.55
MnO	0.17	0.23	0.16	0.17	0.19	0.16	0.19	0.17
NiO	0.11	-	-	-	-	-	0.04	0.02
CaO	3.69	14.10	9.37	10.2	14.1	11.5	9.95	11.5
K ₂ O	-	0.98	3.21	2.13	0.75	1.07	0.69	0.29
Na ₂ O	Not determ'd	1.16 ⁺	2.38 ⁺	1.53 ⁺	1.52 ⁺	2.24 ⁺	1.54 ⁺	1.60 ⁺
LOI	6.13	1.27	1.28	1.06	0.84	3.00	3.87	2.89
Sum	98.16	96.86	98.15	95.94	98.08	99.44	98.01	98.95
Ba	N.D.	258	864	2420	173	120	310	660
Co	170 *	40	40	50	10	60 *	130 *	70 *
Cu	70	55	25	15	10	105	220	90
Ni	1090	95	270	85	25	160	390	205
S (%)	N.D.	0.4	-	0.1	-	N.D.	N.D.	N.D.
Sr	N.D.	719	607	1200	2020	160	470	130
V	N.D.	367	197	215	319	160	120	210
Zn	105	115	80	90	45	55	115	70
Zr	N.D.	63	75	135	68	92	140	96

Sample #	76-PM-R7	76-PM-4	76-PM-10	76-PM-185	77-PM-134	76-PM-316	76-PM-317	G 680 10
SiO ₂	43.4	47.8	46.8	47.9	48.4	50.1	48.3	50.3
TiO ₂	0.92	0.88	0.60	0.87	0.91	1.97	1.12	0.90
Al ₂ O ₃	12.6	13.9	12.2	14.7	14.3	12.7	9.46	17.0
Cr ₂ O ₃	0.03	0.04	0.12	0.04	0.04	-	0.08	0.05
FeO	10.5	12.8	12.1	12.5	11.7	15.2	13.5	9.38
MgO	6.19	8.23	13.0	7.86	7.91	4.63	10.2	5.78
MnO	0.22	0.20	0.16	0.18	0.20	0.25	0.21	0.16
NiO	-	0.07	0.05	0.02	-	-	0.03	0.03
CaO	11.6	10.7	9.39	9.89	10.7	5.57	11.6	7.77
K ₂ O	-	0.63	0.73	0.94	0.48	0.47	0.19	-
Na ₂ O	1.99 ⁺	1.60 ⁺	0.93 ⁺	1.92 ⁺	1.91 ⁺	3.04 ⁺	1.24 ⁺	2.83 ⁺
LOI	12.2	0.71	2.03	0.96	1.06	2.77	3.17	3.33
Sum	99.65	97.56	98.11	97.78	97.61	96.7	99.10	97.53
Ba	25	94	99	100	94	77	71	45
Co	70*	170*	120*	90*	55	70*	100*	30
Cu	155	355	95	60	135	120	220	95
Ni	140	665	485	210	145	65	245	280
S (%)	N.D.	N.D.	N.D.	N.D.	0.1	N.D.	N.D.	0.08
Sr	250	97	69	170	105	180	140	490
V	160	220	200	260	315	180	240	150
Zn	105	70	70	55	75	160	95	90
Zr	160	78	78	68	31	190	150	150

Sample #	76-PM-269	38941-10	45110-880	77-PM-10	77-PM-24	77-PM-8	76-PM-208	77-PM-80
SiO ₂	47.3	40.3	49.9	49.5	45.0	53.8	48.6	55.7
TiO ₂	0.89	0.16	0.73	1.30	0.71	0.71	0.63	0.59
Al ₂ O ₃	16.10	9.23	14.9	12.5	13.7	16.0	16.8	9.75
Cr ₂ O ₃	0.05	0.14	0.03	-	-	0.04	0.05	0.19
FeO	11.1	16.1	8.73	11.3	9.40	7.06	12.5	8.65
MgO	2.92	15.7	6.24	5.69	4.50	4.15	4.62	10.4
MnO	0.22	0.16	0.15	0.18	0.15	0.19	0.15	0.21
NiO	0.05	0.90	-	-	-	-	0.02	0.03
CaO	10.9	6.30	9.56	7.96	11.6	10.4	7.96	9.51
K ₂ O	0.21	0.26	0.44	0.24	0.20	0.68	0.74	1.67
Na ₂ O	1.99 ⁺	0.39	4.21 ⁺	2.36 ⁺	1.79	3.16 ⁺	2.76 ⁺	1.29 ⁺
LOI	7.39	6.69	2.09	6.13	11.0	1.96	2.93	0.80
Sum	99.12	100.33	97.18	97.16	98.05	98.15	97.76	98.79
Ba	76	34	220	93	310	358	210	222
Co	140*	225	35	25	45	35	80*	40
Cu	440	3690	20	25	170	10	175	25
Ni	505	8300	105	105	75	55	210	27
S(%)	N.D.	4.0	0.2	0.1	0.1	-	N.D.	-
Sr	120	28	1360	97	168	678	660	237
V	250	66	191	369	254	105	180	170
Zn	80	70	70	80	55	55	150	80
Zr	120	41	94	101	60	66	190	42

Sample #	76-PM-283	76-PM-286	76-PM-303	76-PM-330	76-PM-331	G 6800 8	G 6800 9	77-PM-71
SiO ₂	53.3	50.7	50.6	50.7	46.9	49.0	50.0	46.9
TiO ₂	0.89	1.89	1.00	1.00	1.07	1.96	1.15	1.90
Al ₂ O ₃	11.3	12.5	13.3	13.5	11.6	12.5	13.9	14.7
Cr ₂ O ₃	0.03	0.01	0.02	0.02	-	0.05	0.04	0.02
FeO	11.1	14.8	12.1	12.3	17.8	15.1	12.2	13.0
MgO	5.22	4.73	6.82	6.75	6.43	5.37	6.98	6.41
MnO	0.16	0.26	0.23	0.20	0.25	0.21	0.18	0.22
NiO	0.07	0.02	0.02	0.01	-	0.01	-	-
CaO	10.5	6.52	9.85	7.92	9.23	8.30	6.88	7.83
K ₂ O	0.28	0.50	0.14	0.55	0.17	0.18	0.22	0.45
Na ₂ O	1.63 ⁺	2.96 ⁺	2.11 ⁺	3.40 ⁺	1.58 ⁺	1.74 ⁺	3.38 ⁺	2.42 ⁺
LOI	2.91	2.40	2.09	1.69	1.51	2.32	2.23	2.71
Sum	97.39	97.29	98.28	98.04	96.54	96.74	97.16	96.56
Ba	130	93	56	94	32	24	67	59
Co	80	90	80	80	110	40	40	45
Cu	260	165	165	150	145	90	130	80
Ni	655	150	130	115	80	165	135	120
S (%)	N.D.	N.D.	N.D.	N.D.	N.D.	.09	.03	-
Sr	140	130	140	100	91	61	95	140
V	220	180	220	220	220	200	270	231
Zn	80	140	90	100	120	140	75	120
Zr	180	200	130	150	140	180	98	100

Sample #	76-PM-55	76-PM-213	76-PM-270	76-PM-R13	77-PM-73	77-PM-107	77-PM-113
SiO ₂	63.8	64.4	61.6	60.4	59.7	71.7	65.3
TiO ₂	0.39	0.38	0.36	0.66	0.51	0.27	0.36
Al ₂ O ₃	16.7	16.3	17.3	14.3	16.5	12.7	15.4
Cr ₂ O ₃	-	-	-	0.02	-	-	0.01
FeO	4.17	3.49	4.00	6.82	3.65	2.25	3.14
MgO	1.81	1.47	0.84	2.99	1.84	0.93	1.85
MnO	0.06	0.04	0.07	0.10	0.09	0.04	0.07
NiO	-	-	-	-	-	-	-
CaO	4.45	2.05	2.89	5.18	3.63	1.74	2.95
K ₂ O	1.21	1.95	2.40	-	5.90	4.06	3.59
Na ₂ O	4.60 ⁺	5.71 ⁺	5.13 ⁺	4.87 ⁺	4.34 ⁺	3.96 ⁺	4.63 ⁺
LOI	1.27	2.44	3.01	1.67	2.04	0.93	1.06
Sum	98.46	98.23	97.60	97.01	98.60	98.58	98.36
Ba	390	720	900	80	2100	266	1700
Co	50	50	50	60	15	40	10
Cu	80	35	85	295	15	100	10
Ni	100	40	100	320	20	120	35
S(%)	N.D.	N.D.	N.D.	N.D.	0.4	0.1	-
Sr	530	320	810	280	773	388	808
V	64	61	60	140	85	47	66
Zn	50	55	60	55	60	80	65
Zr	160	110	240	160	200	65	57

Sample #	76-PM-55	76-PM-213	76-PM-270	76-PM-R13	77-PM-73	77-PM-107	77-PM-113
SiO ₂	63.8	64.4	61.6	60.4	59.7	71.7	65.3
TiO ₂	0.39	0.38	0.36	0.66	0.51	0.27	0.36
Al ₂ O ₃	16.7	16.3	17.3	14.3	16.5	12.7	15.4
Cr ₂ O ₃	-	-	-	0.02	-	-	0.01
FeO	4.17	3.49	4.00	6.82	3.65	2.25	3.14
MgO	1.81	1.47	0.84	2.99	1.84	0.93	1.85
MnO	0.06	0.04	0.07	0.10	0.09	0.04	0.07
NiO	-	-	-	-	-	-	-
CaO	4.45	2.05	2.89	5.18	3.63	1.74	2.95
K ₂ O	1.21	1.95	2.40	-	5.90	4.06	3.59
Na ₂ O	4.60 ⁺	5.71 ⁺	5.13 ⁺	4.87 ⁺	4.34 ⁺	3.96 ⁺	4.63 ⁺
LOI	1.27	2.44	3.01	1.67	2.04	0.93	1.06
Sum	98.46	98.23	97.60	97.01	98.60	98.58	98.36
Ba	390	720	900	80	2100	266	1700
Co	50	50	50	60	15	40	10
Cu	80	35	85	295	15	100	10
Ni	100	40	100	320	20	120	35
S (%)	N.D.	N.D.	N.D.	N.D.	0.4	0.1	-
Sr	530	320	810	280	773	388	808
V	64	61	60	140	85	47	66
Zn	50	55	60	55	60	80	65
Zr	160	110	240	160	200	65	57

Sample #	76-PM-292a	76-PM-2926b	76-PM-R15	76-PM-R6	77-PM-15	77-PM-132	77-PM-133
SiO ₂	61.0	55.8	55.9	63.7	64.3	58.6	60.6
TiO ₂	0.64	0.71	0.74	0.54	0.52	0.74	0.61
Al ₂ O ₃	13.0	16.1	15.4	12.6	16.1	15.7	16.8
Cr ₂ O ₃	0.03	0.02	0.03	0.02	-	-	0.01
FeO	6.51	7.68	6.64	4.99	3.08	6.02	4.80
MgO	2.77	3.75	4.43	3.87	1.28	2.43	1.87
MnO	0.16	0.11	0.14	0.08	0.04	0.08	0.08
NiO	-	-	-	-	-	-	-
CaO	6.29	6.50	5.72	4.13	3.86	3.78	3.78
K ₂ O	1.73	1.39	1.20	0.59	2.73	0.51	0.64
Na ₂ O	3.23 ⁺	3.77 ⁺	2.71 ⁺	3.38 ⁺	3.36	N.D.	4.70
LOI	3.15	2.17 ⁺	5.47	4.40	2.93	2.57	2.44
Sum	98.51	98.0	98.38	98.30	98.20	90.43	97.53
Ba	610	460	360	200	889	474	440
Co	50 ⁺	50 ⁺	50 ⁺	50 ⁺	10	25	15 ⁺
Cu	105	60	40	110	30	80	40
Ni	115	80	135	195	20	60	40
S(%)	N.D.	N.D.	N.D.	N.D.	-	-	0.2
Sr	510	810	370	220	827	998	948
V	130	130	140	94	81	127	65
Zn	60	85	65	40	70	85	75
Zr	190	160	170	170	79	89	54

Sample #	76-PM-218	76-PM-261	76-PM-307
SiO ₂	58.4	55.3	65.9
TiO ₂	0.04	0.14	0.03
Al ₂ O ₃	0.86	5.56	0.65
Cr ₂ O ₃	-	-	-
FeO	32.9	20.2	27.0
MgO	1.24	1.42	1.30
MnO	0.05	0.14	0.04
NiO	-	-	-
CaO	1.08	8.09	0.80
K ₂ O	0.26	-	0.17
Na ₂ O	0.34	0.05	N.D.
LOI	0.17	7.60	0.35
Sum	95.34	98.50	96.24
Ba	38	21	N.D.
Co	90*	80*	80*
Cu	75	40	75
Ni	65	45	50
S (%)	N.D.	N.D.	N.D.
Sr	38	22	N.D.
V	-	-	N.D.
Zn	40	125	45
Zr	130	150	N.D.

Table AII-IV:
Normative Mineralogy

Sample	G-11	G-12	G-14	G-13	G-15	G-16	77-90	77-120	77-140	G-17	G-18	G-19
Quartz	-	-	-	-	-	-	-	-	-	-	-	-
Corundum	2.96	3.04	-	-	-	1.35	1.81	0.24	0.58	1.26	0.72	1.12
Orthoclase	-	-	8.62	-	10.55	-	-	-	-	-	-	-
Albite	0.37	0.47	11.07	4.88	13.06	0.19	-	-	-	0.19	0.10	0.10
Anorthite	12.18	6.02	26.67	20.87	24.79	5.49	3.62	11.00	4.80	1.84	3.01	2.59
Diopside	-	-	6.85	11.93	11.22	-	-	-	-	-	-	-
Hedenbergite	-	-	3.09	3.63	5.41	-	-	-	-	-	-	-
Enstatite	18.27	19.57	6.05	16.77	4.31	15.69	21.10	25.96	12.52	16.13	12.95	14.29
Ferrosilite	5.45	5.70	3.13	5.85	2.38	4.80	6.24	7.13	2.81	5.04	2.94	2.98
Forsterite	44.69	48.22	19.89	24.07	16.63	53.07	45.57	41.45	62.73	53.09	61.71	62.70
Fayalite	14.68	15.49	11.36	9.26	10.13	17.80	14.86	12.54	15.53	18.29	15.45	14.42
Ilmenite	0.48	0.32	0.85	0.69	1.07	0.56	0.53	0.40	0.15	0.34	0.13	0.17
Chromite	0.65	0.87	0.27	0.66	0.26	0.67	0.73	0.66	0.88	2.31	1.27	1.15
Pyrrhotite	0.27	0.31	2.16	1.38	0.20	0.28	5.54	0.61	-	1.51	1.73	0.47
Nepheline	-	-	-	-	-	-	-	-	-	-	-	-
Larnite	-	-	-	-	-	-	-	-	-	-	-	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	0.37	0.47	19.68	4.88	23.60	0.19	0.00	0.00	0.00	0.19	0.10	0.10

Sample	G-20	77-280	G-22	G-23	G-24	G-26	G-25	G-27	77-400	77-420	G-28	Hed-150
Quartz	-	-	-	-	-	-	-	-	-	-	-	-
Corundum	-	1.11	-	-	0.45	-	-	-	-	10.39	-	-
Orthoclase	-	-	-	11.50	-	0.76	-	-	-	-	-	-
Albite	0.29	-	-	2.75	0.47	3.63	0.64	3.39	-	-	3.11	1.22
Anorthite	4.37	1.66	9.38	38.85	18.28	27.24	20.16	10.31	16.90	11.23	11.11	13.33
Diopside	0.77	-	7.71	9.51	-	9.70	11.08	29.24	14.03	-	3.37	0.82
Hedenbergite	0.21	-	2.22	3.04	-	2.54	2.43	4.42	8.95	-	1.08	0.29
Enstatite	11.48	23.4	6.46	-	16.53	14.45	22.24	22.09	19.42	20.70	20.87	17.43
Ferrosilite	3.49	5.16	2.13	-	4.72	4.33	5.58	3.83	14.22	6.31	7.69	7.02
Forsterite	57.24	53.63	51.37	22.82	43.85	27.32	28.61	20.83	13.80	13.47	35.84	40.21
Fayalite	19.16	13.04	18.69	9.23	13.79	9.03	7.92	3.98	11.13	12.58	14.55	17.84
Ilmenite	0.13	0.15	0.24	0.46	0.21	0.41	0.31	0.30	0.95	1.06	1.40	0.78
Chromite	1.05	1.24	0.81	0.42	0.95	0.49	0.49	0.51	0.61	0.26	0.75	0.78
Pyrrhotite	1.82	0.61	0.98	0.09	0.76	0.12	0.53	1.10	-	-	0.24	0.30
Nepheline	-	-	-	1.34	-	-	-	-	-	-	-	-
Larnite	-	-	-	-	-	-	-	-	-	-	-	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	0.29	0.00	6.00	15.59	0.47	4.39	0.64	3.39	0.00	0.00	3.11	1.22

Sample	Hed 165	Hed 175	Hed 195	Hed 205	Hed 218	76-301	76-328	30468-1010	30468-1030	36551-130	36551-230	36551-330
Quartz	-	-	-	-	-	-	-	-	-	-2.15	-2.02	-
Corundum	-	1.57	-	-	3.49	-	-	2.04	0.84	-	-	0.70
Orthoclase	-	-	-	-	-	-	-	-	-	-	-	-
Albite	0.10	0.09	0.10	0.10	0.10	2.42	5.00	0.19	0.10	-	-	-
Anorthite	11.19	6.37	9.91	9.33	1.79	2.59	19.17	7.58	11.11	3.21	4.40	3.23
Diopside	4.07	-	2.87	8.27	-	4.04	4.29	-	-	-	-	-
Hedenbergite	1.26	-	0.90	2.69	-	1.20	2.43	-	-	-	-	-
Enstatite	19.44	27.92	9.82	17.00	19.66	18.97	23.57	22.10	21.68	-	-	9.43
Ferrosilite	6.90	9.73	3.52	6.35	6.07	6.47	15.34	6.95	7.41	-	-	2.49
Forsterite	39.77	38.07	51.11	38.67	50.08	38.47	16.60	41.91	40.79	75.2	70.9	61.58
Fayalite	15.56	14.62	20.20	15.91	17.03	14.46	11.91	14.52	15.36	19.3	20.2	17.91
Ilmenite	0.72	0.62	0.56	0.58	0.54	0.65	1.29	0.40	0.46	0.14	0.15	0.15
Chromite	0.68	0.72	0.69	0.79	0.65	0.74	0.41	0.67	0.68	1.01	1.14	2.05
Pyrrhotite	0.31	0.31	0.31	0.31	0.62	-	-	3.64	1.58	2.32	0.73	2.46
Nepheline	-	-	-	-	-	-	-	-	-	0.39	-	-
Larnite	-	-	-	-	-	-	-	-	-	0.64	4.53	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	0.09	0.09	0.10	0.10	0.10	2.42	5.00	0.19	0.10	-1.76	-2.02	0.00

36551-
440

Sample

Quartz

Corundum

Orthoclase

Albite

Anorthite

Diopside

Hedenbergite

Enstatite

Ferrosilite

Forsterite

Fayalite

Ilmenite

Chromite

Pyrrhotite

Nepheline

Larnite

Leucite

D.I.

	76-19	76-20	76-320	77-75	77-95	77-111	76-332	76-336	76-284	76 R7	76-4
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	1.23	8.57	-	-	13.27	4.40	6.56	4.34	1.79	-	3.85
2.08	8.54	8.85	-	-	13.64	12.75	19.65	13.84	14.99	19.25	13.98
15.32	14.95	26.61	16.58	20.97	19.48	28.65	25.62	24.69	36.60	29.10	29.83
14.92	18.52	11.83	2.00	15.78	16.89	19.68	16.81	13.68	10.64	15.07	10.59
4.18	8.03	5.99	0.67	10.40	10.82	13.77	10.65	9.06	8.21	15.47	10.15
20.53	10.27	5.45	38.97	-	7.30	1.00	2.07	2.86	6.54	3.40	8.47
6.59	5.10	3.17	14.87	-	5.37	0.80	1.51	2.18	5.79	4.01	9.30
25.47	20.37	17.08	17.74	17.38	6.03	9.23	8.86	14.87	7.49	5.07	5.46
9.01	11.16	10.94	7.46	14.47	4.89	8.16	7.10	12.45	7.31	6.58	6.60
0.61	1.52	1.20	0.70	3.11	2.00	1.45	1.02	1.88	1.54	2.00	1.73
0.71	0.31	0.31	1.01	0.09	0.03	0.12	0.14	0.16	0.08	0.05	0.06
0.59	-	-	-	1.15	0.29	-	-	-	-	-	-
-	-	-	-	5.57	-	-	-	-	-	-	-
-	-	-	-	6.33	-	-	-	-	-	-	-
-	-	-	-	4.76	-	-	-	-	-	-	-
2.08	9.77	17.42	0.00	10.34	26.91	17.15	26.21	18.18	15.88	19.25	17.82

Sample	76-10	76-185	77-134	76-316	76-317	G-10	76-269	38941 10	45110 880	77-10	77-24	77-8
Quartz	-	-	-	2.09	-	2.43	2.88	-	-	4.63	1.39	4.20
Corundum	-	-	-	-	-	-	-	-	-	-	-	-
Orthoclase	4.49	5.79	2.96	3.04	1.19	-	1.35	1.68	2.74	1.58	1.36	4.18
Albite	8.19	17.94	17.86	29.82	11.77	26.99	18.35	3.33	33.49	23.61	17.39	27.79
Anorthite	28.06	29.8	30.24	21.44	20.81	35.79	37.48	24.90	21.54	25.42	33.02	28.55
Diopside	10.56	8.85	10.96	2.50	18.09	2.19	5.52	5.60	13.01	7.15	12.35	10.32
Hedenbergite	6.12	8.61	9.66	4.75	14.48	2.09	12.82	1.82	10.41	8.15	15.33	10.55
Enstatite	13.87	6.16	9.18	11.12	13.70	14.26	5.37	27.27	-	12.24	7.14	5.96
Ferrosillite	9.22	6.88	9.27	24.22	12.58	15.57	14.30	10.19	-	16.01	10.18	6.98
Forsterite	10.46	6.98	4.30	-	3.08	-	-	8.99	7.24	-	-	-
Fayalite	7.66	8.58	4.79	-	3.11	-	-	3.70	7.32	-	-	-
Ilmenite	1.19	1.71	1.79	3.98	2.22	1.81	1.84	0.33	1.46	2.71	1.55	1.40
Chromite	0.18	0.06	0.06	-	0.12	0.08	0.08	0.25	0.05	-	-	0.06
Pyrrhotite	-	-	0.28	-	-	0.23	-	11.98	0.56	0.30	0.32	-
Nepheline	-	-	-	-	-	-	-	-	2.17	-	-	-
Larnite	-	-	-	-	-	-	-	-	-	-	-	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	12.68	22.52	19.67	32.54	12.11	28.03	22.59	5.01	38.40	28.40	20.13	36.17

Sample	77-208	77-80	30436 620	76-283	76-286	76-303	76-330	76-331	G-8	G-9	77-71	76-55
Quartz	-	5.88	16.49	10.61	2.28	1.87	-	-	4.84	-	-	17.58
Corundum	-	-	4.97	-	-	-	-	-	-	-	-	-
Orthoclase	4.62	10.08	9.98	1.75	3.12	0.86	3.38	1.06	1.13	1.37	2.84	7.36
Albite	24.62	11.14	28.46	14.60	26.39	18.56	29.86	14.07	15.58	30.12	21.82	40.05
Anorthite	32.97	16.20	17.44	24.02	20.39	27.45	20.71	25.32	27.28	23.29	29.75	21.96
Diopside	2.74	17.19	-	11.37	4.12	9.36	7.95	7.14	5.31	5.17	4.52	0.27
Hedenbergite	4.60	8.79	-	14.73	7.50	10.10	8.79	12.21	8.47	5.38	5.21	0.37
Enstatite	7.21	18.46	9.54	8.49	10.50	13.32	7.15	10.85	11.70	11.35	10.49	4.52
Ferrosilite	13.90	10.83	11.40	12.61	21.90	16.48	9.07	21.27	21.42	13.50	13.88	7.14
Forsterite	2.56	-	-	-	-	-	4.63	1.88	-	3.20	3.10	-
Fayalite	5.44	-	-	-	-	-	6.47	4.07	-	4.19	4.52	-
Ilmenite	1.26	1.14	1.72	1.79	3.78	1.97	1.97	2.14	3.94	2.30	3.85	0.76
Chromite	0.08	0.29	-	0.05	0.02	0.03	0.03	-	0.08	0.06	0.03	-
Pyrrhotite	-	-	-	-	-	-	-	-	0.26	0.09	-	-
Nepheline	-	-	-	-	-	-	-	-	-	-	-	-
Larnite	-	-	-	-	-	-	-	-	-	-	-	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	29.24	27.10	54.93	26.96	31.79	21.29	33.23	15.12	21.56	31.49	24.65	64.99

Sample	76-213	76-270	76 R 13	77-73	77-107	77-113	76 292a	76 292b	76 R 15	76-R 6	77-15	77-133
Quartz	15.10	12.68	13.72	1.45	27.93	14.38	15.93	5.29	12.94	25.55	22.99	13.53
Corundum	1.12	1.07	-	-	-	-	-	-	-	-	0.63	0.44
Orthoclase	12.04	15.01	-	36.20	24.58	21.82	10.86	8.58	7.64	3.72	16.95	10.21
Albite	50.43	45.89	43.22	38.09	34.29	40.26	30.77	33.29	24.68	30.46	29.84	41.86
Anorthite	10.62	15.16	18.00	8.40	4.99	10.92	16.84	23.90	28.32	18.60	20.10	19.74
Diopside	-	-	3.19	4.68	1.42	1.71	5.61	3.67	0.98	1.51	-	-
Hedenbergite	-	-	4.33	3.80	1.79	1.71	7.92	4.49	0.87	1.15	-	-
Enstatite	3.82	2.21	6.33	2.71	1.71	3.94	4.63	8.04	11.42	9.57	3.35	4.90
Ferrosilite	6.11	7.28	9.87	2.52	2.47	4.53	7.50	11.30	11.60	8.34	5.11	7.50
Forsterite	-	-	-	-	-	-	-	-	-	-	-	-
Fayalite	-	-	-	-	-	-	-	-	-	-	-	-
Ilmenite	0.75	0.72	1.32	1.01	0.53	0.70	1.28	1.41	1.51	1.09	1.04	1.22
Chromite	-	-	0.03	-	-	0.02	0.05	0.03	0.05	0.03	-	0.02
Pyrrhotite	-	-	-	1.14	0.28	-	-	-	-	-	-	0.58
Nepheline	-	-	-	-	-	-	-	-	-	-	-	-
Lamnite	-	-	-	-	-	-	-	-	-	-	-	-
Leucite	-	-	-	-	-	-	-	-	-	-	-	-
D.I.	77.58	73.57	56.93	75.74	86.80	76.46	56.38	47.16	45.26	59.72	69.78	65.60

[illegible]

Appendix III

Electron Microprobe Analyses

Appendix III: Mineral Composition

All electron microprobe analyses of silicates and sulphides were performed on a Cambridge MK 5 electron microprobe at Carleton University using the correction program of Rucklidge and Gasparrini (1969). Of the sections analyzed for chromite, 36 were done at Carleton University and 12 were performed on a Cameca MS 46 microprobe at B.R.G.M., Orleans, France. All oxide analyses were recalculated assuming stoichiometry using ILMAG, a program written by Paul Mainwaring.

The X-ray lines and standards used for sulphides were $\text{CuK}\alpha_1$ in covellite, $\text{FeK}\alpha_1$ and $\text{SK}\alpha_1$ in pyrite, $\text{NiK}\alpha_1$ and $\text{CoK}\alpha_1$ in cobalt bearing pentlandite, and $\text{ZnK}\alpha_1$ in sphalerite. A nickeliferous pyrrhotite was used as an internal standard in the analysis of each sample. Analyses of sulphides are tabulated in Table AIII-II. A legend for the analyses is reported in Table AIII-I.

Coexisting orthopyroxene, clinopyroxene and olivine were analyzed in section 30401-300. Clinopyroxene and basaltic hornblende were analyzed in 30401-500 (Table AIII-III). X-ray lines and standards used were: $\text{SiK}\alpha_1$, $\text{MgK}\alpha_1$, and $\text{CaK}\alpha_1$ in Boettcher pyroxene; $\text{AlK}\alpha_1$ in jadeite; $\text{FeK}\alpha_1$ in pure iron; $\text{TiK}\alpha_1$ in ilmenite; $\text{MnK}\alpha_1$ in R1596 and $\text{CrK}\alpha_1$ in chromite. All analyses were done at 15 KV and 0.5×10^{-7} amp., and they are tabulated in Table AIII-III. Analyses 1-4 are orthopyroxene, 6-9 clinopyroxene and 11-13 olivine in 30401-300. 1-4 and 5-6 in 30401-500 are respectively clinopyroxene and basaltic hornblende.

All chromite analyses are listed in Table AIII-IV. Analyses performed at Carleton were done at 15KV. X-ray lines and standards used were $\text{CrK}\alpha_1$, $\text{AlK}\alpha_1$, $\text{MgK}\alpha_1$, in chromite (when Al_2O_3 was greater than 12-13 weight percent; jadeite was used as the Al standard); $\text{FeK}\alpha_1$ in pure iron; and $\text{MnK}\alpha_1$, $\text{TiK}\alpha_1$ in Smith ilmenite.

Twelve samples were analyzed in France. They are: #1 shaft, 30414-240, R16, R22, R23, 76-PM-19, 9445-390, 48806-460, 38921-0, 30442-1400, 26399-420, and 30431-440. For purposes of comparison, 30414-240 was reanalyzed at Carleton University. A comparison of average values for each and a direct comparison of the most Cr_2O_3 rich grain in each ore analyzed is as follows:

	France Average (6)	Carleton Average (5)	France	Carleton
FeO	17.5	22.2	18.8	17.8
MgO	10.5	8.44	10.1	11.0
MnO	.19	.43	.17	.21
Al_2O_3	14.6	12.3	12.2	13.0
Cr_2O_3	43.9	42.4	48.4	45.8
Fe_2O_3	12.4	12.3	11.5	11.4
TiO_2	.25	1.88	.25	.97

Marked differences occur in TiO_2 , FeO, MgO and Al_2O_3 contents for the averaged grains. This is probably a reflection of the grains analyzed. Because the most Cr_2O_3 rich (and probably most Mg-rich) is probably the least altered chromite grain, they are the best grains to compare. Results are favourable, with the exception of TiO_2 content.

All MnO values in chromite were corrected because $K_{\beta_1}\text{Cr}$ and $K_{\alpha_1}\text{Mn}$ wavelengths overlap. Counts on chromite (61% Cr_2O_3) and pure Cr metal were recorded for $K_{\alpha_1}\text{Mn}$. Using Smith ilmenite as a standard, chromite yields 0.45% MnO and Cr, 1.45 wt% MnO. MnO values were corrected in Shebandowan chromite (10-45% Cr_2O_3) by a factor of ~ 0.3 wt% MnO.

Table AIII-I

<u>Sample Number</u>	<u>Location</u>	<u>Ore Type</u>	<u>Assemblage</u>	<u>Minerals Analyzed</u>
SH-50	800L, STOPE 2340	Stringer Ore-Py	Py-Cp-Po-Pn-Mt	Po 1, 2; Pn 1-7; Py 1-10; Cp 1-3
SH-52	800L, STOPE 2340	Pn. Zone, Massive Ore	Py-Cp-Sp-Po-Pn (mt)	Po 3-6; Pn 12-13; Py 15-17; Sp 1-3; Cp 9-12
SH-54	800L, STOPE 2340	Typical Massive Ore	Po-Pn-Cp-(Py-Mt)	Po 7-12; Pn 14-17; Py 18-21; Cp 13-14
SH-55	800L, STOPE 2340	Sulphide in Inclusions in Massive Ore	Py-Cp-Po-Pn	Po 13-15; Pn 18-22; Py 22-28; Cp 15-18
SH-3	800L, 20,000 E	Massive Ore--high % Ni	Po-Pn-Cp-Mt-Py	Po 16-19; Pn 23-29, Py 29-33
SH-9A	800+76L, 2340 STOPE	High grade Cp zone (28% Cu, 2% Ni)	Cp-Po-(Pn-Mt) + Pd min.	Po 20-22; Pn 30-31
SH-6A	800+76L, 2340 STOPE	High grade Cp zone Bx-sulphide ore	Po-Cp-(Pn-Mt) [Py] + Pd min.	Po 23-25, Pn 32-34
SH-14	800+38L, 2340 STOPE	High grade Cp ore	Cp-Pn-Po-Py (+Pd min.)	Pn 8-11; Py 11-14; Cp 4-8

Table AIII-II
Sulphide Analyses

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PYRRHOTITE

	1	2	3	4	5	6
Fe	59.8	59.7	58.9	59.1	59.2	58.9
S	38.6	38.7	39.0	39.2	39.2	39.3
Co	-	.10	.14	.17	.12	.12
Ni	.51	.55	.47	.60	.58	.48
Cu	.19	.14	-	-	-	.53
Zn	-	-	-	-	-	-
Total	99.10	99.19	98.51	99.07	99.10	99.33

	7	8	9	10	11	12
Fe	59.6	59.6	59.4	59.6	59.5	59.4
S	39.2	39.2	39.2	39.3	39.5	39.4
Co	.12	.11	.13	.14	.11	.10
Ni	.37	.35	.41	.28	.30	.47
Cu	.09	-	-	-	-	-
Zn	-	-	-	-	-	-
Total	99.38	99.26	99.14	99.32	99.41	99.37

	13	14	15	16	17	18
Fe	59.6	59.8	59.4	60.8	60.4	60.4
S	39.6	39.5	39.6	39.5	39.6	39.4
Co	-	-	-	-	-	-
Ni	.25	.20	.18	.30	.34	.58
Cu	.09	.09	.08	n.d.	n.d.	n.d.
Zn	-	-	.10	n.d.	n.d.	n.d.
Total	99.54	99.59	99.36	100.6	100.34	100.38

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PYRRHOTITE

	19	20	21	22	23	24
Fe	59.7	59.8	61.4	61.3	60.5	60.4
S	39.7	39.0	40.1	40.1	39.4	39.4
Co	-	.11	.12	.13	.11	.08
Ni	.35	.37	.28	.40	.59	.51
Cu	n.d.	.22	-	-	-	-
Zn	n.d.	-	-	-	-	-
Total	99.75	99.50	101.9	101.93	100.60	100.39

	25				
Fe	60.5				
S	39.1				
Co	.09				
Ni	.55				
Cu	-				
Zn	-				
Total	100.24				

Fe					
S					
Co					
Ni					
Cu					
Zn					
Total					

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PENTLANDITE

	1	2	3	4	5	6
Fe	29.3	29.8	28.8	28.9	29.4	30.9
S	32.8	33.0	32.8	32.6	32.7	32.9
Co	-	.08	-	.12	-	.13
Ni	37.2	37.5	37.2	37.0	36.8	35.0
Cu	-	-	-	.42	.27	.23
Zn	-	-	-	.08	.08	-
Total	99.30	100.38	98.80	99.12	99.25	99.16

	7	8	9	10	11	12
Fe	29.2	29.7	28.0	29.4	28.9	29.4
S	32.6	33.2	33.9	33.1	33.3	33.2
Co	.08	.81	.80	.81	.77	1.14
Ni	37.1	35.6	36.8	35.6	35.5	35.1
Cu	.29	.15	.10	.30	.15	.11
Zn	.11	-	-	-	-	.10
Total	99.38	99.46	99.60	99.21	98.62	99.05

	13	14	15	16	17	18
Fe	29.1	29.6	30.0	29.5	29.5	28.9
S	33.0	33.0	32.8	33.1	32.9	33.1
Co	1.22	1.02	1.02	1.07	.96	-
Ni	35.1	36.6	35.5	35.6	36.0	37.3
Cu	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	98.42	100.22	99.32	99.27	99.36	99.30

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PENTLANDITE

	19	20	21	22	23	24
Fe	30.7	28.7	28.4	29.2	30.6	30.1
S	33.2	34.2	34.0	33.4	33.3	33.4
Co	-	-	-	-	.82	.80
Ni	36.8	36.3	36.2	36.3	35.8	36.7
Cu	-	.17	.25	1.38	n.d.	n.d.
Zn	.12	.09	.11	.21	n.d.	n.d.
Total	100.82	99.46	98.96	100.49	100.52	101.0

	25	26	27	28	29	30
Fe	30.0	29.2	30.2	29.7	30.2	28.8
S	33.2	33.7	33.4	33.3	33.6	34.5
Co	.71	.78	.83	.75	.78	1.19
Ni	35.7	37.2	36.2	37.2	36.5	34.4
Cu	n.d.	n.d.	n.d.	n.d.	n.d.	.28
Zn	n.d.	n.d.	n.d.	n.d.	n.d.	-
Total	99.61	100.88	100.63	100.95	101.08	99.17

	31	32	33	34		
Fe	29.0	30.9	30.4	30.0		
S	34.4	32.9	33.1	33.1		
Co	1.11	.93	.95	.92		
Ni	35.47	36.8	36.6	36.6		
Cu	-	-	-	-		
Zn	-	-	-	-		
Total	99.98	101.53	101.5	100.62		

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PYRITE

	1	2	3	4	5	6
Fe	46.1	45.4	45.6	46.1	46.2	46.2
S	53.3	53.5	53.3	53.4	53.4	53.5
Co	.83	.96	.65	.23	.20	.21
Ni	.18	-	-	.11	-	.10
Cu	.18	-	-	-	.15	.16
Zn	-	-	-	-	-	-
Total	100.59	99.86	99.55	99.84	99.95	100.17

	7	8	9	10	11	12
Fe	45.1	45.0	45.2	45.7	44.8	46.4
S	53.4	53.6	53.2	52.8	53.7	53.7
Co	1.50	1.34	1.14	.95	1.69	-
Ni	.11	-	-	.10	.20	-
Cu	-	-	-	-	.33	.19
Zn	-	-	-	-	-	-
Total	100.11	99.94	99.54	99.55	100.72	100.29

	13	14	15	16	17	18
Fe	44.9	44.6	45.9	45.7	45.9	44.9
S	53.8	54.0	53.9	53.8	54.0	53.3
Co	1.62	1.41	.88	1.00	1.19	1.59
Ni	-	-	-	-	-	.34
Cu	.47	.23	-	.12	.10	.24
Zn	-	-	-	-	-	-
Total	100.79	100.24	100.68	100.62	101.19	100.37

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

PYRITE

	19	20	21	22	23	24
Fe	45.4	45.8	45.6	46.5	46.8	46.8
S	53.2	53.2	53.3	53.9	53.8	53.7
Co	1.53	1.84	1.12	.53	.17	.12
Ni	.20	-	-	-	.16	-
Cu	.20	-	.19	-	-	.12
Zn	-	.15	-	.21	.34	.40
Total	100.53	100.99	100.21	101.14	101.27	101.14

	25	26	27	28	29	30
Fe	46.1	46.7	46.4	46.4	45.0	45.2
S	53.5	53.8	53.8	53.8	53.7	53.7
Co	.25	.10	-	.44	2.11	1.66
Ni	-	-	.34	-	-	-
Cu	.12	.12	-	-	n.d.	n.d.
Zn	.42	.29	.15	.45	n.d.	n.d.
Total	100.39	101.01	100.69	101.09	100.81	100.56

	31	32	33			
Fe	46.0	45.6	45.7			
S	54.1	54.3	54.3			
Co	1.49	1.94	1.08			
Ni	.82	.62	.32			
Cu	n.d.	n.d.	n.d.			
Zn	n.d.	n.d.	n.d.			
Total	102.41	102.46	101.40			

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

SPHALERITE

	1	2	3			
Fe	5.82	5.88	6.15			
S	32.7	32.8	32.9			
Co	-	-	-			
Ni	-	-	-			
Cu	.34	.34	.57			
Zn	63.6	63.9	63.2			
Total	102.46	102.92	102.82			

CHALCOPYRITE

	1	2	3	4	5	6
Fe	29.8	30.4	30.6	30.6	30.5	30.6
S	33.8	34.0	34.6	34.9	34.3	34.3
Co	.15	.15	.17	-	-	-
Ni	-	-	-	-	-	-
Cu	34.1	33.4	33.4	33.9	33.7	33.8
Zn	-	-	-	-	-	-
Total	97.85	97.95	98.77	99.40	98.50	98.70

	7	8	9	10	11	12
Fe	30.6	30.4	30.6	30.5	30.7	30.5
S	34.5	34.7	34.6	34.5	34.5	34.4
Co	-	-	-	-	-	-
Ni	-	-	-	-	-	-
Cu	33.8	33.9	34.0	34.3	34.0	34.1
Zn	-	-	-	-	-	-
Total	98.90	99.0	99.20	99.30	99.20	99.0

ELECTRON MICROPROBE ANALYSES OF SULPHIDE MINERALS

CHALCOPYRITE

	13	14	15	16	17	18
Fe	30.3	30.5	30.6	30.6	30.5	30.5
S	34.6	34.4	34.8	34.9	34.7	34.8
Co	-	.10	-	-	-	-
Ni	-	-	-	-	-	.23
Cu	34.2	33.7	34.1	34.0	34.5	34.0
Zn	-	-	.26	.21	.15	.19
Total	99.10	98.7	99.76	99.71	99.85	99.72

Fe					
S					
Co					
Ni					
Cu					
Zn					
Total					

Fe					
S					
Co					
Ni					
Cu					
Zn					
Total					

Table AIIP-III
Pyroxene, Olivine, and
Hornblende Analyses

	1	2	3	4	5
Sample	30401-300	30401-300	30401-300	30401-300	30401-300 Average
SiO ₂	55.5	55.2	54.8	54.9	55.1
TiO ₂	0.15	0.16	0.24	0.54	0.27
Al ₂ O ₃	0.97	1.19	1.37	1.15	1.17
Cr ₂ O ₃	0.33	0.36	0.44	0.25	0.35
CaO	2.23	1.68	2.16	1.62	1.92
FeO	10.2	11.2	11.3	11.7	11.1
MgO	31.1	31.3	30.6	31.1	31.0
MnO	0.29	0.25	0.31	0.31	0.29
Sum	100.77	101.34	101.22	101.57	101.20

Recalculated on the basis
of 6 oxygens

Si	1.949	1.935	1.929	1.927	1.935
Al	.040	.049	.057	.048	.048
Al	-	-	-	-	-
Cr	.009	.010	.012	.007	.009
Ca	.084	.063	.082	.061	.072
Fe	.301	.329	.331	.342	.326
Mg	1.627	1.634	1.605	1.625	1.622
Mn	.009	.008	.009	.009	.008
Ti	.004	.004	.006	.014	.007
Sum	2.034	2.048	2.045	2.058	2.044

	6	7	8	9	10
Sample	30401-300	30401-300	30401-300	30401-300	30401 Av.
SiO ₂	52.1	52.3	51.5	52.3	52.3
TiO ₂	0.39	0.28	0.29	0.36	0.33
Al ₂ O ₃	2.54	2.10	2.86	2.61	2.53
Cr ₂ O ₃	0.92	0.86	1.02	1.00	0.95
CaO	20.8	20.0	20.1	19.5	20.1
FeO	6.28	6.19	6.15	6.54	6.29
MgO	18.5	18.9	18.3	19.0	18.7
MnO	.22	.22	.23	.25	.23
Sum	101.75	100.85	100.45	101.56	101.43

Recalculated on the basis
of 6 oxygens

Si	1.888	1.905	1.886	1.893	1.896
Al	.109	.090	.114	.107	.104
Al	-	-	.010	.004	.004
Cr	.027	.025	.030	.029	.027
Ca	.807	.780	.788	.756	.780
Fe	.190	.199	.189	.198	.191
Mg	.997	1.028	1.000	1.023	1.009
Mn	.007	.007	.007	.008	.006
Ti	.011	.008	.008	.010	.009
Sum	2.039	2.047	2.032	2.028	2.026

	11	12	13		
Sample	30401-300	30401-300	30401-300		
SiO ₂	39.5	39.5	39.3		
TiO ₂	-	-	-		
Al ₂ O ₃	-	-	-		
Cr ₂ O ₃	-	-	-		
CaO	.09	.09	.08		
FeO	18.0	18.5	18.3		
MgO	44.7	44.7	44.0		
MnO	0.31	0.30	0.36		
Sum	102.60	103.09	102.04		

Recalculated on the basis
of 4 oxygens

Si	.980	.979	.983		
Al	-	-	-		
Al	-	-	-		
Cr	-	-	-		
Ca	.003	.002	.002		
Fe	.374	.384	.384		
Mg	1.654	1.649	1.640		
Mn	.007	.006	.008		
Ti	-	-	-		
Fe	81	81	81		

	1	2	3	4	5
Sample	30401-500	30401-500	30401-500	30401-500	30401-500 Average
SiO ₂	53.8	51.9	52.7	52.1	52.6
TiO ₂	0.17	0.53	0.27	0.31	0.32
Al ₂ O ₃	1.64	2.68	2.24	2.68	2.31
Cr ₂ O ₃	0.58	0.88	0.88	0.97	0.83
CaO	23.6	19.9	19.1	20.6	20.8
FeO	4.31	6.58	6.34	5.73	5.74
MgO	17.6	18.4	19.3	18.6	18.5
MnO	0.18	0.26	0.22	0.18	0.21
Sum	101.88	101.13	101.05	101.17	101.31

Recalculated on the basis
of 6 oxygens

Si	1.936	1.890	1.911	1.892	1.907
Al	.064	.110	.089	.108	.093
Al	.006	.005	.007	.007	.006
Cr	.017	.025	.025	.028	.024
Ca	.909	.776	.743	.800	.807
Fe	.130	.200	.192	.174	.174
Mg	.946	.998	1.041	1.006	.998
Mn	.005	.008	.007	.006	.007
Ti	.005	.015	.007	.009	.009
Sum	2.018	2.027	2.022	2.030	2.025

	6	7			
Sample	30401-500	30401-500			
SiO ₂	47.5	44.0			
TiO ₂	0.97	2.93			
Al ₂ O ₃	7.60	10.8			
Cr ₂ O ₃	0.13	0.92			
CaO	11.8	11.8			
FeO	7.29	7.75			
MgO	19.2	16.9			
MnO	0.09	0.14			
Sum	94.58	95.24			

Recalculated on the basis
of 23 oxygens

Al	6.94	6.447			
Al	1.06	1.553			
Al	.247	.318			
Cr	.015	.106			
Ca	1.842	1.844			
Fe	.890	.949			
Mg	4.180	3.686			
Mn	.011	.017			
Ti	.106	.323			
Sum	7.290	7.243			

Table AIII-IV
Chromite Analyses

AVERAGE
CIRCONITE ANALYSES

CORE R 21	CORE 9445-390	RIM 9445-390	CORE 10442-1400	RIM 10442-1400	CORE 10442-1400	RIM 10442-1400
AV (5)	AV (3)	AV (3)	AV (4)	AV (2)	AV (3)	AV (3)
17.0	20.6	30.9	21.4	29.5	20.2	20.2
11.0	9.07	1.70	8.40	.89	9.54	9.54
.94	.32	.58	.36	.28	.31	.31
.18	-	.14	.36	.56	.23	.23
.11	-	.06	.09	.18	.05	.05
19.8	17.3	16.5	20.2	.74	21.4	21.4
39.3	33.7	36.9	32.2	27.6	38.5	38.5
11.5	12.7	11.7	16.3	41.1	9.46	9.46
.16	.24	.20	.28	-	.11	.11
99.99	99.93	98.68	99.59	100.85	99.80	99.80

OXIDE

COZE 36221-0	RIM 36921-0	CORE 45806-160	RIM 45806-160	CORE R22	30414- 240
AV (8)	AV (8)	AV (3)	AV (3)	AV (3)	AV (6)
31.6	30.5	27.4	29.2	26.8	17.9
1.34	.09	2.97	.13	2.05	10.5
.66	1.01	1.03	1.61	3.46	.19
.22	.08	1.98	.12	.12	.20
.39	.22	.48	.10	.30	.03
18.5	2.75	20.9	1.30	15.7	14.6
32.2	28.2	29.5	26.0	36.6	43.9
14.7	36.4	15.4	39.7	12.6	12.4
.21	.22	.29	.12	.26	.25
99.62	99.49	99.95	98.38	97.97	99.97

OXIDE

FeO	FeO	FeO	FeO	FeO	FeO
MgO	MgO	MgO	MgO	MgO	MgO
MnO	MnO	MnO	MnO	MnO	MnO
NiO	NiO	NiO	NiO	NiO	NiO
ZnO	ZnO	ZnO	ZnO	ZnO	ZnO
Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃
Cr ₂ O ₃	Cr ₂ O ₃	Cr ₂ O ₃	Cr ₂ O ₃	Cr ₂ O ₃	Cr ₂ O ₃
Fe ₂ O ₃	Fe ₂ O ₃	Fe ₂ O ₃	Fe ₂ O ₃	Fe ₂ O ₃	Fe ₂ O ₃
TiO ₂	TiO ₂	TiO ₂	TiO ₂	TiO ₂	TiO ₂
Sum	Sum	Sum	Sum	Sum	Sum

Recalculated on the basis of 32 oxygens

3.602	4.467	7.163	4.629	7.354	4.287
4.169	3.507	.700	3.240	.398	3.411
.202	.071	.136	.078	.072	.067
.036	-	.030	.074	.136	.047
.021	-	.012	.017	.040	.009
8.030	8.061	8.742	8.032	8.000	8.031
5.894	5.296	5.395	6.143	.262	6.410
7.817	8.111	8.074	6.591	6.504	7.716
2.185	2.472	2.445	3.166	9.112	1.809
.070	.016	.043	.054	-	.022
15.968	15.973	15.956	15.953	16.000	15.976

Fe⁺⁺

7.214	7.677	6.124	7.498	6.275	3.878
.547	.041	1.180	.050	.854	4.053
.153	.263	.234	.417	.819	.042
.049	.018	.424	.030	.020	.048
.080	.050	.095	.023	.078	-
8.042	8.049	8.057	8.027	8.055	8.021
5.945	.974	6.552	.471	5.163	4.460
6.952	6.614	6.235	6.302	8.020	9.053
3.015	8.231	3.089	9.172	7.644	2.410
.011	.040	.058	.027	.055	.042
15.955	15.970	15.940	15.972	15.943	15.940

Fe⁺⁺

Mg	Mg	Mg	Mg	Mg	Mg
Mn	Mn	Mn	Mn	Mn	Mn
Ni ⁺⁺	Ni ⁺⁺	Ni ⁺⁺	Ni ⁺⁺	Ni ⁺⁺	Ni ⁺⁺
Zn	Zn	Zn	Zn	Zn	Zn
total	total	total	total	total	total
Al	Al	Al	Al	Al	Al
Cr	Cr	Cr	Cr	Cr	Cr
Fe ⁺⁺⁺	Fe ⁺⁺⁺	Fe ⁺⁺⁺	Fe ⁺⁺⁺	Fe ⁺⁺⁺	Fe ⁺⁺⁺
Ti	Ti	Ti	Ti	Ti	Ti
total	total	total	total	total	total

AVERAGE
CIROMITE ANALYSES

OXIDE	76-PH 19	26399 420-Ti poor	26399 420-Ti rich	26399 420-Ti rich
FeO	30.1	22	34.2	31.8
MgO	.50		1.50	3.80
MnO	1.01		2.65	.62
NiO	-		-	-
ZnO	.49	.07	-	-
Al ₂ O ₃	7.04	12.9	5.39	5.85
Cr ₂ O ₃	44.1	36.7	24.1	28.7
Fe ₂ O ₃	14.6	18.5	24.0	23.1
TiO ₂	.07	.53	7.54	6.29
Sum	97.91	98.51	99.38	100.16

CIROMITE ANALYSES

OXIDE	30414 220	30414 240	30414 260	30414 280	30414 300	30414 320
FeO	23.3	17.9	26.0	20.2	20.6	28.3
MgO	7.06	10.5	5.37	9.12	8.79	3.16
MnO	0.71	0.19	1.11	0.67	1.07	2.91
NiO	0.18	0.20	0.19	0.21	0.09	-
ZnO	0.11	.03	-	-	-	-
Al ₂ O ₃	11.6	14.6	10.2	12.3	11.8	9.97
Cr ₂ O ₃	42.7	43.9	37.5	43.2	40.2	34.8
Fe ₂ O ₃	12.0	12.4	16.4	12.0	14.6	15.2
TiO ₂	1.59	.25	2.44	1.49	1.96	3.86
Sum	99.25	99.97	99.21	99.19	99.11	98.4

Recalculated on the basis of 32 oxygens

Fe**	7.777	7.434	5.005	8.149	7.543
Mg	.014	.222	2.998	.653	1.640
Mn	.059	.252	.054	.055	.149
Ni**	.091	-	.037	-	-
Zn	.065	.106	.015	-	-
total	8.006	8.014	8.109	9.657	9.332
Al	.457	2.447	4.126	1.954	1.955
Cr	7.598	10.289	7.671	5.362	6.436
Fe***	7.931	3.232	3.783	5.272	4.930
Ti	.007	.016	.199	1.655	1.742
total	15.973	15.964	15.609	14.343	14.663

Recalculated on the basis of 32 oxygens

Fe**	5.287	3.878	6.024	4.507	4.631	6.708
Mg	2.858	4.053	2.213	3.628	3.518	1.417
Mn	.164	.042	.260	.151	.242	.698
Ni**	.039	.048	.042	.045	.020	-
Zn	.023	-	-	-	-	-
total	8.370	8.021	8.538	8.132	8.411	8.823
Al	3.712	4.460	3.135	3.059	3.721	3.129
Cr	9.163	2.053	8.206	9.106	8.532	7.794
Fe***	2.443	2.418	3.422	2.412	2.941	3.229
Ti	.355	.049	.503	.229	.117	.221
total	15.641	15.080	15.270	15.177	15.502	15.175

* Analyses done in France - comparison only

AVERAGE
CURCHITE ANALYSES

30414-340	HED 150	HED 165	HED 195	HED 205	HED 218
Av. (9)	Av. (7)	Av. (5)	Av. (7)	Av. (4)	Av. (7)
18.9	31.9	12.2	31.8	34.4	26.6
9.46	1.46	1.39	1.34	0.41	5.15
0.68	1.76	1.97	1.95	1.72	1.31
0.09	0.12	0.10	-	0.09	0.04
0.03	0.13	0.07	-	0.03	0.07
12.9	6.95	8.38	8.06	7.19	10.80
45.2	25.7	25.8	30.2	26.8	34.4
11.7	27.3	24.0	22.1	21.6	15.9
0.35	3.85	4.32	3.51	5.25	3.38
99.31	99.17	98.23	98.96	97.49	97.65

OXIDE

FeO

H₂O

MnO

NiO

ZnO

Al₂O₃Cr₂O₃Fe₂O₃TiO₂

Sum

Recalculated on the basis of 32 oxygens

4.187	7.774	7.846	7.707	8.480	6.239
3.736	.620	.603	.577	.220	2.155
.153	.435	.486	.479	.412	.312
.020	.029	.024	-	.022	.010
.006	.023	.015	-	.007	.014
8.102	8.887	8.975	8.763	9.140	8.730
4.037	2.389	2.876	2.750	2.408	3.351
9.468	5.912	5.915	6.903	5.982	7.636
2.311	5.981	5.266	4.818	5.356	3.354
.079	.014	.045	.764	1.119	.212
15.906	15.126	15.033	15.235	14.865	15.274

Fe**

Mg

Mn

K₂**

Zn

total

Al

Cr

Fe***

Ti

total

CIRCONITE ANALYSES

CIRCONITE ANALYSES

	38921-0	38921-0	38921-0	38921-0	44806-460	44806-460	R22	R23	R23	R23	R23	R23
OXIDE												
FeO	86	87	90	91	94	95	103	126	128	129	130	131
MgO	30.4	31.6	30.3	30.8	28.8	28.4	27.3	16.5	14.6	15.8	20.4	17.7
MnO	.02	.12	.07	.17	2.90	2.67	2.02	11.6	12.3	11.7	9.74	11.0
NiO	.96	.98	.72	1.08	1.11	1.27	3.49	1.43	1.10	.84	.35	.99
ZnO	-	-	-	-	-	1.11	-	-	.08	-	-	-
Al ₂ O ₃	.06	-	.17	.36	.51	.54	.30	.44	.12	-	-	-
Cr ₂ O ₃	.79	3.57	.42	4.10	20.2	20.6	16.5	19.5	20.5	19.6	19.1	20.1
Fe ₂ O ₃	25.4	22.5	20.0	31.8	30.3	29.3	35.5	39.2	39.9	39.6	39.2	38.4
TiO ₂	40.6	42.3	47.2	31.5	14.1	16.1	13.0	11.5	11.6	10.5	11.2	12.5
Sum	.33	.33	.15	.23	.38	.23	.22	.22	.08	.13	.13	.23
	99.56	101.40	99.01	100.04	98.10	100.22	98.31	99.79	101.08	98.17	99.62	100.92

	Recalculated on the basis of 32 oxygens						Recalculated on the basis of 32 oxygens					
Fe ⁺⁺	7.803	7.777	7.776	7.627	6.546	6.351	6.327	3.503	3.031	3.390	4.398	3.709
Mg	.009	.053	.032	.075	1.174	1.063	.836	4.149	4.555	4.452	3.550	4.124
Mn	.250	.244	.187	.271	.255	.287	.821	.308	.231	.182	.076	.210
Ni ⁺⁺	-	-	-	-	-	.238	-	-	.176	-	-	-
Zn	.014	-	.039	.079	.102	.107	.062	.083	.022	-	-	-
total	8.076	8.074	8.034	8.032	8.078	8.046	8.045	8.042	8.014	8.025	8.024	8.043
Al	.286	1.239	.152	1.430	6.463	6.404	5.402	5.836	5.986	5.914	5.796	5.932
Cr	6.179	5.242	4.869	7.417	6.408	6.185	7.790	7.880	7.817	8.005	7.985	7.615
Fe ⁺⁺⁺	9.382	9.371	10.910	7.019	2.881	3.236	2.714	2.198	2.165	2.028	2.167	2.163
Ti	.076	.073	.035	.051	.078	.046	.046	.042	.015	.025	.025	.043
total	15.924	15.926	15.765	15.747	15.920	15.951	15.952	15.956	15.993	15.973	15.973	15.954

CIRONITE ANALYSES

	44806-460	44806-460	44806-460	44806-460	R22	R22
OXIDE	97	96	98	99	100	101
FeO	25.1	28.5	29.2	30.0	26.5	26.7
MgO	3.33	.10	.15	.13	1.99	2.14
MnO	.72	1.76	1.60	1.46	3.47	3.41
NiO	4.82	-	.37	-	.37	-
ZnO	.40	.07	.24	-	.32	.52
Al ₂ O ₃	21.8	1.27	1.85	.79	15.3	15.3
Cr ₂ O ₃	29.1	25.5	26.2	26.3	37.0	37.1
Fe ₂ O ₃	15.9	39.1	39.2	40.9	12.2	12.5
TiO ₂	.25	.03	.15	.17	.27	.30
Sum	101.42	96.33	98.96	99.75	97.42	97.97

Recalculated on the basis of 32 oxygens

Fe ⁺⁺	5.494	7.477	7.411	7.604	6.244	6.254
Mg	1.301	.047	.068	.059	.835	.892
Mn	.160	.467	.412	.375	.827	.808
Ni ⁺⁺	1.016	-	.090	-	.084	-
Zn	.077	.016	.054	-	.067	.107
total	8.048	8.007	8.035	8.038	8.057	8.062
Al	6.724	.469	.662	.282	5.058	5.028
Cr	6.031	6.306	6.301	6.299	8.242	8.211
Fe ⁺⁺⁺	3.144	9.210	8.968	9.340	2.584	2.634
Ti	.049	.007	.034	.039	.057	.061
total	15.949	15.992	15.965	15.961	15.941	15.935

CIROMITE ANALYSES

CIROMITE ANALYSES

	9445-390	9445-390	9445-390	9445-390	9445-390	9445-390	30414-240	30414-240	30414-240	30414-240	30414-240	30414-240
OXIDE												
FeO	132	134	136	133	135	137	119	120	122	123	124	116
MgO	19.5	20.9	21.4	30.5	32.3	30.0	18.3	18.2	15.8	18.2	18.3	18.8
MnO	9.78	8.79	8.64	1.94	.73	2.42	10.2	10.3	11.7	10.2	10.4	10.1
NiO	.27	.36	.34	.61	.59	.54	.14	.06	.34	.27	.18	.17
NiO	-	-	-	.17	.24	-	.41	.09	.66	-	.03	-
ZnO	-	-	-	.17	-	-	.02	-	-	.14	-	.04
Cr	17.4	17.1	17.5	16.6	16.2	16.7	14.4	14.5	16.7	14.3	15.7	12.2
Fe ₂ O ₃	39.8	39.6	39.5	37.3	36.5	36.9	41.5	47.0	41.7	41.4	43.1	48.4
TiO ₂	12.8	12.5	12.90	11.8	11.8	11.7	14.0	9.36	13.2	14.2	11.9	11.5
Sum	.22	.32	.17	.12	.27	.22	.55	.10	.13	.40	.08	.25
	99.77	99.57	100.45	99.21	98.63	98.48	99.52	99.61	100.23	99.11	99.69	101.46

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens

	4.217	4.559	4.625	7.013	7.559	6.924	4.003	3.972	3.164	3.997	3.960	4.087
Fe**												
Mg	3.767	3.419	3.333	.796	.304	.995	3.984	4.014	4.451	3.995	4.014	3.917
Mn	.059	.080	.075	.142	.140	.126	.031	.013	.073	.060	.040	.037
Ni**	-	-	-	.018	.054	-	.086	.019	.135	-	.006	-
Zn	-	-	-	.035	-	-	.004	-	-	.027	-	.008
total	8.013	8.058	8.031	8.023	8.057	8.045	8.108	8.019	8.024	8.079	8.020	8.049
Al	5.233	5.252	5.343	5.400	5.342	5.442	4.443	4.445	5.026	4.440	4.800	3.722
Cr	8.134	8.174	8.086	8.112	8.066	8.014	8.586	9.677	6.400	8.596	8.846	9.939
Fe***	2.485	2.449	2.502	2.437	2.477	2.421	2.752	1.836	2.523	2.800	2.318	2.240
Ti	.213	.063	.032	.025	.057	.046	.108	.020	.025	.073	.016	.047
total	15.955	15.938	15.965	15.974	15.941	15.952	15.890	15.979	15.974	15.919	15.979	15.949

CHROMITE ANALYSES

CHROMITE ANALYSES

	30442-1400	30442-1400	30442-1400	30442-1400	30442-1400	30442-1400	30442-1400	30431-440	30431-440	30431-440	30431-440	77-PM-19	77-PM-19	77-PM-19
OXIDE														
FeO	139	141	143	144	140	142	142	145	146	147	149	150	151	151
MgO	21.2	21.0	21.4	22.0	28.7	30.3	30.3	19.2	19.7	21.6	30.3	30.0	30.9	30.9
MnO	8.61	8.29	8.34	8.37	1.74	.05	.05	10.1	9.90	8.61	.55	.46	.05	.05
MnO	.26	.41	.40	.36	-	.57	.57	.34	.28	.31	1.08	.94	.21	.21
NiO	.06	1.37	-	-	.14	.99	.99	-	.69	-	-	-	.88	.88
ZnO	.15	.14	.06	-	.06	.30	.30	.04	-	.11	.42	.55	.19	.19
Al ₂ O ₃	19.9	18.9	20.0	20.8	.53	.96	.96	21.0	20.8	22.5	7.05	7.03	.30	.30
Cr ₂ O ₃	31.3	33.2	31.7	32.7	28.1	27.0	27.0	38.1	39.1	38.4	46.1	42.1	16.7	16.7
Fe ₂ O ₃	15.8	16.6	16.4	16.2	40.6	41.6	41.6	10.0	11.0	7.33	13.0	16.1	53.6	53.6
TiO ₂	.58	.25	.15	.13	-	-	-	.15	.12	.07	.07	.07	-	-
Sum	97.86	101.16	98.45	100.56	99.87	101.77	101.77	98.93	101.59	98.93	98.57	97.25	102.83	102.83

Recalculated on the basis of 32 oxygens

	4.649	4.493	4.677	4.701	7.176	7.531	7.531	4.100	4.129	4.636	7.416	7.453	7.672	7.672
Fe ⁺⁺	3.365	3.158	3.252	3.189	.777	.022	.022	3.848	3.695	3.288	.240	.204	.022	.022
Mg	.058	.089	.089	.078	-	.144	.144	.074	.059	.067	.268	.237	.053	.053
Mn	.013	.282	-	-	.034	.237	.237	-	.139	-	-	-	.210	.210
Ni ⁺⁺	.029	.026	.012	-	.013	.066	.066	.008	-	.021	.091	.121	.042	.042
Zn	8.114	8.047	8.029	7.968	7.999	8.000	8.000	8.029	8.023	8.012	8.014	8.014	7.999	7.999
total	6.158	5.993	6.149	6.271	.187	.336	.336	6.316	6.143	6.778	2.430	2.464	.105	.105
Al	6.491	6.712	6.554	6.602	6.656	6.356	6.356	7.694	7.735	7.780	10.670	9.903	3.924	3.924
Cr	3.120	3.196	3.236	3.112	9.157	9.307	9.307	1.929	2.075	1.413	2.869	3.601	11.972	11.972
Fe ⁺⁺⁺	.114	.048	.030	.025	-	-	-	.029	.023	.013	.015	.016	-	-
Ti	15.883	15.950	15.964	15.011	16.000	16.000	16.000	15.968	15.975	15.984	15.984	15.984	16.000	16.000

Recalculated on the basis of 32 oxygens

CIRCONITE ANALYSES

CIRCONITE ANALYSES

OXIDE	R 16	R 16	R 16	R 16	R 16	R 16	R 16	26399-420	26399-420	26399-420
FeO	25.2	22.8	17.3	30.3	16.5	154	157	160	20.2	20.2
MgO	6.01	7.73	11.5	1.14	11.8	6.80	6.95	8.47	6.95	8.47
MnO	.62	.87	.33	.91	.81	.28	.25	.17	.25	.17
Al ₂ O ₃	.06	.44	-	.05	.30	.33	.18	-	.18	-
ZnO	.72	-	.57	.20	-	.10	-	.12	-	.12
Al ₂ O ₃	9.70	19.2	19.3	9.89	19.2	10.4	14.5	13.9	14.5	13.9
Cr ₂ O ₃	38.7	36.4	37.7	35.4	38.7	33.1	38.9	38.0	33.1	38.9
Fe ₂ O ₃	10.5	11.9	10.9	11.0	12.3	21.7	15.6	16.3	21.7	15.6
TiO ₂	.24	.60	.61	.56	.47	1.03	.27	.10	1.03	.27
Sum	99.6	100.6	99.94	99.0	98.3	98.34	99.95	97.46	98.34	99.95

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens

OXIDE	R 16	R 16	R 16	R 16	R 16	R 16	R 16	26399-420	26399-420	26399-420
Fe ⁺⁺	6.953	5.494	4.948	3.668	7.334	3.384	5.247	5.193	4.580	5.193
Mg	.784	2.339	2.989	4.368	.491	4.426	2.809	2.766	3.416	2.766
Mn	.14	.192	.073	.071	.223	.173	.066	.057	.039	.066
Al ⁺⁺	.014	.092	-	-	.012	.061	.074	.039	-	.074
Zn	.151	-	.109	-	.042	-	.020	-	.020	.020
total	7.900	8.417	8.119	8.107	8.102	8.044	8.215	8.054	8.139	8.215
Al	3.250	5.909	5.911	5.864	3.368	5.703	3.386	4.547	4.423	3.386
Cr	8.605	7.514	7.727	7.822	8.078	7.707	7.247	8.207	8.139	7.247
Fe ⁺⁺⁺	3.962	2.341	2.123	2.078	4.348	2.704	4.936	3.133	3.315	4.936
Ti	.051	.117	.113	.107	.102	.142	.215	.034	.034	.215
total	15.948	15.764	15.840	15.801	15.496	15.856	15.764	15.944	15.939	15.764

CIROMITE ANALYSES

CIROMITE ANALYSES

[illegible]

Recalculated on the basis of 32 oxygens				Recalculated on the basis of 32 oxygens							
7.245	6.536	7.819	8.967	8.925	8.255	7.028	8.805	8.664	6.236	8.121	7.514
.828	1.577	.362	.106	.049	.187	1.130	.139	.118	2.062	.145	.451
.408	.173	.494	.616	.634	.556	.194	.537	.618	.274	.464	.549
.023	-	.037	.045	.039	-	.051	.045	-	.016	.039	-
-	-	-	.127	.080	-	-	.041	-	-	-	.036
8.514	8.287	8.512	9.862	9.727	8.998	8.404	9.566	9.401	8.607	8.769	8.550
2.583	3.689	2.740	1.294	1.341	2.134	2.784	2.629	2.715	3.187	2.236	3.357
5.779	7.760	5.840	5.433	4.923	5.311	6.155	5.555	5.611	6.912	4.751	6.789
6.640	3.975	6.412	5.721	6.593	6.557	6.304	4.767	4.871	4.520	7.513	4.790
.490	.287	.484	1.732	1.643	.998	.365	1.502	1.401	.500	.712	.522
15.453	15.711	15.495	14.181	14.300	15.001	15.607	14.454	14.598	15.400	15.240	15.458

CIRCONITE ANALYSES

CIRCONITE ANALYSES

	HED 195	HED 195	HED 195	HED 195	HED 195	HED 195	HED 195	HED 195	HED 205	HED 205	HED 205	HED 205	HED 205	HED 205
FeO	81	42	83	84	85	86	87	88	89	90	91	92	93	94
MgO	32.6	34.1	31.6	27.1	33.4	33.2	34.6	32.9	36.0	36.0	34.6	32.9	33.7	34.1
MnO	.99	.47	.54	4.12	.35	.24	.34	.47	.44	.44	.34	.47	.87	.37
NiO	2.07	4.43	2.34	.66	2.27	2.29	1.82	1.34	1.78	1.78	1.82	1.34	1.33	1.95
ZnO	-	-	-	-	-	-	.15	.17	-	-	.15	.17	.15	-
Al ₂ O ₃	8.27	6.48	5.49	11.9	7.15	6.96	7.22	6.05	7.18	7.18	7.22	6.05	5.79	8.29
Cr ₂ O ₃	32.4	28.2	26.8	39.6	27.5	26.0	28.0	25.6	27.40	27.40	28.0	25.6	20.8	26.1
Fe ₂ O ₃	17.7	23.3	26.0	15.6	22.0	25.0	19.3	26.9	20.0	20.0	19.3	26.9	33.9	20.3
TiO ₂	4.08	5.03	4.85	.54	4.68	4.16	5.60	3.69	6.45	6.45	5.60	3.69	4.15	5.26
Sum	98.11	100.01	99.62	99.52	97.35	97.85	97.03	97.12	99.4	99.4	97.03	97.12	100.69	96.37

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens

	7.954	8.297	8.251	6.261	8.319	8.246	6.763	8.775	8.635	8.271	8.194	8.523
Fe ⁺⁺	.431	.204	.236	1.696	.155	.106	1.108	.191	.151	.211	.377	.165
Mg	.522	.599	.582	.154	.572	.577	.383	.439	.460	.341	.327	.493
Mn	-	-	-	-	-	-	-	-	.036	.041	.035	-
Ni ⁺⁺	-	-	-	-	-	-	-	.032	-	-	-	-
Zn	8.897	9.100	9.069	8.112	9.046	8.929	8.254	9.438	9.282	8.964	7.933	9.181
total	2.846	2.222	1.899	3.884	2.508	2.438	3.353	2.466	2.537	2.144	1.903	2.917
Al	7.480	6.475	6.227	8.656	6.478	6.206	6.782	6.309	6.602	6.083	4.773	6.169
Cr	3.881	5.101	5.732	3.235	4.918	5.595	5.353	4.380	4.329	6.082	7.412	4.550
Fe ⁺⁺⁺	.806	1.101	1.071	.112	1.068	.910	.255	1.414	1.256	.815	.907	1.181
Ti	15.102	14.892	14.929	15.886	14.952	15.069	15.744	14.569	14.725	15.144	15.075	14.817

CIRCONITE ANALYSES

CIRCONITE ANALYSES

	HED 218	HED 218 /	HED 219	HED 218	HED 218	HED 218	HED 218	HED 218	30414 220	30414 220	30414 220	30414 220
OXIDE												
FeO	811	812	813	817	818	819	820	81	45	47	47	810
MgO	29.6	34.2	36.0	22.4	23.1	20.3	20.4	35.4	16.9	17.8	17.8	21.0
MnO	3.60	.74	.24	7.20	6.91	6.62	8.75	.89	9.35	10.0	10.0	7.95
MoO	1.67	2.46	2.24	1.14	.55	.55	.59	.79	.70	.66	.66	.77
NiO	.16	.14	-	-	-	-	-	.32	.19	-	-	.20
ZnO	-	.18	.28	-	-	-	-	.45	-	-	-	-
Al ₂ O ₃	8.81	6.66	5.38	13.3	13.7	13.8	13.8	9.37	12.3	12.3	12.3	12.5
Cr ₂ O ₃	33.3	30.5	25.2	37.0	38.0	37.5	38.6	36.0	47.7	47.9	47.9	39.0
Fe ₂ O ₃	17.2	28.0	21.0	14.8	12.8	13.8	13.5	11.0	10.2	10.5	10.5	15.4
TiO ₂	4.46	5.99	7.35	1.58	1.44	1.42	1.40	4.94	0.28	0.18	0.18	0.96
Sum	98.8	98.87	98.39	97.42	96.50	95.99	97.04	99.96	99.82	99.34	99.34	97.78

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens

	7.019	8.367	8.958	5.126	5.330	4.650	4.618	8.448	4.190	3.929	4.793	
Fe**												
Mg	1.522	.323	.106	2.934	2.840	3.514	3.532	.379	2.698	3.959	3.231	
Mn	.401	.610	.564	.264	.128	.127	.135	.191	.157	.148	.162	
Ni**	.037	.033	-	-	-	-	-	.073	.041	-	.044	
Zn	-	.039	.061	-	-	-	-	.095	-	-	-	
total	8.979	9.373	9.689	8.324	8.298	8.292	8.285	9.185	8.086	9.035	8.229	
Al	2.945	2.299	1.884	4.294	4.458	4.458	4.413	3.151	3.810	3.819	4.016	
Cr	7.457	7.067	6.095	8.004	8.278	8.118	8.267	8.115	10.009	10.018	8.415	
Fe***	3.676	3.957	4.703	3.051	2.664	2.818	2.747	2.529	2.027	2.020	3.151	
Ti	.951	1.320	1.643	.325	.229	.229	.245	1.050	.056	.035	.027	
total	15.029	14.644	14.325	15.674	15.700	15.706	15.711	14.855	15.022	15.967	15.780	

CIROMITE ANALYSES

CIROMITE ANALYSES

OXIDE	301414-240	304140240	30414 240	30414-240	30414-240	30414-240	30414-240	30414-240	30414-240	30414-260	30414-260	30414-260	30414-260	30414-260	30414-260
2	3	4	5	6	AV. (5)	84	85	86	88	89	910				
FeO	23.2	26.8	17.6	22.4	22.2	19.7	35.6	21.4	32.7	18.7	28.2				
MgO	8.28	5.58	11.0	7.94	8.44	9.50	0.35	8.06	0.34	9.77	4.18				
MnO	0.51	0.67	0.21	0.41	0.43	0.64	2.07	0.62	1.26	0.64	1.42				
NiO	-	-	-	-	-	0.15	0.37	0.15	0.18	-	0.28				
ZnO	-	-	-	-	-	-	-	-	-	-	-				
Al ₂ O ₃	12.6	12.8	12.1	13.0	12.3	12.5	6.46	11.8	8.87	13.1	8.66				
Cr ₂ O ₃	41.2	43.5	40.3	45.8	42.4	42.4	30.1	43.5	30.7	44.6	33.8				
Fe ₂ O ₃	13.1	11.5	12.2	11.4	12.3	13.8	17.0	14.4	23.2	11.9	18.3				
TiO ₂	1.99	2.28	2.37	0.97	1.88	1.26	6.59	0.57	1.89	0.59	3.73				
Sum	99.41	101.47	100.02	100.18	99.95	99.95	98.54	100.50	99.10	99.30	98.57				

Recalculated on the basis of 32 oxygens

OXIDE	301414-240	304140240	30414 240	30414-240	30414-240	30414-240	30414-240	30414-240	30414-240	30414-260	30414-260	30414-260	30414-260	30414-260	30414-260
Fe ⁺⁺	4.613	5.093	6.073	3.866	5.070	4.941	4.359	8.768	4.765	7.944	4.126	8.672			
Mg	3.708	3.244	2.257	4.278	3.205	3.347	3.739	.154	3.200	.147	3.048	1.766			
Mn	.076	.114	.154	.046	.094	.098	.143	.517	.140	.310	.143	.341			
Ni ⁺⁺	-	-	-	-	-	-	.032	.088	.032	.042	-	.064			
Zn	-	-	-	-	-	-	-	-	-	-	-	-			
total	8.397	8.451	8.484	8.190	8.369	8.386	8.273	9.527	8.137	8.444	8.117	8.843			
Al	3.945	3.787	3.880	3.981	3.745	3.861	3.896	2.244	3.707	3.023	4.079	2.892			
Cr	8.639	9.038	8.651	9.416	8.858	8.924	8.850	7.019	9.159	7.051	9.313	7.583			
Fe ⁺⁺⁺	2.621	2.273	2.500	2.223	2.668	2.464	2.736	3.770	2.888	5.078	2.372	3.901			
Ti	.397	.451	.434	.190	.369	.376	.250	1.461	.114	.413	.132	.205			
total	15.402	15.549	15.515	15.810	15.630	15.625	15.732	14.494	15.869	15.565	15.881	15.171			

Recalculated on the basis of 32 oxygens

DIOPHYTE ANALYSES

	30414-280	30414-280	30414-280	30414-280	30414-280	30414-280	30414-280	30414-280	30414-280	30414-300	30414-300	30414-300
#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13
18.1	17.9	17.9	25.0	20.9	20.2	17.9	17.9	26.3	20.2	18.7	20.7	25.3
10.8	10.5	10.4	5.51	8.43	8.99	10.3	10.3	5.05	9.12	9.49	9.45	5.56
.61	.64	.66	1.33	.85	.61	.74	.74	.99	.67	.82	1.18	2.53
-	-	-	-	-	-	-	-	-	.21	-	.21	.19
.12	-	-	.16	-	-	-	-	-	-	-	-	-
13.5	12.1	12.1	11.9	12.4	12.1	14.5	14.5	11.4	12.3	13.3	10.7	10.5
42.9	45.3	45.9	39.3	40.6	41.8	41.9	41.9	36.4	43.2	43.0	38.9	36.3
12.0	11.7	11.3	13.9	13.2	12.8	12.5	12.5	18.1	12.0	13.6	15.5	15.0
1.58	1.15	0.93	1.70	1.65	1.57	.75	.75	1.60	1.49	.35	3.20	3.57
99.61	99.29	96.19	98.80	98.03	98.07	98.59	98.59	99.84	99.19	99.26	99.84	98.95

CIROMITE ANALYSES

	Recalculated on the basis of 32 oxygens						Recalculated on the basis of 32 oxygens					
Fe ⁺⁺	3.952	3.947	3.951	5.749	4.740	4.565	3.938	6.030	4.507	4.142	4.607	5.846
Mg	4.201	4.139	4.085	2.260	1.401	3.637	4.045	2.068	3.628	3.743	3.757	2.293
Mn	.135	.143	.140	.310	.195	.139	.165	.230	.151	.184	.267	.593
Ni ⁺⁺	-	-	-	-	-	-	-	-	.045	-	.045	.042
Zn	.023	-	-	.033	-	-	-	-	-	-	-	-
total	8.311	8.229	8.185	8.335	8.319	8.148	8.148	8.328	8.332	8.069	8.636	8.724
Al	4.154	3.773	3.778	3.859	3.981	3.846	4.490	3.690	3.859	4.153	3.363	3.425
Cr	8.865	9.443	9.592	8.553	8.688	8.915	8.733	7.905	9.106	9.000	8.213	7.937
Fe ⁺⁺⁺	2.357	2.326	2.258	2.881	2.678	2.600	2.478	3.743	2.417	2.706	3.115	3.129
Ti	.311	.228	.185	.352	.336	.319	.149	.331	.208	.070	.642	.711
total	15.607	15.770	15.813	15.646	15.663	15.679	15.850	15.669	15.677	15.929	15.334	15.235

CIRCONITE ANALYSES

CIRCONITE ANALYSES

	30414-300	30414-300	30414-300	30414-300	30414-300	30414-320	30414-320	30414-320	30414-320	30414-320	30414-320	30414-320
OXIDE												
FeO	816	21.3	20.4	22.0	18.1	32.8	32.4	18.9	26.5	30.8	31.1	22.3
MgO	817	9.53	8.48	9.49	1.11	3.95	3.94	9.13	3.99	1.95	1.63	7.80
MnO	818	.65	1.03	1.02	3.95	3.95	3.94	.61	2.99	3.55	3.49	.64
NiO	819	.16	.16	.16	.16	.16	.16	.16	.16	.16	.16	.16
ZnO	820	.11	.11	.11	.11	.11	.11	.11	.11	.11	.11	.11
Al ₂ O ₃	821	12.0	11.1	11.3	12.5	8.79	8.77	12.6	9.96	9.22	9.15	12.4
Cr ₂ O ₃	822	40.3	39.6	38.7	41.4	32.2	31.3	41.1	34.8	31.0	33.1	41.1
Fe ₂ O ₃	823	13.9	14.3	14.9	15.4	14.8	14.7	14.8	15.6	14.4	14.1	17.7
TiO ₂	824	1.92	2.86	2.90	.41	5.96	5.51	.42	3.44	5.16	5.09	.42
Sum	98.64	98.44	99.47	98.32	99.61	97.25	97.36	97.28	98.08	97.66	102.36	

Recalculated on the basis of 32 oxygens

	4.091	4.805	4.604	4.947	4.057	7.851	7.961	4.267	6.320	7.414	7.548	4.891
Fe ⁺⁺	3.862	3.428	3.826	3.395	3.793	.473	.276	3.678	1.695	.837	.704	3.049
Mg	1.39	.155	.148	.234	.232	.956	.982	.140	.722	.866	.857	.142
Mn	.038	-	-	.035	-	-	-	-	-	-	-	-
Ni ⁺⁺	-	-	-	-	-	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-
total	8.130	8.388	8.578	8.611	8.082	9.281	9.219	8.085	8.736	9.116	9.109	8.084
Al	3.968	3.821	3.507	3.574	3.941	2.961	2.768	4.019	3.344	3.128	3.125	3.839
Cr	9.065	8.586	8.427	8.217	8.782	7.207	7.268	8.791	7.829	7.521	7.576	8.514
Fe ⁺⁺⁺	2.743	2.813	2.906	3.018	3.110	3.188	3.252	3.018	3.351	3.116	3.080	3.489
Ti	.101	.389	.579	.546	.041	1.281	1.219	.085	.717	1.117	1.109	.081
total	15.878	15.610	15.419	15.395	15.916	14.718	14.779	15.913	15.262	14.882	14.889	15.914

CIRCONITE ANALYSES

CIRCONITE ANALYSES

	30414-320	30414-330	30414-340	30414-340	30414-340	30414-340	30414-340	30414-340	30414-340	30414-340	30414-340
OXIDE											
FeO	810	811	812	813	814	815	816	817	818	819	
	31.7	18.2	20.0	20.0	18.7	18.9	20.8	18.2	17.6	18.0	
MgO	.61	10.3	9.00	8.91	9.62	9.41	8.30	9.31	10.4	9.88	
MnO	4.11	.63	.60	.66	.65	.61	.62	1.13	.62	.63	
NiO	-	.16	.19	.17	.16	-	.17	-	-	-	
ZnO	-	.27	-	-	-	-	-	-	-	-	
Al ₂ O ₃	8.90	13.9	13.1	12.4	12.3	12.2	13.3	12.9	13.9	12.5	
Cr ₂ O ₃	31.9	44.5	44.7	45.8	47.1	46.6	42.50	44.0	46.3	45.6	
Fe ₂ O ₃	15.1	11.1	11.5	11.8	11.0	11.3	13.4	12.6	11.1	11.9	
TiO ₂	4.92	.34	.61	.47	.33	.33	.48	.22	.09	.30	
Sum	97.24	99.40	99.70	100.21	99.86	99.35	99.27	98.36	100.01	98.81	

Recalculated on the basis of 32 oxygens

	7.797	3.988	4.421	4.419	4.123	4.201	4.639	4.074	3.832	4.000	
Fe ⁺⁺											
Mg	.267	4.036	3.535	3.516	3.788	3.728	3.307	3.714	4.049	3.917	
Mn	1.023	.140	.135	.148	.145	.137	.140	.256	.137	.142	
Ni ⁺⁺	-	.034	.040	.036	.034	-	.037	-	-	-	
Zn	-	.052	-	-	-	-	-	-	-	-	
total	9.087	9.251	8.151	8.119	8.090	8.065	8.122	8.044	8.018	8.059	
Al	3.081	4.309	4.097	3.856	3.826	3.818	4.177	4.068	4.266	3.912	
Cr	7.415	9.241	9.355	9.503	9.830	9.781	8.980	9.306	9.528	9.592	
Fe ⁺⁺⁺	3.323	2.190	2.283	2.145	2.195	2.259	2.631	2.536	2.168	2.374	
Ti	1.087	.067	.122	.094	.065	.066	.096	.044	.018	.060	
total	14.912	15.808	15.857	15.887	15.916	15.932	15.884	15.954	15.980	15.939	

Recalculated on the basis of 32 oxygens

CIRCONITE ANALYSES

CIRCONITE ANALYSES

OXIDE	30401 300	30401 300	30401 300	30401 300	30401 300	30401 300	30401 300	30401 300	30401 500	30401 500	30401 500	30401 500	30401 500	30401 500
Si	27.2	24.7	24.7	24.7	25.2	25.2	25.2	25.2	25.1	25.1	25.1	25.1	25.1	25.1
FeO	6.10	7.80	7.80	7.80	7.93	7.93	7.93	7.93	7.04	7.04	7.04	7.04	7.04	7.04
MgO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	9.39	18.0	13.4	13.4	12.1	12.1	12.1	12.1	13.9	13.9	13.9	13.9	13.9	13.9
Cr ₂ O ₃	34.5	33.4	36.3	36.3	35.9	35.9	35.9	35.9	37.7	37.7	37.7	37.7	37.7	37.7
Fe ₂ O ₃	23.1	18.0	18.0	18.0	18.0	18.0	18.0	18.0	15.5	15.5	15.5	15.5	15.5	15.5
TiO ₂	2.61	0.61	2.21	2.21	3.19	3.19	3.19	3.19	1.71	1.71	1.71	1.71	1.71	1.71
Sum	102.9	102.51	102.41	102.41	102.32	102.32	102.32	102.32	101.95	101.95	101.95	101.95	101.95	101.95

n.d. Not Determined

Recalculated on the basis of 32 oxygens													
Recalculated on the basis of 32 oxygens													
Si	27.2	24.7	24.7	24.7	25.2	25.2	25.2	25.2	25.1	25.1	25.1	25.1	25.1
FeO	6.10	7.80	7.80	7.80	7.93	7.93	7.93	7.93	7.04	7.04	7.04	7.04	7.04
MgO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	9.39	18.0	13.4	13.4	12.1	12.1	12.1	12.1	13.9	13.9	13.9	13.9	13.9
Cr ₂ O ₃	34.5	33.4	36.3	36.3	35.9	35.9	35.9	35.9	37.7	37.7	37.7	37.7	37.7
Fe ₂ O ₃	23.1	18.0	18.0	18.0	18.0	18.0	18.0	18.0	15.5	15.5	15.5	15.5	15.5
TiO ₂	2.61	0.61	2.21	2.21	3.19	3.19	3.19	3.19	1.71	1.71	1.71	1.71	1.71
Sum	102.9	102.51	102.41	102.41	102.32	102.32	102.32	102.32	101.95	101.95	101.95	101.95	101.95

Fe⁺⁺

Mg

Mn

Ni⁺⁺

Zn

total

Al

Cr

Fe⁺⁺⁺

Ti

total

CHRONITE ANALYSES

CHRONITE ANALYSES

	R350	R350	R350	R350	R350	R350	R350	R350	R350	R350	R420	R420	R420
1	2	3	4	5	7a	7b	7c	7c	7c	10	12	14	
23.9	26.2	28.1	24.2	27.0	21.5	22.1	19.1	20.2	36.1	31.1	30.2		
6.38	4.13	2.24	6.04	4.14	8.15	7.80	9.44	8.76	0.56	1.58	1.81		
0.60	1.42	1.49	0.55	0.99	0.53	0.61	0.54	0.61	1.86	1.36	1.19		
0.14	0.19	0.20	0.21	0.19	-	0.20	0.14	0.14	0.16	0.17	0.29		
-	-	0.30	-	-	-	-	-	-	0.44	-	0.17		
16.9	16.4	13.2	14.8	15.7	19.7	20.2	18.9	19.0	15.1	17.6	18.6		
32.0	30.6	27.6	29.9	34.2	34.9	33.7	34.9	34.8	26.4	26.4	26.9		
17.9	18.8	23.8	22.2	16.8	12.9	13.9	14.4	14.2	16.6	16.4	15.0		
0.51	0.42	0.58	0.64	0.45	0.20	0.22	0.19	0.17	4.95	1.78	1.42		
98.35	98.16	97.51	98.54	99.47	97.88	98.73	97.61	97.88	102.17	96.39	95.58		

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens												
	5.365	6.025	6.703	5.509	6.144	4.724	4.827	4.195	4.438	8.235	7.349	7.552
	2.555	1.689	.952	2.450	1.678	3.198	3.039	3.693	3.431	.278	.665	.763
	.136	0.330	.360	.127	0.228	.118	0.135	0.120	0.136	.430	.325	.285
	.030	.042	.046	.046	.042	-	0.042	.030	.030	.035	.038	.066
	-	-	.063	-	-	-	-	-	-	.089	-	.035
	8.086	8.086	8.124	8.132	8.002	8.010	8.043	8.038	8.035	9.017	8.377	8.301
	5.363	5.299	4.424	4.747	5.020	6.097	6.209	5.841	5.895	4.860	5.861	6.120
	6.803	6.646	6.215	6.437	7.352	7.266	6.972	7.234	7.220	5.700	5.807	6.010
	3.618	3.880	5.110	4.553	3.443	2.557	2.732	2.848	2.817	3.406	3.495	3.184
	.107	.086	.174	.131	.092	.030	.043	.038	.034	1.016	.378	.302
	15.892	15.911	15.873	15.860	15.907	15.959	15.956	15.961	15.966	14.942	15.621	15.616

Recalculated on the basis of 32 oxygens

CIROMITE ANALYSES

CIROMITE ANALYSES

OXIDE	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3
FeO	7	7	9	10a	10b	10c	10d	10e	10f	10g	11	12							
MgO	33.4	31.2	31.2	22.4	18.4	18.2	18.1	18.2	21.5	31.2	21.4	21.0							
MnO	1.09	1.59	2.18	7.83	10.94	10.9	10.8	10.6	8.93	.99	8.92	8.49							
NiO	.14	.18	.24	.45	.18	.16	.22	.15	.16	.30	.36	.41							
ZnO	.22	.23	.17	.4	.20	-	.19	.32	.25	.48	.16	.26							
Al ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-							
Cr ₂ O ₃	13.3	13.3	13.1	17.2	18.8	18.4	18.1	18.1	18.0	6.01	18.2	17.2							
Fe ₂ O ₃	31.3	31.3	31.9	32.3	33.4	33.2	33.5	33.4	33.2	39.3	32.5	32.4							
TiO ₂	18.5	19.2	18.1	16.4	15.9	15.6	16.2	15.8	16.7	32.4	16.6	16.0							
Sum	1.78	.92	1.65	1.10	1.09	1.12	1.04	1.08	1.05	.55	1.20	1.20							
	99.73	97.92	98.54	97.68	98.87	97.58	98.15	97.65	99.79	101.23	99.34	96.96							

Recalculated on the basis of 32 oxygens

OXIDE	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3	CR.3
Fe**	7.817	7.427	7.339	4.999	3.956	3.958	3.933	3.981	4.663	7.510	4.656	4.707							
Mg	.456	.674	.914	3.121	4.174	4.226	4.182	4.131	3.454	.425	3.466	3.386							
Mn	.013	.043	.057	.102	.039	.035	.048	.033	.035	.073	.079	.093							
Ni**	.049	.053	.085	-	.041	-	.040	.067	.052	.111	.034	.056							
Zn	-	-	-	-	-	-	-	-	-	-	-	-							
total	8.335	8.197	8.395	8.222	8.210	8.219	8.203	8.212	8.204	8.119	8.231	8.242							
Al	4.394	4.450	4.358	5.427	5.704	5.622	5.549	5.573	5.519	2.042	5.580	5.430							
Cr	6.936	7.042	7.106	6.833	6.791	6.823	6.877	6.892	6.815	6.686	6.699	6.852							
Fe***	3.917	4.113	3.836	3.206	3.082	3.116	3.167	3.110	3.256	7.033	3.250	3.231							
Ti	.376	.196	.349	.721	.211	.219	.203	.212	.205	.119	.231	.241							
total	15.623	15.801	15.649	15.777	15.788	15.780	15.794	15.787	15.705	15.890	15.764	15.754							

Recalculated on the basis of 32 oxygens

CIRCONITE ANALYSES

CIRCONITE ANALYSES

OXIDE	R430	R430	R430	R430	R430	R360	R360	R360	R360	R140	R140	R140	R140	R140
1	2	3	4	10	11	13	14	1	2	3	4			
29.4	29.6	28.9	29.8	26.6	28.7	24.8	22.9	25.8	27.7	25.2	23.4			
3.18	2.08	3.50	1.83	3.33	1.66	5.96	7.36	6.03	4.14	5.77	7.02			
1.20	1.42	.96	1.57	1.31	1.19	.99	.75	1.36	1.58	1.53	1.08			
n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.			
n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.			
18.3	11.1	21.4	17.3	9.53	6.16	19.4	21.0	17.4	13.7	16.9	17.8			
26.9	27.0	29.9	28.3	30.4	28.5	32.1	32.9	39.8	36.3	39.3	39.9			
18.4	27.3	13.2	18.5	27.8	32.9	14.7	13.8	8.91	17.2	9.15	8.42			
1.35	1.04	.54	.39	.17	.16	0.59	.14	1.60	1.22	1.34	.03			
98.73	99.54	98.40	97.59	99.14	99.27	98.54	98.85	100.90	101.64	99.19	98.55			

Recalculated on the basis of 32 oxygens

OXIDE	R430	R430	R430	R430	R430	R360	R360	R360	R360	R140	R140	R140	R140	R140
6.708	7.005	6.491	6.951	6.315	7.019	5.531	4.998	5.659	6.230	5.626	5.192			
1.292	.876	1.400	.761	1.407	.722	2.364	2.864	2.354	1.657	2.297	2.771			
.277	.340	.218	.371	.315	.294	.223	.166	.302	.359	.346	.242			
-	-	-	-	-	-	-	-	-	-	-	-			
-	-	-	-	-	-	-	-	-	-	-	-			
8.277	8.221	8.109	8.083	8.037	8.035	8.118	8.028	8.315	8.246	8.269	8.205			
5.864	3.711	6.775	5.699	3.185	2.120	6.073	6.449	5.369	4.323	5.330	5.563			
5.806	6.029	6.333	6.245	6.814	6.574	6.754	6.786	8.243	7.700	8.291	8.349			
3.775	5.817	2.673	3.891	5.928	7.235	2.936	2.709	1.757	3.483	1.840	1.677			
.277	.221	.109	.062	.036	.035	.118	.027	.315	.246	.269	.205			
15.722	15.778	15.870	15.917	15.963	15.964	15.881	15.971	15.684	15.752	15.730	15.794			

Recalculated on the basis of 32 oxygens

OXIDE	R430	R430	R430	R430	R430	R360	R360	R360	R360	R140	R140	R140	R140	R140
Fe**	6.708	7.005	6.491	6.951	6.315	7.019	5.531	4.998	5.659	6.230	5.626	5.192		
Mg	1.292	.876	1.400	.761	1.407	.722	2.364	2.864	2.354	1.657	2.297	2.771		
Mn	.277	.340	.218	.371	.315	.294	.223	.166	.302	.359	.346	.242		
Ni**	-	-	-	-	-	-	-	-	-	-	-	-		
Zn	-	-	-	-	-	-	-	-	-	-	-	-		
total	8.277	8.221	8.109	8.083	8.037	8.035	8.118	8.028	8.315	8.246	8.269	8.205		
Al	5.864	3.711	6.775	5.699	3.185	2.120	6.073	6.449	5.369	4.323	5.330	5.563		
Cr	5.806	6.029	6.333	6.245	6.814	6.574	6.754	6.786	8.243	7.700	8.291	8.349		
Fe***	3.775	5.817	2.673	3.891	5.928	7.235	2.936	2.709	1.757	3.483	1.840	1.677		
Ti	.277	.221	.109	.062	.036	.035	.118	.027	.315	.246	.269	.205		
total	15.722	15.778	15.870	15.917	15.963	15.964	15.881	15.971	15.684	15.752	15.730	15.794		

CHROMITE ANALYSES

OXIDE	R230	R230	R230	R230	R230	R230	R230	R230	R19	R19	R19	R19	R19	R19
FeO	14	15	16A	16B	16C	16D	16E	16F	2	3	4	5	6	6
MgO	20.3	18.8	20.5	21.1	21.1	21.1	21.1	21.1	32.9	33.1	33.0	30.9	28.6	28.6
MnO	9.24	9.93	8.94	9.23	8.94	9.09	9.09	9.09	1.38	.55	.64	1.83	4.63	4.63
NiO	1.25	1.38	1.00	.49	.43	.42	.42	.42	0.84	1.23	1.13	0.76	0.44	0.44
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr ₂ O ₃	20.0	18.8	18.7	18.7	19.1	19.1	19.1	19.1	20.4	10.3	10.5	15.7	30.9	30.9
Fe ₂ O ₃	38.4	40.3	41.0	41.1	40.7	41.0	41.0	41.0	19.7	24.5	23.2	27.0	17.4	17.4
TiO ₂	9.37	10.1	8.34	9.43	8.72	9.09	9.09	9.09	22.8	27.5	28.1	21.0	16.3	16.3
Sum	.88	.56	.68	.69	.61	.56	.56	.56	1.22	2.32	2.38	0.91	0	0
	99.44	99.87	99.16	100.74	99.80	100.56	100.56	100.56	99.24	99.50	98.95	98.12	98.27	98.27

Recalculated on the basis of 32 oxygens													
OXIDE	R230	R230	R230	R230	R230	R230	R230	R230	R230	R230	R230	R230	R230
Fe ⁺⁺	4.366	4.019	4.457	4.513	4.594	4.554	4.554	4.554	4.328	7.496	7.967	7.965	7.250
Mg	3.532	3.790	3.456	3.513	3.431	3.463	3.463	3.463	3.606	.561	.236	.275	.766
Mn	.272	.299	.220	.106	.094	.091	.091	.091	.182	.194	.300	.276	.181
Ni ⁺⁺	-	-	-	-	-	-	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-	-
total	8.170	8.108	8.133	8.132	8.119	8.108	8.108	8.108	8.116	8.251	8.501	8.516	8.107
Al	6.056	5.678	5.707	5.614	5.781	5.748	5.748	5.748	5.662	6.567	3.481	3.559	5.189
Cr	7.705	8.157	8.400	8.307	8.293	8.289	8.289	8.289	8.316	4.246	5.558	5.304	5.988
Fe ⁺⁺⁺	1.808	1.949	1.627	1.814	1.689	1.747	1.747	1.747	1.790	4.686	5.957	6.102	4.430
Ti	.169	.108	.133	.113	.118	.107	.107	.107	.116	.250	.502	.517	.196
total	15.828	15.892	15.867	15.864	15.881	15.891	15.891	15.891	15.884	15.749	15.498	15.482	15.803

CHROMITE ANALYSES

CHROMITE ANALYSES

SAMPLE NUMBER	R 18	R 18	R 19	R 18	R 18	R 280	R 280	R 280	R 280	R 280	R 280	R 17
Oxide	1 - rim	2 - rim	4 - core	5 - rim	6 - rim	7	8	9	10	11 - rim	12	1
FeO	29.5	30.1	28.1	29.8	29.9	24.7	24.0	27.2	24.2	29.4	25.3	28.8
MgO	0.22	0.25	5.32	0.19	0.30	6.19	7.08	4.79	7.05	0.86	6.02	4.79
MnO	2.31	2.51	1.29	2.45	2.51	1.41	1.05	1.73	1.10	1.73	1.35	0.70
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al ₂ O ₃	0.23	0.83	17.5	1.74	2.19	16.2	39.1	18.3	18.4	5.62	18.3	20.2
Cr ₂ O ₃	28.5	30.1	33.8	29.6	28.6	42.5	39.7	39.3	40.7	36.0	39.6	28.3
Fe ₂ O ₃	30.5	36.2	12.0	36.3	35.8	8.61	9.20	9.01	9.11	25.5	10.1	16.8
TiO ₂	0.45	1.09	2.89	0.59	1.00	Q.97	0.74	1.09	0.90	0.11	0.69	1.62
Sum	100.71	101.08	100.90	100.67	100.30	100.58	100.87	101.42	101.46	99.22	101.36	101.21

Recalculated on the basis of 32 oxygens

	7.415	7.500	6.197	7.429	7.457	5.444	5.188	5.962	5.223	7.217	5.503	6.298
Fe ⁺⁺	0.099	0.111	2.087	0.084	0.133	2.433	2.726	1.867	2.711	0.376	2.335	1.866
Mg	0.588	0.634	0.288	0.619	0.634	0.315	0.230	0.304	0.240	0.430	0.297	0.155
Mn	-	-	-	-	-	-	-	-	-	-	-	-
Ni ⁺⁺	-	-	-	-	-	-	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-
total	8.102	8.245	8.572	8.132	8.224	8.392	8.144	8.213	8.174	8.023	8.135	8.319
Al	0.082	0.201	5.430	0.611	0.770	5.049	5.810	5.655	5.580	1.946	5.622	6.221
Cr	6.768	7.103	7.043	6.981	6.743	8.856	8.113	8.139	8.300	8.309	8.137	5.837
Fe ⁺⁺⁺	8.945	8.115	2.381	8.141	8.037	1.710	1.789	1.774	1.770	5.636	1.969	3.304
Ti	0.102	0.244	0.572	0.132	0.224	0.192	0.144	0.214	0.375	0.024	0.135	0.318
total	15.897	15.753	15.426	15.865	15.774	15.807	15.856	15.782	15.825	15.975	15.863	15.7

Recalculated on the basis of 32 oxygens

CIRCONITE ANALYSES

CIRCONITE ANALYSES

SAMPLE NUMBER	R 17	R 17	R 17	R 17	R 20	R 28	R'28	R 28	R 28	R 28
2 f.m.	3	4	5	6	7	8	9	10	11	
FeO	26.2	25.4	26.3	28.4	28.7	28.9	29.3	28.8	29.3	
MgO	6.25	6.35	5.48	3.50	4.19	3.97	3.20	3.49	2.98	
MnO	0.59	0.78	1.06	2.07	0.90	1.44	0.94	1.27	1.34	
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	
Al ₂ O ₃	11.1	23.9	26.2	24.7	19.9	18.7	18.5	16.3	15.8	
Cr ₂ O ₃	25.5	33.0	28.6	28.5	33.5	34.9	35.2	35.8	35.6	
Fe ₂ O ₃	31.6	10.6	11.7	13.0	12.5	12.2	11.4	15.1	14.5	
TiO ₂	0.52	0.42	0.16	0.26	0.69	0.71	0.66	0.64	0.79	
Sum	102.30	100.96	99.19	99.30	100.56	100.22	99.20	101.40	100.31	

Recalculated on the basis of 32 oxygens

	Fe ⁺⁺	Mg	Mn	Ni ⁺⁺	Zn	total	Al	Cr	Fe ⁺⁺⁺	Ti	total
7.038	5.581	5.440	5.704	6.289	6.331	6.473	6.530	6.450	6.647		
0.751	2.372	2.422	2.114	1.383	1.645	1.343	1.289	1.391	1.206		
0.319	0.127	0.169	0.232	0.465	0.201	0.326	0.215	0.288	0.308		
-	-	-	-	-	-	-	-	-	-		
-	-	-	-	-	-	-	-	-	-		
6.108	8.080	8.031	8.051	8.137	8.177	8.142	8.134	8.128	8.461		
3.618	7.167	7.902	7.530	6.217	5.721	5.861	5.992	5.140	5.062		
5.960	6.649	5.788	5.828	7.019	7.142	7.369	7.513	7.574	7.649		
6.584	2.022	2.247	2.560	2.487	2.783	2.453	2.226	3.029	2.965		
0.108	0.080	0.031	0.051	0.138	0.176	0.143	0.134	0.129	0.161		
15.890	15.918	15.968	15.949	15.861	15.822	15.856	15.865	15.872	15.837		

CIRCONITE ANALYSES

CIRCONITE ANALYSES

Oxide	30468										30468		
	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1030	1030
A		B	C	D-1	D-2	E							
FeO	31.79	31.2	31.4	30.7	31.4	30.3		27.2	28.9	20.9	29.3	27.0	
MgO	1.58	0.98	0.16	1.23	0.39	1.73		5.60	4.22	5.85	2.01	5.09	
NaO	1.66	1.89	1.99	1.54	1.76	1.56		1.03	1.39	1.33	1.74	0.70	
HfO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.	n.d.	
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.	n.d.	n.d.	
Al ₂ O ₃	18.1	17.9	13.1	15.0	13.5	17.9		21.5	17.8	0.77	19.9	20.9	
Cr ₂ O ₃	38.6	33.6	32.6	31.5	30.6	38.7		35.2	34.2	19.2	32.6	27.2	
Fe ₂ O ₃	8.21	13.1	19.4	18.7	21.1	8.82		9.69	14.1	50.2	9.94	17.0	
TiO ₂	0.46	0.31	0.21	0.30	0.20	0.07		1.19	1.54	0.18	1.33	0.88	
Sum	99.61	98.98	98.86	98.97	98.95	99.08		101.41	102.15	98.23	97.52	98.77	

Oxide	Recalculated on the basis of 32 oxygens										Recalculated on the basis of 32 oxygens		
	7.069	7.219	7.500	7.184	7.354	6.947		5.859	6.343	5.178	6.705	6.004	
Fe ⁺⁺	.442	.403	.068	.514	.165	.706		2.146	1.652	2.579	1.145	2.014	
Mg	.383	.442	.480	.366	.474	.362		0.224	0.309	0.283	0.403	0.157	
Mn	-	-	-	-	-	-		-	-	-	-	-	
Ni ⁺⁺	-	-	-	-	-	-		-	-	-	-	-	
Zn	-	-	-	-	-	-		-	-	-	-	-	
total	8.094	8.064	8.048	8.064	8.043	8.015		8.229	8.304	8.040	8.253	8.175	
Al	5.804	5.812	4.411	4.961	4.521	5.779		6.510	5.520	0.268	6.417	6.532	
Cr	8.322	7.334	7.339	6.972	6.872	8.374		7.154	7.091	94.478	7.033	5.712	
Fe ⁺⁺⁺	1.684	2.725	4.159	3.739	4.571	1.818		1.874	2.780	11.172	2.044	3.403	
Ti	.694	.064	.085	.663	.043	.014		0.230	0.104	0.000	0.252	0.175	
total	15.904	15.936	15.954	15.935	15.957	15.985		15.768	15.655	15.558	15.746	15.822	

CHROMITE ANALYSES

OXIDE	SAMPLE NUMBER	45110	45110	45110	#1 shaft	#1 shaft	#1 shaft
	3		4	5	46	47	48
FeO	19.8	20.8	20.7	20.7	13.9	14.6	13.0
MgO	10.5	9.91	9.27	9.27	13.3	13.2	14.3
MnO	0.15	0.27	0.45	0.45	.60	.56	.35
NiO	n.d.	n.d.	n.d.	n.d.	.14	-	-
ZnO	n.d.	n.d.	n.d.	n.d.	.13	.13	.27
Al ₂ O ₃	20.3	21.1	18.9	18.9	20.6	20.7	20.9
Cr ₂ O ₃	40.3	40.9	42.0	42.0	45.1	45.7	45.8
Fe ₂ O ₃	10.2	8.71	8.98	8.98	4.55	4.50	4.37
TiO ₂	0.34	0.37	0.32	0.32	.21	.29	.35
Sum	101.59	102.06	100.62	100.62	98.4	99.68	99.34

Recalculated on the basis of 32 oxygens

Fe**	4.137	4.337	4.430	4.430	2.921	3.036	2.682
Mg	3.896	3.676	3.534	3.534	4.962	4.876	5.260
Mn	0.032	0.056	0.098	0.098	.127	.118	.073
Ni**	-	-	-	-	.028	-	-
Zn	-	-	-	-	-	.024	.049
total	8.066	8.069	8.062	8.062	8.038	8.054	8.064
Al	5.973	6.186	5.656	5.656	6.100	6.069	6.104
Cr	7.975	8.045	8.491	8.491	8.959	8.980	8.951
Fe***	1.924	1.630	1.729	1.729	.861	.842	.813
Ti	0.064	0.069	0.052	0.052	.060	.054	.065
total	15.936	15.930	15.938	15.938	15.970	15.945	15.933

MAGNETITE ANALYSES

MAGNETITE ANALYSES

OXIDE	26399-420	R22	R22	30414-240	30414-240	30414-240	30414-240	30414-240	30414-240
FeO	153	102	105	107	111	118	125	131	125
MnO	31.4	29.7	30.6	31.3	30.8	31.3	31.2	31.2	31.2
MnO	.08	.07	.05	.03	-	.12	-	.12	-
NiO	-	.12	-	-	.09	-	-	-	-
ZnO	-	1.40	-	-	.32	.13	-	-	-
Al ₂ O ₃	-	-	-	-	-	.22	-	.14	-
Cr ₂ O ₃	-	3.87	1.26	.45	.32	.72	1.05	1.05	.25
Fe ₂ O ₃	69.0	65.5	66.8	68.9	69.0	70.0	68.9	68.9	69.1
TiO ₂	-	-	-	-	-	-	-	-	-
Sum	101.48	100.66	98.71	100.68	100.53	102.49	101.41	101.41	100.55

Recalculated on the basis of 32 oxygens

Recalculated on the basis of 32 oxygens

OXIDE	26399-420	R22	R22	30414-240	30414-240	30414-240	30414-240	30414-240	30414-240
FeO	153	102	105	107	111	118	125	131	125
MnO	31.4	29.7	30.6	31.3	30.8	31.3	31.2	31.2	31.2
MnO	.08	.07	.05	.03	-	.12	-	.12	-
NiO	-	.12	-	-	.09	-	-	-	-
ZnO	-	1.40	-	-	.32	.13	-	-	-
Al ₂ O ₃	-	-	-	-	-	.22	-	.14	-
Cr ₂ O ₃	-	3.87	1.26	.45	.32	.72	1.05	1.05	.25
Fe ₂ O ₃	69.0	65.5	66.8	68.9	69.0	70.0	68.9	68.9	69.1
TiO ₂	-	-	-	-	-	-	-	-	-
Sum	101.48	100.66	98.71	100.68	100.53	102.49	101.41	101.41	100.55

FeO

MnO

MnO

NiO

ZnO

total

Al

Cr

FeO

Ti

total

Legend

10F

LATER MAFIC DYKES & SILLS

Diabase
Hornblendite

10

10a
10b

Geological contact

observed

PEEWATAI LAKE STOCK

Porphyritic quartz-monzonite
Equigranular coarse grained granite
Syenite
Felsic dykes

9

9a
9b
9c
9d

inferred

from magnet.

flow contact

SHONKONITE

Coarse-grained magnetic
ultramafic rock
Shonkonite

8

8a
8b

Strike & dip of

Strike & dip of

SHEBANDOWAN LAKE STOCK

Granodiorite
Quartz-feldspar porphyry
Fine-grained felsic dykes

7

7a
7b
7c

Strike & dip of
direction known
graded bedded

pillowed basal

MAFIC INTRUSIVE ROCKS

Gabbro, diorite

6

6a

flow-top breccia

Ultramafic rock, serpentinite, talc-
carbonate schist
Highly altered ultramafic rock now
quartz-ankerite-pyrite-fuchsite

6b

6c

flame structure
scours

cryptic zone

ULTRAMAFIC EXTRUSIVE ROCKS

6d

Azimuth & Plunge
lineation

YOUNGER THOLEIITIC SUCCESSION

kink band

BASALT

5

drag fold

Figure II- 2

contact:

erved

rrred

magnetic data

contact observed

dip of bedding

dip of overturned bedding

dip of bedding, younging
known from:
bed bedding

lowed basalt

w-top breccia

me structures or channel
urs

ptic zoning in chromite

& Plunge
eation

ak band

ag fold

dip of foliation

20F

Crayfish Creek Fault

Loch McLean

30F

Geology of The Shebandowan Mine Area

Area

40F

5 of

60F

YOUNGER THOLEIITIC SUCCESSION

BASALT

Pillowed basalt
Hyaloclastite
Amygdular basalt
Hornblende porphyritic basalt
Chert/ash tuff
Red-black jasper-magnetite, Iron
formation
Black-white chert-magnetite, Iron
formation
Shales and graphitic horizons
Breccia

5

5a
5b
5c
5d
5e
5f
5g
5h
5i

HIGH-MAGNESIUM BASALT

Pillowed
Flow breccia
Picrite
Tuff
Iron formation

8 of

4

4a
4b
4c
4d
4e

FELSIC PYROCLASTIC ROCKS

Debris flow
Proximal facies conglomerate

3

3
3a

OLDER THOLEIITIC SUCCESSION

VOLCANICLASTIC ROCKS

Greywacke-iron formation
Conglomerate
Siltstone
Fic tuff

2

2a
2b
2c
2d

BASALT

Feldspar porphyritic flows
Massive and coarse-grained flows
Pillowed basalt
Variolitic lava
Mafic tuff
Shale
Mafic flow breccia

1

1a
1b
1c
1d
1e
1f
1g

kink ba

drag fo

Strike & dip

second

Strike & dip

Geological f

Diamond drill
direction, l

Mine shaft

Mine building

Road

Swampy area

Sample number
analyses

Location of

kink band

drag fold

strike & dip of foliation

second foliation

strike & dip of joints

geological fault

diamond drill hole: number,
direction, length

mine shaft

mine buildings

road

wampy area

sample number: refer to chemical
analyses

Location of cross-section

90F

76 - PM-301

tech McLean

55

OF / DE

k Fault

HIGH-MAGNESIUM BASALT

Pillowed
Flow breccia
Picrite
Tuff
Iron formation

4

4a
4b
4c
4d
4e

Diamond drill
direction, le

Mine shaft

FELSIC PYROCLASTIC ROCKS

Debris flow
Proximal facies conglomerate

3

3
3a

Mine building

Road

OLDER THOLEIITIC SUCCESSION

Swampy area

VOLCANICLASTIC ROCKS

Greywacke-iron formation
Conglomerate
Siltstone
Mafic tuff

2

2a
2b
2c
2d

Sample number
analyses

BASALT

Feldspar porphyritic flows
Massive and coarse-grained flows
Pillowed basalt
Variolitic lava
Mafic tuff
Shale
Mafic flow breccia

1

1a
1b
1c
1d
1e
1f
1g

Location of

160F

Diamond drill hole: number,
direction, length

Shaft

Buildings

d

Empty area

Sample number: refer to chemical
analyses

76-PM-301

Location of cross-section

170F

NW

5

10F

D

N

C

7a

6

1

100

1

1

A

•

1

1

1

1

3

1

1

• • •

•

20F

NW

2d

1a

IF

S

30F

40F

B

A

60F

N

A

7a

4

4a

2

2

2

62

3*

b

2

2

2

2

2

2

2

2

2

2

2

2

2

2

70F

THOUSAND FEET

KM

Figure II-6

FOR GEOLOGICAL LEGEND SEE FIGURE II-2

VERTICAL SCALE IS THE SAME AS HORIZONTAL

● PLUNGE OF FOLD IS WEST

▲ PLUNGE OF FOLD IS EAST

90F9

90° 17'

10F

STRUCTURAL GEOLOGY OF THE SH

20F

E SHEBANDOWAN MINE AREA

30F

Figure 11-8

Legend

9 Peewat

8 Shonko

7 Sheban

6 Ultrama

Younger B

5 Basa

4 Mg-r

3 Felsic P

Older Bas

1

40F

Legend

5 of

9 Peewatai Lake Stock

8 Shonkonite

7 Shebandowan Lake Stock

6 Ultramafic Rock

Younger Basaltic Succession

5 Basalt

4 Mg-rich Basalt & Tuff

3 Felsic Pyroclastic Rock

48° 34'

60F

Feet

1000

5000

0.3

1.5

Km

90° 17'

3 Felsic Pyroclastic

Older Basaltic

2 Greywacke,
Siltstone

1 Basalt

Younging Direction

Fault

Antiformal, Synformal

90° F

3 Felsic Pyroclastic Rock

Older Basaltic Succession

**2 Greywacke, Conglomerate,
Siltstone**

1 Basalt

Younging Direction

Fault

Antiformal, Synformal Axis

Figure II-19

10F

Schematic Plans of Shebandowan Mine

Shebandowan Lake Stock
unit 7

Ultramafic Rock
unit 5b

Basalt
unit 4

Pyroclastic Debris Flow
unit 3

2000 level

1800 level

20F

13.45a 11

unit 4

Pyroclastic Debris Flow

unit 3

Ni-Cu Ore

30F

000 level

000 level

000 level

000 level

END

1 3 0 9 8 4

FIN