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GEOLOGICAL ENVIRONMENTS OF THE PLATINUM GROUP ELEMENTS

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INTRODUCTION

The platinum group elements (PGE) include platinum, palladium, rhodium, ruthenium, iridium and osmium. The PGE are valued both for their industrial applications and as precious metals. The largest uses are in automotive emission control systems and electrical components. Other important applications are in the chemical and petroleum industries, jewellery and dentistry. A relatively recent development has been the significant demand for platinum as an investment. Current world consumption of the PGE amounts to about 235 tonnes annually, and it is anticipated that demand will increase substantially between now and the end of the century. This optimism is fueled in part by the introduction of automobile emission standards in the European Economic Community, Australia and Korea which will almost certainly lead to increased use of PGE in the form of catalytic converters. In the longer term, it is expected that widespread use of fuel cells for electrical energy generation would also have a significant impact on demand for PGE.

PGE supply is currently dominated by the Republic of South Africa and the U.S.S.R. which together account for more than 90 percent of world primary production. Canada was the world's leading producer from 1934 to 1955, but now ranks a distant third accounting for about 5 percent. Production began at the Stillwater Complex in Montana in 1987 at a rate which will make the United States the fourth ranking primary producer.

The positive outlook for PGE demand as compared to most other metals, coupled with the perception that supplies from the dominant producing countries may be subject to disruption for political reasons, has contributed to the current unprecedented interest in PGE exploration. Despite some notable successes (e.g., Conn, 1979), there has been relatively little PGE exploration in the past. This of course was a result of the supply and demand situation, and the fact that PGE have been regarded as being mainly by-products of nickel-copper mining. However, it also reflects the state of knowledge of PGE mineralogy, geology and analytical technology.

In this volume, we describe the geological setting of some of the world's significant current and prospective PGE producers and of many significant occurrences and deposits in Canada. A brief summary of the theoretical basis for understanding the genesis of PGE deposits is also provided, along with some suggested guidelines for PGE exploration. This is not intended to provide either a comprehensive or in-depth review. Rather, our objective is to provide mineral exploration geologists with a useful summary and an introduction to the literature. The interested reader is also referred to a number of other volumes and collections of articles devoted to the PGE. These include, among others, review articles by Mertie (1969), Naldrett and Duke (1980), Naldrett (1981b), and MacDonald (1987), CIM Special Volume 23, and three special issues of the journal Economic Geology (volume 71, no. 7; volume 77, number 6; and Volume 81, no. 5). A summary of world resources was recently presented by Sutphin and Page (1986).

CLASSIFICATION OF PGE DEPOSITS

Introduction

Although a number of different classifications of PGE deposits have been proposed (Naldrett, 1981; Cabri, 1981; Cabri and Naldrett, 1984; MacDonald, 1987), none has yet become universally accepted. This is not surprising given the relatively small number of productive deposits and the state of our knowledge of their genesis. We propose the classification scheme outlined in Table 1 wherein PGE deposits are grouped into three genetic categories: magmatic, hydrothermal and surficial.

Magmatic Deposits

Magmatic deposits occur in igneous rocks and involve concentration of the PGE by magmatic processes. These generally involve conventional magmatic segregation of an immiscible sulphide melt which effectively concentrates PGE from the parent silicate melt. Chromite may act as a collector of PGE in some cases but the evidence for this is by no means clear. We would also include in this category deposits formed by hydrothermal concentration of the PGE so long as the hydrothermal activity occurred in the magmatic environment.

The magmatic deposits are subdivided according to their relationship with their host rocks. The first group, and the most important from the standpoint of PGE production and resources, comprises deposits which are stratabound with respect to the igneous stratigraphy within layered intrusions. Examples include the Merensky Reef and UG-2 chromitite in the Bushveld Complex, the JM Reef and the Picket Pin deposits in the Stillwater Complex and the Main Sulphide Zone (MSZ) of the Great Dyke. These deposits have been described as "stratiform" by some authors (e.g., Naldrett et al., 1987; Stumpfl and Ballhaus, 1986), but we believe that the term "stratabound" more accurately reflects their character. "Stratiform" implies that the ore is "...strictly coextensive with...igneous layers" (AGI Glossary). Whereas this is essentially true in the case of the Merensky Reef, for example, it cannot be said of the J-M Reef.

The second group comprises mineralization which is clearly discordant with respect to igneous layering: the dunite pipes of the Bushveld Complex are the best known examples. Sulphide concentrations in the marginal zones of intrusions make-up the third group. These include the majority of productive Ni-Cu-PGE deposits such as those of Sudbury and Noril'sk but also PGE-Ni-Cu deposits such as the Platreef of the Bushveld. We also include magmatic sulphides that occur as basal accumulations in lava sequences and hypabyssal intrusions in this third category. The principal examples are nickel sulphide deposits of the Kambalda type which are hosted by komatiite lava flows. The fourth category includes magmatic deposits which are not readily assigned to one of the three preceding groups, either because they

Table 1. Classification of Platinum Group Element Deposits and Occurrences

Class	Subclass	Examples
MAGMATIC	Stratabound	Merensky Reef, Bushveld, southern Africa UG-2, Bushveld, southern Africa J-M Reef, Stillwater, Montana Picket Pin, Stillwater, Montana MSZ, Great Dyke, Zimbabwe Cyclic units, Muskox intrusion, N.W.T ULCZ, Fox River, Manitoba Lower Chromitites, Bird River, Manitoba Cyclic Zone, Crystal Lake Gabbro, Ont. Delta North, Ungava, Quebec
	Discordant	Dunite pipes, Bushveld, southern Africa
	Marginal	Platreef, Bushveld, southern Africa Coldwell Complex, Ontario Noril'sk, U.S.S.R. Sudbury, Ontario Marginal sulphides, Muskox, N.W.T. Katiniq, Ungava, Quebec Donaldson West, Ungava, Quebec Bravo, Ungava, Quebec Rottenstone, Saskatchewan Coryell, British Columbia Wellgreen, Yukon
	Other	Roby Zone, Lac des Iles Werner Lake - Gordon Lake Tulameen, British Columbia Zoned Complexes, U.S.S.R.
HYDROTHERMAL	Pt-Pd-Au-(Cu)	New Rambler, Wyoming Messina, southern Africa Peter Lake, Saskatchewan Unst, Shetland Islands, U.K.
	U-Au-Pt-Pd	Nicholson Bay, Saskatchewan Coronation Hill, N.T., Australia Shinkolobwe, Zaire
SURFICIAL	Alluvial	San Juan and Attrato Rivers Choco District, Colombia Ural Mountains, U.S.S.R Tulameen, British Columbia Goodnews Bay, Alaska
	Eluvial	Gilgarnia Rocks, Western Australia

Table 2. Grades and Resources of Principal Magmatic PGE Deposits

	Price[1]	Merensky Reef	UG-2	Platreef	J-M Reef	Great Dyke	Noril'sk Talnakh	Sudbury
Ni	$1.76/lb	0.18 %	0.09 %	0.3 %	0.24 %	0.25 %	2.4 %	1.3 %
Cu	$0.62/lb	0.11 %	0.03 %	0.2 %	0.14 %	0.25 %	3.0 %	1.1 %
Pt	$ 462/oz	4.8 g/t	3.7 g/t	3.1 g/t	4.2 g/t	2.5 g/t	0.95g/t	0.34g/t
Pd	$ 116/oz	2.0 g/t	3.0 g/t	3.4 g/t	14.8 g/t	1.7 g/t	2.7 g/t	0.36g/t
Rh	$1157/oz	0.24g/t	0.70g/t	0.22g/t	1.7 g/t	0.22g/t	0.12g/t	0.03g/t
Ir	$ 414/oz	0.08g/t	0.20g/t	0.06g/t	0.53g/t	0.03g/t	?	0.01g/t
Ru	$ 73/oz	0.65g/t	1.0 g/t	0.29g/t	0.89g/t	0.22g/t	0.04g/t	0.03g/t
Os	$ 625/oz	0.06g/t	?	0.04g/t	?	0.03g/t	?	0.01g/t
Au	$ 368/oz	0.26g/t	0.06g/t	0.25g/t	0.12g/t	?	?	0.12g/t
Grade - PGE + Au		8.1 g/t	8.7 g/t	7.3 g/t	22.3 g/t	4.7 g/t	3.8 g/t	0.9 g/t
Gross In Situ Value[2]		$ 103/t	$ 102/t	$ 87/t	$ 203/t	$ 66/t	$ 163/t	$ 75/t
% of Gross Value (PGE + Au)		92 %	96 %	83 %	94 %	80 %	18 %	12 %
Resources[3] (tonnes contained PGE)		17,500	32,400	11,800	1,100	7,900	6,200	394

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[1] Average 1986 price in U.S. dollars

[2] Gross value of contained metals per metric tonne of ore in the ground; no allowance is made for dilution, metallurgical recovery, etc.

[3] Generally equivalent to United Nations resource categories R1E and R2E: that is, reliable estimates of economically exploitable ore in known deposits and preliminary estimates of economically exploitable ore in extensions to known deposits and newly discovered deposits. Data from ISMI (International Strategic Minerals Inventory), except for Great Dyke which is from Naldrett et al. (1987).

are not yet well enough understood or because they are truly distinctive. The most relevant example is the Roby Zone deposit at Lac des Iles, Ontario.

Magmatic deposits account for more than 95 percent of past production of PGE and more than 98 percent of current measured resources. The resources and grades of the principal magmatic deposits are given in Table 2. The relative abundance of the various PGE and the base metals are extremely variable among the deposits. This is of economic importance because of the very different prices of the metals. Grades are often quoted in terms of total PGE, particularly in the popular press, and it is obvious that the relative proportions of Pt and Pd, and the amounts of valuable minor PGE such as Rh, will have an important bearing on the value of the deposit. While the J-M Reef, for example, is described as being palladium-rich by virtue of its high Pd:Pt ratio, it is noteworthy that the Pt grade approaches that of the Merensky Reef and the Rh grade is significantly higher. Table 2 also illustrates the natural two-fold division of magmatic sulphide deposits into those in which PGE are the primary product and those in which the PGE are by-products. Upon first reflection, it may seem that there should be a complete spectrum of PGE-Ni-Cu ratios and that this is a simply an economic subdivision. However, the genetic principles which we will review below suggest a phenomenological explanation for this observation.

Hydrothermal Deposits

Hydrothermal PGE deposits involve PGE transport in and deposition from hot aqueous fluids, and may occur in a variety of host rocks. This class includes not only veins and other clearly epigenetic mineralization but also concentration of PGE in diagenetic and sedimentary exhalative environments.

There have been relatively few productive PGE-rich vein deposits: the copper deposits at New Rambler, Wyoming and Messina, South Africa are the best known examples. A significant quantity of PGE is recovered as a by-product of copper refining operations in the United States and the PGE are derived ultimately from porphyry copper deposits. However, the absolute abundance of PGE in porphyry and related skarn deposits is generally low (typically <200 ppb), and it would be stretching a point to refer to these as PGE deposits. Significant concentrations of PGE are also reported from stratabound copper deposits of the Kupferschiefer, Poland (Kucha, 1982).

Although hydrothermal PGE deposits have heretofore made a negligible contribution to world production, they may offer exciting exploration targets. In particular, it is worth noting that such deposits are characterized by exceptionally high grades.

Surficial Deposits

PGE are known to be concentrated in both alluvial and eluvial deposits and, in fact, stream placers were the only commercial source of PGE about 1920. The most productive placers were in the San Juan and Atrato Rivers district of Colombia and the Ural Mountains of the Soviet Union. In North America, placers in the Tulameen River in British Columbia and at Goodnews Bay Alaska have been important producers. The concentration of PGE by eluvial processes has been documented, for example, in laterites but there has been no significant commercial recovery (see Cabri, 1981 for brief summary).

Summary

The summary of the geological characteristics of PGE deposits which follows is organized in the first instance under the primary classification headings magmatic deposits, hydrothermal deposits and surficial deposits. The magmatic category is further subdivided into PGE dominant deposits and Ni-Cu dominant deposits. The treatment is in terms of geological entities, usually an igneous complex, or mining camps rather than the secondary deposit types defined above. This is because an igneous complex, for example, may contain several deposit types which is in itself an interesting observation.

Both Bushveld and Stillwater complexes contain stratabound, discordant and marginal PGE-Ni-Cu deposits. Both the Bird River Sill and Crystal Lake Gabbro contain not only stratabound PGE-Ni-Cu mineralization, but also a marginal Ni-Cu-PGE deposits. Moreover, some bodies contain deposits of more than one genetic class. Thus the Peter Lake Complex hosts hydrothermally remobilized PGE-Ni-Cu as well as primary Ni-Cu-PGE mineralization, and the zoned dunite-clinopyroxenite complexes of the Urals have PGE mineralization in bedrock and also related stream placers.

Table 3. The more common platinum group minerals, listed alphabetically

Mineral	Ideal Formula
Braggite	(Pt,Pd)S
Cabriite	Pd_2SnCu
Cooperite	PtS
Erlichmanite	OsS_2
Isomertieite	$Pd_{11}As_2Sb_2$
Irarsite	IrAsS
Iridosmine	(Os,Ir)
Isoferroplatinum	Pt_3Fe
Kotulskite	PdTe
Laurite	RuS_2
Merenskyite	$PdTe_2$
Michenerite	PdBiTe
Moncheite	$PtTe_2$
Osmiridium	(Ir,Os)
Platarsite	PtAsS
Plumbopalladinite	Pd_3Pb_2
Polarite	Pd(Bi,Pb)
Rutheniridosmine	(Os,Ir,Ru)
Sperrylite	$PtAs_2$
Stannopalladinite	Pd_5Sn_2Cu
Sudburyite	PdSb
Taimyrite	$Pd_9Sn_4Cu_3$
Vysotskite	PdS

MINERALOGY OF THE PGE

Our knowledge of the mineralogy of the PGE has increased substantially in the last 10 -15 years with many new species having been found and characterized. For example, the number of known platinum group minerals (PGM) increased from just 23 in 1965 (Wright and Fleischer, 1965) to 64 in 1972 (Cabri, 1972) to 84 currently. These minerals include arsenides, tellurides, sulphides, native metals and alloys, antimonides, and even intermetallic compounds with tin and copper or lead. Platinum and palladium minerals account for over 70 percent of the known PGM species, a reflection of their abundance relative to the other four PGE (Rh, Ru, Os, and Ir). The most common PGM is sperrylite ($PtAs_2$), which occurs in all deposit types. Michenerite (PdBiTe) is also quite common. Interestingly, both minerals were first described from the nickel-copper sulphide ores of the Sudbury area. Table 3 lists the names and chemical formulae of 23 of the more important PGM, but not including two unnamed PGE-sulphides which are abundant in the UG-2 chromitite. Detailed descriptions of 75 PGM are given by Cabri (1981).

The application of modern analytical techniques for the in-situ analysis of trace elements, such as the electron and proton microprobes, has confirmed that the PGE can also occur dispersed in dilute solid solution in other minerals, particularly sulphides such as pentlandite and pyrrhotite (Cabri and Laflamme, 1981). It should be stressed, however, that there are currently few available data on the trace PGE content of individual minerals for many, if not most, deposits. Genetically and geochemically related deposits may have similar mineralogy and PGE distribution, but there are usually enough distinctive mineralogical features to make each deposit unique in detail. Knowledge of the exact distribution of the PGE is an important factor when potential ores are being evaluated for exploitation and is critical to their metallurgical recovery.

MAGMATIC PGE DEPOSITS

BUSHVELD COMPLEX, SOUTHERN AFRICA

Introduction

The Bushveld Complex in southern Africa is the largest body of mafic-ultramafic rocks in the world (Fig. 1). It contains approximately 70 percent of the world's reserves of PGE (NYMEX, 1986), and hosts the largest known deposits of PGE, Cr, Fe-Ti-V and low-grade Cu-Ni mineralization.

Platinum mineralization was first discovered near Naboomspruit, in the central Transvaal, in 1923 by Adolf Erasmus. This platinum mineralization was found outside the Rustenburg Layered Suite and was confined to quartz veins infilling brecciated fault zones within the felsites in the roof of the complex. Although these quartz veins were only exploited from 1924-1926, they created new interest in PGE prospecting in the Transvaal. As a result, Andries Lombaard panned a platinum concentrate from a stream bed on the farm Maandagshoek in the Lydenburg district in 1924. Lombaard brought this to the attention of Dr. Hans Merensky and an extensive prospecting program was initiated which eventually led to the discovery of the Merensky Reef and the UG-2 Chromitite.

Geological Setting

The mafic rocks of the Bushveld Complex extend over an area of about 480 by 380 km in the Kaapvaal craton in southern Africa (Fig. 1). They outcrop in three crudely arcuate bands referred to as the eastern, western and northern Bushveld which are superficially similar but differ considerably in detail. It is believed that the complex was emplaced as seven shallow, partly overlapping conical intrusions, which eventually coalesced into three larger magma chambers corresponding to the eastern, western and northern "compartments" (Von Gruenewaldt, 1979; Vermaak and Von Gruenewaldt, 1981). The basaltic and boninitic magmas that gave rise to this complex were introduced at approximately 2050 Ma into the 2223 Ma volcanic and sedimentary sequence of the Transvaal basin (Von Gruenewaldt et al., 1985). Subsequent cooling and fractional crystallization gave rise to a well developed stratified sequence of mafic-ultramafic rocks (cumulates) known as the Rustenburg Layered Suite.

The Rustenburg Layered Suite (Fig. 2) is approximately 7 to 9 km thick, dips gently towards the centre of the complex, and has been divided into four zones in upward stratigraphic succession as follows: 1) The lower zone consists of pyroxenites, harzburgites, minor dunites and, at Potgietersrus, rare high-grade chromitites. 2) The critical zone is composed of bronzite-pyroxenites, chromitites, norites and anorthosites, and has been divided into upper and lower subzones. The lower critical zone hosts the LG-6 or Steelpoort chromitite which is the main source of chromite from the Bushveld. The Merensky Reef and UG-2 PGE deposits occur within the upper critical zone. 3) The main zone is composed of gabbros, gabbronorites, anorthosites, norites and minor pyroxenites, however, the bulk of the zone consists of a thick monotonous succession of massive to weakly layered gabbronorites and gabbros. 4) The upper zone consists of a series of well layered magnetite gabbros, norites, gabbronorites, anorthosites, troctolites, olivine gabbros and diorites and magnetite layers. Twenty-one magnetite layers are found in this zone and range in thickness from less than 30 cm to 10 m.

PGE Mineralization

Five distinct settings of economically significant PGE concentrations are currently recognized in the complex. These are, in order of importance and from the highest to lowest stratigraphic levels in the Rustenburg Layered Suite: the Merensky Reef, UG-2 Chromitite, Platreef in the Potgietersrus area, the discordant platiniferous dunite pipes from the eastern

Bushveld and a mineralized lower zone pyroxenite from the Potgietersrus area.

Merensky Reef

The Merensky Reef, which is the world's largest single source of PGE, occurs in the upper part of the critical zone. In general, it is a pyroxenite layer which occurs in all sectors of the Bushveld Complex, has an average thickness of 0.8 m, and dips gently ($<10^{\circ}$) towards the centre of the complex. Vermaak (1976) defined the Merensky Reef as a "coarse-grained feldspathic pyroxenite" that is underlain by mottled or spotted anorthosite or norite, and is overlain by a porphyritic feldspathic pyroxenite. The two pyroxenites together define the basal portion of the Merensky cyclic unit which extends upwards through spotted anorthosite to mottled anorthosite. The Bastard cyclic unit overlies the Merensky cyclic unit and is also characterized by a basal feldspathic pyroxenite member. The remaining portion (approx. 30 m) of this unit consists of spotted and mottled anorthosites, anorthositic norites and norites. Figure 3 illustrates the succession of rocks found in the Merensky and Bastard cyclic units, its position relative to the underlying UG-1 and UG-2 chromitite layers and the changes encountered in the succession of rock types from "normal reef" to "pothole reef" in the western Bushveld.

The largest production from the Merensky Reef comes from the Rustenburg and Impala areas. The first mining operations on the Merensky Reef were in the Rustenburg area and for this reason it has always been considered the "type locality". At Rustenburg "normal reef" consists of a coarse-grained pegmatoidal feldspathic pyroxenite. It is very thin, varying in thickness from 15 to 40 cm. The top and bottom contacts are marked by thin chromitite layers a few millimeters thick; the highest PGE values in the Rustenburg area are associated with these chromitite layers (Hochreiter et al., 1985). A brownish pyroxenite known as the "Merensky pyroxenite" occurs above the top chromitite (Fig. 4A). In the Impala area, the Merensky Reef is typically a coarse-grained to pegmatoidal pyroxenite with either one or two thin chromitite layers, and the reef is approximately one metre thick. The "pegmatoidal reef" (Fig. 4E) usually has a thin footwall chromite layer and a well developed chromitite layer (20 mm thick) above the pegmatoid. The coarse pegmatoid is up to 0.3 m thick. The coarse-grained "pyroxenite reef" (Fig. 4D) may have a weakly developed chromitite layer near its base. In the pyroxenitic reef, the PGE-bearing zone is associated with the footwall chromitite layer whereas in the pegmatoidal reef the PGE are associated with the upper chromitite layer (Mostert et al., 1982).

It should be pointed out that the Merensky Reef varies considerably throughout the Bushveld Complex as well as within the Rustenburg area itself. In the eastern and southern sectors of the Bushveld Complex, the pyroxenite is strongly developed and much of the mineralization is located within it. In these sectors the pegmatoidal phase may be absent or, if it is present, it may be virtually barren. In the western and southwestern sectors of the complex, the pegmatoidal phase is strongly developed as are the chromite contact layers. In the northwestern sector, the Merensky Reef is underlain by a cyclic unit with a basal feldspathic pegmatoidal harzburgite. This unit is known as the "Pseudo Reef" and is absent elsewhere in the complex (Fig. 3). Here, the ore in the Union section is associated with chromitite layers in an olivine-rich pegmatoid. This is the only sector of the complex where the Merensky Reef is rich in olivine. In contrast, the Merensky Reef at the Western Platinum mine (15 km east of Rustenburg) is considerably thicker and finer-grained than at the other localities. Here the reef is a two to six m thick porphyritic pyroxenite layer. The bulk of the PGE and sulphides are associated with a 2 to 5 mm thick chromitite that occurs 0.2 to 0.5 m below the upper contact (Vermaak and Von Gruenewaldt, 1981).

In some parts of the complex, the reef is characterized by "potholes" where the reef plunges into depressions where the footwall stratigraphy has been removed (Fig. 3 and Fig. 5). The potholes may be circular or irregular in plan, up to hundreds of metres across and tens of metres deep. In the Union section of the northwest sector, the "Pothole reef" occurs at the top of the "pseudoreef marker" layer, because its immediate footwall succession, which averages approximately 14 m in thickness, has been removed (Fig. 5). A number of different types of Merensky Reef are developed within a pothole structure. "Contact reef" forms from the convergence of the top and bottom chromitite layers of the normal reef. It is found on the margins of the pothole structures and represents the transition between "normal" and "pothole" reef. "Pothole reef" starts at the point where "contact reef" is a pegmatoidal feldspathic pyroxenite and/or harzburgite with good mineralization and the same general features as normal reef. "Lens reef" contains lenses of leuconorite or anorthosite which occur immediately above the "pseudoreef" marker layer and range from 0.1 m to 100 m in length. In the area of lens development the mining is confined to the "pothole reef" (Fig. 5). The origin of potholes is problematic but models involving scour by magmatic currents resorbtion by unsaturated magma (Irvine et al., 1983), or "plutonic fumaroles" (Buntin et al., 1985) have been proposed.

The base-metal sulphides and associated PGE are not restricted to the Merensky Reef itself but are disseminated into the footwall norite or anorthosite and in the hangingwall pyroxenite. However, the bulk of the PGE are restricted to the chromite-rich intervals regardless of the type of reef (Fig. 4). Vermaak and Von Gruenewaldt (1981) and Vermaak (1985) state that the average PGE + Au grade for the Merensky Reef is 6.47 ppm. The grades are variable within the complex as well as within sectors. Naldrett (1981) suggests an average grade of 8.1 ppm for the western Bushveld, whereas at the Western Platinum mine in the southwest sector the average grade is 5.67 ppm. The Pt:Pd ratio is higher in the Merensky Reef than in any of the other PGE environments of the Bushveld (Table 4).

Mineralogical and geochemical studies indicate a strong association between PGE and Ni-Cu sulphides. The principal PGM are braggite, cooperite, Pt-Fe alloys and sperrylite. Next in abundance are moncheite, laurite and kotulskite. The pentlandite contains some Pd in solid solution (up to about 3%) as well as traces of Ru and Rh may also be present. In addition, the pyrrhotite may also contain Ru. Whereas the Pt-Pd sulphides are the most abundant PGM in normal reef, the Pt-Fe alloys dominate the PGM assemblage in the pothole reef. Kinloch (1982) compiled a wealth of quantitive data on the types, volume distribution and mode of occurrence of the PGM in the Merensky Reef, the UG-2 and Platreef. He found complex regional trends in the PGM but observed that in any given location, the PGM in the three mineralized horizons are related. Thus, if in a particular area the Merensky Reef contains Pt-Pd sulphides as the dominant PGM, then it can be safely inferred that Pt-Pd sulphides will be a significant component of the UG-2 layer in that same area.

UG-2 Chromitite

Whereas the Merensky Reef in the largest source of current PGE production, the UG-2 chromitite contains larger resources of higher grade material and ranks as the largest single concentration of PGE in the world (Vermaak, 1985). Although the Pt grade in the UG-2 is lower than that in the Merensky, the grade of Rh, the most valuable PGE, is three times as great. Moreover, in addition to the base and precious metals, the potential recovery of by-product chromite could add to the value of the ore. The disadvantages of the UG-2 includes the fine grain size, which means that the ore must by ground more finely, and the friable nature of the ore which produces a large proportion of fines rich in PGE. Both of these factors adversely affect recovery rates. However the technology to overcome the metallurgical problems was developed in the mid to late 1970's and the UG-2 is currently being mined in at least two localities in the Bushveld.

The UG-2 chromitite occurs in the upper critical zone, as little as 15 m and as much as 370 m stratigraphically below the Merensky Reef (McLaren and De Villiers, 1982). It ranges from 0.15 to 2.55 m in thickness with an average of 0.60 m. It dips from 5° to 70° towards the center of the complex with an average of 15° (Vermaak, 1985). The steeper dips are encountered in the vicinity of dunite pipes.

The UG-2 cyclic unit is 16.5 m thick at the farm Maandagshoek where it has been studied in considerable detail by Gain (1985). The base of the unit here is marked by a "hairline" chromitite layer (Figure 6). This is overlain in turn by medium grained porphyritic melanorite (<1 m), pegmatoidal pyroxenite with irregular layers of harzburgite and chromitite (0.5 - 1.0 m), the UG-2 chromitite layer (0.5 - 0.6 m), fine-grained melanorite (10-15 cm), a chromitite "leader" (5-10 cm), porphyritic melanorite (9.5 m), and norite/leuconorite with a thin anorthosite layer at the top (4.5 m). Minor lenses, layers and disseminations of chromite occur over about a metre in the porphyritic melanorite overlying the chromitite leader.

Gain (1985) reports that bulk analyses of the UG-2 chromitite show that Pt, Pd, Ru, Rh, Ir, Au, S, Ni, Cu, and Co are concentrated close to the top and base of the main chromitite layer, in the leader layer and in minor chromitite layers and lenses in the footwall pegmatoid and hangingwall melanorite. The distribution of the various elements is illustrated in Fig. 7. Based on 17 boreholes, 4 channel samples and one underground bulk sample, Gain (1980) calculated an average grade of 3.22 ppm Pt, 3.24 ppm Pd, 0.87 ppm Ru, 0.54 ppm Rh, 0.27 ppm Ir and 0.07 ppm Au. The grades at Maandagshoek are somewhat higher than the average grade for the UG-2 in the Bushveld as given by Vermaak and Von Gruenewaldt (1981) and Vermaak (1985) in Table 4.

McLaren and DeVilliers (1982) found that the PGE values in the UG-2 chromitite are mainly confined to the basal and middle portions of the main chromite layer in the southeastern, southwestern and northwestern sectors of the Bushveld Complex. Different PGM assemblages characterize the UG-2 in the different sectors of the complex. In the southeast, braggite, laurite, vysotskite, cooperite and an unnamed Pt-Rh-Ir-Cu-S mineral predominate. In the northwest, laurite, braggite, cooperite and Pt-Fe alloy and an unnamed Pt-Rh-Ir-Cu-S mineral are the main species. In the southwest sector laurite, braggite, cooperite and unnamed Pt-Rh-Cu-S, Rh-S and Pt-Pd-Cu-S minerals are the most common minerals. Sulphides of the PGE predominate in the northeast sector (Naldrett, 1981).

Platreef

Major resources of PGE, Ni, Cu and Co occur in the Platreef. The reef occurs in the Potgietersrus compartment (i.e., northern limb) of the Bushveld Complex where the mafic rocks of the Rustenburg Layered Suite intrude in a northerly direction, downwards through the Pretoria and Chuniespoort groups, to come to rest on the Archean granitic basement (Fig. 1). The Platreef is composed of a complex sequence of medium- to coarse-grained pyroxenites, melanorites, and norites, in places pegmatoidal and serpentinized, containing numerous xenoliths of metasediments. It is distinct from the other zones of the Rustenburg Layered Suite. It contains sporadic Ni, Cu and PGE mineralization which locally make it of economic significance. The reef has a strike length of over 60 km, a thickness of up to 350 m and dips 45° to the west. It is estimated that the average recovery grade for Platreef is 3.0 ppm PGE + Au, 3600 ppm Ni and 1800 ppm Cu (Vermaak and Von Gruenewaldt, 1981).

The Platreef lies between the main zone and the Archean granites, in the northern part of the Potgietersrus compartment, and the Transvaal sedimentary sequence in the central and southern parts (Fig. 8). The base of the reef consists of feldspathic pyroxenite which varies in thickness from 40 to 80 m and may contain a chilled margin. This feldspathic pyroxenite is overlain by a 170 m-thick sequence of norites and melanorites which are capped by a 10 to 30 m pyroxenite layer that forms the top of the reef. The sequence commonly contains metasedimentary xenoliths of dolomitic character that range in size from a few centimeters to 90 m in diameter (Gain and Mostert, 1982).

The sulphide (with associated PGE) is heterogeneously distributed in the Platreef and seldom makes-up more than 5 percent of the rock. It is found as blebs and disseminations along the floor, as uneconomic disseminations in unaltered igneous rocks, as enrichments in the reaction aureoles of dolomite xenoliths and as relatively high concentrations in serpentinized zones. Rare massive sulphide concentrations, from a few tens of centimeters up to two metres in thickness, have been found close to the basal contact and in brecciated contact rocks (Fig. 8). The distribution of Ni, Cu, Pt and Pd in the Platreef is illustrated in Figure 9A and 9B. It is apparent that the best grades occur in the upper portion of the Platreef. The main base metal sulphides present are, in order of abundance, pyrrhotite, pentlandite, chalcopyrite and, in places, pyrite. Minor amounts of cubanite, sphalerite, bornite, millerite, cuprite, galena and alabandite occur. The dominant sulphide assemblage in the lower 150 m is pyrite (32 percent), pentlandite (34 percent), pyrrhotite (17 percent) and chalcopyrite (17 percent). The mineral assemblage in the upper 100 m consists of pyrrhotite (67 percent), pentlandite (21 percent), and chalcopyrite (12 percent) with or without troilite and cubanite. The variation may indicate that the sulphide liquid changed in composition from sulphur-rich to metal-rich during crystallization of the Platreef. It is interesting to note that the highest PGE values are associated with this metal-rich assemblage in the upper half of the reef.

The PGM in the Platreef have been extensively studied and vertical and lateral zoning of the PGM have been noted. PGE sulphides tend to occur near the base of Platreef while electrum and isoferroplatinum, when present, occur towards the top. A large amount of Pd occurs in solid solution in pentlandite.

Platiniferous Dunite Pipes

Transgressive bodies of postcumulus iron-rich ultramafic pegmatite, composed predominantly of varying proportions of hortonolite, clinopyroxene, ilmenite, and Ti-magnetite, are distributed throughout the critical zone of the Bushveld Complex. Three of these bodies are known for their extremely high platinum contents. These are the Onverwacht, Mooihoek and Driekop pipes which occur in the northeast sector of the complex (Fig. 1) and were mined in the past for their Pt content.

The Onverwacht pipe transects the LG-6 chromitite (Steelpoort layer) and thus occupies the lowest stratigraphic position in the layered suite (Fig. 10). The pipe consists of a central carrot-shaped core of hortonolite dunite (olivine composition - Fo_{47-54}) which is no greater than 15 m in diameter. The core is surrounded by 40 m of dunite (Fo_{77-84}) and wehrlite. There is a transition zone of intermediate olivine compositions (Fo_{60-70}) between the core and the dunite. Large blocks of chromitite occur in the dunite, but these are considerably more iron-rich than the adjacent LG-6 chromitite. The Onverwacht pipe was mined during the 1920's and exceptional grades of up to 2000 ppm Pt were reported. On the 65-ft level of the mine, the central 8 m of the core averaged 31 ppm and the outer 1 m shell surrounding this had a grade of between 15-30 ppm. The average grade for the mine was 9-11 ppm (Wagner, 1929).

The Mooihoek pipe is located about 200 m higher in the succession than the Onverwacht pipe. It occurs in spotted leuconorite and intersects two chromitite layers (Fig. 10). It also has a central core of hortonolite dunite, which is 10-15 m in diameter, and is encased in a 220 m diameter shell of olivine dunite and wehrlite. This is rimmed by a coarse pegmatitic diallagite and feldspathic pyroxenite. The Pt content increases from the margin towards the core of the hortonolite dunite where maximum values of 80 ppm were recorded. The average grade for the mine was 12-14 ppm. Some high values were also found in the adjoining olivine dunite. The olivines in this body show a similar range in forsterite content as that of the Onverwacht pipe (Stumpfl and Rucklidge, 1982).

The Driekop pipe occurs about 700 m above the LG-6 chromitite and cuts norites, leuconorites and melanorites of the upper critical zone (Fig. 10). The Driekop pipe had the largest pay area of the three pipes, 20 x 25 m in the centre of a 100 to 150 m diameter olivine dunite. The composition of the olivine ranges from Fo_{67} to Fo_{84} and apparently has no concentric compositional distribution or relation to the distribution of ore. The body plunges at 77 degrees and was mined to a depth of 200 m. Unlike the other two pipes, the country rock to the Driekop pipe forms a collapse structure around the pipe with the layered sequence becoming almost vertical near the contact. The highest Pt values (approximately 120 ppm) occurs in small pegmatitic segregations and patches in the olivine dunite. The average Pt grade for the mine was 5-6 ppm.

The mineralogy of the pipes differs greatly from that of either the UG-2 or Merensky Reef in that there are no PGE tellurides and PGE sulphides are rare. Pt-Fe alloys make up 50 percent of the PGM, with sperrylite and geversite making up 30 percent and the remaining 15 percent is accounted for by hollingworthite and irasite.

Lower Zone South of Potgietersrus

The lower zone at Potgietersrus is at least 1600 m thick and consists of 37 cyclic units. In comparison to the lower zone in the other sectors of the complex, the cumulates at Potgietersrus are richer in olivine and compositionally more primitive. The mg-numbers of olivine and orthopyroxene are 5-6 mole percent higher, and chromitites are chrome- rather than iron-rich. It is inferred that equivalents of the lower zone cumulates at Potgietersrus may be found in the deeper unexplored levels of the lower zone in the main portion of the Bushveld Complex.

The most significant sulphide and PGE

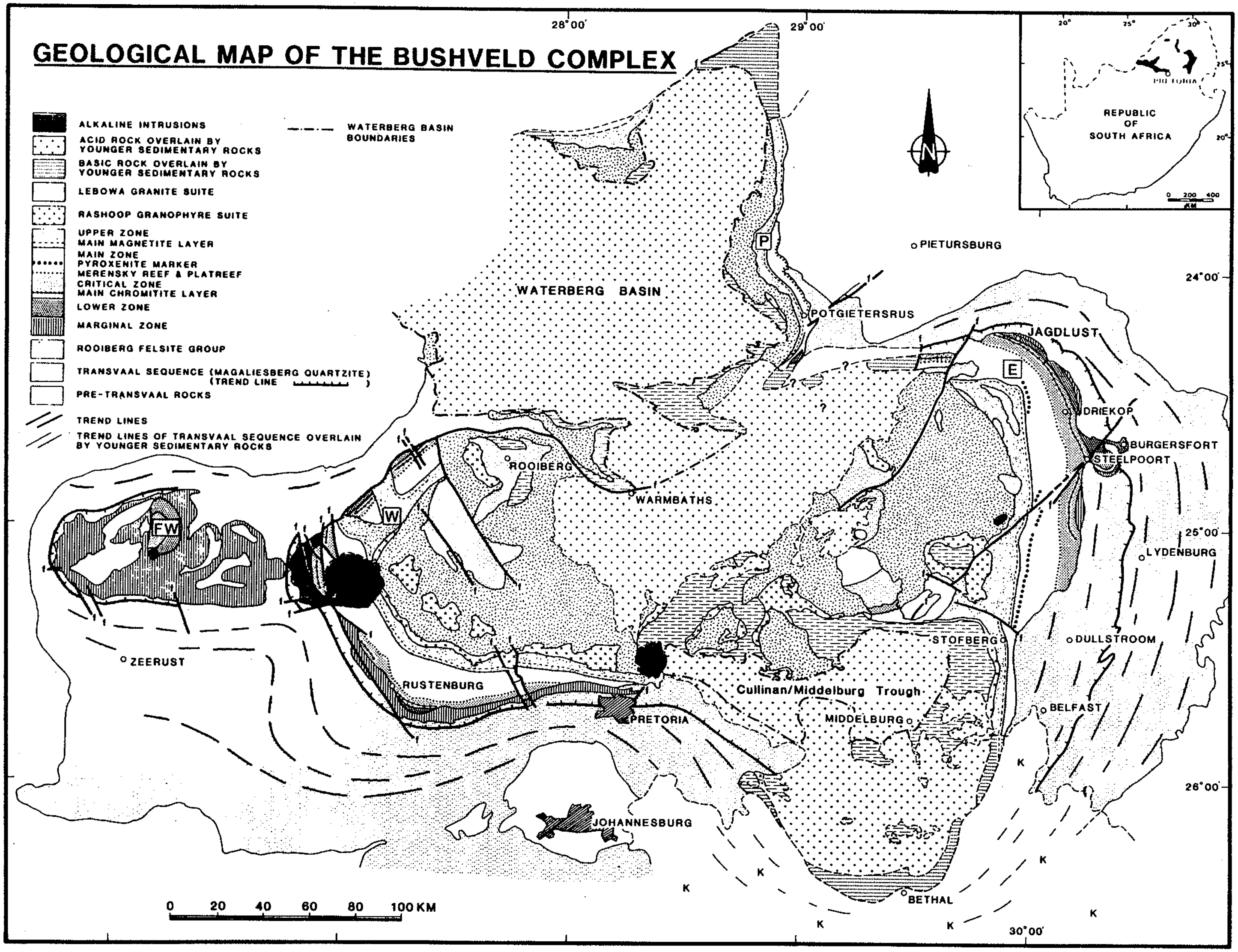

Figure 1. Generalized geological map of the Bushveld Complex.

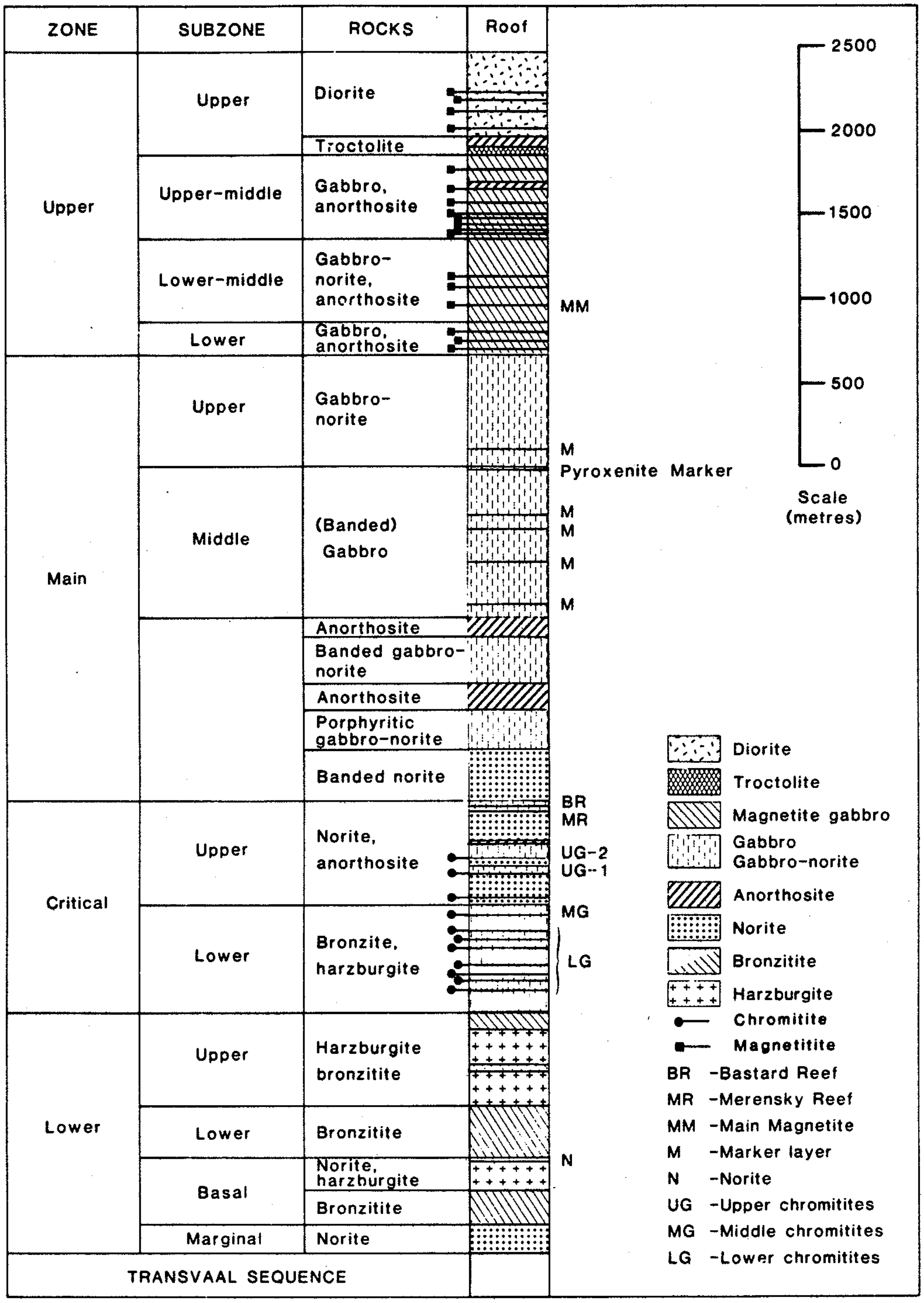

Figure 2. Stratigraphic column of the Rustenburg Layered Suite in the eastern portion of the Bushveld Complex.

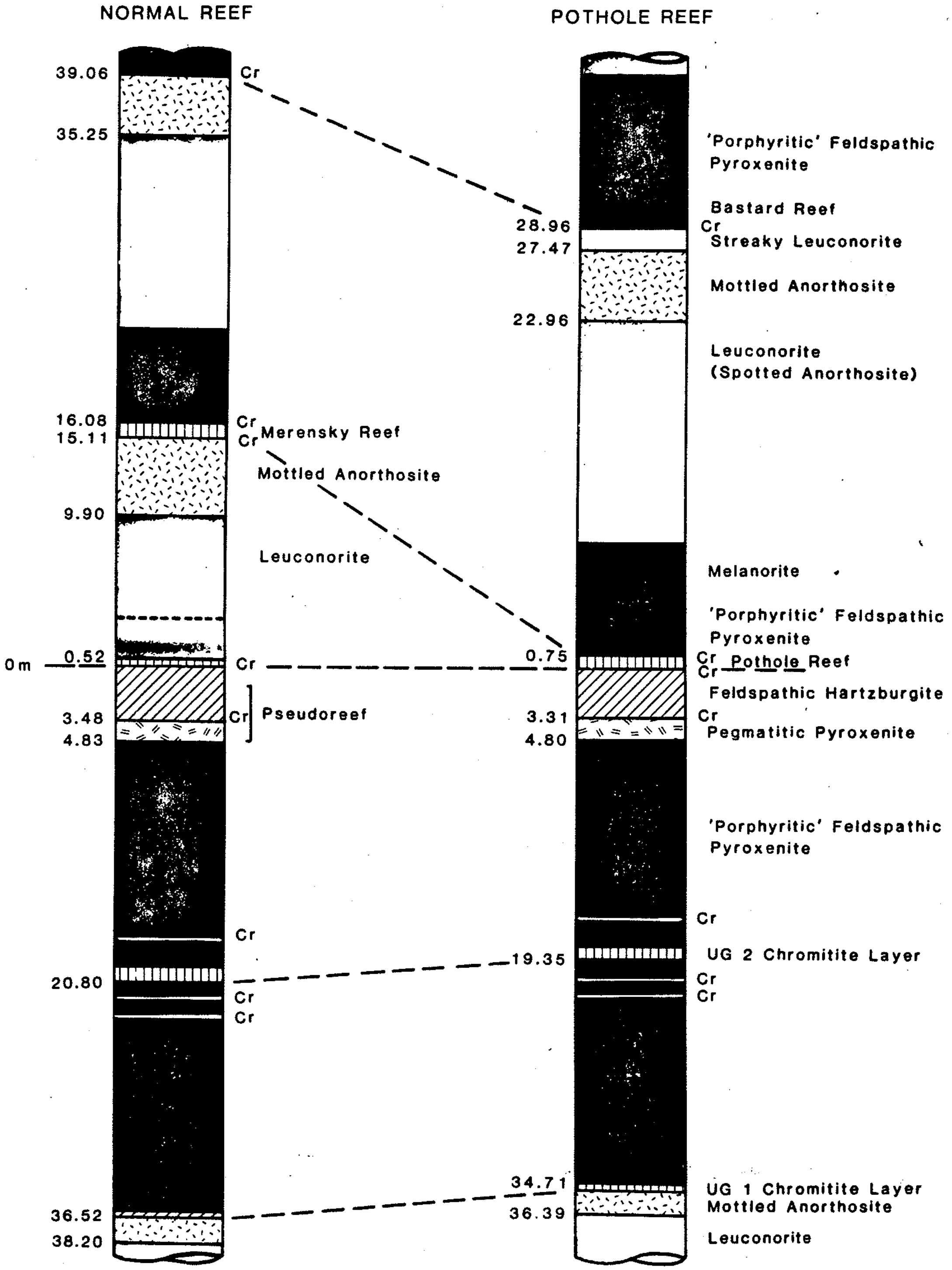

Figure 3. Columnar sections illustrating changes in the succession of rock types from a normal reef (left) to pothole reef (right) (After Vermaak and von Gruenewaldt, 1981).

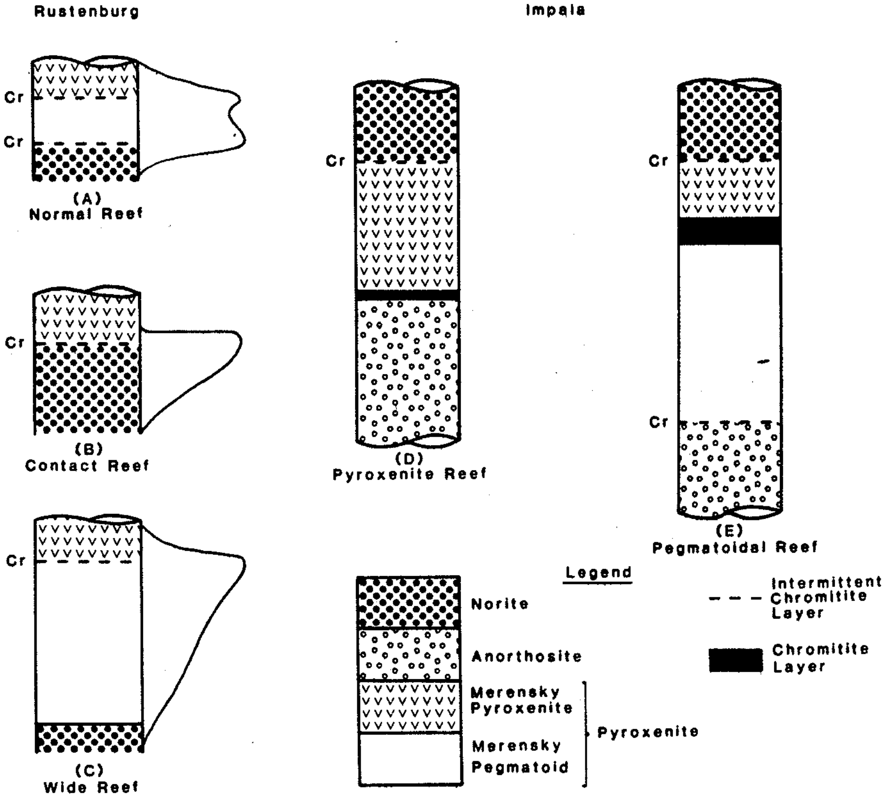

Figure 4. Schematic diagrams of the various reef types at the Impala Platinum mines and the Rustenburg Platinum mines (after Mostert et al., 1982 and Horchreiter et al., 1985).

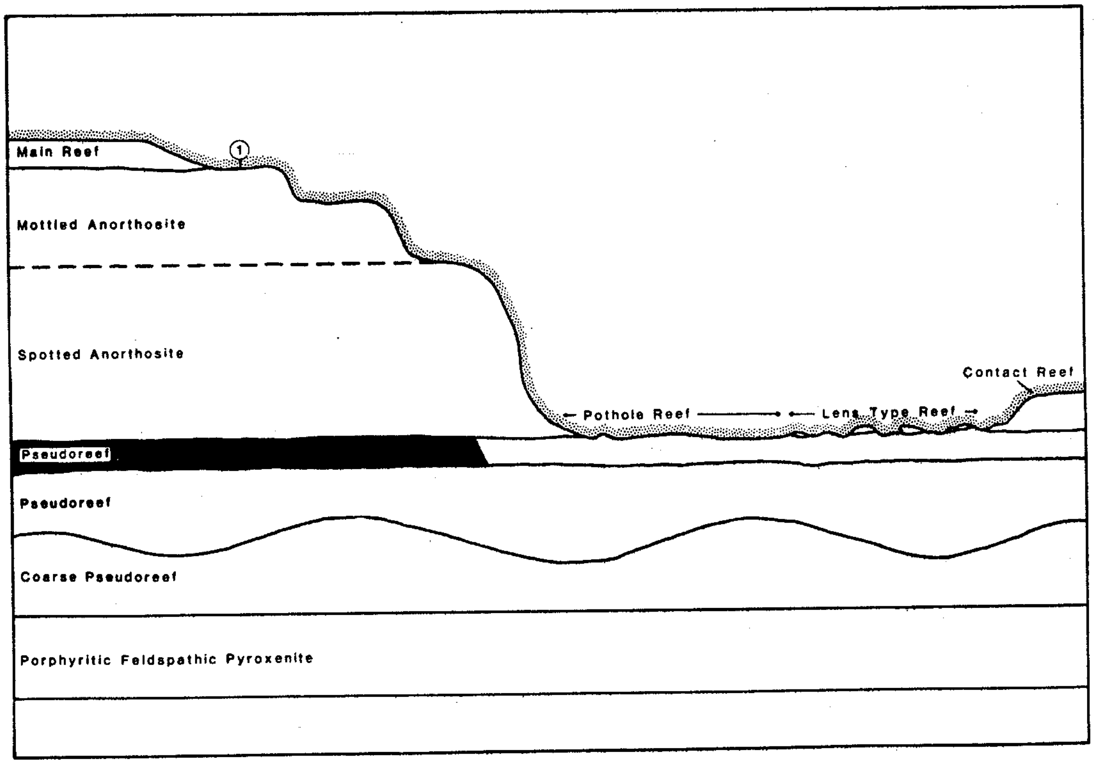

Figure 5. Schematic section through a pothole illustrating the relationship between the different reef-types at the Union section, Rustenburg Platinum mines (after Vermaak and von Gruenewaldt, 1981).

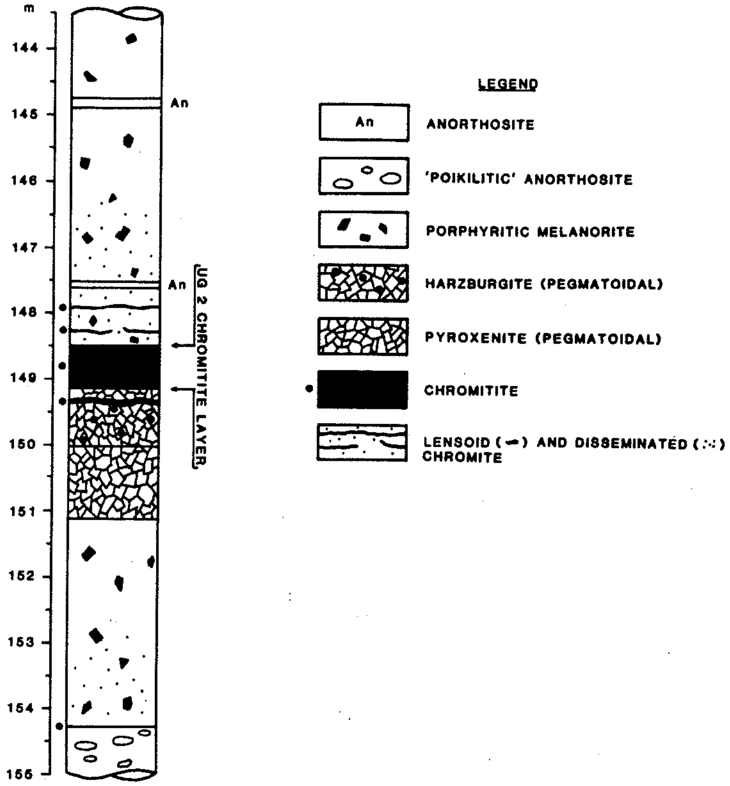

Figure 6. Detailed section of the UG-2 chromitite layer on the farm Maandagshoek, eastern Bushveld Complex, illustrating its relationship to the enclosing lithologies (after Gain, 1985).

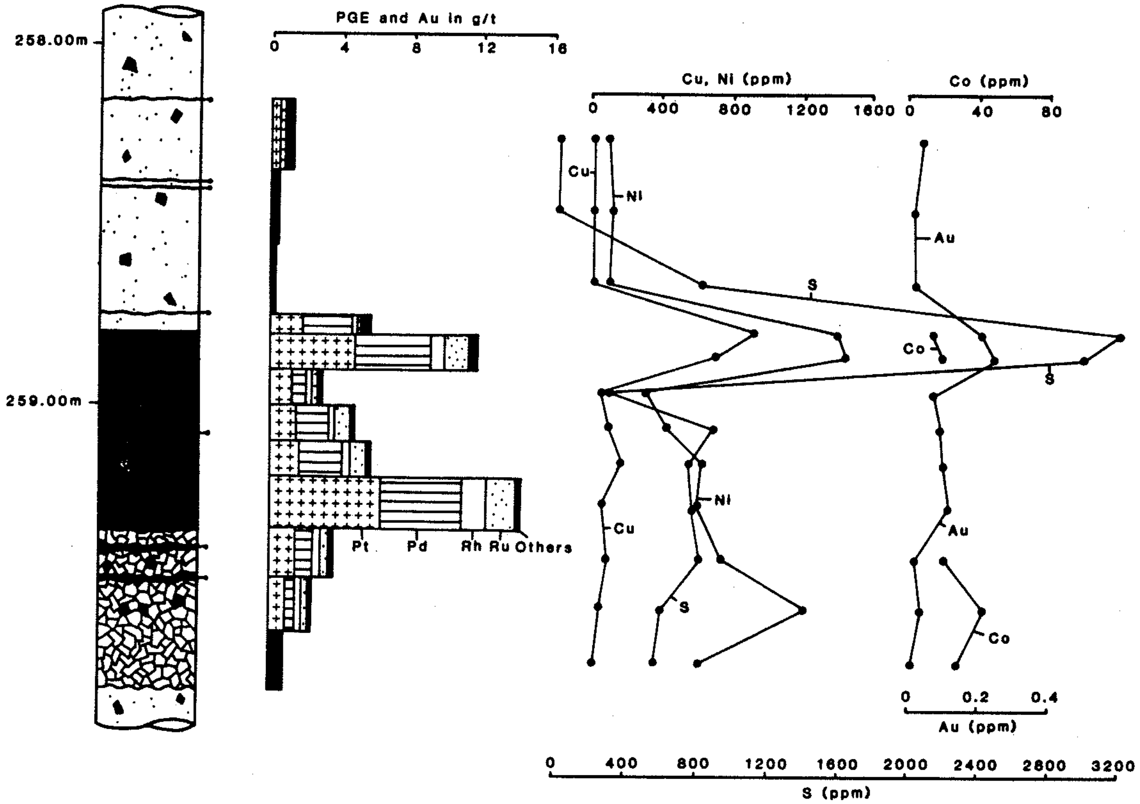

Figure 7. Distribution of Pt, Pd, Rh, Ru, Au, Co, Ni, Cu and S in borehole MDH-5A on the farm Maandagshoek (after Gain, 1985).

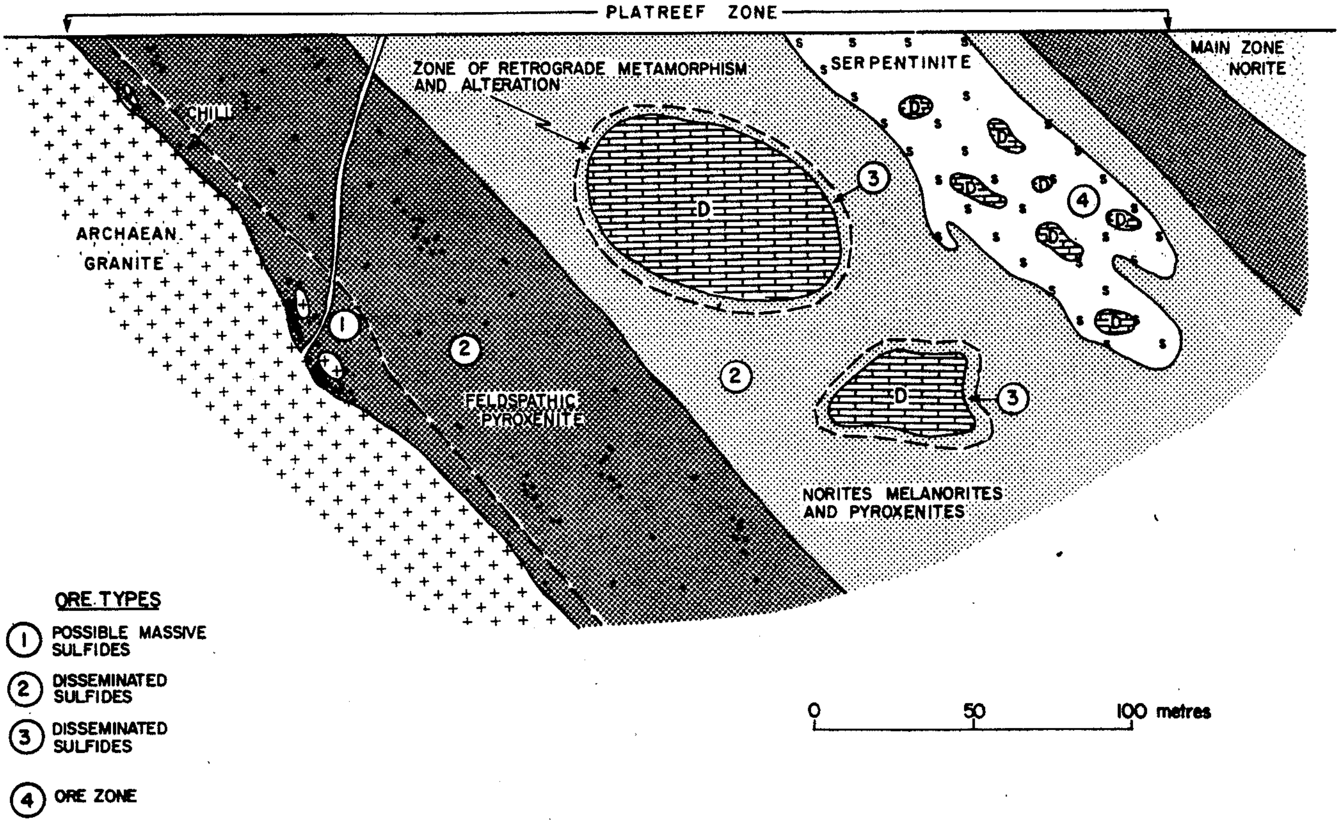

Figure 8. Cross-section through the Platreef on the farm Drenthe, north of Potgietersrus (after Gain and Mostert, 1982) (D=Dolomite).

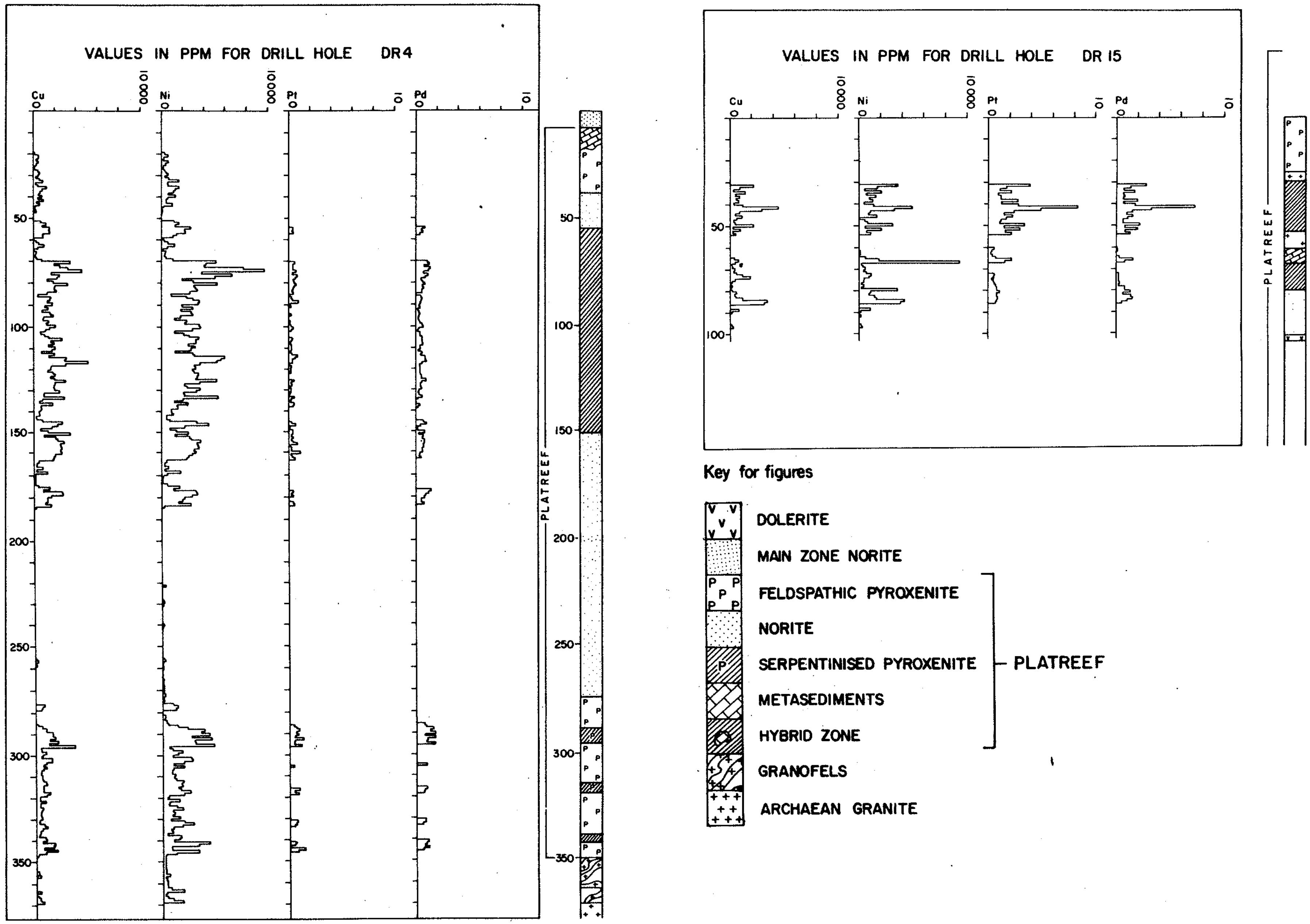

Figure 9. Simplified borehole profile and distribution of Cu, Ni, Pt and Pd in boreholes DR4 and DR5 on Drenthe (after Gain and Mostert, 1982).

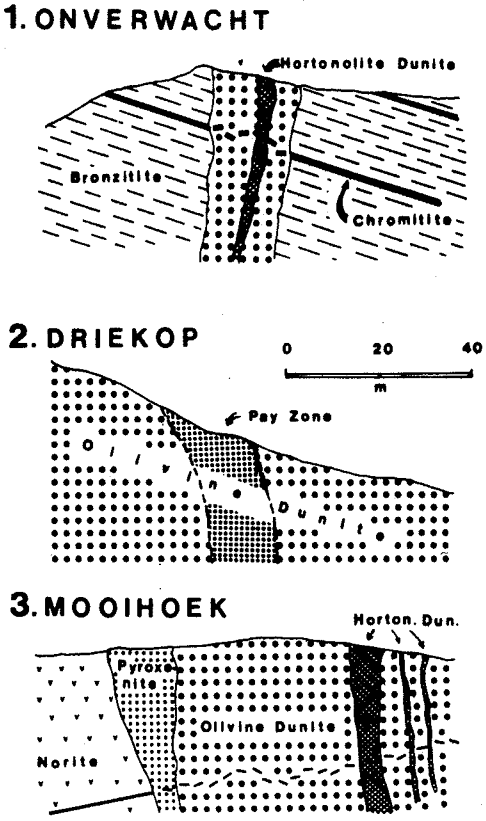

Figure 10. Sections through the platiniferous dunite pipes of the eastern Bushveld Complex (after Wagner, 1929 and Stumpfl and Rucklidge, 1982).

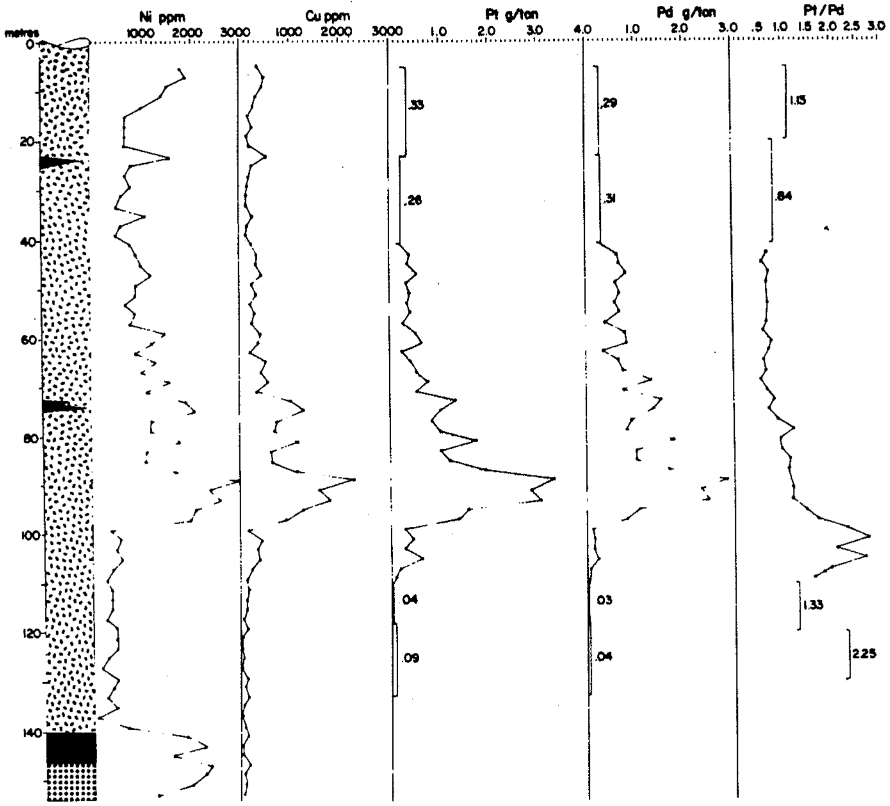

Figure 11. Ni, Cu, Pt and Pd variation through the PGE-enriched mineralization in the lower zone Volspruit pyroxenite south of Potgietersrus (after Hulbert and von Gruenewaldt, 1982).

Table 4: Comparison of Base Metal, PGE and Gold Contents of Mineralized Horizons of Bushveld Complex

PGE + Au Proportions	Merensky Reef	UG2 Chromitite	Platreef	Volspirit	
				East	West
Pt	59	41	42	32	
Pd	25	34	46	52	
Ru	8	12	4	3.6	
Rh	3	9	3	9.0	
Ir	1	1.9	0.8	1.0	
Os	0.8	1.7	0.6	1.0	
Au	3.2	0.4	3.4	1.9	
Total in Raw Ore	6.47	7.06	3.50*	3.51	6.00
Estimated Recovery Grade	5.50	6.04	3.00		
Ni (ppm)	1667	368		2400	2100
Ni (recov.)	1210	270	3600		
Cu (ppm)	948	218		1100	1400
Cu (recov.)	680	160	1800		

* Estimated

Values taken from Vermaak and Vow Gruenewaldt (1981) and Vermaak (1985).

mineralization found in the lower zone to date occurs on the farm Volspruit in the Potgietersrus compartment of the Bushveld Complex. The mineralization is confined to a beheaded orthopyroxene-chromite- sulphide cyclic unit (#11) in the basal portion of the lower zone. The highest grades are always found in the basal 6 m of the mineralized zone where sulphides constitute 3-4 percent of the rock. The average grades are on the order of 3.51-6.03 ppm PGE+Au, 2700-2400 ppm Ni and 1900-1100 ppm Cu. The lower grades occur in the eastern up-dip section of the mineralized zone (Table 4). The Ni, Cu, Pt and Pd variations through the down-dip western section of the mineralized zone are shown in Figure 11. Hulbert and von Gruenewaldt (1982) attribute the decrease of the Pt/Pd the upward from the base of the mineralized zone to fractionation.

The sulphide assemblage in consists of, in order of decreasing abundance, pyrrhotite, pentlandite, chalcopyrite and cubanite. It is distinct from mineralization elsehwere in the lower zone in that troilite and hexagonal pyrrhotite and cubanite are more abundant. Probably the most significant aspect of this mineralization is its location. Its presence in the lower zone calls into question the hypothesis that mineralized horizons like the UG-2 and the Merensky Reef only occur in more extensively fractionated rocks. Also, it suggest an entirely new environment in layered intrusions to explore for PGE.

STILLWATER COMPEX, MONTANA

Introduction

The Stillwater Complex, located in southwestern Montana, has long been known as one of the world's major layered intrusions. Sulphide-rich rocks were discovered in the Complex in 1883 and the occurrence of PGE was first reported by Howland et al. (1936). This report was not seriously followed-up until 1967 when the Johns-Manville Corporation initiated an exploration program which resulted in the discovery in 1973 of the stratigraphic zone rich in PGE known as the J-M Reef (Conn, 1979). The discovery of this zone has boosted the U.S. share of world reserves of PGE from well less than one percent to about five percent. The economically exploitable PGE resources of the J-M Reef are estimated to be 1100 tonnes (Table 2). Production began in 1987 at an estimated annual rate of about 3.4 tonnes of PGE, but this will likely double by 1991 (Johnson, Matthey, 1987).

Geological Setting

The Stillwater Complex occurs in the Beartooth Range which consists of an elevated block of Precambrian rocks covered in the south by Tertiary volcanics and in the north by Paleozoic and Mesozoic marine and continental sediments (Fig. 12). The Stillwater Complex and adjacent hornfels occupy the north flank of the Beartooth Mountains. Hornfelsed metasediments (diamictite, iron formation, blue metaquartzites) at least 3270 Ma (Page et. al., 1985), occur as a wedge between the base of the complex and the Mill Creek-Stillwater fault (Fig. 12). The lower part of the complex is intruded by a suite of 2700 Ma quartz monzonite rocks (Nunes and Tilton, 1971) on the east side of the Mill Creek-Stillwater fault. Two generations of mafic dykes are found in the area. The oldest are 2560 m.y. metamorphosed dolerites and the younger are 1800-1500 m.y. unmetamorphosed dolerites.

The Stillwater Complex is Archean in age with the most reliable date given as 2701 m.y. (De Paolo and Wasserburg, 1979a). The intrusion consists of a sequence of differentiated mafic and ultramafic rocks striking WNW to ESE for 48 km and having a maximum stratigraphic thickness of 7400 m (Fig. 13). The layering has an average dip of 65 degrees to the NNE, but along the eastern end of the complex the upper layers have been overturned. The complex has been extremely dislocated by strike faults, dip faults as well as by thrusting in the upper and lower layers in the middle and eastern portions of the intrusion.

The stratigraphic succession of rocks in the complex has been divided by McCallum et al. (1980) into five series: basal, ultramafic and lower, middle and upper banded (Fig. 14). The basal series is discontinuous due to faulting but is about 50-150 m thick. It has a basal norite member consisting mainly of norite and gabbronorite some of which is fine-grained and apparently chilled, and this is overlain by the basal bronzitite member which is mainly cumulate.

The ultramafic series is generally 800-1200 m thick and has been divided into a peridotite zone and an overlying bronzitite subzone. The peridotite zone consists of 15 cyclic units, each 50 to 150 m thick. The cyclic units reflect the crystallization order olivine + chromite, bronzite, plagioclase and augite (Jackson, 1961, 1971). In the ideal cyclic unit, the following rock succession is observed: olivine-chromite cumulate (poikilitic harzburgite), olivine-bronzite cumulate (granular harzburgite), and bronzite cumulate (bronzitite). Chromitite layers ranging from a few centimetres to several metres in thickness occur within the poikilitic harzburgites. Thirteen of these chromitite layers, labelled A through K sequentially from the base upwards, are developed in the peridotite subzone. The bronzitite zone is dominantly bronzite cumulate but contains some thin discontinous layers with cumulus olivine or chromite. A fairly well developed chromitite occurs near the top of the bronzitite zone. The lower, middle and upper banded series together include a succession of gabbro, norites, anorthositic and troctolitic rocks up to 4700 m thick. The lower banded series is a complex succession of norites and gabbronorites with minor anorthosites, troctolites and gabbro layers. The lower banded series includes the J-M Reef which occurs some 400-450 m above the top of the ultramafic zone in olivine-bearing zone I. The middle banded series consists dominantly of anorthosite with two complex subzones of olivine-bearing rocks. The most significant horizon in this series is the anorthosite II Zone, which is about 3000 m above the top of the Ultramafic Series and hosts the Picket Pin PGE deposit. The upper banded zone consists of a lower olivine-bearing zone and an upper gabbronorite zone.

PGE Mineralization

PGE-bearing sulphide mineralization have been found in all series of the complex. Although the J-M Reef and the Picket Pin deposit are the most signficant, other lesser occurrences warrant mention.

Basal Series

Sulphide mineralization is common in the basal series and underlying hornfelsed sediments of the Stillwater Complex. Resources of 150 million tonnes grading 0.25 percent Cu and 0.25 percent Ni have been reported by Page and Dohrenwand (1973) with the possibility that the resources may be two to ten times as high. Although higher-grade blocks of massive sulphides are known, their limited size, the finely intergrown nature of pentlandite and pyrrhotite, the high proportion of pyrrhotite relative to pentlandite, and the unusually high Fe/(Cu + Ni) ratio of the mineralization pose problems. The conentrations of PGE and Au in this deposit are low. Mineralization with 0.90 to 1.20 Ni + Cu have Pt, Pd, Rh, Ru, Ir and Au values of 20, 44, 9, 5, 3, and 15 ppb respectively (Page et al., 1985).

Ultramafic Series

Anomalous concentrations of PGE occur in the peridotite zone in association with chromitite layers. The highest PGE concentrations are associated with the A chromitite and, to a much lesser extent, the J chromitite. Values of Pt (999 ppb), Pd (2290 ppb), Rh (246 ppb), Ru (534 (ppb), Ir (513 ppb) and Au (86 ppb) have been recorded for the A chromitite (Page et al., 1985). Page and Dohrenwand (1973) state that the average grade for this chromitite is about 3.1 g/t. Small massive sulphide pods in the base of the thickest chromitite, the G layer, were found to only contain about 63, 61, 51, 178, 34 and 1 ppb Pt, Pd, Rh, Ru, Ir and Au respectively. Pt and Pd-rich discordant dunite and chromitite bodies located between the C and E chromitite contain close to 5 ppm Pt + Pd with ratio of the elements near 1:1. These same samples contain approximately 100 ppm sulphur.

Lower Banded Series

Discordant Lenses

Discordant bronzitite lenses, with disseminated and matrix sulphides, at the base of the banded series were found to contain 2700 ppb Pt + Pd. Similar sulphide-free bodies slightly higher up in the basal portion of the banded series contain values of 7200 ppb (Page et al., 1985).

J-M Reef

The J-M Reef is 1 to 3 m thick PGE-enriched horizon that contains between 0.5-1.0 volume percent disseminated sulphides, occurs 400-450 m above the base of the banded series and can be traced for 40 km within the intrusion. It occurs in olivine-bearing zone I (McCallum et al., 1980), also known as troctolite-anorthosite zone I (Todd et al., 1982), which is typically about 100 m thick. This zone comprises a complex succession of olivine-, plagioclase-, bronzite-, and augite-bearing cumulates and pegmatoidal rocks. In contrast to the Merensky Reef of the Bushveld Complex which is a lithological layer unit, the J-M Reef is defined as a Pt-Pd rich stratigraphic interval and it is not strictly stratabound. Todd et al (1982) noted that the Reef is everywhere associated with the unit they refer to as "olivine-bearing member 5". This member comprises two 1 to 2 m thick peridotite layers separated by 1 to 3 m of anorthosite and overlain by 3 to 8 m of interlayered troctolite and anorthosite. The J-M Reef occurs most commonly in the troctolite immediately above the upper peridotite layer, but may also be above or below this level. The olivine-bearing units, especially the peridotites, contain scattered grains of chromite but chromitite layers similar to those of the Merensky Reef have not been found. Although the host rock differs, and the J-M Reef is less well defined than the Merensky Reef, it is striking that similar PGE-enriched zones occurs at equivalent stratigraphic positions in both intrusions (Fig. 15).

The main sulphides are, in order of decreasing abundance, chalcopyrite, pyrrhotite and pentlandite. Associated with these sulphides are tiny grains of PGM, which consist of mainly moncheite, braggite, cooperite, kotulskite and Pt-Fe alloy. One 5.5 km long segment of the reef averages 22.3 g/t over 2.1 m with a typical Pd to Pt ratio of 3.5:1 Naldrett (1986) gives a grade of 0.24 percent Ni, 0.14 percent Cu, 4.2 ppm Pt, 14.8 ppm Pd, 1.7 ppm Rh, 0.53 ppm Ir, 0.89 ppm Ru and 0.12 ppm Au. It is interesting to note that these ores have 7 times more Rh than the Merensky Reef ores, and 2.4 times more than the UG-2 ores, yet they have a much higher Pd/Pt ratio than Bushveld ores.

Sulphide Zones Above the J-M Reef

Two additional horizons of disseminated sulphides occur in the lower banded series above the J-M Reef. Of these, the lower one has sulphide concentrations similar to those of the underlying J-M Reef but the grades are considerably lower; 3800 ppb Pt and 3250 ppb Pd. An unusual type of mineralization occurs approximately 200 m above this where values of Pt (5100 ppb) and Pd (3400 ppb) are found in selvages of chromite-rich and sulphide-bearing material adjacent to granitic intrusions.

Middle Banded Series

Picket Pin Deposit

Disseminated sulphides have been observed at six horizons within the Middle Banded Series but, with the exception of the uppermost - the Picket Pin deposit, these contain relatively low levels of PGE (Page et al., 1985).

The Picket Pin deposit occurs within the top 10 to 20 m of the Middle Banded Series in the anorthosite II zone (Boudreau and McCallum, 1985,

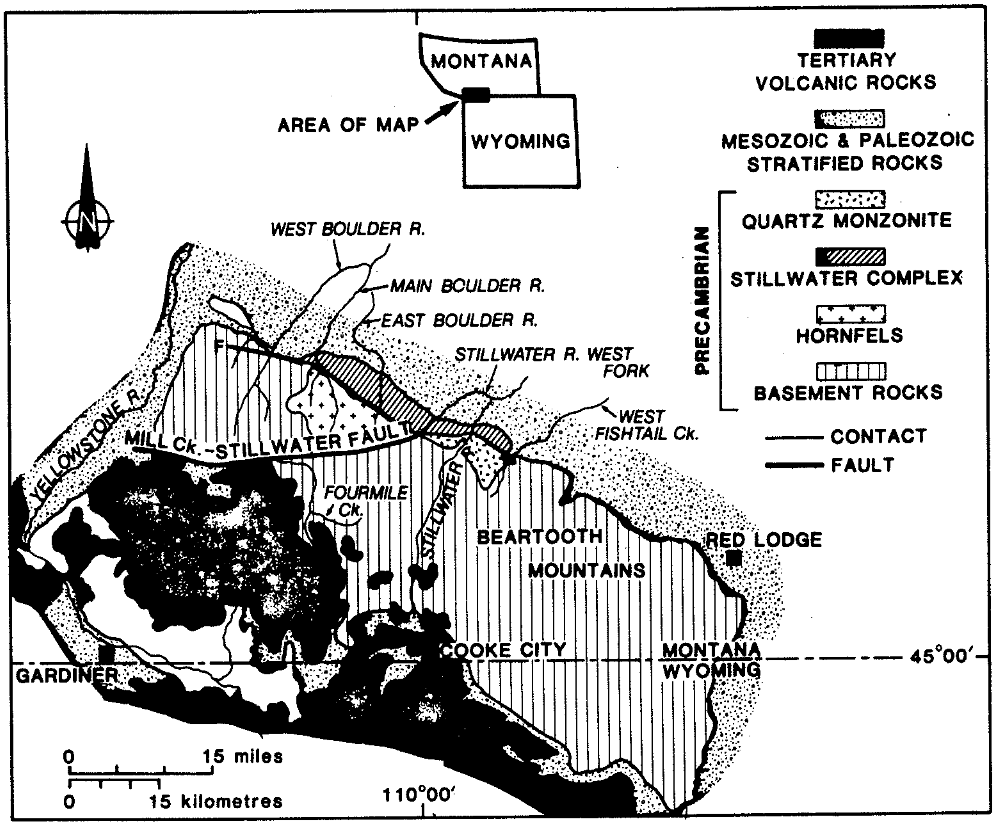

Figure 12. Generalized geological map of the Beartooth Mountains showing the position of the Stillwater Complex (after Page, 1977).

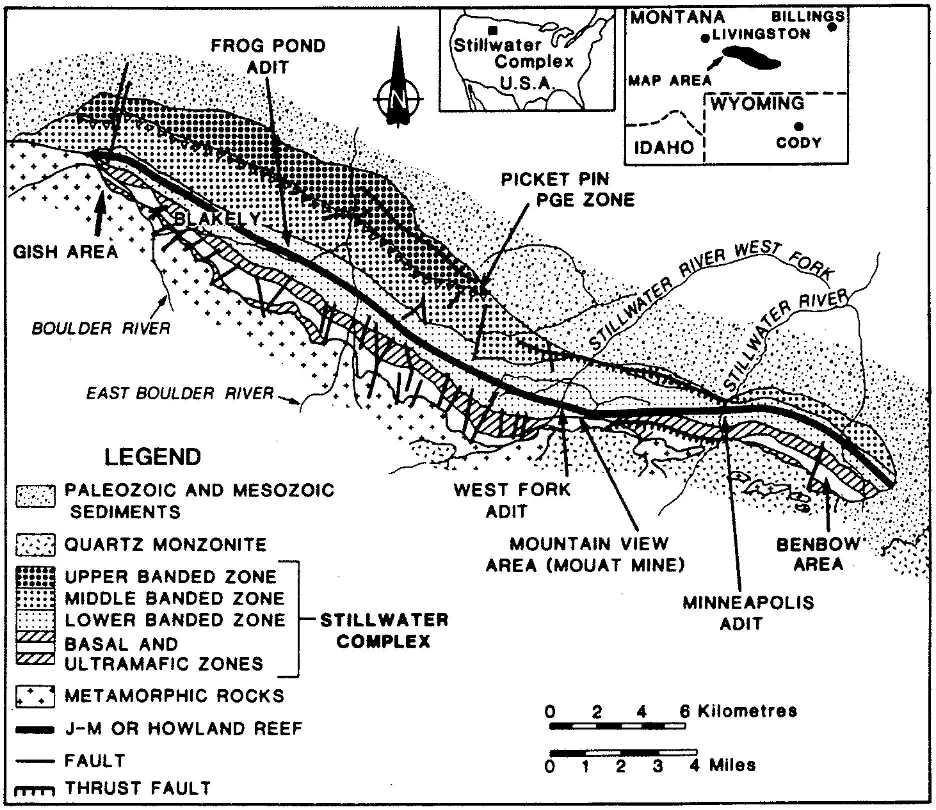

Figure 13. Generalized geological map of the Stillwater Complex, Montana showing the position of the J-M Reef and the Picket Pin deposit (after Todd et al., 1982 and Boudreau and McCallum, 1986).

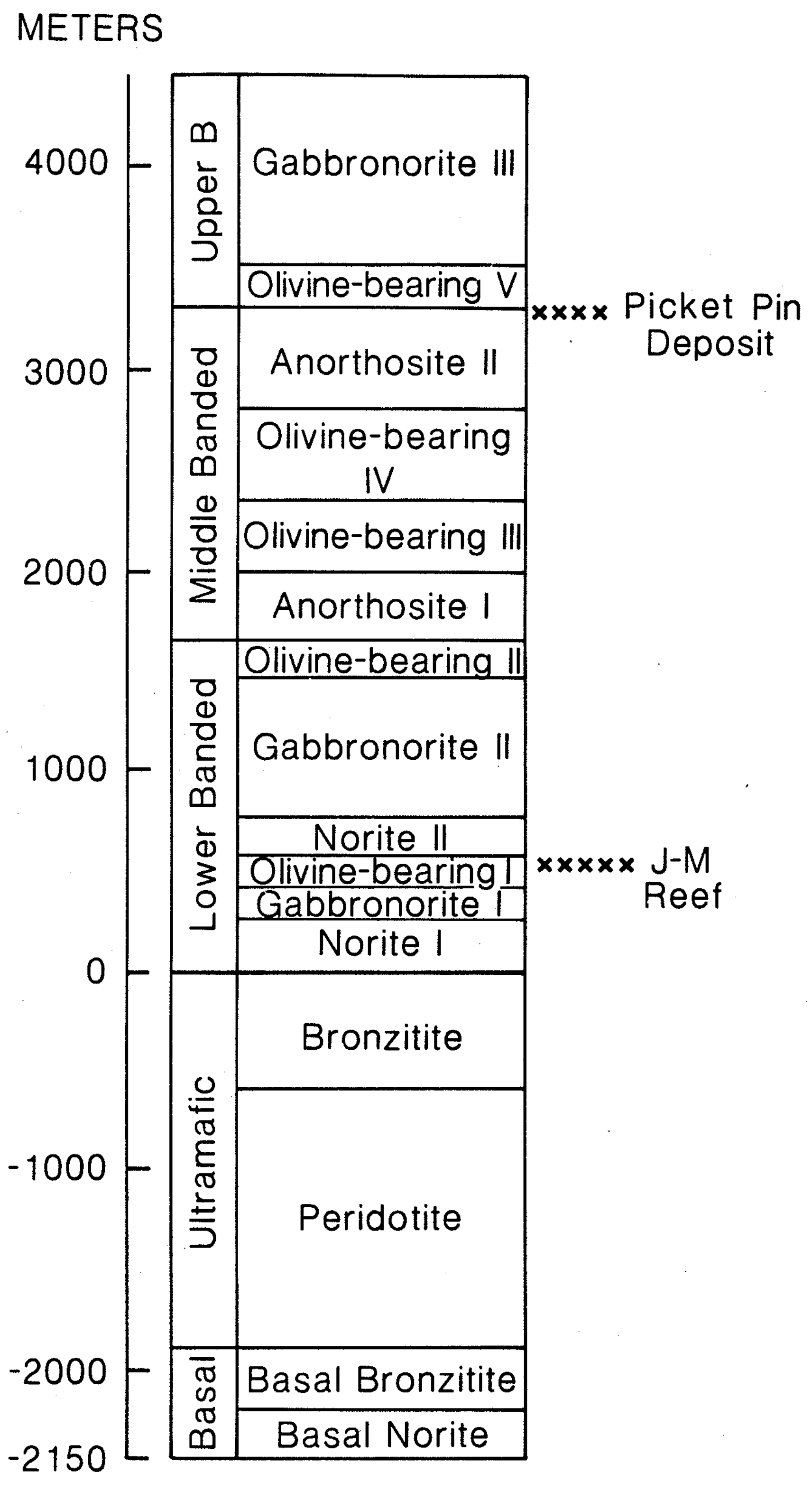

Figure 14. Stratigraphic column of the Stillwater Complex illustrating the various zones and subzones of the complex and the position of the J-M Reef and the Picket Pin deposit (after McCallum et al., 1980 and Boudreau and McCallum, 1986).

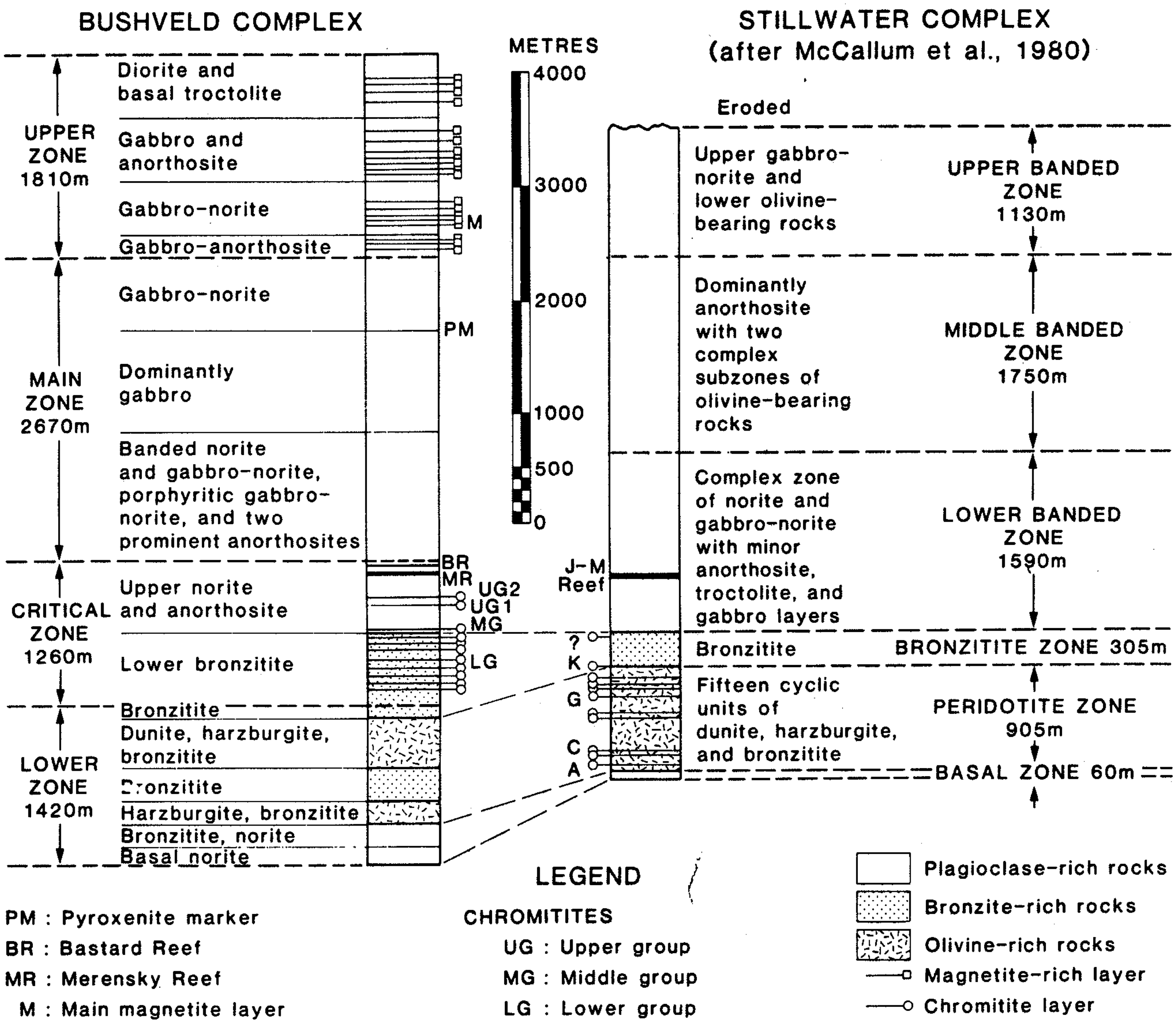

Figure 15. A comparison of the generalized stratigraphy of the Stillwater Complex of Montana with that of the Bushveld Complex of South Africa, and the position of the J-M Reef relative to that of the Merensky Reef (after Vermaak, 1985).

1986). The deposit is a stratabound zone of disseminated sulphide mineralization occurring in the same stratigraphic interval over a strike length of 22 km. A sharp contact between coarse-grained anorthosite and overlying medium grained anorthosite lies 5 to 15 m below the top of the anorthosite II zone. The bulk of the sulphide mineralization occurs at or below this contact, although sulphides are locally present up to the base of the overlying Upper Banded Series.

The medium-grained anorthosite is essentially monomineralic (< 5% interstitial pyroxene and olivine) and locally may show modal layering. This differs considerably from the underlying coarse-grained anorthosite which is characteristic of almost all of the anorthosite II zone. The plagioclase grains in the coarse-grained anorthosite are two to three times larger than those that make up the norites, gabbronorites and troctolites of the Banded Series. Unlike the overlying medium-grained anorthosite, it is unlayered and has about 20 percent interstitial pyroxene.

The sulphides are stratabound on a regional scale, but on the local scale they are typically present as podiform, and less often, lenticular concentrations of 1 to 5 percent sulphides interstitial to plagioclase. The interstitial sulphides are usually angular, wedge-shaped bodies of monoclinic pyrrhotite, chalcopyrite and pentlandite, in order of decreasing abundance. The lenses have a maximum strike length of 20 to 30 m, a maximum thickness of about 1.5 m and are conformable to layering (Boudreau and McCallum, 1986).

Boudreau and McCallum (1985) describe podiform and pipelike bodies which occur as much as 150 m below the stratabound mineralization. The PGE-bearing pipes may cut across igneous layering for 50 m or more and typically occur as metre-sized podiform concentrations containing 1-5 % sulphides. Trails of centimeter-sized patches of spotty sulphides occur above and below the pods. The mineralogy and grade of these pods is similar to the stratabound mineralization.

A strong correlation exists between Pt + Pd and S for sulphides associated with the coarse-grained anorthosite. No such correlation exists for the mineralization in the medium-grained anorthosite. It would appear that values of approximately 3.8 ppm Pt + Pd are assoicated with the most sulphide-enriched sample (1.4 wt. percent S). Boudreau and McCallum (1986) do not give an average grade for this deposit. However, based on their graphs it would appear that the average grade of samples obtained from the coarse-grained anorthosite is approximately 1.7 ppm Pt + Pd. Similarily, the average grade for equally well mineralized material from the medium-grained anorthosite is < 200 ppb Pt + Pd. In terms of the PGE content of the sulphide fraction, the J-M Reef mineralization contains 44, 155, 55 and 4 times as much Pt, Pd, Au and Ir as the Picket Pin deposit and 1.5 and 0.47 times as much Ni and Cu respectively.

Upper Banded Series

Mineralized anorthosites within the olivine-bearing V zone have been found to contain 0.5 - 1.0 percent sulphides (pyrrhotite, pentlandite and chalcopyrite) with assays of up to 1200 ppm Cu and 1200 ppm Ni and an average Cu/Ni ratio of 1.15. No significant PGE have been recorded (Boudreau and McCallum, 1986).

THE GREAT DYKE, ZIMBABWE

Introduction

The Great Dyke of Zimbabwe is one of the world's major layered igneous complexes. Chromite has been mined from the Great Dyke since 1919 but production has never rivalled that of the nearby but geologically distinct Selukwe Complex. PGE were discovered in what is now known as the Main Sulphide Zone (MSZ) of the Great Dyke in 1924, and the Wedza Mine operated unsuccessfully from 1926 to 1928 (Wilson and Prendergast, 1987) . Subsequent exploration has delineated a substantial resource (Table 2), and while there has been no commercial production to date, the possibility of exploitation in the future should not be discounted.

Geological Setting

The Great Dyke is 530 km in length and averages about 6 km in width. It is in fact not a dyke at all but a series of four coalescing funnel-shaped bodies which are, from north to south, the Musengezi, the Hartley, the Selukwe and the Wedza complexes (Worst, 1958). Each complex consists of a lower ultramafic layered series and an upper mafic layered series. In the Hartley complex, the largest of the four, more than 2100 m of ultramafic rocks and 900 m of mafic rocks are observed (Figure 16). The layering dips gently inward at the margins of each complex and flattens out near the centre, giving the bodies a synclinal form in cross section. Each of the complexes is thought to represent an intrusive centre, and Hamilton (1977) reported a Rb-Sr age of 2461±/-16 Ma.

Worst (1958) observed that the ultramafic sequence comprises a number of cyclic units and Wilson (1982) outlined 14 such units in the Hartley complex. The ideal sequence in each unit is, from the base upward, chromitite, dunite, harzburgite, olivine bronzitite, bronzitite; however, cumulus bronzite is absent towards the base of the layered series, whereas dunite and chromitite are missing from some of the upper units. The top of the ultramafic series is marked by websterite in each complex and this is overlain by mafic rocks.

PGE Mineralization

The MSZ occurs within the P1 pyroxenite layer in the uppermost cyclic unit of the ultramafic series and about 6 to 10 m below the overlying mafic series (Worst, 1960). It is a 1-2 m thick zone of PGE-rich sulphides disseminated in

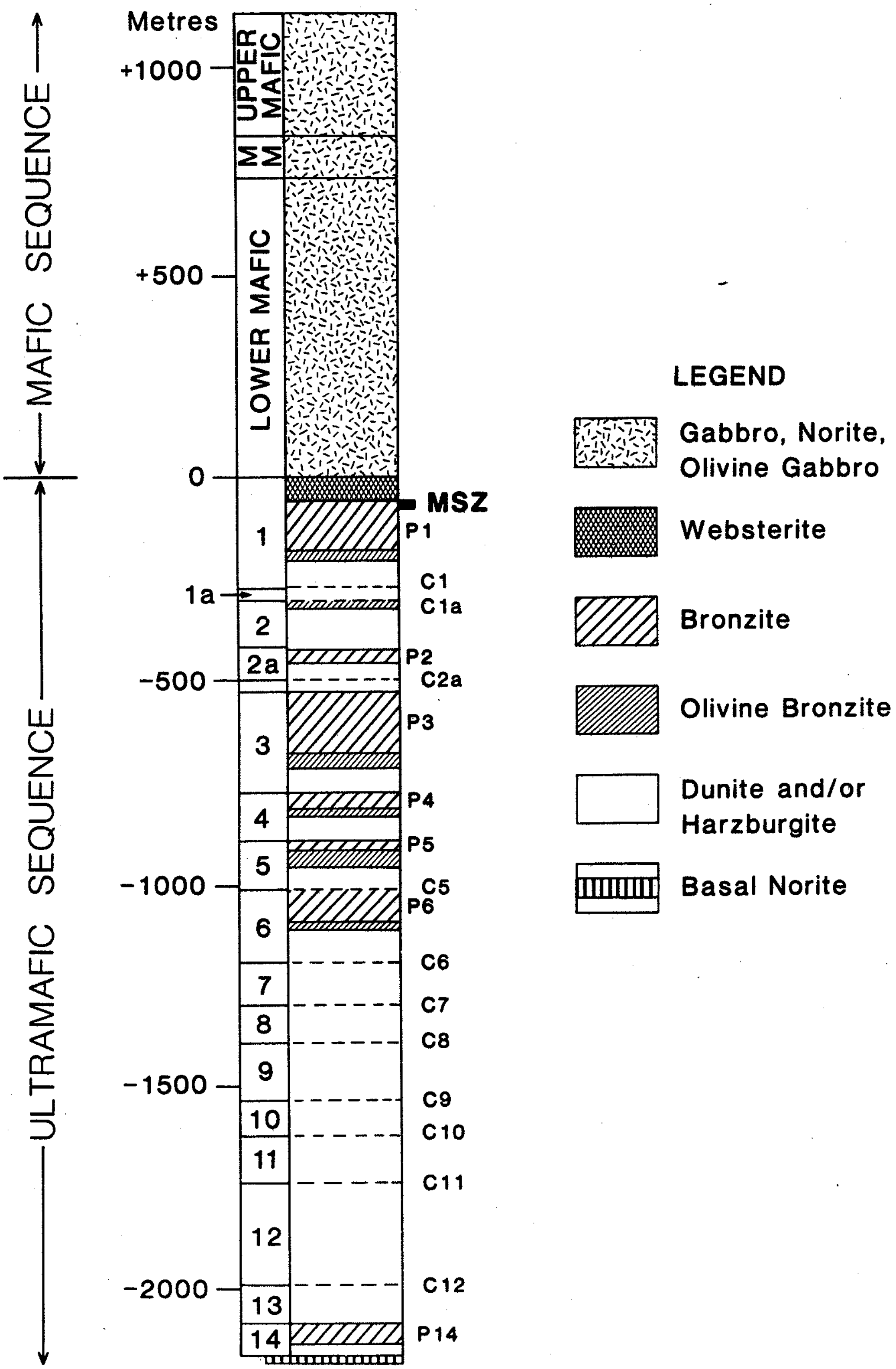

Figure 16. Igneous stratigraphy of the Hartley Complex of the Great Dyke showing the position of the PGE-enriched Main Sulphide Zone (MSZ), the chromitites (C1, C2a, etc.), and the pyroxenite members (P1, P2, etc.). After Wilson (1982), with modifications based on Wilson (1981), and Wilson and Prendergast (1987).

bronzitite directly at the contact or up to several metres below the Main Websterite which overlies the bronzitite (Wilson and Prendergast, 1987). It should be noted that the MSZ does not occur within the "potato reef", a websterite with plagioclase oikocrysts, but rather just below it (cf. Worst, 1960). Nevertheless, the distinctive weathering of the "potato reef" makes it a useful marker horizon.

The major sulphides are pyrrhotite, pentlandite, chalcopyrite and pyrite and the principal PGM are sperrylite, moncheite, merenskyite and hollingworthite. The Pt:Pd ratio is 1.3:1.

MUSKOX INTRUSION, NORTHWEST TERRITORIES

Introduction

The Muskox Intusion, located on the Arctic Circle about 110 km east of Great Bear Lake, is an outstanding intrusion in that: (a) it is exceptionally well developed and preserved structurally and completely exposed in cross section, with a feederlike dyke at the bottom, inward-dipping footwall contacts, and a gently dipping roof; (b) it features a complete rock differentiation series from high-temperature dunitic cumulates, through various intermediate peridotitic, pyroxenitic, and gabbroic units, to low-temperature granophyric rocks; and (c) it is closely related in space, time, and genesis to the extensive plateau-type basaltic lavas of the Coppermine River Group. The intrusion was discovered in 1956 by the H. Vuori of the Canadian Nickel Company when his attention was attracted during an aerial reconnaissance by gossans developed on sulphide-bearing skarns along the footwall contacts. Extensive exploration in the next few years failed to detect economically signficant mineral deposits, but the body has continued interest in the mining industry from time to time, and it is currently under exploration for the platinum-group elements (PGE).

The intrusion was originally mapped by Smith (1962; also Smith and others, 1966), and in an ensuing research program by the Geological Survey of Canada, it was further investigated by way of three deep diamond drill holes spanning the rock succession from roof to floor (Findlay and Smith, 1965). Publications on relevant petrologic aspects of the body include papers by Smith and Kapp (1963), Irvine and Smith (1967, 1969), Irvine (1970a, 1975, 1977a, 1977b, 1980, 1981), and Irvine and Baragar (1972). The sulphide mineralization and its sulphur isotopic characteristics were investigated by Chamberlain (1967; also Chamberlain and others, 1965) and Sasaki (1969), respectively. The present report is based on PGE analyses of whole rock samples, the majority of them cores from the three deep drill holes (known as the Muskox North, South and East holes), the others mostly from an extensive outcrop collection of the skarn material made under the direction of D.C. Findlay during the original mapping (Findlay, 1963). A more comprehensive paper on the study is in preparation.

Geological Setting

Muskox is situated in the Bear Structural Province of the Canadian Shield where it is emplaced in an Aphebian basement complex of metasediments, metavolcanics, granitic gneiss, and granite, just at the base of a gently northward-dipping Helikian supracrustal succession comprising the Hornby Bay sandstone, the Dismal Lakes dolomite, and the Coppermine River basalts (Fig. 17). As exposed, the intrusion is about 125 km long and up to 11 km wide, it trends NNW, and it is crossed in the middle by the Coppermine River. South of the river the intrusion is essentially a vertical dyke, 150-500 m wide, that tails out in four en echelon segments. In the overall structure of the intrusion, this dyke appears to project beneath the main chamber to the north as a keel-like feeder dyke. The successions of layered rocks within the main chamber show, however, that as the magma body crystallized, it was frequently replenished through repeated injections of fresh liquid and concurrent removal of partly fractionated residual liquid. However the dyke to the south does not cut the layering; thus it appears that most of the magma injections entered the chamber by another route (see below), and that the dyke to the south was the supply channel for only the first few injections. The practice adopted here, therefore, is to refer to the dyke as the "keel dyke".

North of the Coppermine River, the main body of the intrusion broadens upward, and in consequence of plunging gently northward (at angles of 3° to 5°) in the relatively flat shield terrain, it gradually increases in width to a maximum where it disappears beneath its roof contact. This part of the body is cut by one major and a few minor faults, but otherwise it is intact. Aeromagnetic and gravity anomalies show that the intrusion extends on for another 250 km to the north and northwest beneath its roof rocks and younger cover, and the large magnitude of the gravity anomaly indicates that its cross section becomes much larger where it is concealed (Hornal, 1975). Petrologic considerations suggest that the anomaly probably reflects both the main feeder to the intrusion and the feeder system to the Coppermine River lavas.

Compositionally, the keel dyke south of the Coppermine River consists largely of fine-grained bronzite gabbro, but much of it also contains either one or two internal zones of picrite that are parallel with its outer contacts. These zones are up to about 100 m wide. The main body of the intrusion north of the river divides naturally into four parts: two marginal zones, a layered series, and a granophyric roof zone. The marginal zones line the inward-dipping footwall contacts and are each 130-230 m thick. Broadly speaking, they grade inward and upward from bronzite gabbro along the footwall contacts through picrite and feldspathic peridotite to peridotite. In outcrop, the gabbro is best developed immediately north of the river, where it forms double units alternating with picrite along each side of the intrusion. Northward, the amount of gabbro gradually diminishes, and by 30 km distance it has vanished. It probably continues at depth, however, because the double zones were intersected by the South drill hole opposite where the rock pinches out at the surface. The gabbro is fine grained (and locally chilled) near the river, but to the north, it becomes coarser, and commonly it appears siliceous because of wallrock contamination. The picrite, feldspathic peridotite, and peridotite are roughly equivalent to combinations of gabbro plus progressively increasing cumulus proportions of granular olivine and accessory chromite.

The layered series and roof zone occupy the trough formed by the two marginal zones. The layered series embodies 42 layers of 18 different rock types totalling about 1800 m in thickness. The layers are from 3 m to 350 m thick; they typically have sharp contacts; and with a few local exceptions, they show little internal layering or structure other than weak planar lamination. The series as a whole dips gently to the north, usually at 3° to 5°, parallel with the overall plunge of the intrusion and the inclination of its Helikian roof rocks. Most layers are continuous laterally from one marginal zone to the other, and some can be traced in outcrop for more than 25 km. From drill hole intersections it is evident that many have areal extents in excess of 250 km^2.

The layered rocks are all ultramafic and gabbroic cumulates--that is, they are accumulations of various mafic minerals and plagioclase concentrated by crystal fractionation processes, in this case, on the floor of the magma body. Their succession ranges from dunite at the base, through peridotite, various pyroxenites, and some olivine gabbro at intermediate levels, to orthopyroxene-bearing pyroxenites and two-pyroxene gabbros at the top (see Fig. 19). There are two thin layers containing about 50 percent cumulus chromite that are probably more that 100 km^2 in extent. The upper is as much as 20 cm thick and is fringed by a similar thickness of lesser chromite enrichment; the lower layer is only 2-5 cm thick. Both are accompanied by a percent or so sulphides. The topmost gabbro in the Muskox East drill hole contains 5-10 percent cumulus magnetite and ilmenite, but this unit could not be identified in outcrop (Irvine and Smith, 1969).

At the top of the layered series, the two-pyroxene gabbro grades into an irregular capping of granophyric rocks called the "roof zone" because it is extensively charged with xenoliths of quartzite and other roof rocks. The granophyre has extremely high K_2O/Na_2O and very high $^{87}Sr/^{86}Sr$, evidently because it is mostly formed from roof-rock materials melted by the heat of the parent liquid of the ultramafic and mafic cumulates. Large amounts of the granophyric melt that escaped from the intrusion can be seen in part as stratified sills in the Hornby Bay and Dismal Lakes formations to the northwest of the Muskox outcrop area (Kerans, 1983; also see Fig. 17). About 20 km west of the intrusion, two of these sills intrude the main (upper) dolomite section of the Dismal Lakes Group, one about half way up, the other within a metre or two of the first basalt flow (so close that some of the flows must have been present when the sill was emplaced). In a previous study (Irvine, 1970b), the writer incorrectly concluded that Muskox was older than the main dolomite section and the basalt (see Hoffman, 1980; Kerans, 1983), but these two sills constitute the first relatively unequivocal evidence that has been cited that it is younger. They have not been reported previously, although the upper one may have been mistakenly described as a flow.

Diabase dykes of the Mackenzie swarm are numerous in the vicinity of Muskox and tend to parallel to it. One alternates positions with the keel dyke in a way that suggests that it might be older, but this possibility could not be confirmed because contacts are not exposed. On the other hand, many diabase dykes cut the marginal zones, layered series, and granophyre, and commonly they show chilling on their contacts, so they are considerably younger. As a rule, the keel dyke and marginal zone gabbros can be readily distinguished from the diabase in that they carry less magnetite, ilmenite, and granophyre, and more bronzite, and they more fequently contain olivine.

There are no basic dykes visibly feeding from Muskox to the Coppermine River Flows, but there is a previously unmapped mafic sill in the basalt a few hundred metres above Muskox that may be coeval with the intrusion (Fig. 17). A distinctive feature of the sill is that it contains substantial amounts of cumulus orthopyroxene toward its base. The basalt flows rarely carry orthopyroxene phenocysts (Annells, 1970), but as noted above, Muskox contains four layers of orthopyroxenite, so the sill may represent an offshoot of its magma released at about the time these layers were forming. Baragar and Donaldson (1971) mapped another, much larger mafic sheet higher in the Coppermine River Group, about 30 km north of the Muskox outcrop area, and they reported that it has olivine near its base. It lies across the Muskox gravity and magnetic anomalies and therefore might also be a Muskox offshoot.

Crystallization History

The Muskox layered series is distinguished by a dominance of olivine cumulates and by frequent lithologic repetitions. Dunite and peridotite comprise about 1200 m of the 1800-m thickness of the layered series (Fig. 19), and together with their counterparts in the marginal zones, they make up about 60 percent of the cross section of the whole intrusion (Fig. 17). Olivine by itself forms more than 50 percent of the layered series by volume, and it invariably is accompanied by 1-2 percent chromite. These amounts are grossly disproportionate compared to the composition of gabbroic liquid chilled on the margins of the intrusion, which at most might yield 10 percent olivine and 0.2 percent chromite.

Part of the explanation of this discrepancy is that the chilled gabbro is only the residual of a more primitive parent liquid after fractionation of olivine and chromite. The rest of the explanation is that the magma body was repeatedly replenished, and the evidence here lies in the lithologic repetitions. The layered rocks recur in specific sequences that can be identified with the crystallization orders of the cumulus minerals from their parental liquids. The marginal zones and layered series can be divided into at least 25 of these repetitive divisions, which are called cyclic units, and it is evident that the start of each unit records a major addition of fresh liquid. Moreover, comparison of the estimated amounts of these liquids with the space available for them in the exposed part of the intrusion shows that, to make room for all 25 or more injections, there had to be concurrent removal of large amounts of fractionated residual liquid. In effect, each batch of liquid was partly fractionated along some part of its total possible crystallization path, yielding a cyclic unit; then it was partly displaced by fresh liquid, generally with only limited mixing. The fresh magma almost certainly came from a feeder system in the region of the large gravity anomaly to the north, and most probably the displaced magma was pushed on to the south and then to the surface to form lava flows that have since been lost to erosion. There is an alternative to this last possibility, however. In recent years it has been realized that in intrusions like Muskox, the liquids probably become density stratified by virtue of their composition and temperature differences, and these liquid layers tend physically to behave rather independently. Accordingly, it now appears possible that, as batches of the dense primitive Muskox liquid flowed south along the cumulate floor, the less dense overlying layers of fractionated liquid may have flowed in the opposite direction, returning to the north to be erupted as lavas that might still be preserved among the Coppermine River flows.

From the cyclic units, it is evident that the composition of the Muskox magma changed in such a way that it had three different crystallization orders:

I. olivine; clinopyroxene; plagioclase; orthopyroxene

II. olivine; clinoproxene; orthopyroxene; plagioclase

III. olivine; orthopyroxene; clinopyroxene; plagioclase.

This progression is essentially defined by the advance of crystallization of orthopyroxene, but the proportion of olivine cumulates produced also decreased. The first order is reflected in the rock sequence: dunite; olivine clinopyroxenite; olivine gabbro (including interstitial orthopyroxene in all members). It is fully developed only once, in Cyclic unit 7. Units 2, 3, 6, 14, 15, and 16 each consist of the first two rock types, and units 4, 5, and 9-13, composed only of dunite, probably represent the first stage. Crystallization order II is represented by: dunite; olivine clinopyroxenite; websterite. This succession is found only in the west part of Cyclic unit 19, but its first two stages may be represented in unit 20. Order III is identified by: peridotite; orthopyroxenite; websterite; bronzite gabbro. This sequence is fully developed in unit 22, and its first three rock types form unit 17, part of unit 19, and unit 21. Various reasons might be suggested for the change from I to III, but the most likely is that the the magma body became gradually more contaminated by granophyre melted from the intrusion roof rocks. The silica in the granophyre would have the effect of advancing the crystallization of orthopyroxene at the expense of olivine. The last two cyclic units, 24 and 25, begin with prominent layers of an olivine-bearing rock called picritic websterite. This rock does not fit the above scheme in any simple way but appears to be a somewhat mixed cumulate of olivine, augite, and local bronzite. In both units, it is directly succeeded by granophyric, two-pyroxene gabbro.

Principal Element Distribution Controls

Element distribution patterns in Muskox largely reflect the effects of crystallization differentiation. For most major elements and even some trace elements, the principal controls are simply the kinds of cumulus minerals and their stages of crystallization. Thus: Mg, Fe^{2+}, Ni, and Cr are concentrated in dunite and peridotite units because they are major constituents of cumulus olivine and chromite; Ca and Sc are concentrated by augite in the clinopyroxenite and websterite units; Al and Sr are enriched in in the gabbroic rocks by virtue of entering plagioclase; and Ti and primary Fe^{3+} are enriched in the gabbro containing cumulus ilmenite and magnetite. Primary mineral composition variations have only relatively minor effects.

The two thin chromite-rich layers and their associated sulphide concentrations are thought to be the products of anomalous crystal fractionation events induced by magma mixing. The layers occur in Cyclic units 21 and 22, and the mixing could have been accomplished through the process of magma replenishment. The basis of this idea is that upward trends of decreasing chromite abundance in Cyclic units 4-7 suggest that, in chemographic space, the olivine-chromite cotectic boundary followed by the Muskox magma was curved convexly away from the composition of the spinel phase (Irvine, 1975, 1977a). Given this relationship, (which has been supported experimentally; Irvine, 1977b, 1980), subsequent mixing of a parent liquid at a high-temperature point on the cotectic with derivative liquid at a low-temperature point would yield a hybrid that could precipitate chromite by itself for a brief period, as apparently is required to form chromite-rich layers. The phase relations of immiscible sulfide liquid in mafic silicate systems suggest that it too might be locally have been concentrated by this kind of process (Irvine, 1975).

The current view for Muskox is that the parent liquid was picritic in composition, and the low-temperature liquid was a derivative basaltic liquid. The picritic liquid was probably substantially contaminated by this stage, however, in view of the change of crystallization order through Cyclic units 17 to 20. There is an possible alternative origin for the chromite-rich layers that is less likely but warrants mention because it relates to the Bushveld and Stillwater Complexes. In these intrusions, the chromitite layers and PGE-enriched sulphide zones appear to have formed in response to the mixing of two parent melts: one, an early liquid (designated "U") that initially yielded ultramafic cumulates; the other, a later liquid (denoted "A") that initially produced anorthositic cumulates. All Muskox liquids appear initially to have yielded ultramafic differentiates, but it is intriguing that the one rock layer that is slightly anorthositic occurs somewhat anomalously at the top of Cyclic unit 19 (in outcrops only, not in any of the drill hole sections), not far below the two chromite-rich layers. The suggested possibility is that Muskox too was invaded by a small amount of A-type liquid, which then induced precipitation of the concentrated chromite.

Next to primary crystallization, the strongest controls on Muskox element distribution relate to the postcumulus products of pore (intercumulus) liquid. Their development depends on the amount of pore liquid and the evolutionary stage it had reached while it was still part of the main magma body (including the degree to which it had been contaminated), and they also reflect the rate of crystallization and movement of the pore liquid in the cumulate pile. Figure 18 shows the approximate distribution of "discrete postcumulus materials" in the rocks intersected by the Muskox deep drill holes. These comprise all normative constituents that are not major components of the cumulus minerals. Thus, in dunite and peridotite, they include everthing except forsterite, fayalite, Ni and Mn olivine, and chromite; in olivine clinopyroxenite, they are everything except the olivine components plus diopside and hedenbergite; in olivine gabbro, everything except the olivine and augite components plus anorthite and albite; and so forth. It is seen that postcumulus materials make up more than 50 percent in the gabbro and picrite in the footwall marginal zone; then they decrease rapidly upward through Cyclic unit 2 to less than 10 percent, and more slowly through units 4-13 to about 5±3 percent. A general step-like increase follows in units 14-22, to about 15 percent in the North drill hole and 20-30 percent in the East hole; then comes a general decrease in the largely gabbroic cumulates of units 22-24: to less than 5 percent in the North hole, and to about 5-10 percent in the East hole. These last decreases are undoubtedly too large, because it has not been possible to distinguish postcumulus plagioclase in the gabbroic cumulates, but certainly there is more postcumulus material in the East hole rocks than in the North. The rapid increase at the top of the intrusion in Cyclic unit 25 reflects the increase of granophyre toward the roof of the intrusion.

Evidence for the movement of intercumulus liquid comes from discrepancies at the basal contacts of several of the thicker cyclic units between the cryptic discontinuities of Mg/Fe and Ni expected from magma fractionation and replenishment and the visible modal discontinuities by which the contacts are defined (Irvine, 1980). In several cases, the cryptic discontinuities are at distinctly higher positions (5-20 m higher) than their modal counterparts, and simulation of these relations by computer models showed that they can be produced by metasomatic element exchange between the cumulus minerals and intercumulus liquid that was being filter pressed upward by compaction of the cumulate pile. The modeling indicated the compacting zone at times was as much as 250 m thick. The feature of interest here is that several of the discrepant boundary intervals show small peaks of Cu, suggesting that the metasomatic reactions may have caused the intercumulus liquid to precipitate small amounts of immiscible sulphide liquid, thereby concentrating the Cu.

Muskox has also had metasomatic effects on its country rocks in association with the footwall skarns marked by the prominent gossans. For example, in the South hole intersection, FeO has been enriched to 10-30 percent and MgO to 5-15 percent, as compared to the their typical levels in the footwall gneiss of 3-4 percent and 1-4 percent, respectively. CaO, TiO_2, and MnO are also higher.

Along its roof contact, Muskox has caused extensive melting of its granitoid roof rocks and strong thermal metamorphism of the sandstone units that it has intersected. Apparently, however, it did not generate much of a hydrothermal system in its roof rocks. The evidence here comes from the main dolomite units of the Dismal Lakes Group. Although these units are possibly within as little as 350 m of the roof contact where they extend across the intrusion, in outcrop at least, they show virtually no metamorphism, and the only conspicuous hydrothermal effects that might be related are half a dozen zones of ankeritic replacement, measuring a few metres in width and several tens of metres in length. Two of the ankerite zones are in the east flank of a shallow syncline developed in the dolomite directly over Muskox (see Fig. 17); the others are in the west flank, probably just off the edge of the intrusion. No comparable zones were found elsewhere in the dolomite for several tens of kilometres on either side of the intrusion. An extensive study of the carbon and oxygen isotopic composition of the dolomite has confirmed the paucity of hydrothermal effects. Except in the ankerite zones, most isotopic variations are readily attributed to primary sedimentation and diagenesis.

The Muskox olivine-rich rocks were extensively serpentinized at a post-magmatic stage, most probably in association with the emplacement of the Mackenzie diabase dyke swarm, and the gabbroic and granophyric rocks were considerably altered to chlorite, kaolin, and zeolites, apparently at the same stage. Besides adding H_2O, the serpentinization introduced large amounts of oxygen, producing abundant secondary magnetite, and locally it removed sulphur, producing various native metals including Ni, Cu, Co-Fe alloy (Chamberlain et al., 1965). Metals rich in PGE have not been reported.

Distribution of Sulphides

The sulphide distribution patterns described by Chamberlain (1967) are closely reflected in the whole-rock data for Cu (Fig. 18 & 20). The highest sulphide concentrations are along the footwall contacts and chromite-rich layers. The early exploration work revealed small amounts of sulphide mineralization almost everywhere along the footwall contacts, plus local "massive" sulphide deposits up to a few meters in width. The latter are typically just outside the intrusion, 15-20 m below the footwall contact and they generally consist of a breccia of country rock fragments in a matrix rich in pyrrhotite. Within the marginal zones, sulphides are disseminated in a pattern resembling that of the discrete postcumulus materials (Fig. 19)in that they are most abundant in the bronzite gabbro and decrease to low concentrations in the peridotitic rocks. Concentrations are also low through the olivine-rich lower part of the layered series, where the main features of interest are the small Cu peaks at the bottoms of Cyclic units 5, 6, and 7, mentioned above. Larger, but erratic sulphide disseminations occur in the upper part of the layered series, starting with Cyclic unit 8 in the North drill hole, and abundances tend to be greater toward the marginal zones, as indicated by the differences in Cu between the North and East holes. The upward increase in Cu (and sulphides) probably reflects the primary composition trend of the pore liquid, whereas the increase toward the margins apparently reflects changes in its amount. Sulphide concentrations along the roof contact are weak in comparison to those on the footwalls.

Chamberlain (1967) and Sazaki (1969) defined a rough zonation in sulphide mineralogy. They found relatively Ni-rich sulphides in the dunitic units of the lower part of the layered series, grading to assemblages richer, first in Fe, then Cu, progressing both upward through the layered series into the roof zone and outward through the marginal zones and footwall sulphide deposits into the country rocks. In the South hole core, Ni and Cr have clearly moved outward into the country rocks in gradually decreasing amounts for about 10 m, and Cu, Pb and Zn are distinctly enriched in the footwall sulphide zone.

Sasaki (1969) found a wide range of sulphur isotopic compositions associated with the intrusion. Expressed in standard delta notation relative to meteoritic sulphur, the composition averaged about +5 per mil, much higher than the zero value expected for mantle sulphur. Also, samples from near the footwall contacts tended to divide into two groups, either greater or less than 9 per mil, depending on whether the country rock was orthogneiss or metasedimentary schist. Sasaki (1969) suggested that this contrast indicated that the sulphur was largely of external derivation (i.e. from the metasediments). The most unusual results, however, came from the South drill hole, where values of -5 to +2 per mil were obtained from the footwall sulphides just below the footwall, and values of +15 to +30 came from gneiss at the bottom of the hole. The significance of these variations is still uncertain, but clearly the metasomatic processes ere complicated.

Distribution of PGE

The distributions of Pt and Pd in the deep drill holes are shown in Figs. 21 and 22, and more detail is given for the upper chromite-rich layer in the North drill hole in Fig. 23. Data from the footwall sulphides are plotted in Figs. 24 and 25. It is seen that in both environments, most samples showed only a few parts per billion (ppb) of platinum and palladium, and in many samples, concentrations were below detection limits (10 ppb for Pt; 2 ppb for Pd). The highest values recorded in the drill cores, from just below the upper chromite-rich layer in the North hole, were 140 ppb Pt and 650 ppb Pd; the highest from the footwall sulphides in the South hole were 30 ppb Pt and 333 ppb Pd. The outcrop footwall sulphide samples showed maxima of 582 ppb Pt and 4009 ppb Pd, but only about 15% of the samples exceeded 50 ppb Pt and 800 ppb Pd (Fig. 25). Much higher concentrations have been reported for the footwall sulphides by exploration companies. Technigen Platinum Corporation and Equinox Resources originally reported values of 1.65 oz. per ton (52000 ppb) PGE for grab samples from two deposits (Northern Miner, October 27, 1986); and International Platinum has reported 0.62 oz. per ton (19400 ppb) from another (Northern Miner, February 16, 1987).

In choosing samples of the drill cores for PGE analyses, although ore-grade concentrations were not expected, an attempt was made to cover all the environments that seemd from other information (especially the Cu data in Fig. 20) to have the potential as sites for PGE enrichment.

The results for Pt and Pd strongly resemble that of Cu in Figure 20, obviously reflecting their similar affinity for sulphide. Of the two PGE, Pd is most similar in its distribution to Cu as it shows a distinct peak in the footwall sulphides just below the footwall contact, a weaker peak in the marginal zone bronzite gabbro, a peak in the lowest dunite layer just above (or inside) the marginal zone, and several small peaks in Cyclic units 4-6. Also like Cu, it shows more frequent peaks in the upper part of the layered series, starting with Cyclic unit 8 (especially in the North hole), and it too is generally more abundant in the East hole cumulates than in the same layers in the North hole. The main difference is that Pd decreases to very low concentrations in the topmost gabbro and the granophyre, whereas Cu is relatively enriched in these rocks. Platinum differs principally in that it is not enriched in the footwall sulphides, and it increases rather than decreases through the first major dunite layer (in Cyclic unit 2). From there upward, its pattern is essentially the same as Pd and Cu.

Neither Pt nor Pd shows peaks exactly coincident with the small Cu peaks in Cyclic units 5, 6, and 7 that were mentioned as possible effects of infiltration metasomatism. It seems clear that, whatever their origin, these peaks are not significant sites of PGE enrichment.

Through the upper chromite-rich layer in the North hole (Fig. 23), Cu, Ni, Pt, and Pd correlate closely. They all increase abruptly in the peridotite layer (layer 28A) that forms the base of the Cyclic unit, and they each show a weak second peak about 60 cm higher covering the chromite-rich zone. In the East hole, the peridotite-chromitite combination of layer 28 is only about 45 cm thick, and a sample contained 40 ppb Pt and 204 ppb Pd. The lower chromite-rich layer contained 120 ppb Pt and 250 ppb Pd in the North hole, 140 ppb Pt and 380 ppb Pd in the East. It is notable that, apart from the association with the chromite-rich layers, neither Pt nor Pd correlates in detail with Cr or chromite. Their distributions are clearly controlled by their affinities for sulphide, not by any attraction to the oxide mineral.

Discussion

The two general environments in Muskox where ore-grade deposits of PGE might be expected are the footwall sulphides and the layered series. The footwall deposits clearly offer much the better prospects, but from present data, their grades would appear to be highly rratic and frequently low. Notably in Fig. 25, the samples richest in sulphide (or S) are not very rich in PGE, which accords with the Sasaki (1969) evidence that the S came from outside the intrusion, but it is seen also that the PGE are not enriched on the footwall contacts even where S is relatively poor, as in the South drill hole (Figs. 20, 22). The main observation that can be offered on the footwall deposits that might be of exploration interest pertains to structural relations, not compositional features. In previous publications on Muskox, its footwall contacts have always been shown as being regular or smooth. In the cross section in Fig. 17, however, prepared by projecting the map relations of the intrusion down its plunge, the footwall contacts are distinctly stepped, and it is apparent that the room for the magma chamber was essentially made by progressive downward displacements of its floor on a series of longitudinal faults in the underlying basement. Of interest here is that the main zones of footwall mineralization identified in the early exploration occur approximately where some of these inferred faults meet the footwall contacts. The suggestion is that the faults influenced the circulation of the metasomatizing (hydrothermal) fluids that produced the footwall sulphides. To map the faults (given that they exist) would no doubt be difficult because of a paucity of critical markers, but they might be defined through geophysical surveys. Their suggested locations in Fig. 17 have been loosely transposed back to the geologic map in Fig. 24.

As for the layered series, the data obtained in this study obviously are not suggestive at face value of any economically interesting PGE deposits. The question is whether they are indicative in some indirect way. A common tenet concerning PGE in magmas, supported by the present observations, is that they have enormous affinities for immiscible sulphide liquid. The coefficients that describe PGE partitioning between sulphide and silicate melts are not well known, but certainly they are very large, probably in the range 10^4 to 10^5 (see below). Accordingly, when sulphide liquid forms in a well mixed magma body, the PGE should separate almost entirely into it. Also, under fractionation conditions, the first sulphide liquid should be the most enriched; thereafter, PGE concentrations are expected to drop rapidly because of the depletion of the magma in PGE.

These simple concepts can, however, be complicated in many ways. In Muskox, the effects of replenishment are of particular interest, and they can be diverse. Replenishment should ordinarily cause regressions in the compositional evolution of a magma body--thus, trends of Pt, Pd, and S enrichment as might develop prior to sulphide precipitation could be set back; or if the magma body had reached sulphide-liquid saturation, but the fresh liquid had not, the sulphide precipitation might be curtailed until further crystallization of the hybrid liquid caused it to resume. These kinds of effects could be represented in the recurrent small Cu and PGE peaks that are scattered through the Muskox cyclic units.

But in certain circumstances, replenishment can result in extraordinary element-enrichment trends. O'Hara (1977; also O'Hara and Mathews, 1981) has shown that, through repeated replenishments, the concentrations of incompatible trace elements can be raised by more than two orders of magnitude, whereas major element patterns evolve very little. For this effect to be significant in the present context, PGE and sulphur would probably have to originate from different magma units, such as different injections of liquid, or different liquid layers. If PGE and sulphur had the same residence, then until sulphide liquid was actually precipitating, S like the PGE would effectively be an incompatible element, so they all would be expected to be enriched at about the same rate. Thus, whatever that rate, by the stage that sulphur saturatation was achieved, the level of PGE enrichment should tend be about the same, and most probably it would not be exceptionally high. On the other hand, if PGE could be rapidly enriched in one liquid body, while S was only slowly enriched in another, and if sulphide liquid precipitation was then induced by mixing the liquids, very PGE-rich sulphide might be produced. This mechanism appears appropriate to the formation of the PGE-rich reefs of the Stillwater and Bushveld Complexes, where the U liquid evidently carried most of the PGE, and the A liquid, most of the S (Irvine et al., 1983). Notable in this regard is that the J-M Reef is the first truly persistent zone of sulphide enrichment in Stillwater, and the UG2 and Merensky Reefs are similarly first in Bushveld. In Muskox, a more complicated process might be envisaged whereby PGE were enriched in one magma layer while S was absorbed from the country rocks by another; sulphide precipitation might then have been induced by mixing.

The part of Muskox that is most obviously of interest by comparison with Bushveld and Stillwater covers the repetitions of peridotite, chromitite, orthopyroxenite, and websterite in Cyclic units 17-22. The orthopyroxenite and chromite-rich layers are comparable to those associated with the Bushveld Merensky and UG2 reefs, and as noted earlier, the anorthositic olivine gabbro that occurs in outcrop at the top of Cyclic unit 17 might be counterpart to the Bushveld and Stillwater anorthosites. The sulphides that occur along the Muskox chromite-rich layers commonly have globular forms, and some occur as small spheres (droplets?) within chromite grains, suggesting strongly that the magma was saturated with sulphide liquid when the layers were formed. However, their low Pt and Pd contents are not encouraging, and it would appear that, if any significant zone of PGE enrichment exists in this interval, it has to be downdip from the most northerly drill hole intersections, namely, those in the East drill hole.

The relatively low levels of PGE in the sulphides associated with the chromite-rich layers

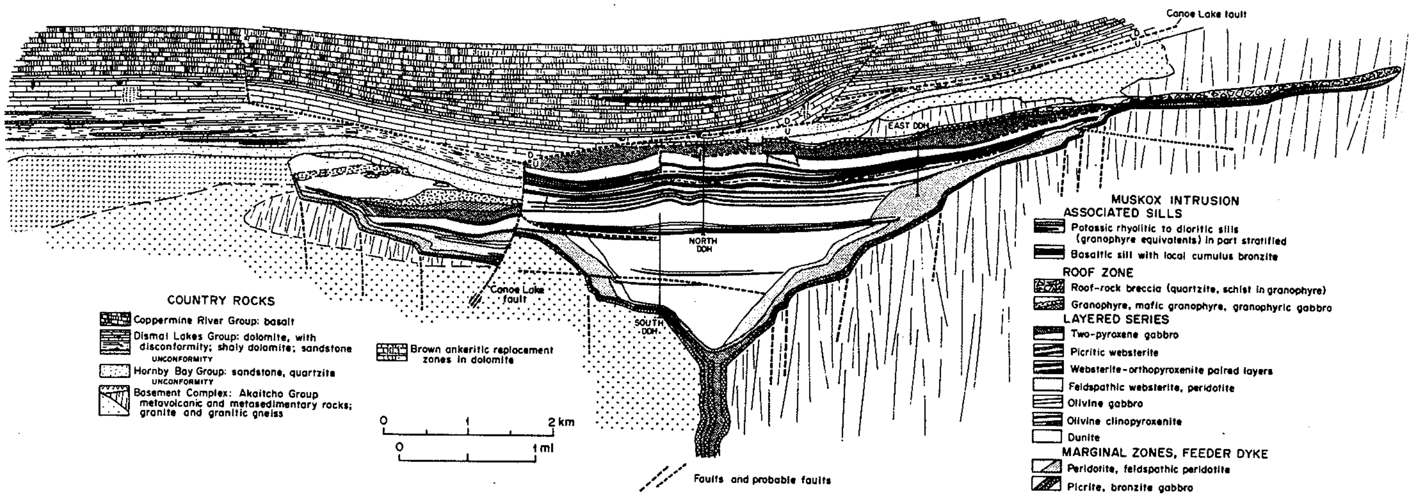

Figure 17. Cross section of the Muskox Intrusion, prepared by down-dip projection of surface geology, showing the locations of the North, South, and East drill holes.

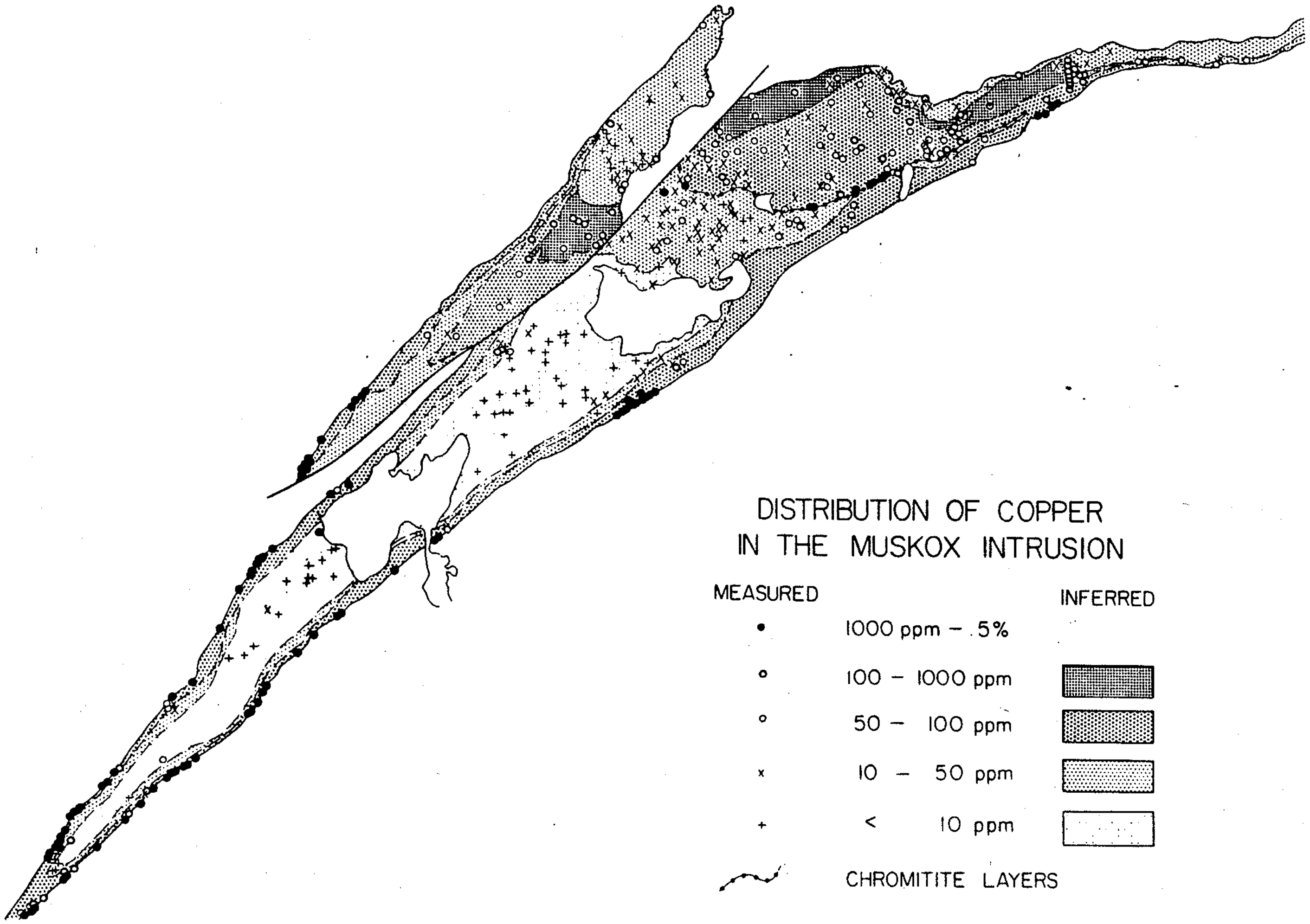

Figure 18. Map showing the distribution of Cu in the Muskox Intrusion as measured in outcrop samples (after Irvine and Baragar, 1972, Fig. 12).

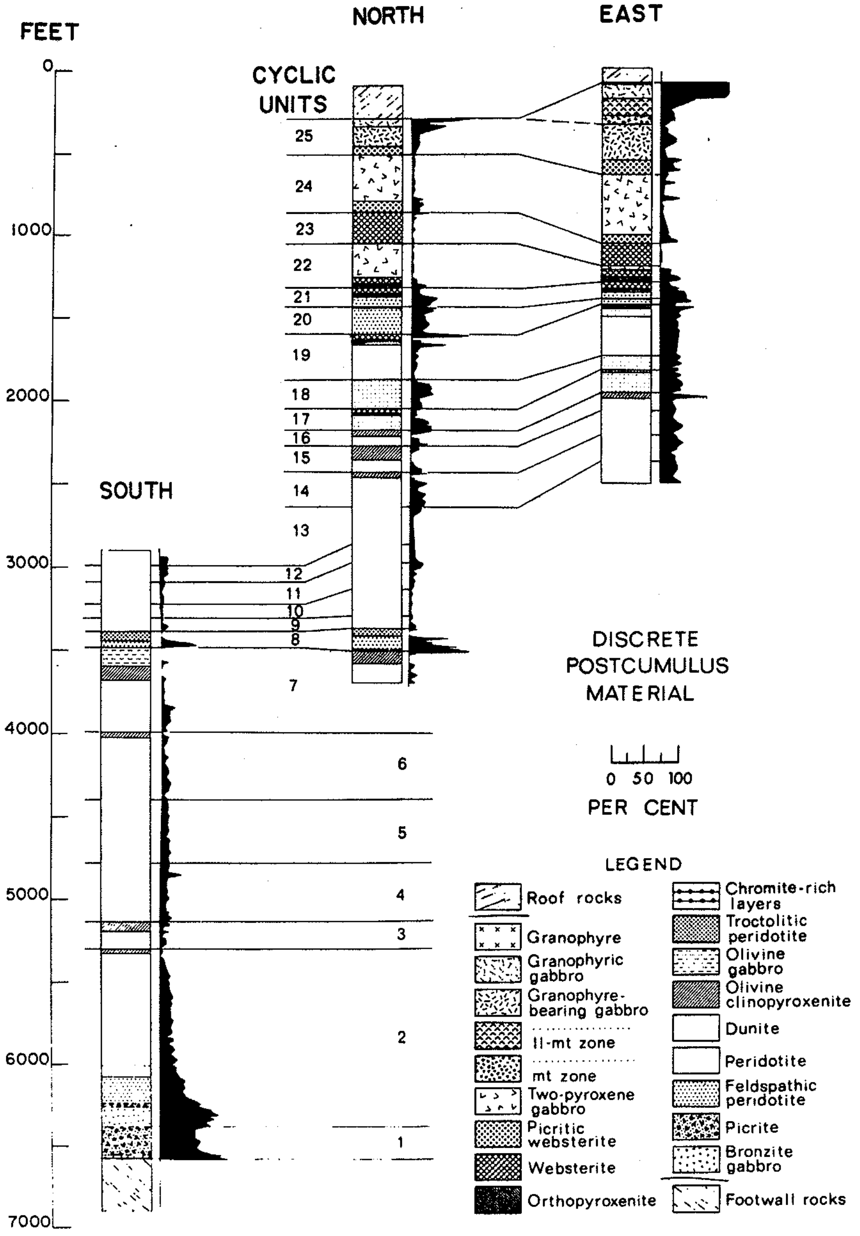

Figure 19. Distribution of discrete postcumulus materials in core samples from the Muskox deep drill holes, based on whole-rock chemical analyses.

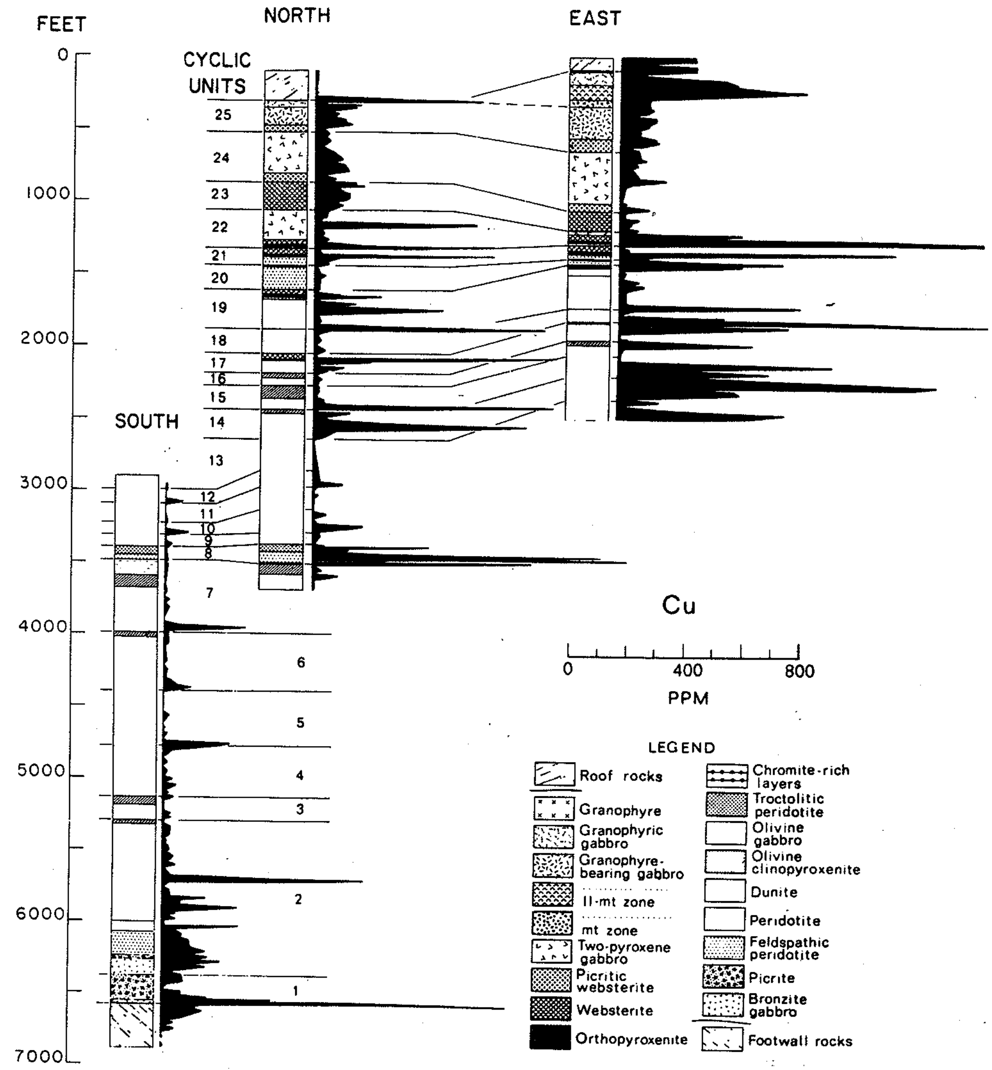

Figure 20. Distribution of Cu in the Muskox deep drill holes.

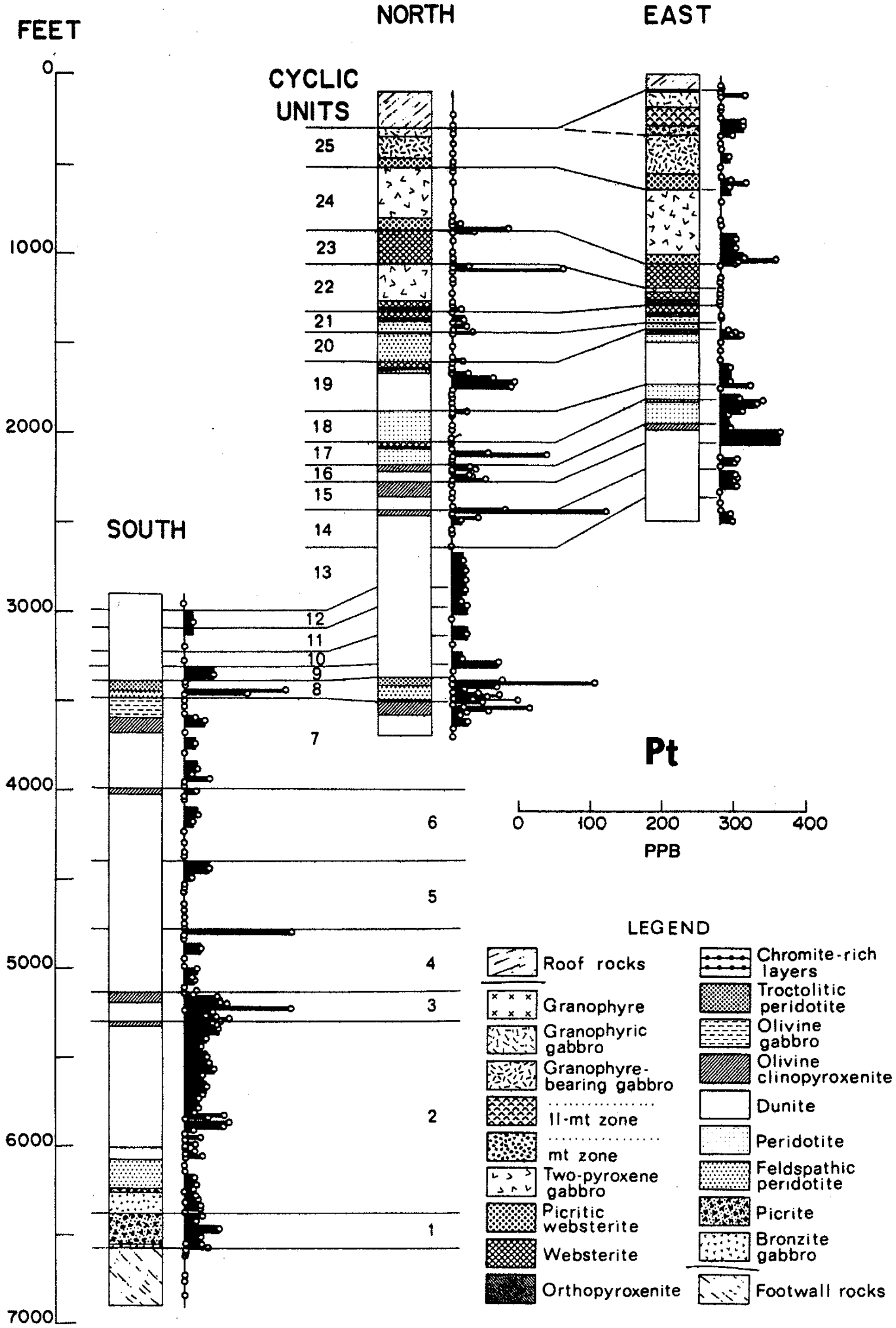

Figure 21. Distribution of Pt in the Muskox deep drill holes.

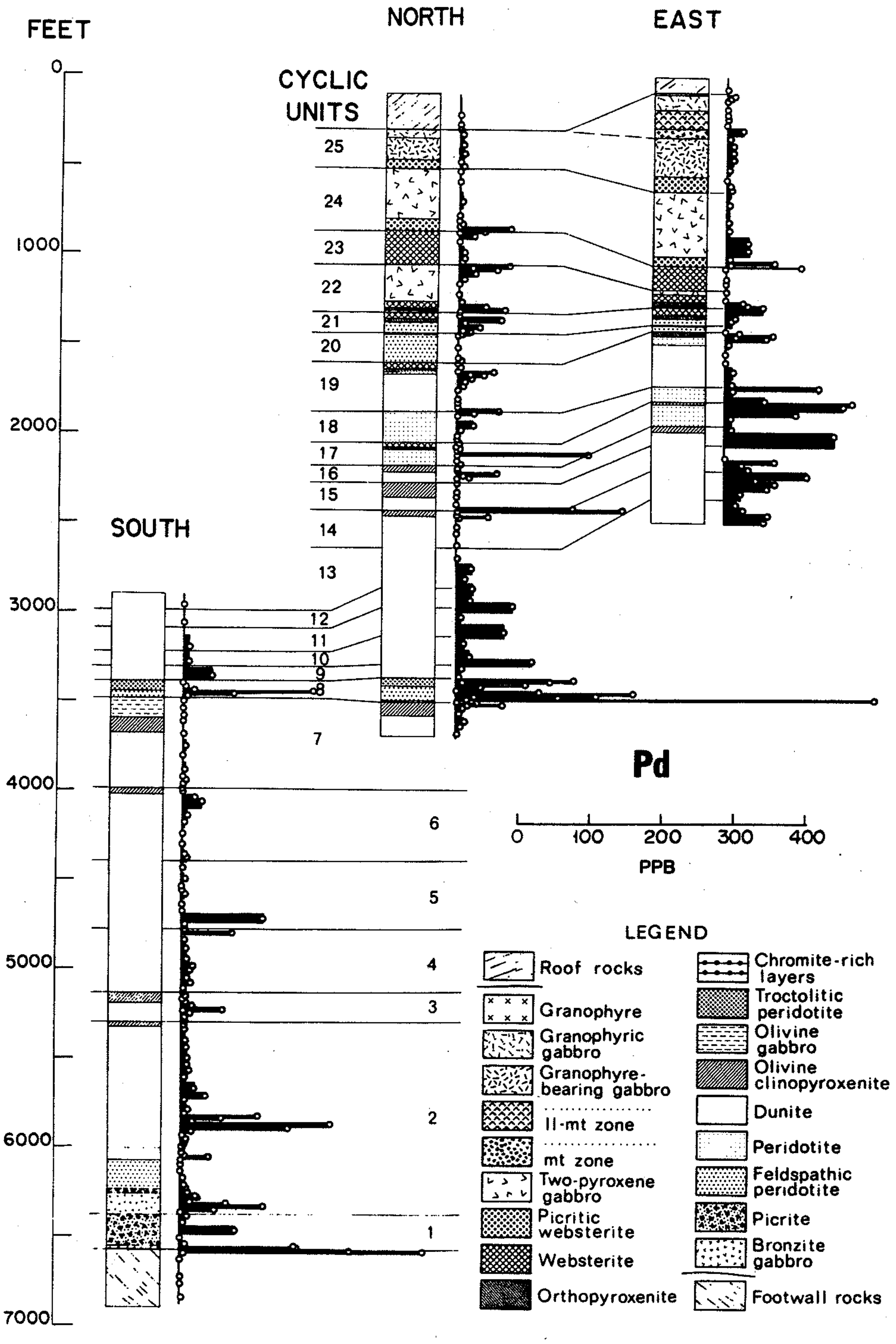

Figure 22. Distribution of Pd in the Muskox deep drill holes.

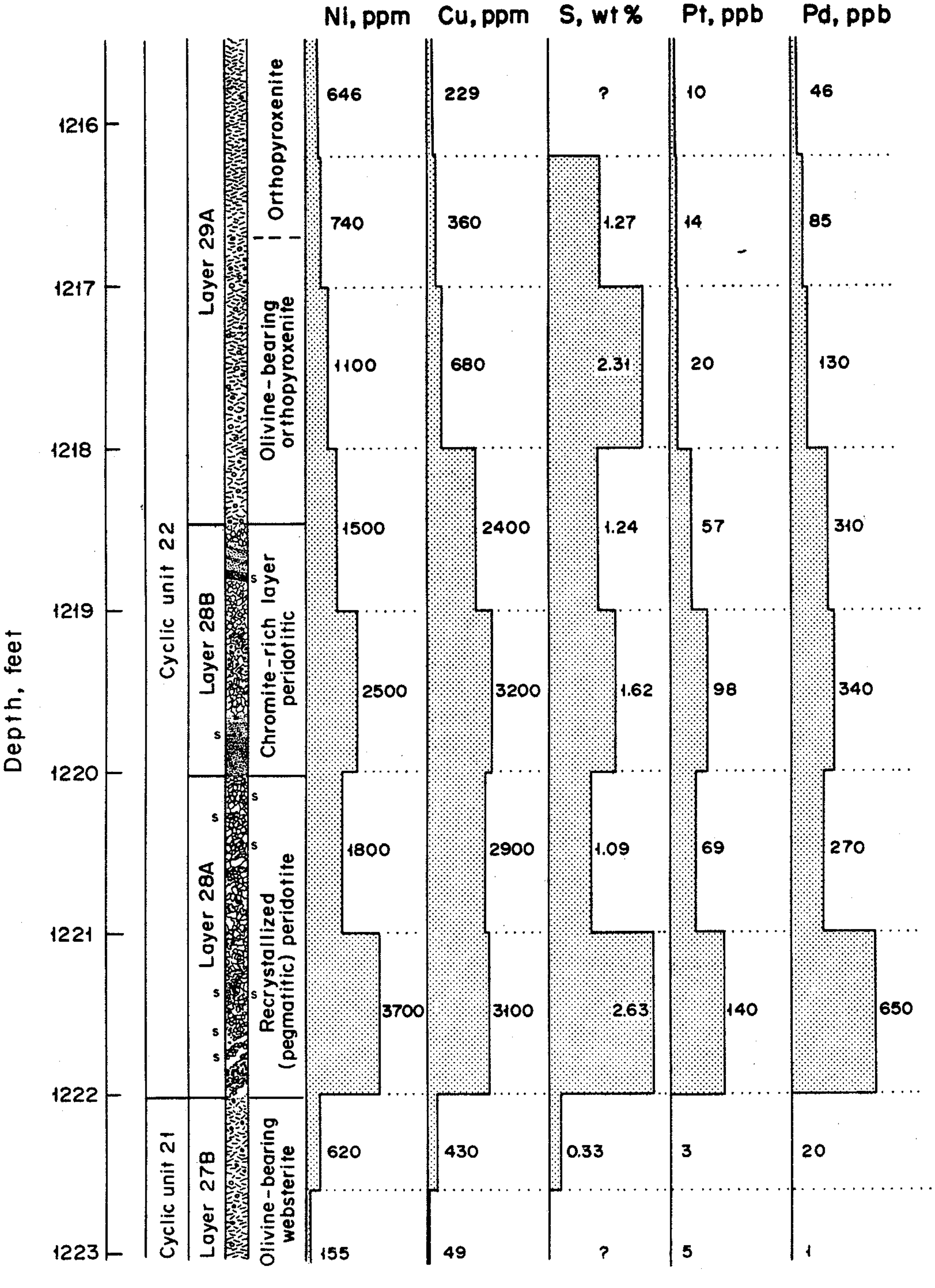

Figure 23. Concentrations of Ni, Cu, S, Pt, and Pd through the upper chromite-rich layer in the Muskox North drill hole. In the graphic log, visible sulphides are shown in black and marked by letter S.

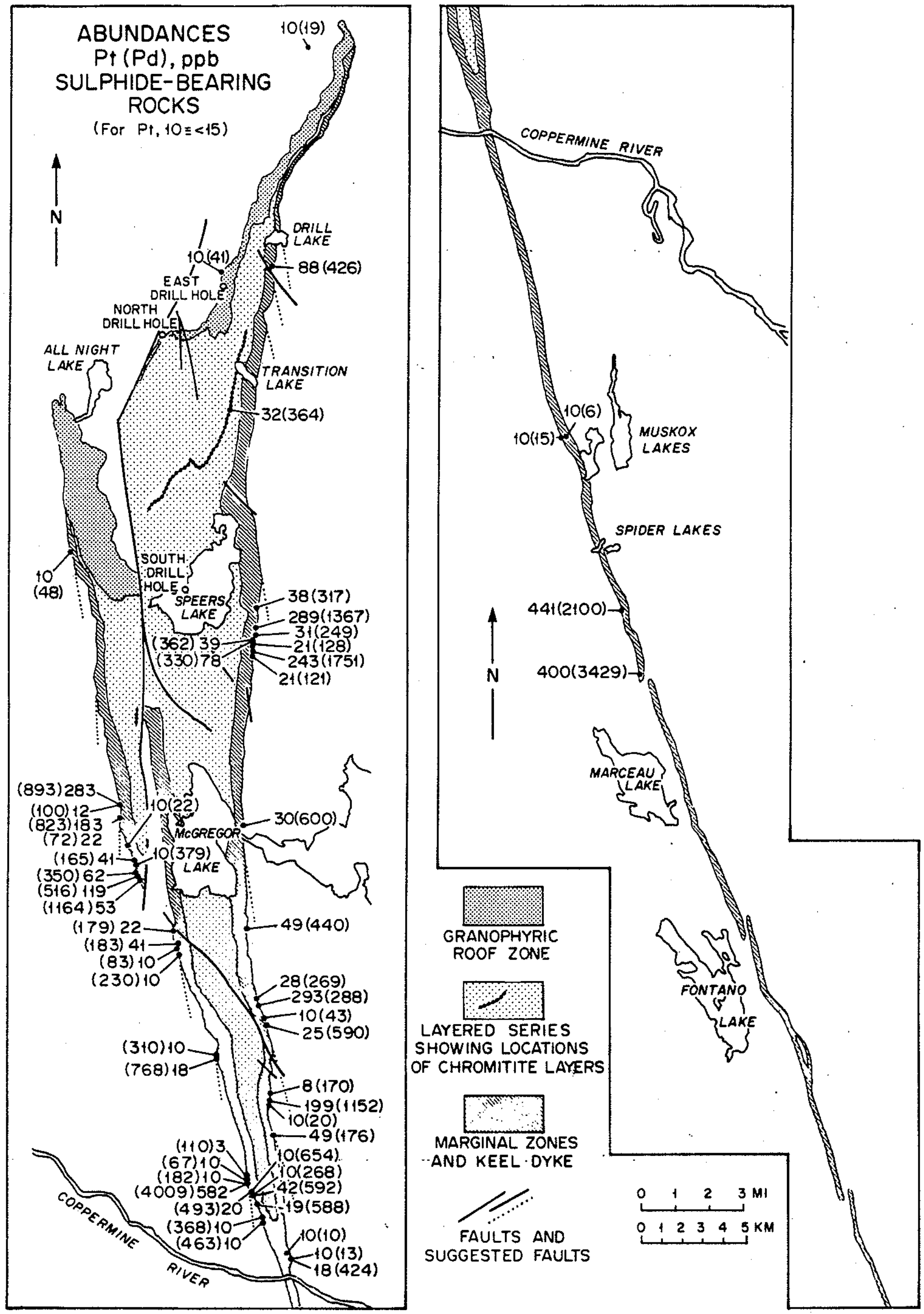

Figure 24. Map showing data on Pt and Pd in samples from the Muskox footwall sulphide deposits. Values for Pd are in parentheses.

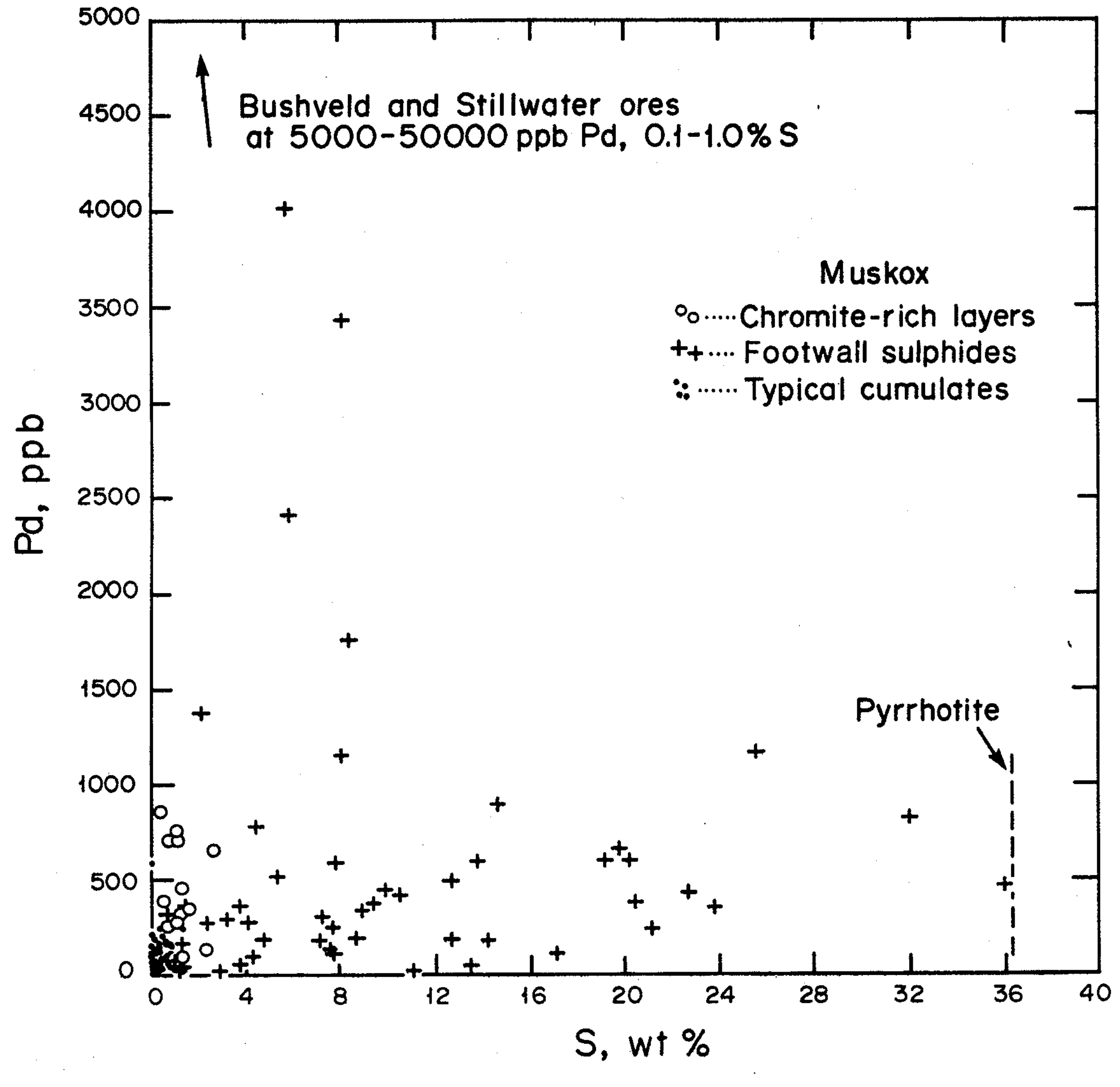

Figure 25. Plot of Pd vs. S for samples of the Muskox footwall sulphide deposits.

also suggest, however, that they do not mark the first episode of sulphide liquid precipitation in the intrusion. A further question of interest, then, is whether there are earlier stratigraphic sulphide zones that might somewhere be enriched in PGE.

In principle, almost any of the small PGE peaks in Cyclic units 2-16 could be indicative, but two intervals of the layered series appear to warrant most attention. The first is just at the top of Cyclic unit 3. In the South hole, this unit, which consists of dunite overlain by olivine clinopyroxenite, is succeeded directly by a thick layer of dunite assigned to Cyclic unit 4. But in outcrops south of MacGregor Lake, the top part of unit 3 additionally contains a few metres of thinnly layered troctolitic peridotite. The plagioclase in this rock is the first cumulus feldspar in the layered series, so the return to dunitic cumulate in Cyclic unit 4 marks a substantial regression in the compositional path of the magma and, therefore, might have involved a significant episode of magma mixing. The intriguing feature in the PGE data is that Pt increases upward through units 2 and most of 3, then decreases abruptly to very low concentrations in unit 3 pyroxenite. This pattern may indicate enrichment through fractional crystallization, followed by sudden depletion by the onset of sulphide liquid precipitation. If so, then the Pt discontinuity possibly marks the first precipitation of sulphide liquid during formation of the layered series. But Pt and Pd peak only slightly in only one sample in Cyclic unit 3, so it would appear that, if any significant zone of PGE enrichment exists in this stratigraphic interval, it most probably is down dip (down plunge) from the South hole intersection, which is at about 2350 ft (716 m) depth.

The other interval of interest comprises the rocks assigned to Cyclic unit 8. This is not a typical cyclic unit, however; in fact, its assignment was largely a matter of convenience. The interval spans an unusually complicated alternation of olivine-rich pyroxenite, gabbro, and peridotite, including a peculiar zone of thinnly layered gabbroic peridotite in which the layers are slightly cross bedded and show faint reverse modal grading. This succession is only poorly exposed in outcrop (just south of Speers Lake), but it was intersected by both the South and North holes, so it is persistent. The preceding Cyclic unit 7 is the type example of crystallization order I, and its gabbro layer represents the first episode of widespread plagioclase precipitation in the layered series. The succeeding units, 9-13, are all composed only of dunite; thus the interval of unit 8 marks a major regression in the magma composition path, and its stratigraphy suggests a complex episode of magma mixing. As for PGE, the interval is distinguished in the North hole by some of the strongest peaks encountered for Pt, Pd, Cu, and S (Figs. 21 and 22). The peaks are smaller in the South hole, but the rocks there are strongly serpentinized, so sulphides may have been largely destroyed. But if there is any strong PGE enrichment in the interval, it too probably has to be down dip from the northernmost drill hole intersection, which in this case is near the bottom of the North drill hole. Its depth is considerable, however, about 3450 ft (1050 m).

ACKNOWLEDGEMENTS

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FOX RIVER SILL, MANITOBA

Introduction

The Fox River Sill, a stratiform ultramafic-mafic intrusion, forms an integral part of the Fox River Belt in northeastern Manitoba. The Fox River Belt borders the northern edge of the Superior Province craton for approximately 300 km (Fig. 26), where it forms a portion of the Churchill - Superior boundary zone. The belt forms a segment of the Circum - Superior Belt, a sequence of Proterozoic supracrustal rocks of similar stratigraphy and lithologies, that occurs around the margin of the Archean Superior Province (Baragar and Scoates, 1981).

The Fox River Sill, which occurs as a number of segments that extend along strike for 250 km (Fig. 26), and which ranges from 2 to 2.5 km in thickness, intrudes a siltstone - sandstone sequence (Middle sedimentary formation, Fig. 27). Volcanic rocks (Upper volcanic formation), which range in composition from komatiitic basalt to tholeiitic basalt, overlie the Sill and are separated from it by several hundred metres of Middle sedimentary formation rocks (Fig. 27). These volcanic rocks are interpreted to represent lavas expelled from the underlying Fox River Sill magma chamber at different times during its crystallization history (Scoates, 1984).

The Sill has been subdivided into four zones (Scoates, 1981; in prep.); marginal zone, lower central layered zone, upper central layered zone and hybrid roof zone (Fig. 28). Each zone is characterized by distinctive lithologic units, and except for the hybrid roof zone, by distinctive cyclic arrangement of units. The intrusion is predominantly ultramafic in composition, more than 75 percent consisting of olivine-rich, olivine cumulates.

Main Layered Series

The Main Layered Series of the intrusion comprises the lower and upper central layered zone successions, which represent approximately 2,200 m of cumulates. The lithologic units have been mainly grouped into cyclic units based on the disappearance and abrupt reappearance of cumulus olivine. In each cyclic unit the basal layer generally contains abundant cumulus olivine, the upwardly succeeding layers containing more siliceous and more felsic cumulus phases. In the western part of the intrusion, the 1000 m thick lower central layered zone is composed of ten cyclic units, nine of which consist of two layers, thick (30 - 225 m) basal olivine + chromite cumulate layers and thin (6 - 12 m), clinopyroxene

± olivine cumulate layers. The other cyclic unit contains an uppermost plagioclase + clinopyroxene cumulate layer in addition to the olivine + chromite and clinopyroxene ± olivine cumulate layers. The rocks are predominantly adcumulates, although clinopyroxene occurs as sporadically distributed oikocrysts in olivine cumulates, and plagioclase and orthopyroxene occur as rare postcumulus phases in clinopyroxene cumulates. Each olivine cumulate-clinopyroxene cumulate pair represents an incomplete or beheaded (in the sense of Jackson, 1971) cyclic unit.

In contrast with the lower central layered zone succession, the upper zone cyclic units consist of the following cumulate layers (listed from base to top of a cycle): (1) olivine + chromite, clinopyroxene ± olivine; 2) olivine + chromite, clinopyroxene ± olivine, plagioclase ± clinopyroxene; 3) olivine + chromite, plagioclase ± clinopyroxene; (4) clinopyroxene ± olivine, plagioclase ± clinopyroxene; and (5) rare olivine + chromite, orthopyroxene ± olivine (Table 5). The variation in cyclic units illustrates that the order of crystallization was variable during crystallization of upper central layered zone rocks. In the western part of the intrusion, the 1,200 m of this succession is composed of a minimum of 40 layers and 19 cyclic units, twice as many layers and cyclic units as the 1000 m of lower central layered zone rocks. Upper zone rocks are predominantly orthocumulates. Common postcumulus phases include clinopyroxene, orthopyroxene, and plagioclase in olivine cumulates, orthopyroxene and plagioclase in clinopyroxene cumulates, orthopyroxene and olivine in plagioclase cumulates, and clinopyroxene and plagioclase in orthopyroxene cumulates (Table 5).

Sulphide Minerals

Sulphide minerals, which are rare in lower central layered zone rocks and common though not abundant accessory phases in upper central layered zone rocks, constitute less that 1 percent (by volume) of the Fox River Sill. In the western part of the intrusion disseminated sulphides occur at the base of the upper zone succession. Here they are present in olivine and clinopyroxene cumulate layers of the first three upper central layered zone cyclic units and in cyclic unit 6 (Fig. 29). Within cyclic units 5 and 7 they are present in the upper part of olivine cumulate layers and/or in the overlying clinopyroxene cumulate layer (Fig. 29). Only one example of sulphide minerals associated with a plagioclase cumulate layer (cyclic unit 9) has been observed (Fig. 30). Toward the top of the upper central layered zone succession disseminated sulphides are present in the uppermost part of an olivine cumulate layer and in the overlying clinopyroxene cumulate layer (Fig. 30). Disseminated sulphides are also present in orthopyroxene cumulate layers and their associated olivine cumulate layers.

Sulphides occur mainly as sparsely disseminated blebs, interstitial to olivine crystals or to a lesser extent, as fine replacements of various other minerals. Texture of the sulphides is commonly well preserved especially where the rocks are little altered or recrystallized. Pyrrhotite and pentlandite are the main minerals, pyrrhotite generally constituting 75 to 95 percent of the inter-olivine blebs. Pentlandite usually occurs as a few discrete grains within pyrrhotite, and commonly has in part altered to mackinawite. Chalcopyrite rarely exceeds 5 percent of the sulphide and is generally most abundant in olivine-poor, plagioclase-rich rocks.

With significant serpentinization of the olivine-rich host rocks, magnetite replaces sulphide, incipiently along cleavages in both pyrrhotite and pentlandite and in more advanced cases as complete pseudomorphous replacement of pyrrhotite. Conversion of pyrrhotite cores to a fine-grained spongy mass of pyrite, with possibly 10 percent of fine-grained silicate, has also been observed in serpentinized olivine-rich rocks.

Mobilization of sulphides on a small scale is common. Pyrrhotite and pentlandite, and especially chalcopyrite are observed as replacements of olivine and orthopyroxene in a variety of textures. The sulphides are presumably derived locally from intercumulus blebs.

Platinum Group Elements

Platinum-group elements were analyzed by the fire assay-neutron activation technique of Hoffman et al., (1978) (Table 6). Sample locations are shown in Figures 29 and 30. The samples were chosen because they contain the most abundant megascopically visible sulphides (estimated between 3 and 7%).

Samples consisted of short pieces of small-diameter drill core, estimated to range in the order of 20 to 100 g per sample. Modal proportions of sulphides, chromite, and magnetite were measured in polished thin section by an image analyzer (Table 6), but the resulting data are not expected to be precise because of the obviously variable distribution of sulphides.

Correlations Among PGE

In order to identify possible processes that have produced the observed variation among the PGE, some simple statistical characteristics were examined. All of the succeeding statistical calculations are based on the analytical data shown in Table 6, with the following modifications: all data for Os and for sample 11 were deleted because many of the results were below detection limits, and the three analyses of Ru below the detection limit (5 ppb) were arbitrarily assigned values of 2 ppb.

Ir-Rh-Pt-Pd-Au

The correlation matrix shown in Table 7 indicates that some pairs of platinum-group elements are highly correlated. Pd and Rh are exceptionally strongly correlated having a correlation coefficient of 0.996. Pt is well correlated with Ir, Rh, and Pd, and Ir with Pd and Rh. Au is weakly correlated with Rh, Pt, and Pd.

Because platinum-group elements are trace elements and are expected to have (and for the most part do have) lognormal distribution, a case can be made for using the logarithmically transformed values rather than the raw data for statistical charcterizations. A correlation matrix of the logarithmically transformed data (not shown) reveals that the correlation coefficients of all the element pairs involving Ir, Rh, Pt and Pd remain essentially unchanged and highly significant. Most interesting, however, is the marked enhancement of the correlation of Au with Pd (0.73), Rh (0.72), Pt (0.59), and Ir (0.48). A similar enhancement of Au correlation with these elements is obtained (0.71, 0.69, 0.67, and 0.59) using the raw data but omitting the anomalously high Au value (sample 6). It seems clear, therefore, that there is a significant correlation between Au and these elements.

Factor analysis of the untransformed platinum-group element data (Table 8) produces a first factor with high loadings (>0.9) of Ir, Rh, Pt, and Pd and a lower loading for Au (0.44). Logarithmic tranformation of the data yields a first factor with about the same high loadings of Ir, Rh, Pt, and Pd but increases the loading of Au to 0.75. The only element with significant loading in the second factor is Ru.

From the foregoing statistical characterizations of the PGE data, two generalizations seem valid: that Ir, Rh, Pt, and Pd and to a lesser degree Au are closely mutually associated, and that the bulk of the variation in abundance of these elements can be accounted for by one single factor or mechanism. Because of the association here and elsewhere of PGE with sulphides, it seems possible that this factor could be a sulphide-factor in the sense than an immiscible sulphide melt in the magma acted as a collector of platinum-group elements. Thus, for low levels of sulphide the amounts of Ir-Rh-Pt-Pd(-Au) should be a function of the amount of sulphide present. Sulphur analyses are not available to test this relationship. Modal analyses of bulk sulphides (Table 6) show little correlation with platinum-group elements, possibly indicating only that the two types of analytical results are not comparable representations of the population being sampled. Lee (1983) has demonstrated that in the Merensky unit of the Bushveld Complex, strongly intercorrelated Ir-Rh-Pt-Pd are also significantly correlated with sulfur.

There may be two effects contributing to this sulphide factor. The first simply involves the partitioning of Ir-Rh-Pt-Pd (-Au) between a silicate melt of constant composition and the small amount of sulphide liquid that separates immiscibly from it. Constant relative values of partition coefficients of these platinum-group elements would produce their observed correlation in the sulphide factor, such that the greater the amount of sulphide, the greater the amounts of platinum-group elements. The second effect is the variation in the amount of Ir-Rh-Pt-Pd(-Au) contained in the silicate melt during its fractional crystallization. Most of these elements are considered to behave incompatibly with respect to olivine and chromite, and thus, become concentrated in the residual melt as crystallization progresses. If other parameters are constant (e.g., platinum-group element partition coefficients), then the later the separation of the immiscible sulphide, the richer in platinum-group elements it will be. It is not clear how these two effects could be distinguished on the basis of the currently available data. The operation of either one or both mechanisms could produce the strong correlations observed.

An important corollary of the strong correlations among Ir, Rh, Pt, and Pd (and Au) is that they apparently have not been modified by any superimposed later process. This is consistent with the disseminated magmatic textures of the sulphides, the low grade of metamorphism, and the absence of tectonic disruption. The minor mobilization of sulphides observed in polished sections has not influenced these platinum-group elements on a scale greater than the dimensions of the samples analyzed in this study.

PGE Profiles

The platinum-group element data are presented as chondrite-normalized profiles in Figure 31. They have not been recalculated to 100 percent sulphide, because sulfur analyses were not available. It is questionable in any case whether such a recalculation would be appropriate. The practice of recalculating to 100 percent sulphide was originally devised for massive sulphide or very sulphide-rich ores, whereas in Fox River rocks sulphides are sparse. Nevertheless, the chondrite-normalized profiles may still be compared to 100 percent sulphide platinum-group element profiles because the slopes remain the same, regardless of which normalization method is used.

The chondrite-normalized profiles (Fig. 27) have positive slopes similar to those of various magmatic sulphides in mafic and ultramafic rocks (Naldrett and Duke, 1980). However, it is notable that the profiles tend to form two groups, one (group 1) being richer in Rh, Pt, and Pd and having as a result a steeper slope than the other (group 2). These groupings are also reflected in both the Pd/Ir and (Pt + Pd)/(Os + Ir + Ru) ratios (Table 6 and Fig. 27) as would be expected. The plot of Pd vs. Rh (not shown) shows that group 2 (shallow slope) samples are clustered at the lower end of the best-fit line and that the group 1 (steep slope) samples are spread out along the remainder of the line. This distribution of group 1 and group 2 samples is typical for all pairs of the well-correlated platinum-group elements. The average group 1 profile is similar in slope to those of Sudbury and the Merensky reef, whereas the average group 2 profile is intermediate in slope between Sudbury and komatiites. In veiw of the previously described strong correlations of Ir-Rh-Pt-Pd(-Au), which indicate that the whole suite of Fox River samples appears to constitute a single population, the suggestion of two separate groups based on platinum-group element profiles merits further consideration.

Group 1 samples (steep profiles; samples 1, 2, 3, 6, 7, Table 6, Fig. 29) are located within 150 m of the lower and upper central layered zones contact. Three of these profiles represent samples from thin cyclic units, the other two profiles may also represent samples from a thin

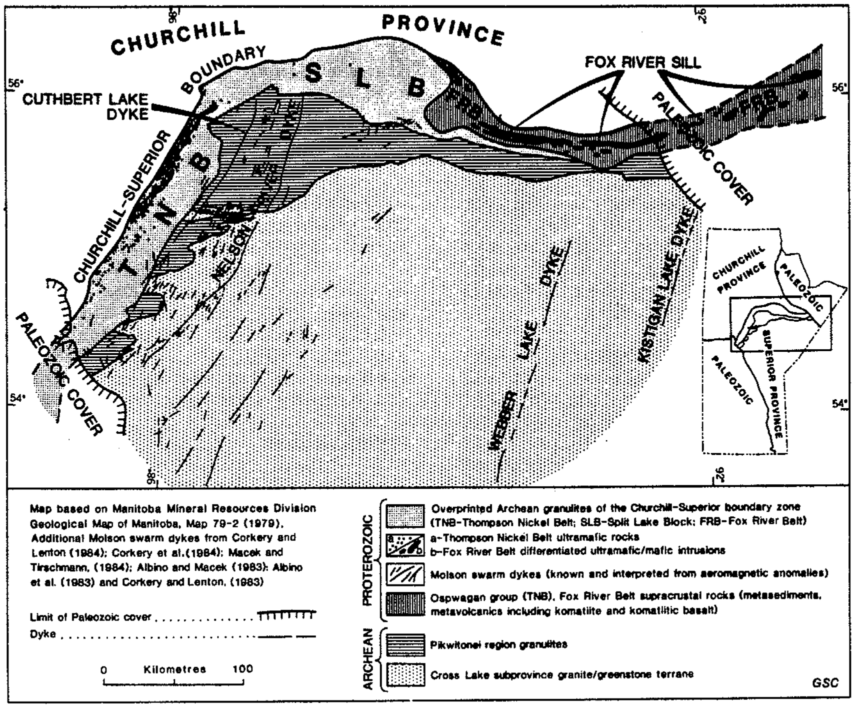


Figure 26. Geology of northwest part of the Archean Superior Province craton, including the Churchill-Superior boundary Zone illustrating the Fox River Belt, and Fox River Sill. (after Scoates & Eckstrand, 1986).

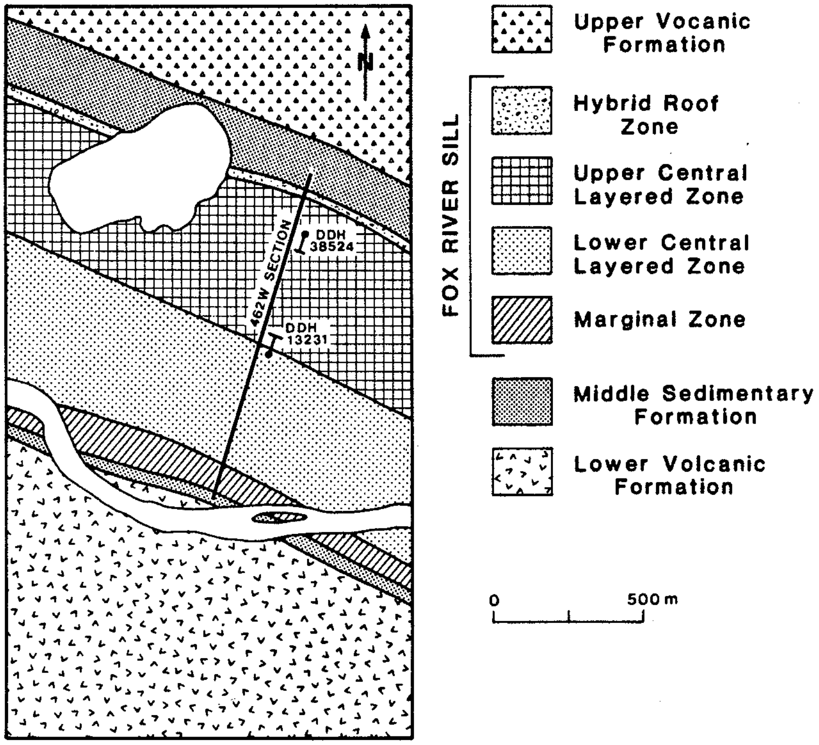


Figure 27. Position of 462W section and drill holes 13231 and 38524. See Figure 1 for location. (after Scoates & Eckstrand, 1986).

Table 5: Cumulus Phases and Lithologic Units of the LCLZ-UCLZ Succession
Fox River Sill

Zone	Cumulus Phase[1]	Lithologic Unit[2]
Upper central layered zone	orthopyroxene ± olivine (opx ± ol)	plagioclase-bearing olivine websterite, plagioclase-and olivine-bearing orthopyroxenite
	plagioclase ± clinopyroxene (pl ± cpx)	olivine-bearing mela gabbronorite, olivine-bearing gabbronorite, gabbro
	clinopyroxene ± olivine (cpx ± ol)	plagioclase-bearing olivine websterite
	olivine + chromite[3] (ol + cr)	plagioclase-bearing lherzolite, plagioclase-bearing wehrlite, dunite
Lower central layered zone	plagioclase ± clinopyroxene cpx ± ol (rare)	olivine-bearing gabbro, olivine-bearing gabbronorite
	clinopyroxene ± olivine cpx ± ol	olivine clinopyroxenite
	olivine + chromite[3] ol + cr	dunite, wehrlite

[1] Cumulus phases are listed in order of decreasing abundance.
[2] Lithologic units are listed in order of decreasing abundance and are based on total modal mineralogy using the Streckeisen (1976) scheme.
[3] Chromite is a cumulus phase in most olivine cumulate rocks.

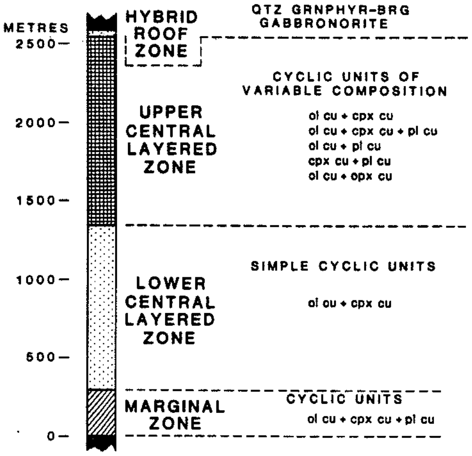


Figure 28. Composite stratigraphic section with the main subdivisions of the Fox River Sill. (after Scoates & Eckstrand, 1986).

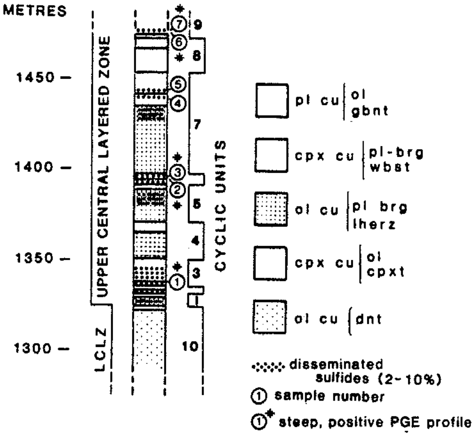


Figure 29. Stratigraphic section showing the lower central layered zone - upper central layered zone contact and location of mineralized intervals. (after Scoates & Eckstrand, 1986).

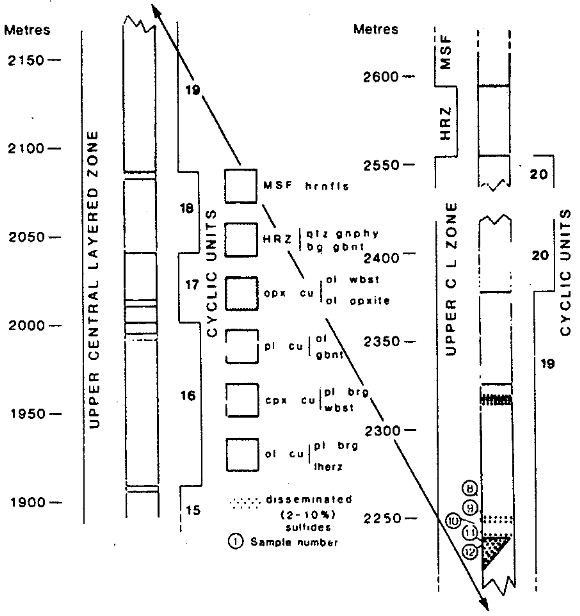


Figure 30. Composite section for upper part of the upper central layered zone (462W section, drill hole 38524) showing location of mineralized intervals. (after Scoates & Eckstrand, 1986).

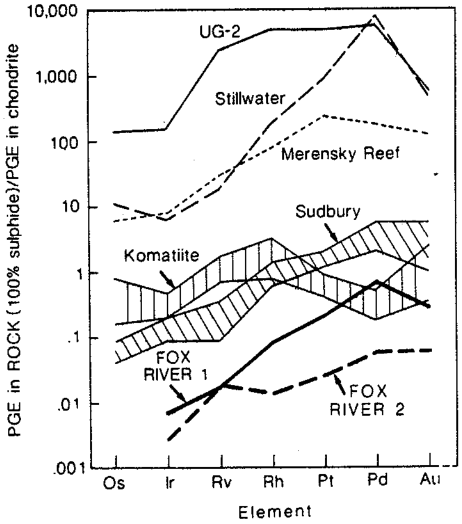


Figure 31. Chondrite normalized profiles of Fox River mineralized rocks. (after Scoates & Eckstrand, 1987).

Table 6. Platinum-Group Element Analyses of Sulfide-bearing Rocks of the Fox River Sill (ppb)

	1	2	3	4	5	6	7	8	9	10	11	12	Detection limits
Ru	<5	20	23	16	12	10	<5	13	10	<5	<5	21	5
Rh	33	10	9	3	2	18	10	3	3	2	2	4	1
Pd	810	200	230	47	26	430	180	39	32	13	<5	33	5
Pt	350	220	190	23	26	190	110	18	26	21	<5	46	5
Os	<3	3	3	<3	3	<3	<3	<3	<3	<3	<3	4	3
Ir	5.4	4.3	3.6	1.1	1.6	3.0	1.9	1.3	1.2	0.7	1.4	2.7	0.1
Au	24	8	23	14	4	140	15	9	14	4	8	10	1
Pd/Ir	150	47	64	43	16	143	95	30	27	19	[1]	12	
(Pt+Pd) / (Os+Ir=Ru)	>87	15	14	3.4 to 4.1	3.1	39 to 48	>29	3.3 to 4.0	4.1 to 5.2	[1]	[1]	2.9	
Sulfides[2]	14.1 (4.7)	7.7 (5.4)		3.6 (1.8)	11.4 (3.9)	9.9 (6.0)		10.3 (7.7)		5.7 (4.6)	8.3 (10.4)	18.3 (14.2)	
Chromite[2]	0	0.03 (0.11)		0	0	0.05 (0.10)		0.6 (1.0)		0.4 (0.3)	0.6 (0.7)	0	
Magnetite[2]	17 (2.1)	0.8 (2.9)		0	0	0.2 (0.5)		0		0	0	0.7 (1.2)	

Analyses by Nuclear Activation Services Limited, Hamilton, Ontario

[1] Platinum-group element levels too low to calculate meaningful values

[2] Volume percent by image analysis (Cambridge Instruments Quantimet 920); average of four to seven fields (50X magnification); one standard deviation in parentheses

Table 7. Correlation Coefficients of Platinum-Group Elements, Fox River Sill

	Ir	Ru	Rh	Pt	Pd	Au
Ir	1.00000	0.15606	0.82132	0.94543	0.81944	0.22126
Ru	0.15606	1.00000	-0.34919	-0.08821	-0.32619	-0.08068
Rh	0.82132	-0.34919	1.00000	0.92119	0.99627	0.42923
Pt	0.94543	-0.08821	0.92119	1.00000	0.92385	0.34179
Pd	0.81944	-0.32619	0.99627	0.92385	1.00000	0.44184
Au	0.22126	-0.08068	0.42923	0.34179	0.44184	1.00000

n= 11; critical valure for significance at 0.05 level = 0.602, and and at 0.005 level = 0.776

Table 8. Factor Analysis of Platinum-Group Elements, Fox River Sill

	Raw data		Log 10 transformed data	
	Factor 1	Factor 2	Factor 1	Factor 2
Ir	0.94817	0.25368	0.90725	0.19767
Ru	-0.04725	0.96542	-0.02757	0.99819
Rh	0.94308	-0.30545	0.97379	-0.21184
Pt	0.98182	-0.00839	0.96057	-0.08758
Pd	0.94651	-0.28943	0.97879	-0.11581
Au	0.43538	-0.27424	0.75307	0.05785

-mode factor loadings; VARIMAX rotation after Kaiser normalization;
= 11; two-factor solutions for raw and log 10 transformed data

cyclic unit; however, the unit extends beyond the end of the drill hole. All Group 1 samples represent incomplete cyclic units. Samples 1, 2 and 3 (Fig. 29) are from cyclic units that lack a capping plagioclase cumulate layer, and samples 6 and 7 are from a cyclic unit that lacks a basal olivine + chromite cumulate layer.

Group 2 samples (shallow profiles) represent complete and incomplete thick cyclic units. The former (samples 4, 5, 8, 9, 10, Figs. 29 and 30) are cyclic units composed of olivine + chromite-clinopyroxene ± olivine-plagioclase ± clinopyroxene cumulate layers. The latter (samples 11, 12, Fig. 30) represent orthopyroxene ± olivine cumulate layers that are part of incomplete cyclic units composed of olivine + chromite and orthopyroxene ± olivine cumulate layers. Samples 8 to 12 are within 300 m of the top of the upper central layered zone.

In summary, the samples with steep slopes or strong Rh-Pt-Pd enrichment are mostly (or all?) from thin cyclic units, whereas those with shallow slopes or weak Rh-Pt-Pd enrichment are from thick cyclic units. Petrochemical studies (Scoates et al., 1986) of a successive sequence of upper central layered zone cyclic units indicate that thick olivine cumulate layers (90-240 m thick), which have relatively forsteritic olivines (Fo_{88-89}), resulted from large volumes of introduced magma. Thin olivine cumulate layers (10 m thick) from the same sequence, which have less forsteritic olivines (Fo_{82-84}), are considered to result from small volumes of introduced magma mixed with evolved residual magma. If all thin upper central layered zone cyclic units have originated from more evolved magma, then the Rh-Pt-Pd-enrichment of platinum-group elements associated with thin cyclic units may be attributable to their derivation from a more evolved magma enriched in incompatible platinum-group elements. This would be consistent with the dependence of platinum-group element abundances on the crystal fractionation of host magmas as proposed by Barnes et al. (1985).

BIRD RIVER SILL, MANITOBA

The Bird River sill, a differentiated ultramafic to mafic layered intrusion of Archean age in southeastern Manitoba, is well known as the repository of Canada's most significant chromite resource. Several nickel-copper sulphide deposits are also associated with the sill of which the most important are the Dumbarton and Maskwa West deposits.

The sill is exposed discontinuously along both limbs of an eastward plunging anticline, the core of which is occupied by the Maskwa Lake batholith (Fig. 32).The sill has a strike length of at least 25 km along the south limb, and is exposed over a strike length of 4 km in two widely separated localities along the north limb of the structure (Fig. 32). The exposed width rarely exceeds 600 m and, since the dip is commonly near vertical, this reflects the true thickness of the body.

The sill intruded metabasalts of the Lamprey Falls Formation, the second oldest of six formations that constitute the Bird River greenstone belt (Trueman, 1980). The upper contact of the sill is interpreted to be a fault which separates anorthositic gabbro of the intrusion from a series of debris flows that contain inclusions of anorthositic gabbro in addition to inclusions of metabasalt. The intrusion was apparently unroofed subsequent to its emplacement (Trueman, 1980).

The sill is differentiated with a lower Ultramafic Series and an upper Mafic Series. Where the section has been measured, the Ultramafic Series is about 200 m thick and the Mafic Series is 400 m thick (Fig. 33 and 34). However, as the top of the sill has been eroded, the latter thickness is a minimum. A U-Pb zircon age of 2745 ± 5 Ma (Timmins et al., 1985) was determined for Mafic Series gabbro.

Scoates (1983) established a stratigraphy for the Ultramafic Series which is illustrated in Figure 34. This is based largely on observations on the Chrome claims (Fig. 33) but would appear to apply also to other exposures which are about 4.5 km along strike to the east. At this time the lateral extent over which this stratigraphy applies is not known. The Chromitiferous Zone is further subdivided, and contains six groups of chromitite layers (Scoates, 1983). These have been designated in ascending order the Lower, Disrupted, Lower Main, Banded and Diffuse, Upper Main and Upper Paired Groups.

Three main rock types have been identified in the course of mapping the Ultramafic Series: peridotite, dunite and chromitite. Peridotites are typically olivine-chromite cumulates with conspicuous amounts of intercumulus material. Olivine and chromite occur in their typical cotectic proportions: that is, chromite makes up form 1 to 5 modal percent. Pervasive alteration makes the identification of primary intercumulus minerals uncertain. Some relict clinopyroxene has been observed but it is unclear how much orthopyroxene, hornblende or plagioclase may have been present. Gabbro (plagioclase cumulate) is interlayered with peridotite at the top of the Layered Zone.

PGE Mineralization

Anomalous PGE concentrations in Bird River sill Ultramafic Series rocks are defined as those greater than 100 ppb combined Pt, Pd and Au. Four intervals containing anomalous PGE concentrations occur in the Ultramafic Series. Two have been reported from the western part of the Chrome Property in Ultramafic Series rocks stratigraphically below the Chromitiferous Zone (Theyer, 1985). A third occurs within and immediately below Lower Group chromitite (Lower Group platinum-bearing unit, Fig. 34). The fourth interval is the Disrupted Group (Fig. 34) where sporadically distributed anomalous PGE concentrations occur. Of the four intervals, the Lower Group platinum-bearing unit is the most continuous and the most consistently anomalous.

Lower Group Platinum-bearing Unit

This unit of anomalous PGE mineralization has

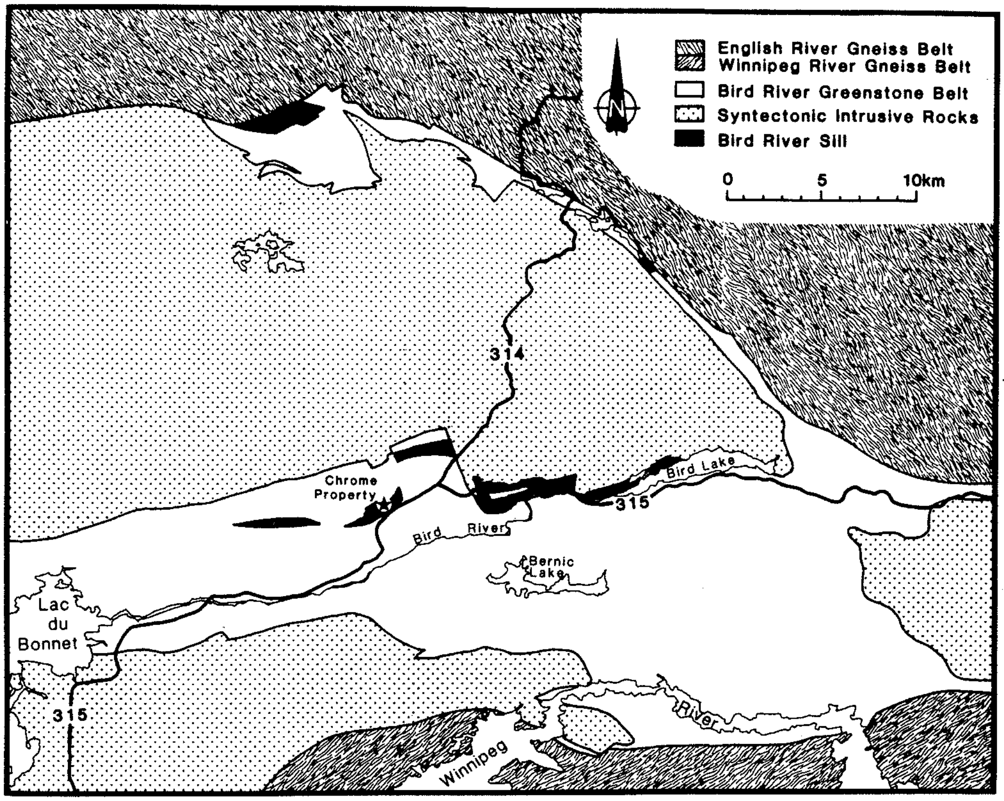


Figure 32. Generalized geology of the Bird River greenstone belt, southeastern Manitoba, showing the disposition of the Bird River sill and the location of the Chrome Property.

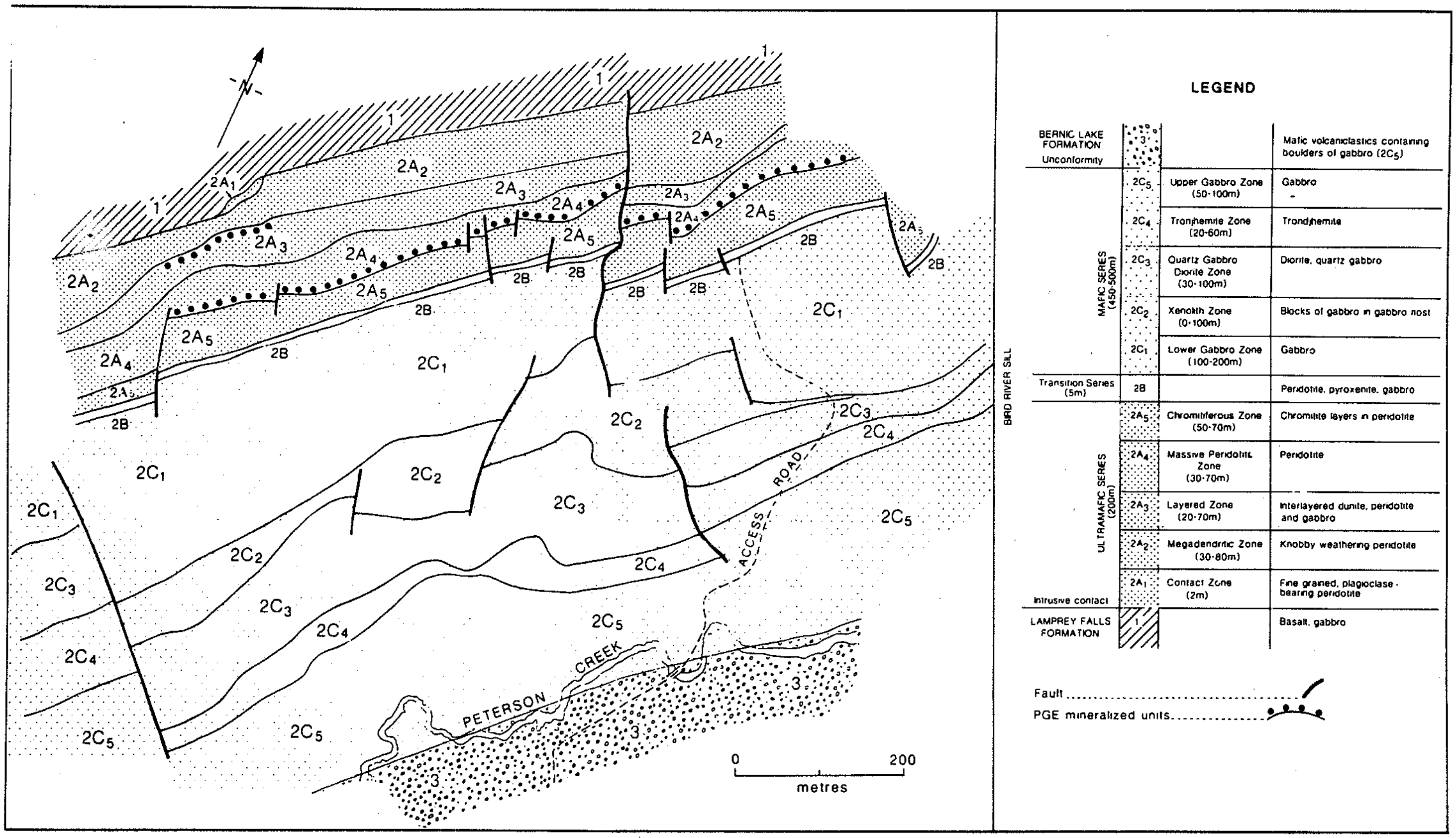


Figure 33. Geology of the Chrome Property.

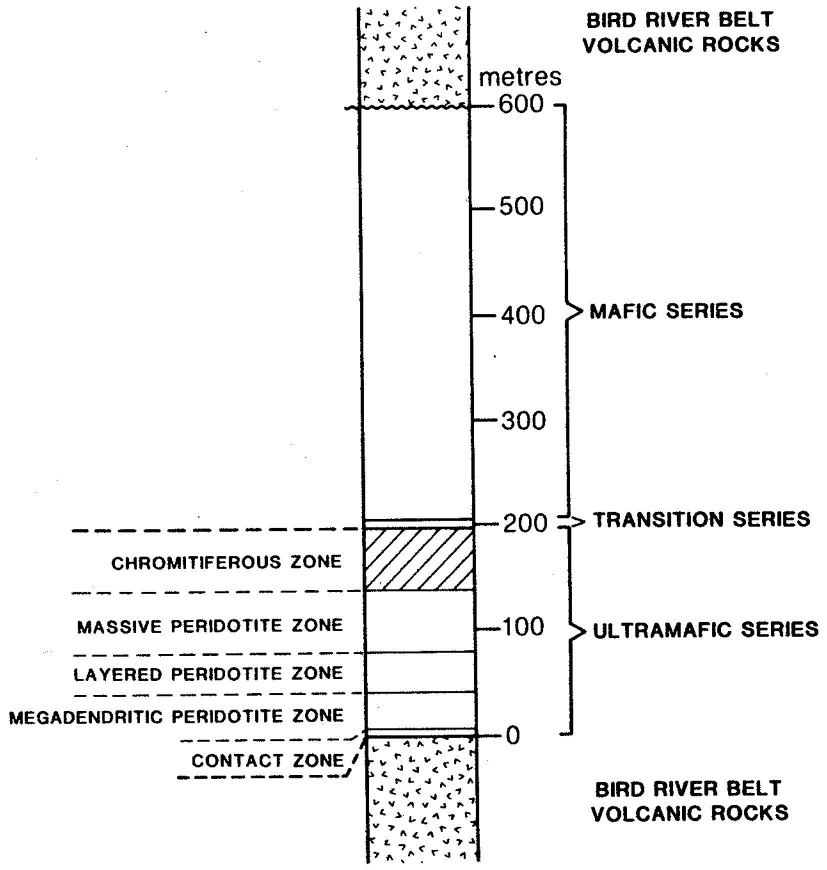


Figure 34. Igneous stratigraphy of the Bird River sill.

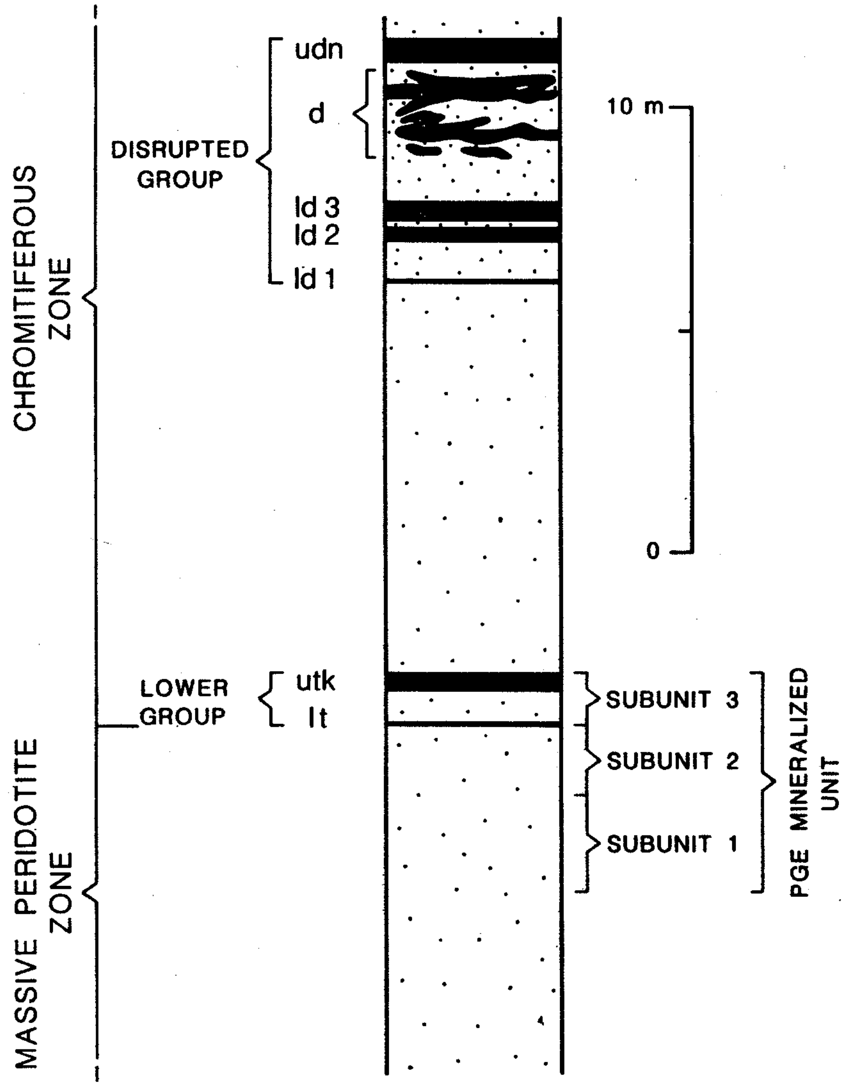


Figure 35. Detailed stratigraphy of the contact between the Massive Peridotite Zone and the Chromitiferous Zone illustrating the subdivisions of the PGE mineralized unit.

Table 9. BIRD RIVER SILL - PGE ASSAYS

(ppb - 66 samples)

	LOW *	HIGH *
Os	1	100
Ir	0.1	53
Ru	3	510
Rh	1	160
Pt	17	720
Pd	2	1800
Au	4	520

* "Low" = minimum value obtained;
"High" = maximum value obtained

Table 10. Bird River Sill - Geometric Means* of PGE in mineralized subunits

	Subunit 1	Subunit 2	Subunit 3
Os	4 ppb	6 ppb	15 ppb
Ir	2	5	10
Ru	18	35	91
Rh	6	19	19
Pt	75	165	147
Pd	110	370	187
Au	15	17	8
	230 ppb	617 ppb	477 ppb
Ni	2192 ppm	2936 ppm	1846 ppm
Cu	314	441	175
Cr	3511	5942	25811

* The geometric mean (of Os, for example) = the antilog of the mean of the logarithms of all values of Os.

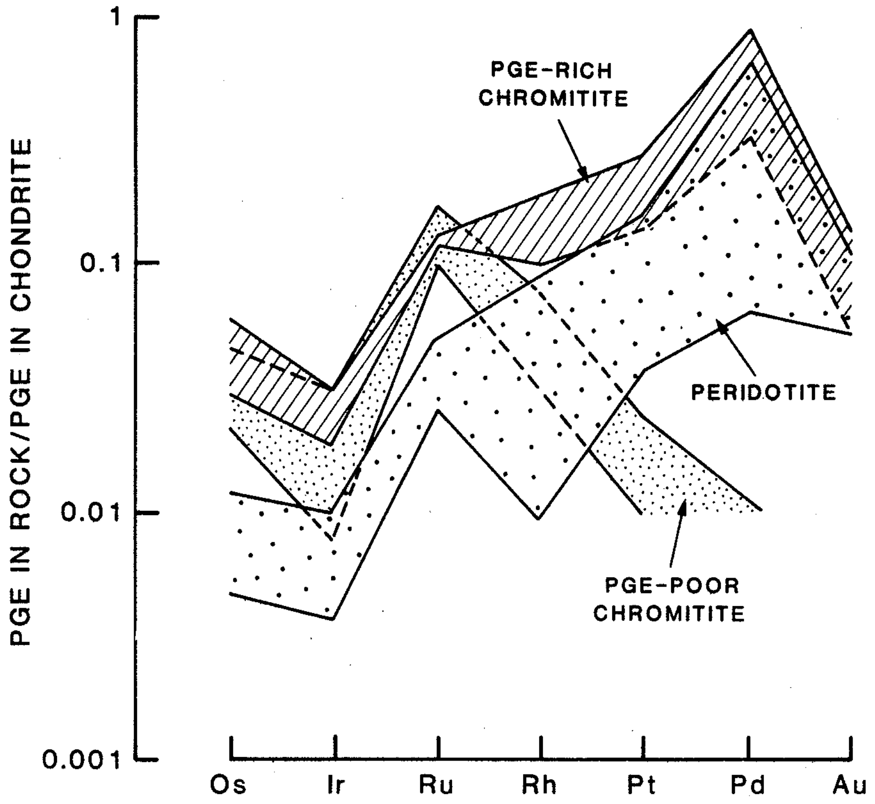


Figure 36. PGE profiles for rocks of the Bird River sill. Data were normalized to the chondrite values used by Naldrett and Duke (1980). The range shown for peridotite is based mainly on subunits 1 and 2; the range for PGE- rich chromitite is based on the Lower Group (= subunit 3) and some values from the Disrupted Group; the PGE-poor chromitite range is based on other chromitites (Talkington et al., 1983) in the sill.

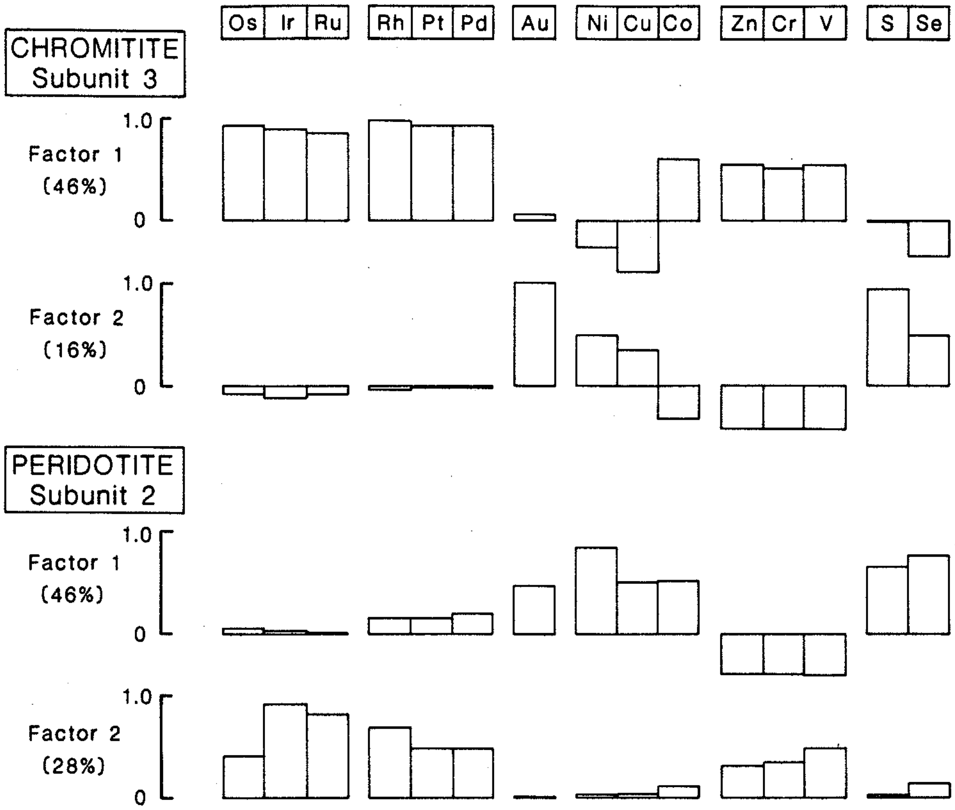


Figure 37. Factor analysis of PGEs and related elements in peridotite (subunit 2) and chromitite (subunit 3) of the Bird River sill. Data were log-transformed. Varimax-rotated factors were calculated using the SPSS mainframe program. The histograms represent the squares of the loadings for each element in the factors, and the percentage value shown represents the portion of total variance accounted for by each factor. Two-factor solutions appeared optimal for both subunits.

been traced for 800 m along strike on the Chrome Property (Fig. 33). The unit pinches and swells, ranging from several tens of centimetres up to three metres thick. The mineralized unit includes the Lower Group chromitites and extends downward below the base of the Lower Group into peridotite of the underlying Massive Peridotite Zone.

The mineralized unit has been divided provisionally into three subunits (Fig. 35) on the basis of mineralogy and texture. Subunit 1, the stratigraphically lowest subunit, consists of disseminated-sulphide-bearing peridotite. The rocks are medium grained, original olivine crystals averaging 2mm in size. Rounded to subangular chromitite inclusions are sporadically distributed throughout subunit 1 as are discontinuous, mm-scale chromitite layers. Coarser grained, harrisitic peridotite has been noted in places. Subunit 1 extends downward from 70 cm below to as much as 3 metres below the base of the Lower Group. Subunit 2 overlies subunit 1 and represents the 70 cm interval from the top of subunit 1 to the base of the Lower Group. Subunit 2 consists of disseminated-sulphide-bearing peridotite, much of which is characterized by coarse grained olivine crystals (up to 2 cm), many of which are harrisitic. The volume of original postcumulus material increases from 5 to 10 percent in subunit 1, to 20 percent in subunit 2. Chromite, as dense disseminations and disrupted fragments of dense chromitite is also more abundant than in subunit 1. Normal, fine grained peridotite is also present. Subunit 3 consists of the lower and upper chromitite members and the intervening olivine cumulate member of the Lower Group. The lower member is a 4 to 6 cm thick diffuse chromitite (chromite-olivine cumulate) layer that is disrupted in places and that locally bifurcates into two or more layers separated by peridotite. The chromitite is characterized by numerous peridotite inclusions up to 1 cm in size. The upper member ranges from diffuse to dense chromitite (10 to 25 cm thick) that commonly contains entrained peridotite inclusions. The chromitite locally bifurcates into two layers separated by up to 15 cm of peridotite. The olivine cumulate member that separates the lower and upper members ranges from fine grained peridotite (1 to 2 mm olivine) to coarse grained (1 to 2 cm olivine), harrisitic peridotite. The latter is commonly present where the lower member is disrupted. Disseminated sulphides are sporadically distributed throughout subunit 3.

The sulphides commonly occur as small clusters (a few millimetres in diameter) of tiny grains, suggestive of intercumulus magmatic droplets. However recrystallization (under upper greenschist to lower amphibolite facies of metamorphism or during serpentinization) has produced fine grained sulphide-silicate intergrowth textures.

Platinum Group Minerals

All six platinum group elements are accounted for mineralogically by discrete platinum group minerals (PGM). These include in approximate order of abundance sperrylite ($PtAs_2$), kotulskite (PdTe), merenskyite ($PdTe_2$), laurite (RuS_2) hollingworthite (RhAsS), irarsite (IrAsS), keithconnite ($Pd_{3-x}Te$), and mertieite II (Pd_8Sb_3). The most common association of the PGMs is as tiny grains (usually <5p m) in silicate gangue (77% by volume, 91% by frequency) but some grains occur associated with sulphide (22% by volume, 3.6% by frequency) or included within chromite and magnetite (<1% by volume, 2.7% by frequency).

Platinum Group Element Geochemistry

Pt ranges up to 700 ppb and Pd up to 1800 ppb in assays of 66 samples from Ultramafic Series rocks (Table 9). Geometric means for subunits 1 through 3 (Table 10) show that the highest average concentration for total PGEs occurs in subunit 2, where Ni and Cu have the highest grades. Os, Ir and Ru have their highest concentrations in subunit 3 which contains the chromitite layers of the Lower Group.

Chondrite normalized profiles of PGEs are grouped according to their association (Fig. 36). Peridotite-hosted sulphidic PGE mineralization displays a steep positive slope, similar to that of other PGE-bearing magmatic sulphide deposits. PGE-poor chromitite has a negative slope, similar to the negative slopes shown by ophiolitic chromitites in general (Barnes et al., 1985). As in ophiolitic chromitites, this enrichment of Os, Ir and Ru in PGE-poor chromitites of the Bird River sill expresses the tendency for laurite (RuS_2) and iridosmine (Os,Ir) to be the most common platinum group minerals (Talkington et al., 1983, Ohnenstetter et al., 1986). The third group in Figure 36, PGE-bearing chromitite has a shallow positive slope, intermediate between those of the other two groups. This profile appears to result from a combination of the high Os-Ir-Ru values of chromitite and the high Pt-Pd values of mineralized sulphidic peridotite.

Factor analysis of chemical data for 66 samples (Fig. 37) reveals a clear association of PGE and chromite. This is indicated by the fact that significant loadings of Cr, Zn and V (reflecting their co-occurrence in chromite) occur in the same factors as the heavy loadings of PGE (factor 2 in subunit 2, factor 1 in subunit 3). The association of Os, Ir and Ru with chromite is to be expected, as mentioned previously, but the fact that Rh, Pt and Pd are also associated with chromite is surprising. This association is based on analyses of hand samples, and consequently reflects spatial association of the elements at hand sample scale. It is present in both chromitite (subunit 3) and peridotite (subunit 2), even though only accessory amounts of chromite are present in the latter. In both subunits the other significant factor corresponds to base metal sulphide (Ni-Cu-S-Se). There is no suggestion in the factor analysis of any association of PGE with sulphide. This is despite the fact that the PGE-enriched samples were derived from the mineralized unit, which is the only unit that is characteristically sulphide-bearing.

CRYSTAL LAKE GABBRO, ONTARIO

Introduction

The Crystal Lake gabbro is a rift-related Proterozoic layered intrusion emplaced in

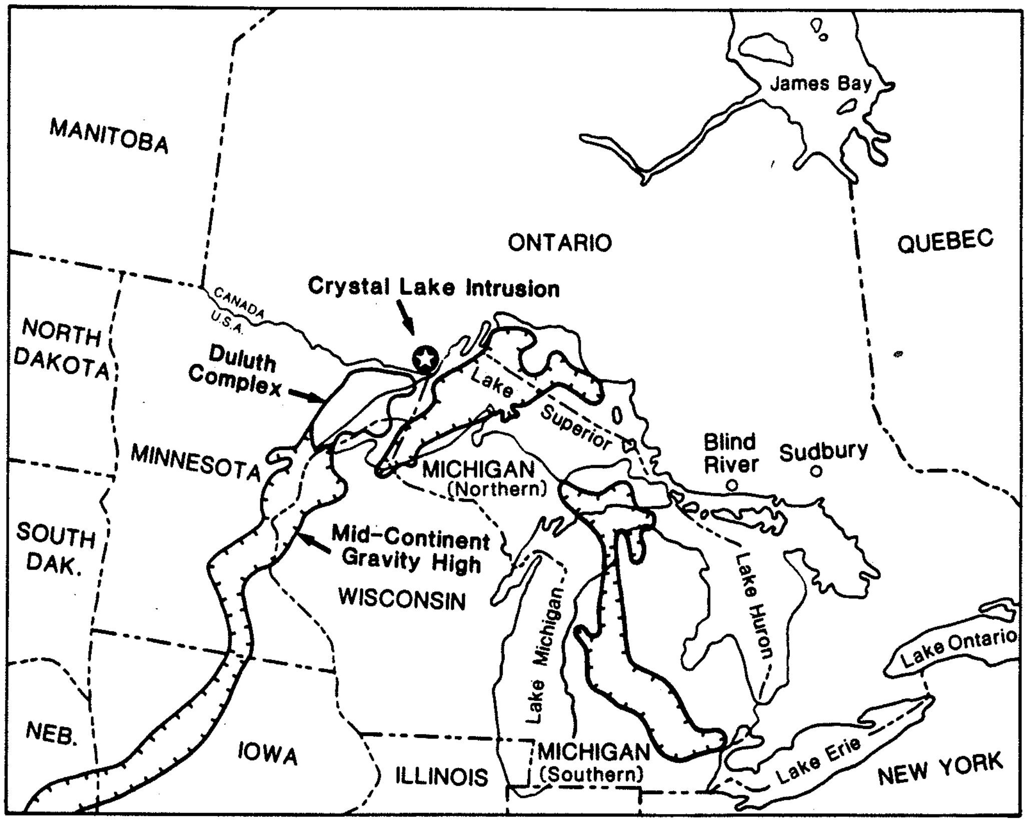


Figure 38. Location of the Crystal Lake intrusion in relation to the Duluth Complex and the Mid-Continent Gravity High (after Klasner et al., 1982).

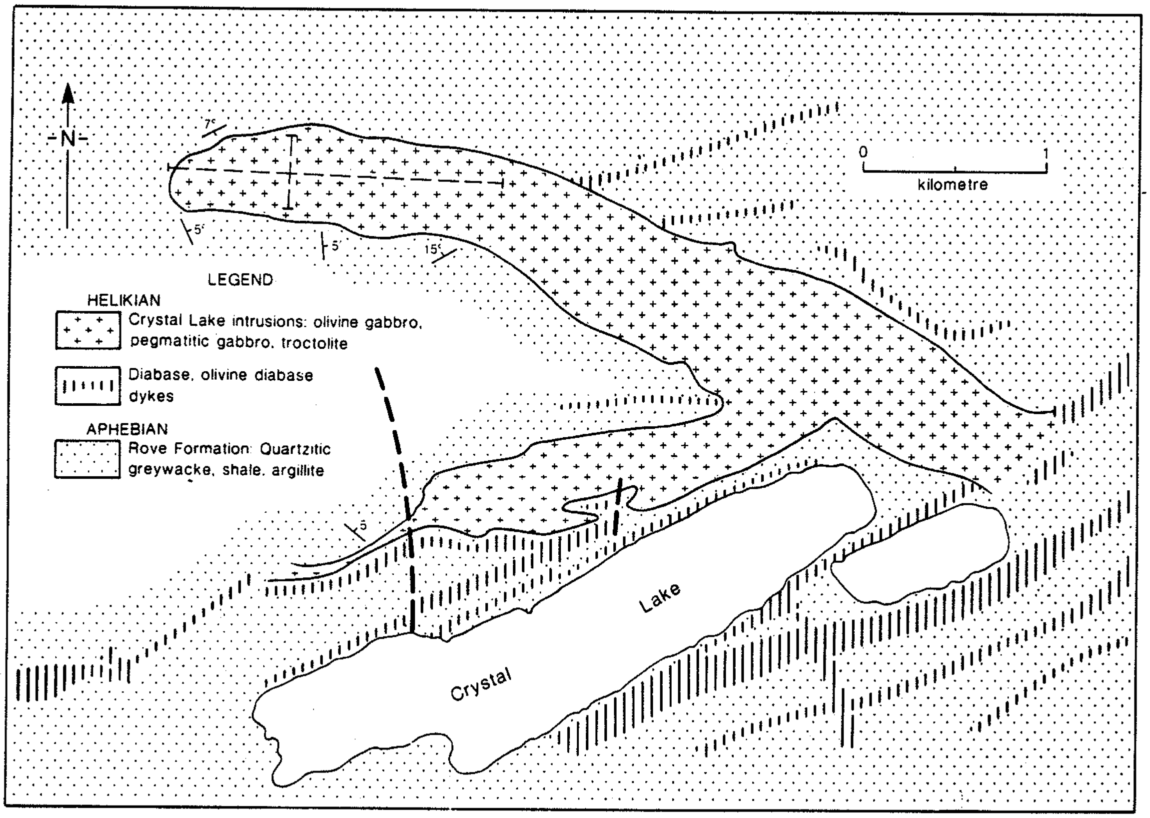
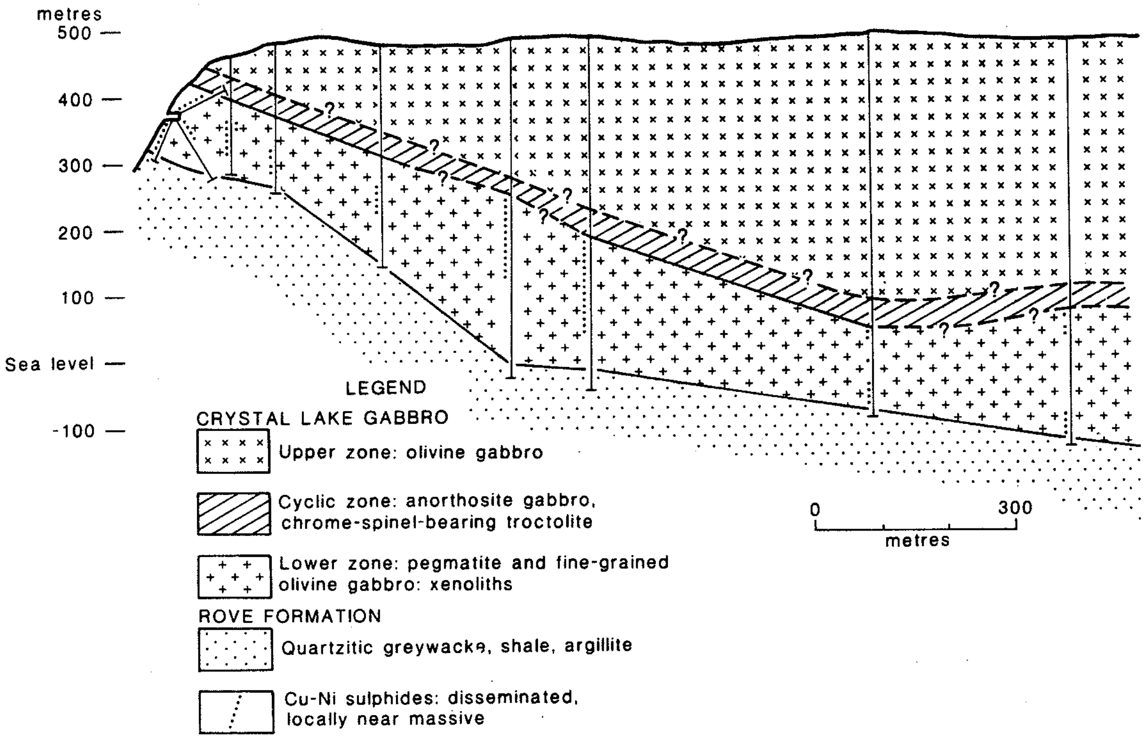


Figure 39. Geological plan of the Crystal Lake intrusion (after Geul, 1970). Location of longitudinal and cross sections through the intrusions are shown by dashed lines.



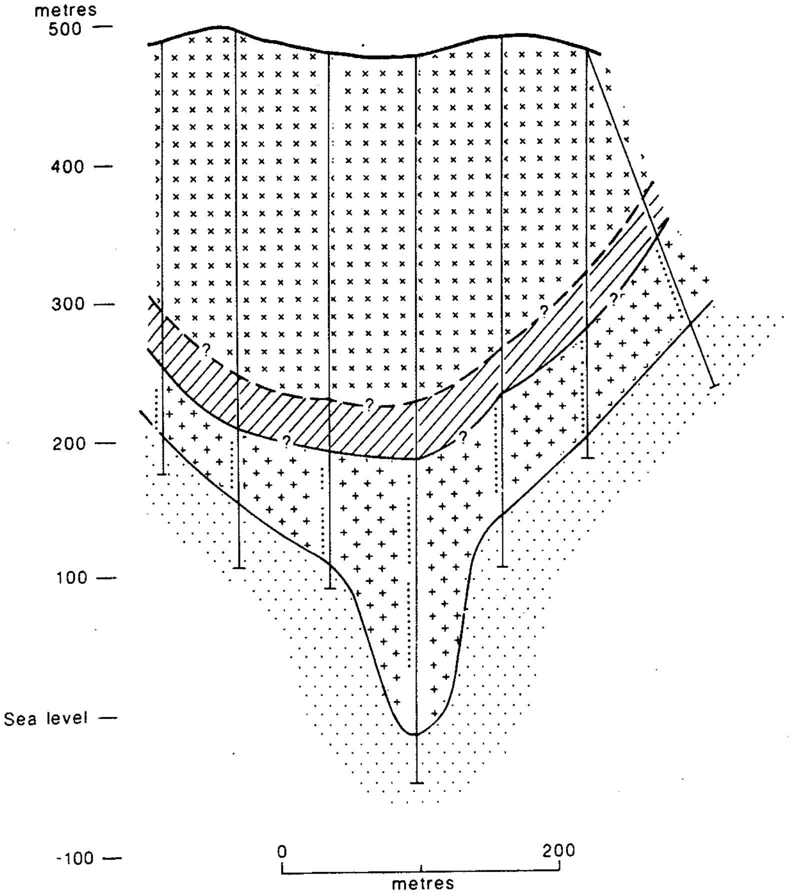


Figure 40. Longitudinal section (looking North) and cross section (looking West) of the western part of the Crystal Lake intrusion (modified after Geul, 1970). Thickness of the cyclical zone is not well known.

Table 11. Average compositions of mineralized, Crystal Lake gabbro.

	Cu-Ni Zone (1)	Chrome-Spinel layers (2)
Ni	0.36%	0.047%
Cu	0.69	0.039
Co	0.016	-
Cr	-	3.1
S	3.2	0.14
Pt	361 ppb	533 ppb
Pd	1420	500
Rh	37	10
Ru	21	40
Ir	4.9	11.5
Os	6	25
Au	166	220
No. of samples	29	9

(1) Calculated from the same analytical data used to compute the sulphur-normalized averages given in Naldrett, 1981; through courtesy of A.J. Naldrett.

(2) Calculated from Cogulu, 1985.

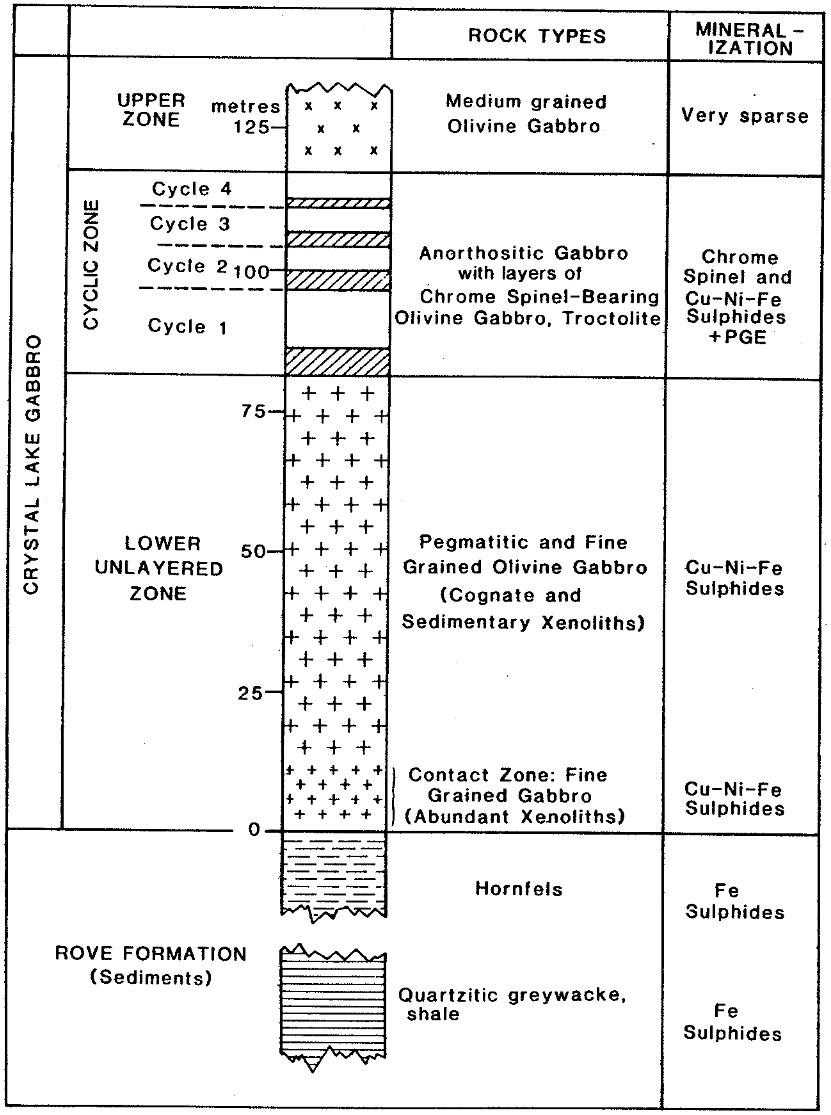


Figure 41. Simplified stratigraphic column of the Crystal Lake intrusion, west end (after Geul, 1970 and Cogulu, personal communication).

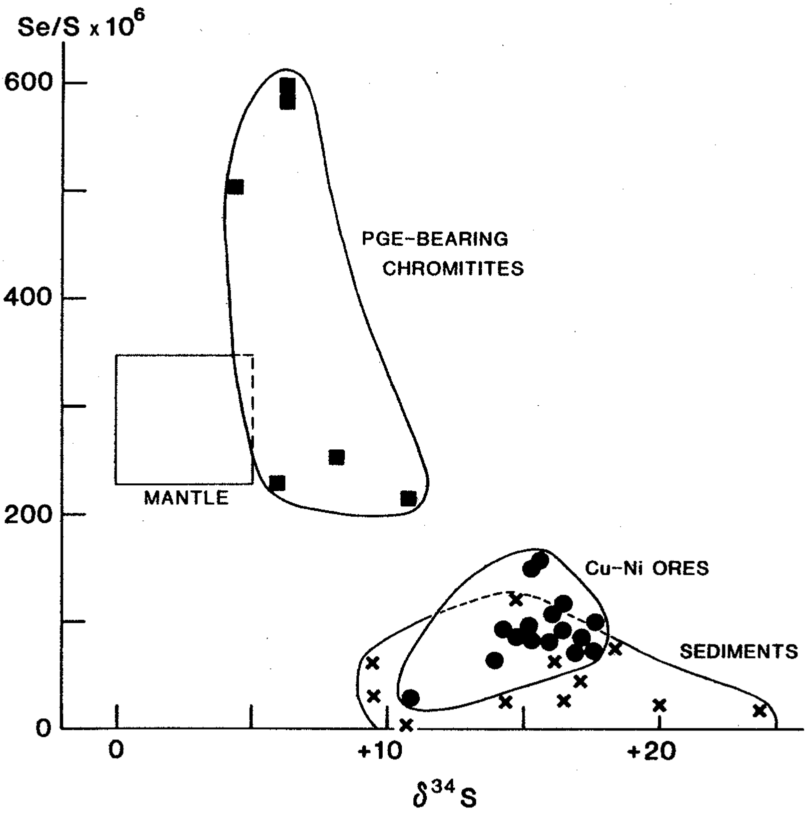


Figure 42. Sulphur isotope and Se/S ratios of sulphides of the Crystal Lake Gabbro and sedimentary hostrocks.

flat-lying Aphebian sediments 40 km south of Thunder Bay (Geul, 1970). It contains an unmined low-grade Cu-Ni deposit, and anomalous PGE values associated with thin chromitite layers.

Geological Setting

The region is underlain in large part by the Rove Formation, part of an intracratonic Aphebian wedge of southward thickening sediments representing detritus shed off the Archean Superior province craton to the north (Sims et al., 1981). These strata were invaded along the Keweenawan Rift Zone by both volcanic and intrusive rocks of Helikian age (1120 - 1100 Ma, Silver and Green 1972). This mainly mafic suite is a major regional feature which forms the Mid-Continent Gravity High (Fig. 38).

The Crystal Lake gabbro together with the similar but much larger Duluth Complex form part of the Helikian intrusive suite. They both comprise olivine gabbro, troctolite and anorthositic gabbro, display some layering; and contain low-grade disseminated copper-nickel sulphides in their basal zones.

The Crystal Lake gabbro outcrops as a Y-shaped body (Fig. 39). Drilling has shown that the northern arm, which contains the Cu-Ni deposit, is canoe-shaped in cross section in its western portion, and plunges gently (15-20°) eastward. This part of the intrusion is distinctly layered (Fig. 40), and consists of four main zones (Geul 1970, and Cogulu 1985, Fig. 41). In descending stratigraphic order, they are the following: (i) upper zone: medium-grained gabbro is massive to weakly layered. The upper portion has been removed by erosion. ii) cyclic zone: four similar cyclical units make up a distinct layered sequence about 40 m thick. Each cycle consists of an upper anorthositic gabbro and a lower chrome-spinel-bearing olivine gabbro and troctolite. (iii) lower unlayered zone: massive gabbro, the main rock type, is characterized by highly variable textures ranging from fine-grained to pegmatitic, and by randomly scattered xenolithic material. The xenoliths appear to include both cognate and sedimentary rock types. (iv) basal contact zone: the variably-textured gabbro grades downward into a fine-grained gabbro with abundant xenoliths near the basal contact. Footwall sediments at the contact are converted to hornfels and cut by anastamosing felsic veins which are probably the product of partial melting (Mainwaring and Watkinson, 1981).

Mineralization

Two main zones of distinctly different mineralization occur within the Crystal Lake intrusion.

(1) Cu-Ni-PGE sulphides form low grade dissemination (36,000,000 tonnes, 0.40% Cu, 0.20% Ni) of interstitial pyrrhotite, chalcopyrite, pentlandite and cubanite through most of the lower and contact zones. These sulphides also occur as massive stringers and patches in the contact zone. Low levels of PGE are associated with the sulphides (Table 11).

(2) Chrome-spinel-rich layers occur at the base of all four cyclical units of the layered zone (Cogulu 1985, Mainwaring and Watkinson 1981). The chrome-spinel is present in amounts up to 20 modal % and occurs as 0.2 to 0.5 mm euhedral or rounded crystals poikilitically included within olivine, plagioclase, clinopyroxene and biotite. The chrome-spinel layers of the uppermost cycle are straight and persistant, whereas those of the underlying cycles are disrupted and irregular. The chrome spinel layers have minor amounts of associated sulphides (pyrrhotite, chalcopyrite, pentlandite, cubanite) and up to 4 g/T PGE (Table 11).

The two types of mineralization have comparable levels of PGE, but the Pt/Pd ratios are quite different and the chrome-spinel type is highly enriched in PGE, relative to the amount of sulphide with which it is associated (Table 11).

Data for sulphur isotopes and Se/S ratios (Fig. 42) clearly indicate that the sulphur in the Cu-Ni zone is largely derived from the footwall sediments, and that this deposit formed by contamination of the magma (Eckstrand and Cogulu, in preparation). Sulphur in the chrome-spinel zone, by contrast, has more mantle-like characteristics, and presumably was uncontaminated by crustal rocks.

The anomalously high values of Pt + Pd in the chrome-spinel layers relative to the amount of sulphide present and the elevated values of Se/S of those sulphides are unusual, and are comparable to those of the Merensky Reef and the JM Reef. Consequently it is considered that the chrome-spinel layers may hold significant economic potential for PGE, especially in areas of higher sulphide content.

RATHBUN LAKE, ONTARIO

A small but very PGE-rich sulphide deposit occurs within the Wanapitei intrusion at Rathbun Lake, about 40 km northeast of Sudbury, Ontario (Dressler, 1982; Finn et al, 1982; Rowell and Edgar, 1986). The intrusion is a ring-shaped body belonging to the 2.2 Ga Nipissing diabase suite, and was emplaced within gently folded graywackes of the Gowganda Formation. It is made up predominantly of medium-grained gabbronorite with minor monzodiorite, granodiorite, quartz diorite and granite. Regional metamorphism is of lower to middle greenschist facies but the magmatic minerals and textures of the intrusion are virtually unaltered.

The sulphide zone is 14 m long by 3 m wide and occurs close to the basal contact of the intrusion but is oriented perpendicular to it. The zone has a 30 to 60 cm wide core of massive sulphide which grades outward through disseminated sulphide to barren gabbronorite. The primary silicate minerals have been altered to the assemblage chlorite-quartz-epidote- sericite-biotite near the mineralization. Chalcopyrite and pyrite account for about 95 % of the opaque assemblage and millerite, violarite and magnetite are the most common accessory minerals. Merenskyite, kotulskite, michenerite and temagamite are the most common PGM (Rowell and Edgar, 1986).

The deposit is extremely high grade: for example, eleven samples tabulated by Rowell and Edgar (1986) averaged 0.24 % Ni, 9.32 % Cu, 9.7 g/t Pt, 20.8 g/t Pd and 3.1 g/t Au. The concentrations of Rh, Ru, Ir and Os are by contrast very low, averaging 13, 17, 5.8 and <9 ppb, respectively.

Rowell and Edgar (1986) conclude that the Rathbun mineralization is hydrothermal in origin, citing as evidence the dominance of Pd bismuthotelluride minerals among the PGM, the extremely high Pd+Pt/Os+Ir+Ru ratio, the altered nature of the silicate assemblage, and the association of PGM with the secondary silicates. However, the sulphide-silicate textures we have observed in the surface exposures are strongly suggestive of a primary magmatic origin of the mineralization.

LAC DES ILES COMPLEX, ONTARIO

Introduction

The Lac des Iles Complex is located approximately 100 km NNW of Thunder Bay, Ontario and contains one of Canada's more promising PGE deposits. The complex is the largest of some 20 known mafic to ultramafic plutons occurring in a 200 km long east-northeast trending zone from Atikokan, to Lake Nipigon. Anomolous levels of PGE have been reported from the Tib Lake and Demars Lake to the northwest and southwest of Lac des Illes respectively (Fig. 43, Sutcliffe, 1986) as well as in the vicinity of Atikokan. This suggests that the entire belt of intrusions has important potential as a PGE metallogenic province.

Geological Setting

The Lac des Iles Complex is a late Archean mafic-ultramafic body that intrudes granitic and gneissic rocks of the Wabigoon greenstone belt (Pye, 1968). Brugmann and Naldrett (1987) have reported a Nd/Sm age of 2738 ± 27 Ma for ultramafic rocks of the Complex. The complex consists of a northern ultramafic part and a southern gabbroic part. The gabbroic portion was divided into the western and eastern gabbros by Dunning (1979). The western gabbro is the larger of the two gabbroic bodies. Orthopyroxene, clinopyroxene and plagioclase are cumulus phases and the body consists of interlayered variable-textured gabbroic (70%), noritic (20%), pyroxenitic (10%) and minor anorthositic rocks. Plagioclase and clinopyroxene are the typical cumulus phases in oxide-rich, sulphide-poor, medium-grained gabbro and leucogabbro. Strong concentric magnetic anomalies distinguish it from the western body which has a weak magnetic expression. The eastern gabbro is also distinctly more evolved than the western gabbro, as demonstrated by lower Mg-numbers and less calcic plagioclase compositions.

Two coalescing intrusive centres were recognized within the ultramafic part of the Complex by Sutcliffe and Sweeney (1985). The northern centre is layered in places and consists of dunite, wehrlite, olivine-clinopyroxenite, clinopyroxenite, and websterite. It is circular in plan with a websterite core and increasingly olivine-rich rocks towards the margin. The southern centre is elliptical in plan with an irregular wehrlite core and websterite margins. It lacks well defined layering.

PGE Mineralization

Exploration by Gunnex Ltd. in 1963-64 led to the discovery of eight zones of PGE-bearing sulphide mineralization which were designated "A" through "H". Further exploration by Boston Bay Mines Ltd. and Texas Gulf Canada Ltd. in 1975-76 led to the delineation of a significant deposit in the "E-Zone" which became known as the "Roby Zone" (Sweeney and Sutcliffe, 1986).

The Roby Zone (Figs. 44 & 45) occurs within the western gabbro adjacent to its contact with the eastern gabbro (Dunning, 1979; Watkinson and Dunning, 1979). Sutcliffe and Sweeney (1985) note that the mineralization is largely confined to a heterogeneous gabbro unit which is from 60 to 300 m thick. This unit is extremely complex with alternating layers of gabbronorite and leucogabbro which resemble the western and eastern gabbros, respectively (Sutcliffe and Sweeney, 1985). The gabbros are coarse grained to pegmatitic, are cut by pegmatitic gabbro dykes, and contain numerous inclusions of gabbronorite, gabbro and amphibolite. Macdonald (1985) described this unit as a gabbro megabreccia.

The mineralization consists of up to 5% disseminated magmatic sulphide blebs in the coarse to pegmatitic gabbros. Macdonald (1985) emphasized the association of mineralization with cross cutting pegmatitic gabbro dykes.

Sweeney and Sutcliffe (1986) report the presence of a pyroxenite unit several metres thick at the eastern gabbro-western gabbro contact which locally discordantly intrudes the eastern gabbro. This pyroxenite contains up to 16 ppm PGE. Macdonald et al., (1987) recognize three categories of mineralization: (a) <1 ppm PGE + Au occurring in leucogabbro, pegmatitic gabbro and gabbro breccia; (b) <15 ppm PGE + Au associated with a websterite-gabbronorite dyke; (c) <35 ppm PGE + Au in gabbro pegmatite dykes.

Pyrrhotite, pentlandite, chalcopyrite and pyrite are the most common sulphide minerals in the deposit. Pyrite, millerite and violarite are common in sheared and altered rocks. Watkinson and Dunning (1979) found that vysotskite is the most abundant PGM. Cabri and Laflamme (1976) confirmed this and also report the presence of kotuluskite, merenskyite, sperrylite, moncheite, isomertiete, stillwaterite, and a unnamed Pd-arsenide in the ore concentrates. Cabri and Laflamme (1976) reported that the pentlandite contains 0.19% Pd in solid solution.

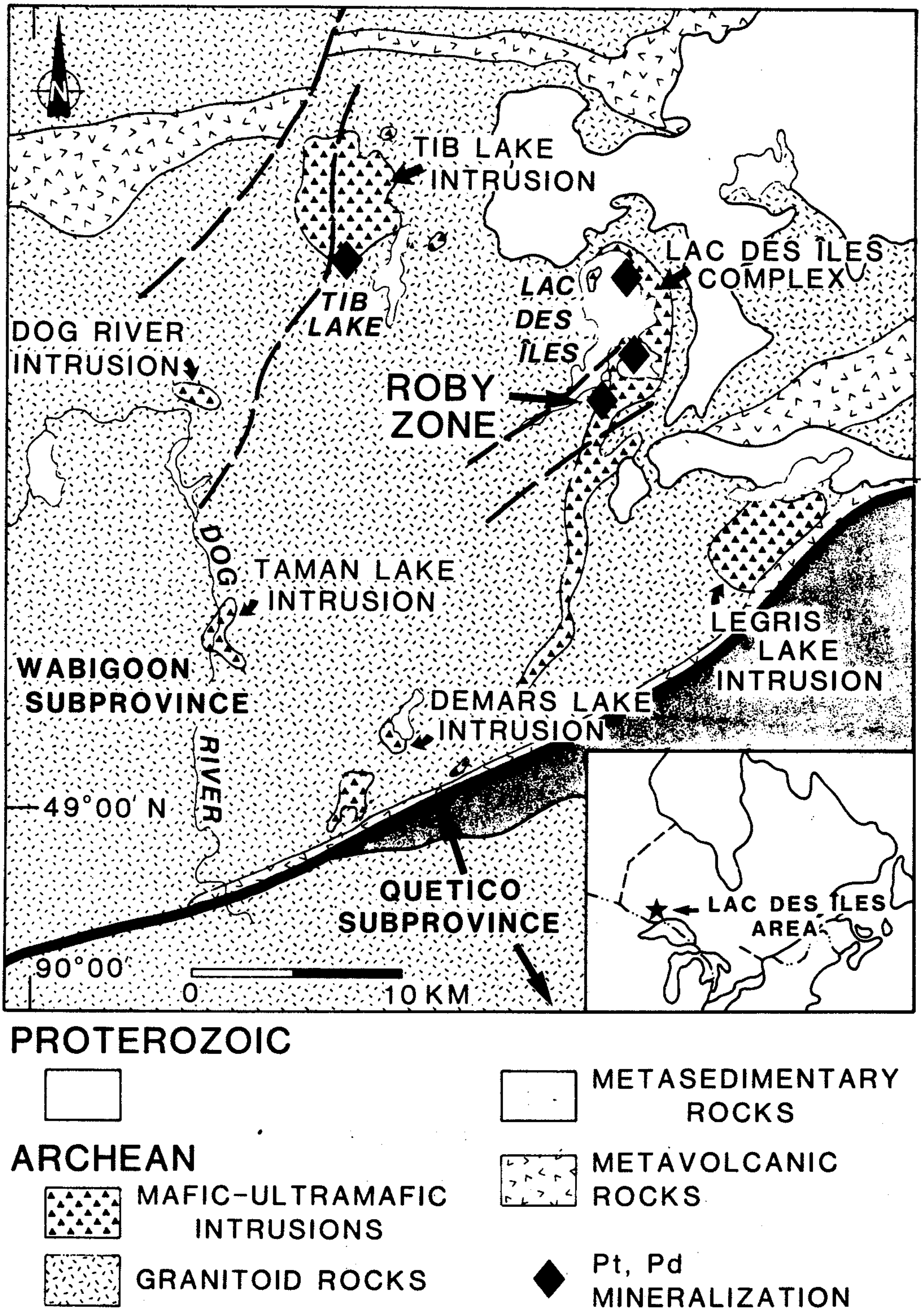


Figure 43. Generalized geological map of the Lac des Iles area (after Sutcliffe, 1986).

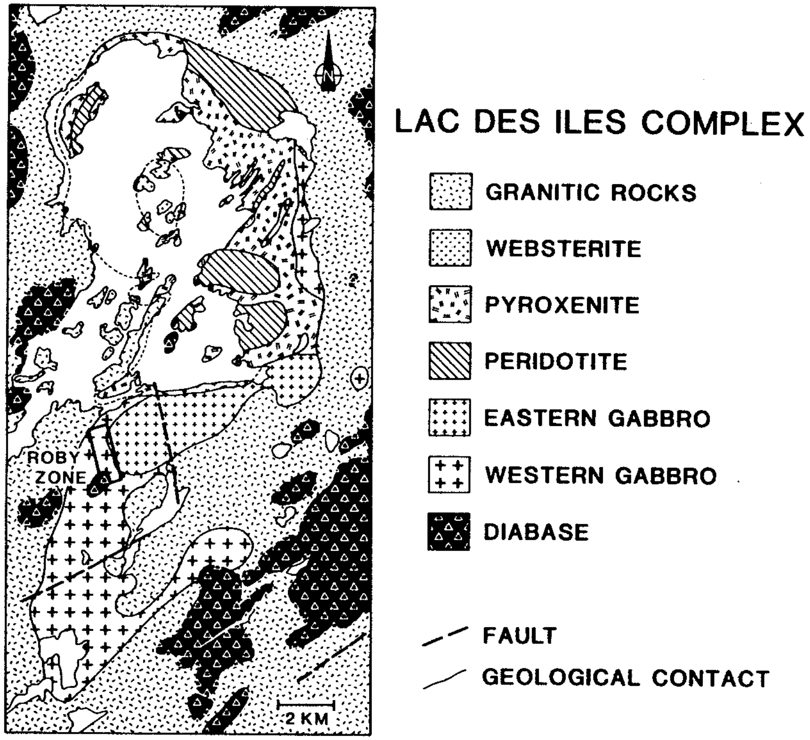


Figure 44. Geology of the Lac des Iles complex (modified from Pye, 1968).

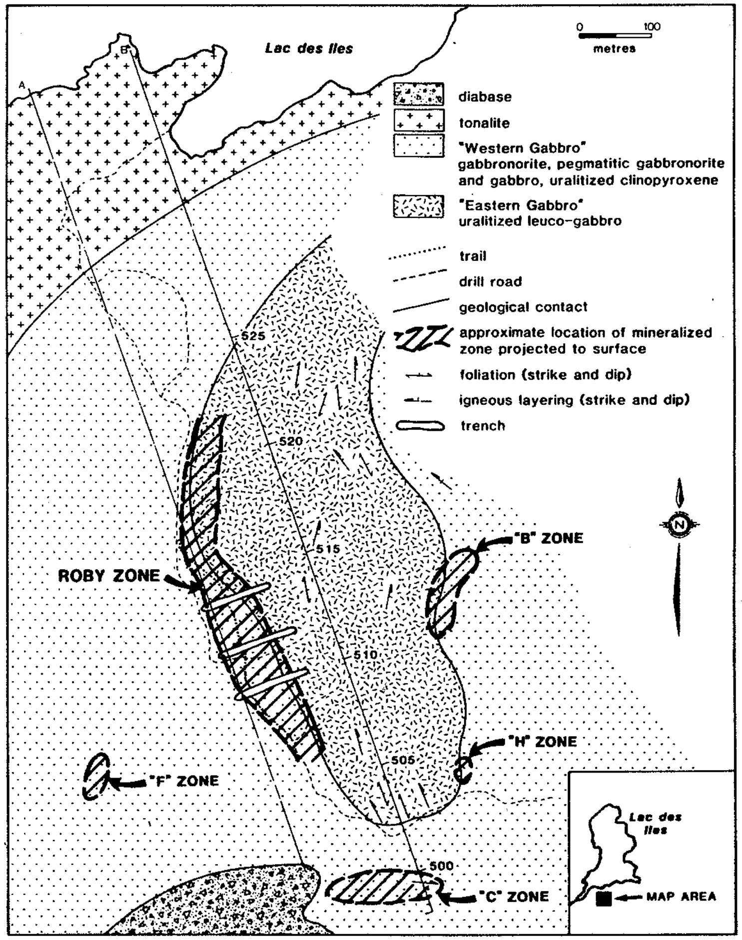


Figure 45. Geology of the Roby Zone (after Sweeney and Sutcliffe, 1986).

Estimated resources at the Roby deposit are 22.5 million tons grading 6.17 g/t PGE with a Pd:Pt ratio of about 7:1. The average grade for the other elements is 0.22% Ni, 0.22% Cu and 0.7 g/t Au (Northern Miner; April 7 and Nov. 10, 1986). Naldrett (1981) analyzed 25 samples of typical ore and obtained an average of 0.172% Ni, 0.128% Cu, 0.32% S, 0.9 ppm Pt, 16 ppm Pd, 0.011 ppm Rh, <0.003 ppm Ru, 0.0004 Ir, <0.0002 ppm Os and 0.06 ppm Au. The Roby Zone has a strike length of 610 m, a width of 30 to 100 m and has been confirmed to a depth of 305 m (Northern Miner, March 16, 1987). The width of this deposit and the limited depth of overburden (1.5 to 3 m) make it most amenable to open pit mining.

Significant levels of PGE have also been reported in magmatic sulphide occurrences in the ultramafic centres of the Lac des Iles Complex (Sutcliffe and Sweeny, 1985; Sutcliffe, 1986). The mineralization is described as being stratiform and associated with gabbronorite and websterite. Maximum concentrations were 870 ppb Pt and 1170 ppb Pd in one occurrence and 350 ppb Pt and 2200 ppb Pd in another. It is noteworthy that these occurrences have higher Pt:Pd ratios than the Roby Zone.

ZONED DUNITE-CLINOPYROXENITE COMPLEXES, U.S.S.R.

Introduction

In the Soviet Union, PGE deposits related to zoned ultramafic rocks of the dunite-clinopyroxenite +/- gabbro association occur in the middle Urals and the Aldan Shield. Primary PGE deposits in these zoned ultramafic bodies were first discovered in 1890 in the Nizhneitagil district of the Ural Mountains and are commonly referred to as Ural-type ultramafic rocks. Similar zoned ultramafic bodies occur along the west coast of North and South America from the Alaska to Colombia and are referred to as the Alaskan-type ultramafic rocks. These bedrock deposits in the Soviet Union, their derived placers and similar placers elsewhere were the worlds' major source of PGE until the extraction of PGE from the Sudbury ores commenced around 1912. Also, due to the unusual coarseness of the PGM in this type of deposit, much of our knowledge of PGM before the advent of the electron microprobe came from these deposits. Razin (1976) proposed that there are two main types of zoned ultramafic associations in the Soviet Union: (a) in eugeosynclinal zones of fold regions [Nizhnetagil or Ural-type] and (b) in the stable platform environment [Inagly or Aldan-type]. The bedrock deposits of each type will be discussed.

Nizhnetagil or Ural-Type Deposits

The Nizhnetagil-type PGE deposits are restricted to concentrically zoned bodies of forsterite dunite-clinopyroxenite +/- gabbro of Middle Devonian age in the eugeosynclinal zone of the eastern slope of the Ural Mountains for approximately 600 km between latitudes 63^{o} and 57^{o} north (Fig. 46). They are believed to have intruded prior to the major folding event in the region (Magak'yan, 1968). The deposits studied in most detail in the Urals are those in the type area, the Nizhnetagil massif. The Nizhnetagil massif and similar intrusions are pipe-like zoned igneous complexes, somewhat elongated in plan, consisting of a forsterite dunite central mass which is partly or entirely surrounded and covered by a zone consisting largely of clinopyroxenite which in turn passes outward and upward into gabbro and diorite. The lengths of the dunite bodies in the Ural or Nizhnetagil-type complexes vary from 1,200 to 10,584 metres and widths from 1,000 to 5,250 metres (O'Neill and Gunning, 1934).

The PGE mineralization is restricted to segregations of chromite in the deeply eroded dunitic central mass. Mertie (1969) records that 600 irregular chromitites have been found within the dunite although many (approximately sixty percent) of these contain little or no PGE. These chromitites occur as pockets, lenses, vein-like and shoot-like bodies, and vary from small pockets several centimetres in diameter to shoot- or vein-like bodies extending for tens of metres along strike, 6 to 7 m in thickness and to depths of 150 m (Fig. 47). The ore bodies generally have a N-S strike and dip steeply to the east. In many cases the ore bodies are intersected by dunite and coarse pyroxenite dykes which suggests formation of the ore bodies prior to complete solidification of the complex.

The ores consist of chromite, uvarovite, chrome chlorites, micas and the PGM. Pt-Fe alloy, mainly isoferroplatinum, is the principal PGM and platiniridium is the next most common (Razin, 1976). Other rare and very rare PGM include osmiridium, iridosmine, cooperite, tulameenite, laurite, tetraferroplatinum and irarsite (Cabri, 1981). The platinum group minerals occur moulded upon the chromite as tiny, brilliant grains, either isolated or in small nest-like concentrations, or lying in the centre of the chromite segregations, or along the contact with the surrounding rock. Minor amounts of Ni and Cu sulphides are occasionally present. The silicate-rich dunite host rock to these chromitite segregations are poor in PGE. In only one case are PGM disseminated in dunite without associated chromitite (Magak'yan, 1968).

The PGE grades for these ores ranged from 10's to 100's of ppm (Magak'yan, 1968). Some of the chromite-PGE mineralization in the Nizhnetagil district contain very rich concentrations of PGE. For example, at the Krutoy Log property a 2 m thick mass of high-grade chromite-platinum ore produced 965 oz. of PGE (Mertie, 1969). In general the bedrock deposits supplied very little PGE relative to the placer deposits, most of the production came from alluvial and eluvial placers. The eluvial placers were not very continuous. However, the alluvial placers commonly extended for several kilometres and in some cases even tens of kilometres. The grain size of the placer PGM are generally in the 0.5 to 18 mm range. The grade of the placers varied from 5 to 20 ppm, and nuggets as large as 11.3 kg have been discovered.

PGE occur in association with titanomagnetite segregations in Uralian zoned complexes of the Kachkanar and Volkovo-types. PGE occur in segregated and uniform

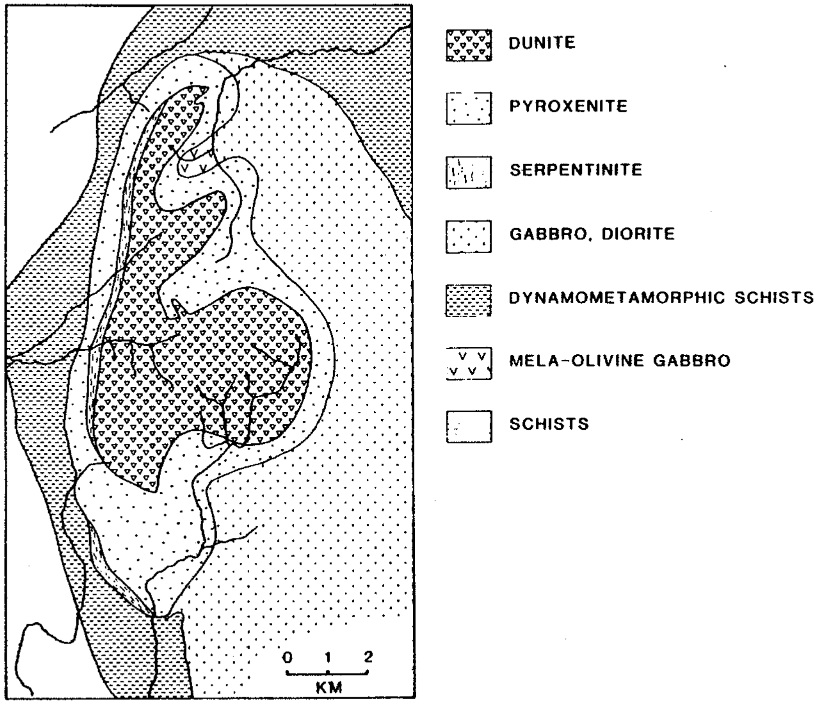


Figure 46. Geological map of the Nizhnetagil ore-bearing region (after O'Neill and Gunning, 1934).

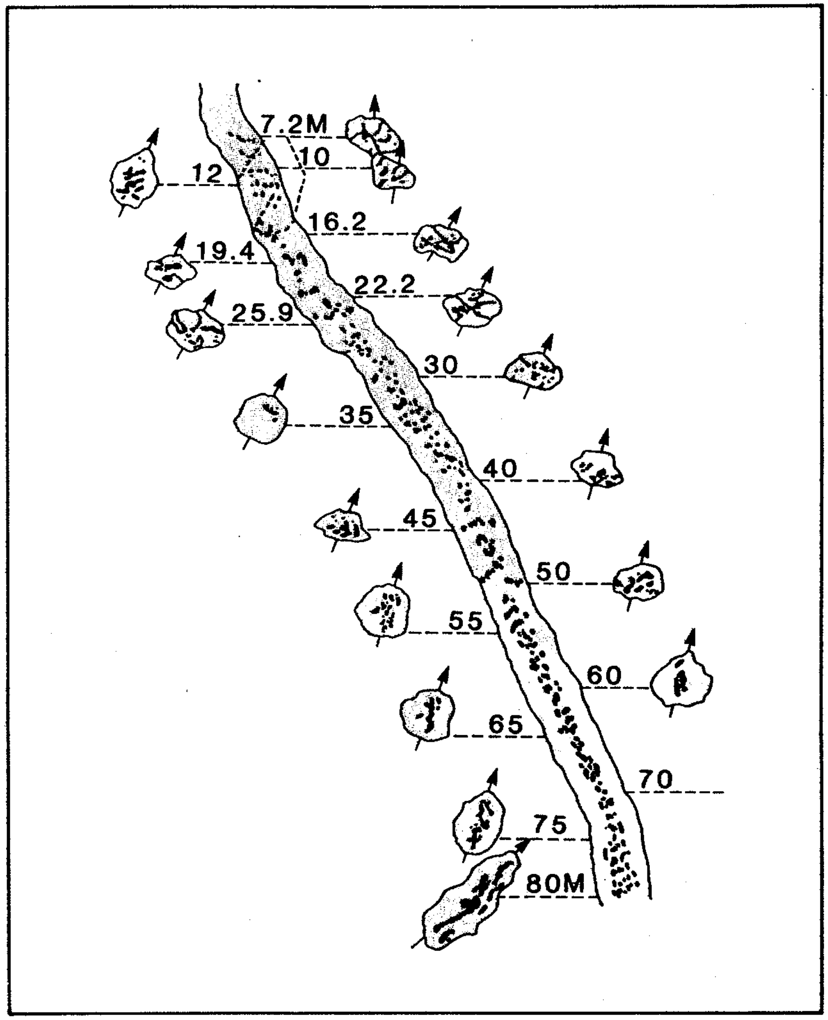


Figure 47. Shoot-like segregations of Pt-bearing chromite in forsteritic dunites of the Nizhnetagil' massif (after Smirnov, 1977).

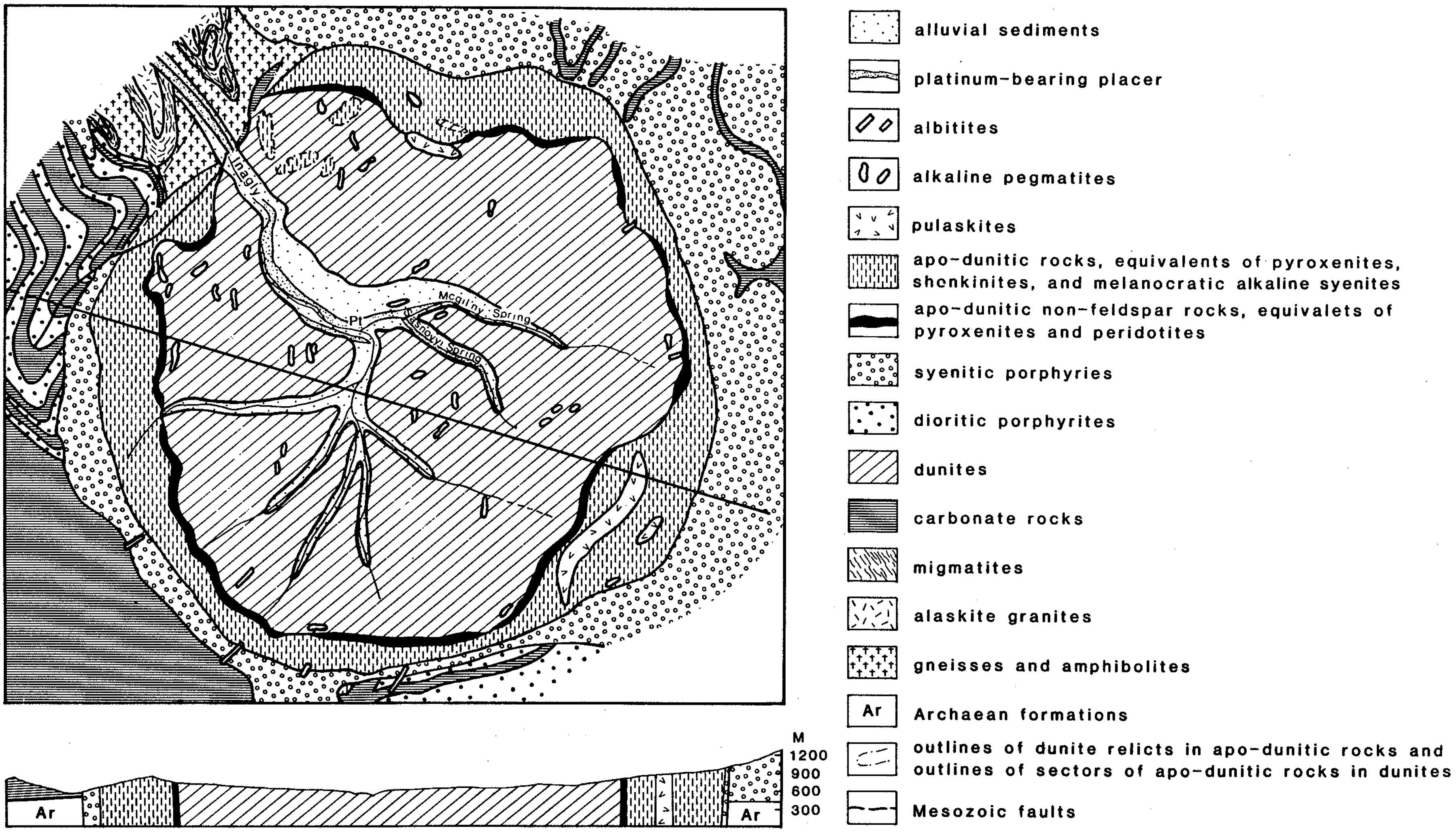


Figure 48. Geological map and section of the Inagly Pt-bearing massif (after Smirnov, 1977).

vanidiferous-titanomagnetite ores in apo-dunitic diallage rocks which are associated with large gabbro-clinopyroxenite massifs similar to those at Kachkanar in the middle Urals. This type of mineralization is best developed in the Gusevogorsk deposit. Unfortunately, the PGE mineralization is distributed extremely unevenly. Pt-Fe alloys predominate, iridosmine, platiniridium, cooperite and native osmium occur much less frequently (Razin and Yurkina, 1971b). Native gold is also found associated with the PGM. In the Volkovo-type, palladium enriched copper sulphide- titanomagnetite ores occur in meso-and melanocratic gabbros associated with the pseudostratified clinopyroxenite- gabbro Barancha massif. The palladium tends to be associated with the chalcopyrite and bornite (Smirnov, 1977).

Inagly or Aldan-type Deposits

The in situ PGE deposits of the Inagly-type are similar to the Nizhnetagil-type deposits with respect to the nature of the mineralization, morphology and dimensions of the chromitite segregations and the rock association. However, this type of deposit occurs in a different tectonic environment.

The Inagly-type PGE-bearing ultramafic and alkaline massifs occur along the periphery of the Aldan Shield and are usually confined to the intersection of deep-seated faults activated during the Alpine epoch. A simplified geological map and cross section of the Inagly massif is shown in Figure 48. The core of this pipe-like complex consists of forsterite dunite and is surrounded by a rim of a younger alkaline and alkaline-ultramafic rocks.

The dunite contain numerous segregations of chromitite enriched in PGE (1 to 40 ppm) which tend to concentrate in the central portion of the dunites (Smirnov, 1977). The number of these platinum-rich chromitite segregations increase with depth, and it has been observed that the most deeply eroded intrusions have the largest number of ore bodies. The chromitite segregations form schlieren, veins and lens-like bodies that vary from centimetres up to a few metres. The chrome spinels are ferrichrome-picotite and ferrichromite in composition. The PGM in the chromitite and dunite are the same as for the Nizhnetagil-type deposits except they have a higher concentration of sulphides and arsenides which Razin (1976) believes reflect the shallower depth (<2 km) of the intrusion.

TULAMEEN COMPLEX, BRITISH COLUMBIA

Introduction

The Tulameen Complex is located near Princeton in southern British Columbia, about 200 km east of Vancouver. The Tulameen River which cuts the Complex is well known for gold and platinum placers discovered in 1860. Platinum was recovered from the placers intermittently between 1885 and 1936 with total production estimated as 20,000 oz (Rublee, 1986). The likely source of the placers is the Tulameen Complex itself which is currently being explored for in situ PGE mineralization.

The Tulameen Complex is one of the relatively few Canadian examples of the Alaskan-type zoned intrusion. Others occur in central B.C. (e.g., Polaris, Turnagain) and Yukon. Intrusions of this type are more common in the Alaskan panhandle, the Urals, Columbia and Venezuela. They are characteristically circular or elliptical in plan, crudely zoned, and composed of dunite, peridotite, clinopyroxenite, hornblendite and gabbro. Plagioclase and orthopyroxene are rare in the ultramafic rocks.

Geological Setting

The Tulameen Complex intrudes Upper Triussic metasedimentary and metavolcanic rocks of the Nicola Group, and is unconformably overlain along part of its eastern margin by basalts of the Tertiary Princeton Group (Findlay, 1969). A Middle Jurassic age is indicated by the 174 ± 4 Ma K-Ar age of hornblende (Roddick, 1970) and 186 Ma age of biotite (Leech et al., 1963).

The ultramafic rocks of the complex form an elongate body that dips steeply to the west and is bordered and partly overlain by gabbroic rocks. The ultramafic and gabbroic rocks are present in about equal amounts, with the gabbroic rocks restricted to the eastern and southeastern parts of the complex (Fig. 49).

Dunite, olivine clinopyroxenite and hornblende clinopyroxenite are the principal ultramafic rock types. Subordinate amounts of peridotite, clinopyroxenite, hornblende-olivine clinopyroxenite and hornblendite are present but generally do not constitute mappable units. The ultramafic rocks display the characteristic zonal pattern in the northern part of the complex, consisting of a dunite core surrounded by shells of olivine clinopyroxenite and hornblende clinopyroxenite. Gabbroic rock types are represented by syenogabbros and syenodiorites with the former being most abundant. The distribution of the gabbroic rock types suggests that these rocks probably represent an original capping to the ultramafic mass.

Disseminated iron-rich chromite generally occurs in the dunite and olivine clinopyroxenite in amounts of 1 to 10%, and small (<0.5 m) pods, lenses, veins and schlieren of chromitite are scattered throughout the dunite (Findlay, 1969). Magnetite is the spinel phase in the clinopyroxenites and hornblende clinopyroxenites where it usually constitutes 10-20% of the rock. However, near the summit of Lodestone Mountain and on Tanglewood Hill, magnetite concentrations of greater than 50% have been observed (Eastwood, 1959). Both magmatic and hydrothermal sulphide minerals occur in the complex but these are rarely abundant (St. Louis et al., 1986).

PGE Distribution

Although no economic PGE occurrences have yet been discovered in the Tulameen, the similarity of the geology to zoned ultramafic complexes in the Urals (see above) and the placer deposits in the Tulameen River suggests that this

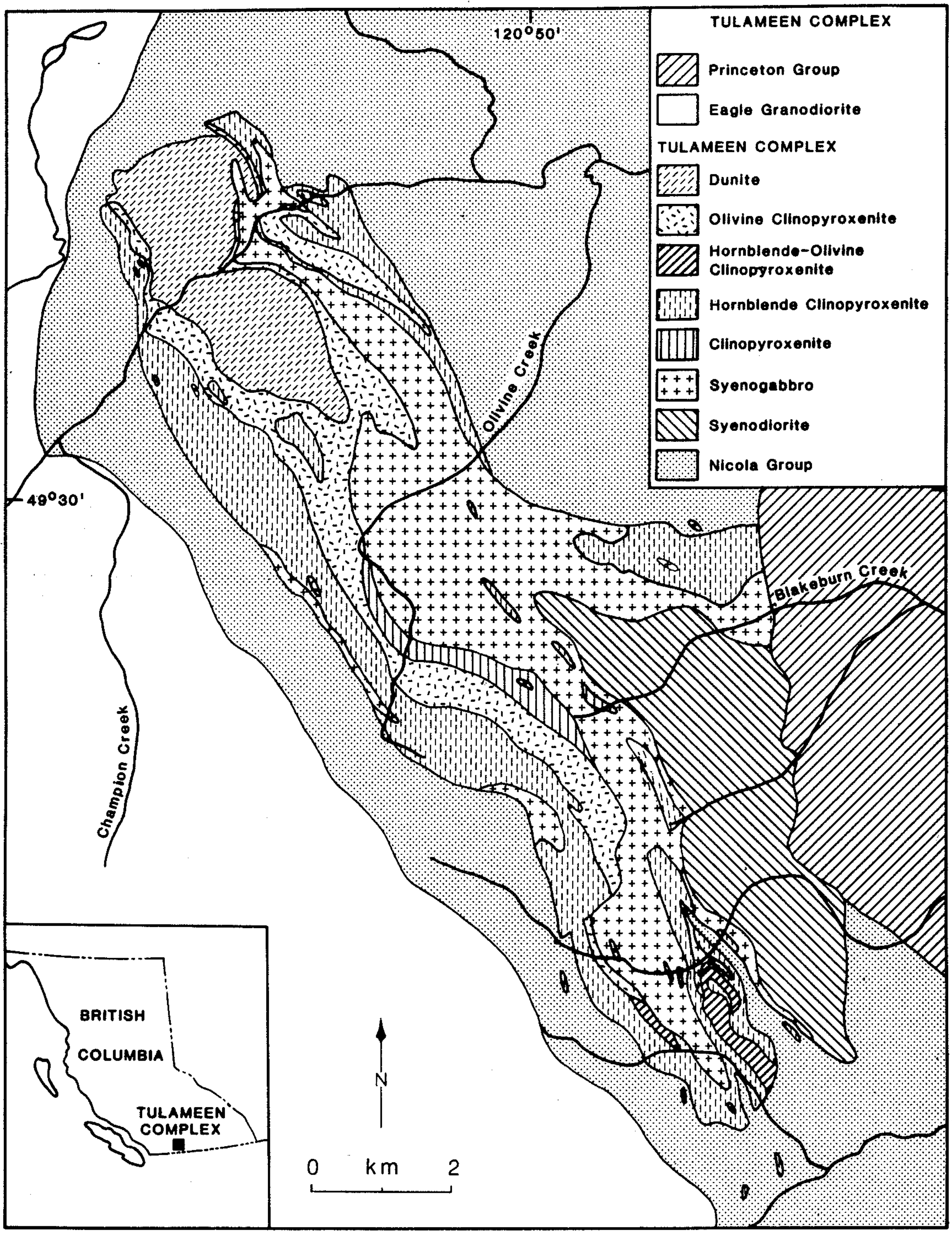


Figure 49. Local geology of the Tulameen Complex (after Rice, 1947 and Findlay, 1963 and 1969).

Table 12: Mean PGE and Au Content of various Rock Types of the Tulameen Complex (after St. Louis, et al., 1986)

Lithology	Pt	Ir	Au	Os	Pd	Rh
	ppb at 95% confidence limits					
Dunite and peridotite	48 ± 12 (17)	0.5 ± 0.1 (21)	0.29 ± 0.05 (19)	BLQ	BLQ	1.2 ± 0.2 (21)
Serpentinite and serpentinite-dunite	180 ± 60 (19)	2.1 ± 0.6 (21)	4.1 ± 3.4 (20)	2.7 ± 0.1 (2)	BLQ	1.9 ± 0.5 (20)
Dunite, peridotite, serpentinite, and serpentinite-dunite	110 ± 30 (37)	1.2 ± 0.3 (42)	1.9 ± 1.5 (39)	2.7 ± 0.1 (2)	BLQ	1.5 ± 0.3 (41)
Olivine clinopyroxenite and clinopyroxenite	30 ± 10 (5)	2.7 ± 2.3 (6)	0.4 ± 0.2 (8)	BLQ	BLQ	0.8 ± 0.3 (8)
Hornblende clinopyroxenite and hornblendite	50 ± 20 (4)	0.10 ± 0.01 (2)	3.4 ± 2.9 (4)	BLQ	140 ± 80 (4)	0.2 ± 0.1 (3)
Magnetite rich	40 ± 10 (7)	0.4 ± 0.1 (4)	0.5 ± 0.3 (7)	2.9 ± 0.9 (5)	40 ± 20 (1)	0.5 ± 0.2 (5)
Syenogabbro and syenodiorite	20 ± 10 (2)	0.10 ± 0.01 (1)	40 ± 40 (6)	BLQ	25 ± 15 (2)	0.2 ± 0.1 (1)
Sulphide rich	50 ± 20 (5)	0.13 ± 0.03 (3)	30 ± 30 (8)	1.8 ± 1.0 (1)	120 ± 60 (5)	0.2 ± 0.1 (4)
Chromite rich	3,510 ± 2,220 (12)	100 ± 40 (14)	8.2 ± 5.4 (14)	40 ± 20 (6)	BLQ	40 ± 20 (14)
Average[1]	12 ± 3	0.4 ± 0.1	1.5 ± 1.2	0.5 ± 0.1	30 ± 10	0.4 ± 0.1
Average[2]	80 ± 20	1.3 ± 0.4	7.8 ± 6.2	2.7 ± 0.6	100 ± 50	1.2 ± 0.2

Number of samples in each case is given in parentheses; BLQ below limit of quantification

[1] Weighted on the volume percentages of the lithologies, with the standard error of the mean

[2] Arithmetic mean with standard error of the mean

complex is worthy of exploration.

Findlay (1963) reported Pt analyses for 100 representative rock samples and 26 chromite and magnetite samples. The highest values were in chromite concentrates which typically contained 1 to 5 m/t and ranged as high as 7.34 m/t. The massive magnetites contained between 0.12 and 0.47 m/t.

St. Louis et al. (1986) analysed more than 80 samples for Pt, Pd, Rh, Ir, Os and Au with the results summarized in Table 12. They confirmed the high concentrations of Pt (avg. 3410 ppb) as well as Ir (avg 100 ppb) in chromitites. Pd, on the other hand, was not detected in either the chromite-rich rocks or the olivine-rich ultramafic rocks but is most abundant in hornblende clinopyroxenite (avg. 140 ppb). It is significant that the serpentinized dunites and peridotites are enriched in PGE and Au relative to their unserpentinized equivalents. This may indicate secondary enrichment of PGE during serpentinization.

PGM have only been found in the massive chromitites from dunites. With the exception of irarsite (St. Louis et al., 1986) all the PGM identified to date are Pt species. These include tulameenite, Pt-Fe alloys, stumpflite, geversite, genkinite, sperrylite, Pt, and irarasite of which Pt-Fe alloys, sperrylite and irarsite are the most abundant. PGM occur in two distinct modes in the chromities: as euhedral to subhedral inclusions in the chromite grains, and as anhedral grains interstitial to chromite. The most common sulphides associated with the PGM are pentlandite, violarite and occasionally bravoite. Most of the sulphides occur interstitial to the chromite and, more rarely, as inclusions in chromite.

Noril'sk - Talnakh, U.S.S.R.

Introduction

Copper-nickel sulphide mineralization was discovered in 1920 at the site of what is now known as the Noril'sk I deposit. Since then, the Noril'sk II, Gora Chernaya, Talnakha, Oktyabr'sk, and Imangda deposits and a large number of occurrences have been discovered. Recovery of PGE as a by-product of Cu-Ni production has made the Noril'sk - Talnakh camp the most important source of PGE in the Soviet Union and second only to the Bushveld Complex in terms of world production and reserves. The Pd/Pt ratio in the Noril'sk ores is 3:1 making that district the world's most important source of palladium.

The discussion which follows is based largely on translations of the Russian literature wherein the terminology differs in certain respects from western usage. In numerous instances, the meaning of the translation is ambiguous and we have therefore retained the original transliteration.

Geological Setting

Noril'sk is located on the northwest margin of the Siberian Platform which is separated from the Taimyr craton to the north by the Khatanga Trough and from the East European - Urals block to the west by the Yenesei Trough (Fig. 50). All three cratonic blocks have been stable since the Paleozoic. The Noril'sk - Talnakh region comprises several tectonic domains (Fig. 51) of which the Noril'sk and Kharaelakh troughs are of particular interest because they contain the major Cu-Ni-PGE ore deposits.

The most significant structural elements in the region are the NNE to NE trending faults of late Permian and Triassic age which control the location of the ore-bearing mafic intrusions. The Noril'sk-Kharaelakh fault is not only the locus of the major deposits at Noril'sk and Talnakh but apparently also of the recently described North Kharaelakh ore field some 375 km to the north (Naldrett, 1981).

Approximately 4500 m of middle Cambrian to lower Carboniferous marine sediments including limestones, marls, dolomites, limey slates and evaporites constitute the lower part of the supracrustal sequence in the region. During the middle Carboniferous, accumulation of lagoonal and continental deposits of the Tunguska series attained a maximum thickness of 450 m in the western part of the district. These consist of arenaceous to argillaceous coaly shales, coal seams, sandstones, arkoses, thin conglomerate layers and rare limestone lenses (Smirnov, 1966). Resting unconformably on the Tunguska series are approximately 1500 m of flood basaltic rocks which cover an extensive area of the Siberian Platform and are known as the "Siberian traps".

Four cycles of trap volcanism were recognized by Godlevsky (1959). The earliest is of Permian age and consists of both flows and sills of subalkaline titanaugite basalt. This was followed by three cycles of Triassic volcanism. The earliest consisted of andesite-basalt followed by picritic basalts and doleritic sills. The next cycle includes basaltic flows and the differentiated gabbro-dolerite intrusions which host the Cu-Ni-PGE sulphide ores. The final cycle is made up of basalts and gabbro-dolerite dykes. The trap volcanism accompanied intense tectonic activity which produced the major folds and faults in the supracrustal sequence. Smirnov (1966) believed that the intrusions formed near the end stages of volcanism when magmatic feeders became plugged by crystallization.

The intrusive traps of the Noril'sk-Talnakh region occur as i) sheet-like bodies ranging from thin sills to huge masses of several hundred cubic kilometres, ii) thin dykes less than a few tens of metres in width, iii) chonoliths (intrusions of undetermined shape). The majority of the intrusions are undifferentiated and barren. It is only the differentiated intrusions of the second cycle of Triassic volcanism that are ore-bearing: these account for only 1-2 percent of the intrusive population.

Most of the mineralized intrusions are chonoliths. A characteristic that distinguishes them from the sills of the region, apart from their irregular shape, is that they do not push apart their wall rocks, but tend to completely assimilate them. The layered intrusions in the

Noril'sk area are localized in the Noril'sk-Kharaelakha fault system, the most prominent structural element in the region (Figure 52). Isolated intrusions outside the main fault are controlled by a system of NE trending "feather faults". Groups of chonoliths appear to spread out radially from common intrusive centres. Three such centres occur in the Noril'sk ore field. The Noril'sk I, Noril'sk II and Chernaya Gora bodies are related to one centre, the north intrusion of Noril'sk II and the TES intrusion spread out from a second, and the Gorostroevskaya, Gorozubovskaya and Mt. Rudnaya intrusions emanate from a third centre.

The varied nature of the differentiated intrusions are illustrated in Figure 53. They are typically less than 250 m thick, less than 1.5 km wide, and up to 12 km long. In cross section they are lenticular, trough-shaped or, less often, tabular. Their shape may vary substantially along strike and down dip, depending upon the structure of the country rocks. An important feature of the differentiated intrusions is the extensive development of metamorphic and metasomatic rocks in wide aureoles at the upper and lower contacts.

The ore-bearing differentiated intrusions are characterized by a regular sequence of lithological units which are, from the top downwards, as follows:

1. Upper contact gabbro-dolerites occur at the contact with the overlying terrigenous sediments and basalts. They are compact and massive with a typical ophitic to poikilophitic texture. Olivine composition is Fo_{65}. This unit may be absent where hybrid rocks or eruptive breccias occur. At Noril'sk I, for example, a breccia consisting of angular fragments of clay and graphitized coaly shales set in a pegmatitic diabase matrix occurs in places and attains a thickness of up to 20 m.

2. Upper taxitic gabbro-dolerites, quartz-bearing gabbro dolerites, gabbro-diorites and diorites The upper taxitic gabbro-dolerites, which are best developed in the Noril'sk I intrusion, are typically coarse-grained and pegmatitic and extensively altered. It commonly occurs as lenses or veins from a few to 20 m thick which, in some cases, truncate or dislodge the underlying pyroxene gabbro-diorite and olivine gabbro-dolerite. Characteristic features of the quartz-bearing gabbro-dolerites, which are best developed in the Talnakh intrusion, are the coarse grain size and the presence graphic intergrowths of quartz and K-feldspar at the interstices of plagioclase grains. The gabbro-diorites are composed of bluish prehnitized labradorite and fresh pyroxene, with olivine occurring sporadically in the lower parts of the unit. It forms coarse-grained to pegmatoidal veins and apophyses which cut the underlying medium-grained differentiates. The gabbro-diorites in the Noril'sk I intrusion range from 0 to 140 m in thickness (Smirnov, 1966).

3. Olivine-free and olivine-bearing gabbro-dolerites The medium-grained equigranular fabric of the olivine-free rocks distinguishes this unit from the overlying one. Also, the graphic intergrowth of quartz and K-feldspar disappears with the appearance of olivine towards the base of the unit. Olivine is present here in amounts of 5-7 percent with compositions in the range of Fo_{66-73}.

4. Olivine gabbro-dolerites constitute the core of the differentiated ore-bearing intrusions and makes up 20 to 30 percent of the stratigraphic section. The upper portion contains 10 to 15 percent olivine whereas the lower part contains 15 to 20 percent. Olivine compositions are in the range of Fo_{66-70}. Also, the lower part is enriched in biotite and is characterized by chromite and sparsely disseminated sulphides. The contact with the underlying picrite gabbro dolerite is sharp and recognizable in outcrop.

5. Picrite gabbro-dolerites host much of the sulphide ore and include true picrite, picrite gabbro-dolerite, feldspathic peridotite, feldspathic dunite and occasionally troctolite. These are the finest-grained rocks in the intrusions with the exception of the chilled marginal facies. The unit varies from a few to 40 m in thickness. It is generally thickest at the centre of the intrusions and thins out towards the margins. Irregular lenses of peridotite and dunite from a few centimetres to a few metres thick are interlayered with the picrites. Chromite occurs as an accessory mineral in the ultramafic differentiates in amounts up to 1.5 percent and as agglomerations with up to 25-30 percent. The central parts of these chromite agglomerations are characterized by globular or spherulitic growths of prehnite, biotite, anhydrite, carbonate, zeolites, chlorite, talc and occasionally sulphide intergrowths. Olivine composition is Fo_{82} at the centre of the unit and becomes more iron-rich towards the top (Fo_{76}) and the base (Fo_{73}).

6. Taxitic gabbro-dolerites are characterized by textural irregularity with pegmatoidal patches of plagioclase and pyroxene set in a fine to medium grained groundmass. In contrast to the overlying unit, plagioclase and clinopyroxene predominate over olivine and chromite is absent. Olivine is unevenly distributed, constituting from 0 to 30 percent of the rock. Its composition is also extremely variable (Fo_{55-75}). Sulphide is invariably present.

7. Lower contact gabbro-dolerites are texturally and mineralogically very similar to the upper contact gabbro-dolerites except that olivine is somewhat more abundant but less magnesian (Fo_{56}). The unit generally is 2-3 m thick. However, when in contact with sulphate and carbonate rocks, as at Talnakh, these rocks occur as a multitude of subparallel apophyses.

Cu-Ni-PGE Mineralization

The bulk of current production comes from the Talnakh deposits which contain significantly higher grades and reserves than the Noril'sk deposits to the south. However, most aspects of the geology and mineralization of the two groups of deposits are similar. Most ores occur in the lower parts of their host intrusions with the so-called "exo"- and "endocontact" mineralization being the richest. Only a few bodies of

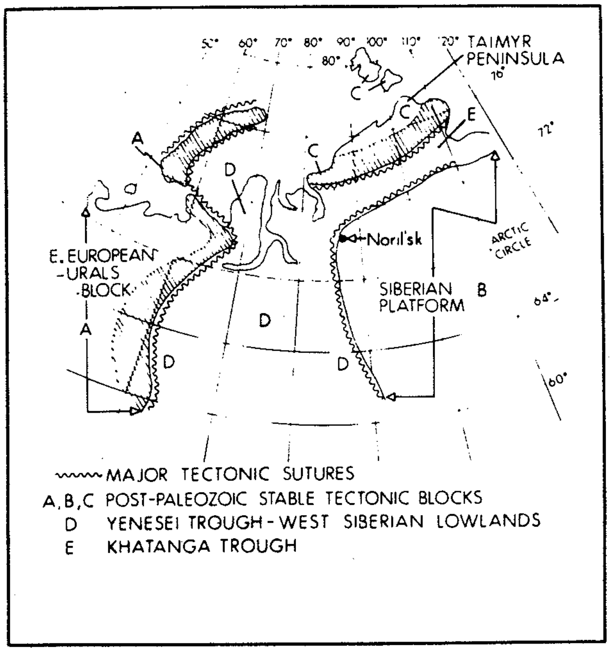
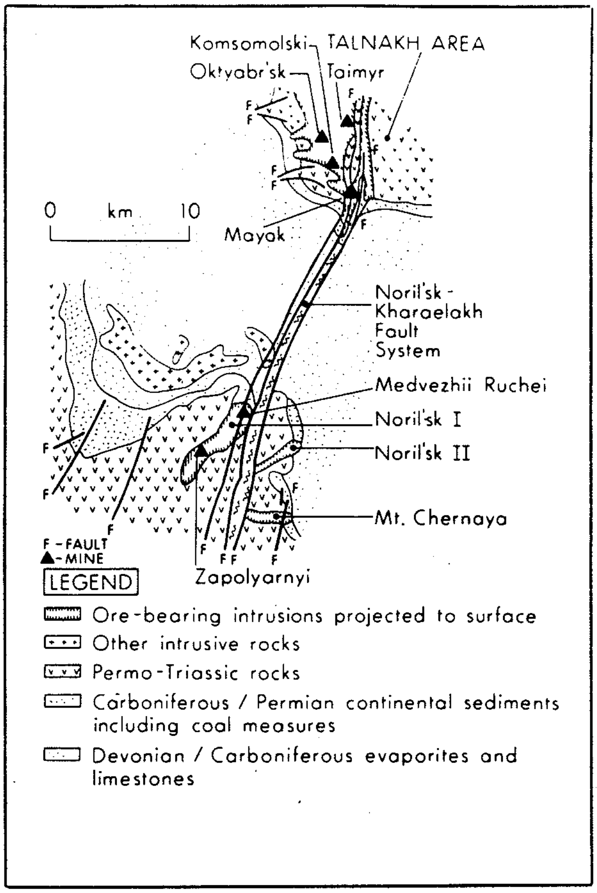


Figure 50. The tectonic setting of the Noril'sk-Talnakh camp (modified after Naldrett and Macdonald, 1980).

Figure 52. Geology of the Noril'sk-Talnakh area (after Naldrett and Macdonald, 1980).



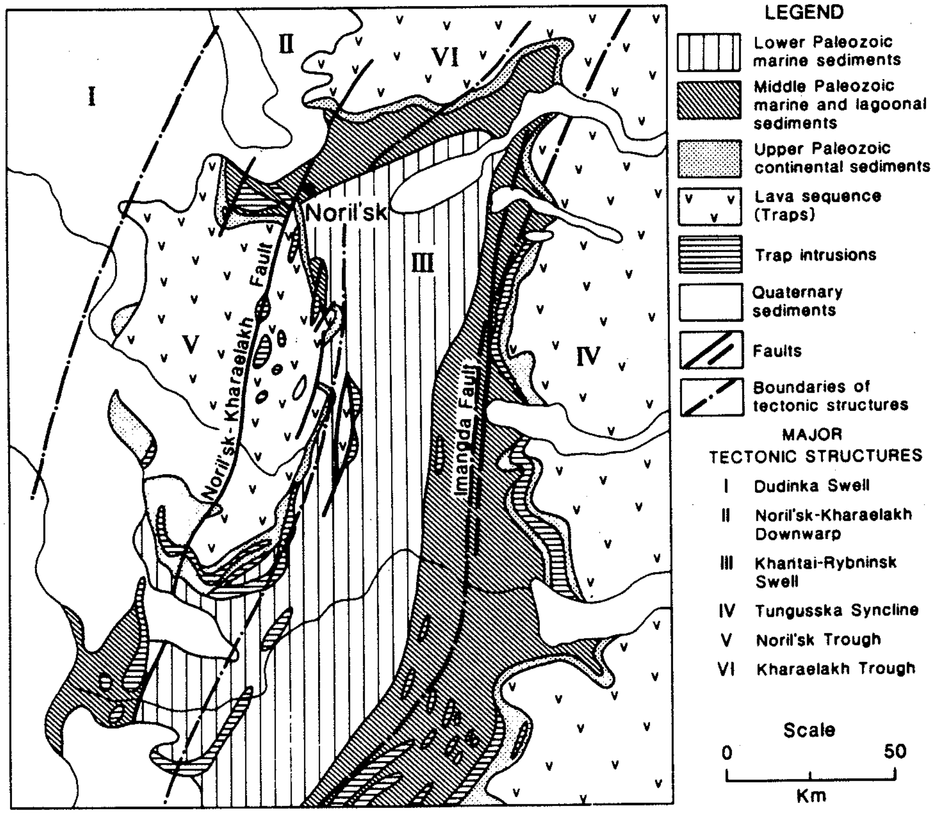


Figure 51. Geology of the Noril'sk region (after Smirnov, 1977).

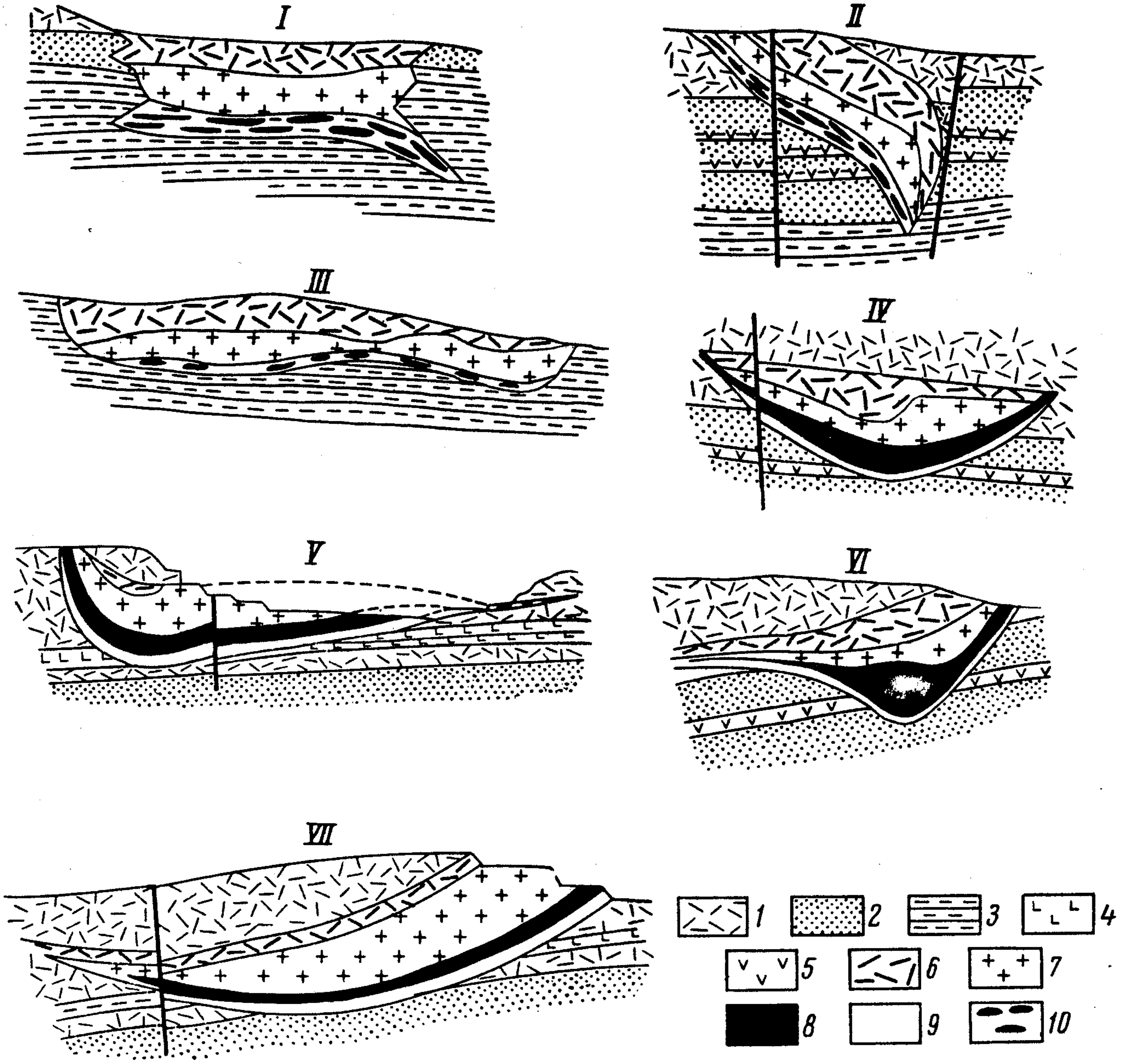


Figure 53. Schematic sections of the differentiated intrusions in the Noril'sk area (after Smirnov, 1966). Lithologies: (1) volcanic series; (2) Tunguska series; (3) Devonian deposits; (4) labradorite porphyry; (5) titano-augite-dolerite; (6) olivine-free differentiates; (7) olivine-gabbro-dolerite; (8) picrite-gabbro-dolerite; (9) taxitic-gabbro dolerite; (10) alternating picrite and taxitic gabbro-dolerites. Intrusions: I - Mt. Chernaya; II - Noril'sk; III - Mt. Zub; IV - south section of Noril'sk I; V and VI - western and eastern branches of the Noril'sk I intrusion; VII - north depression in the floor of Noril'sk I.

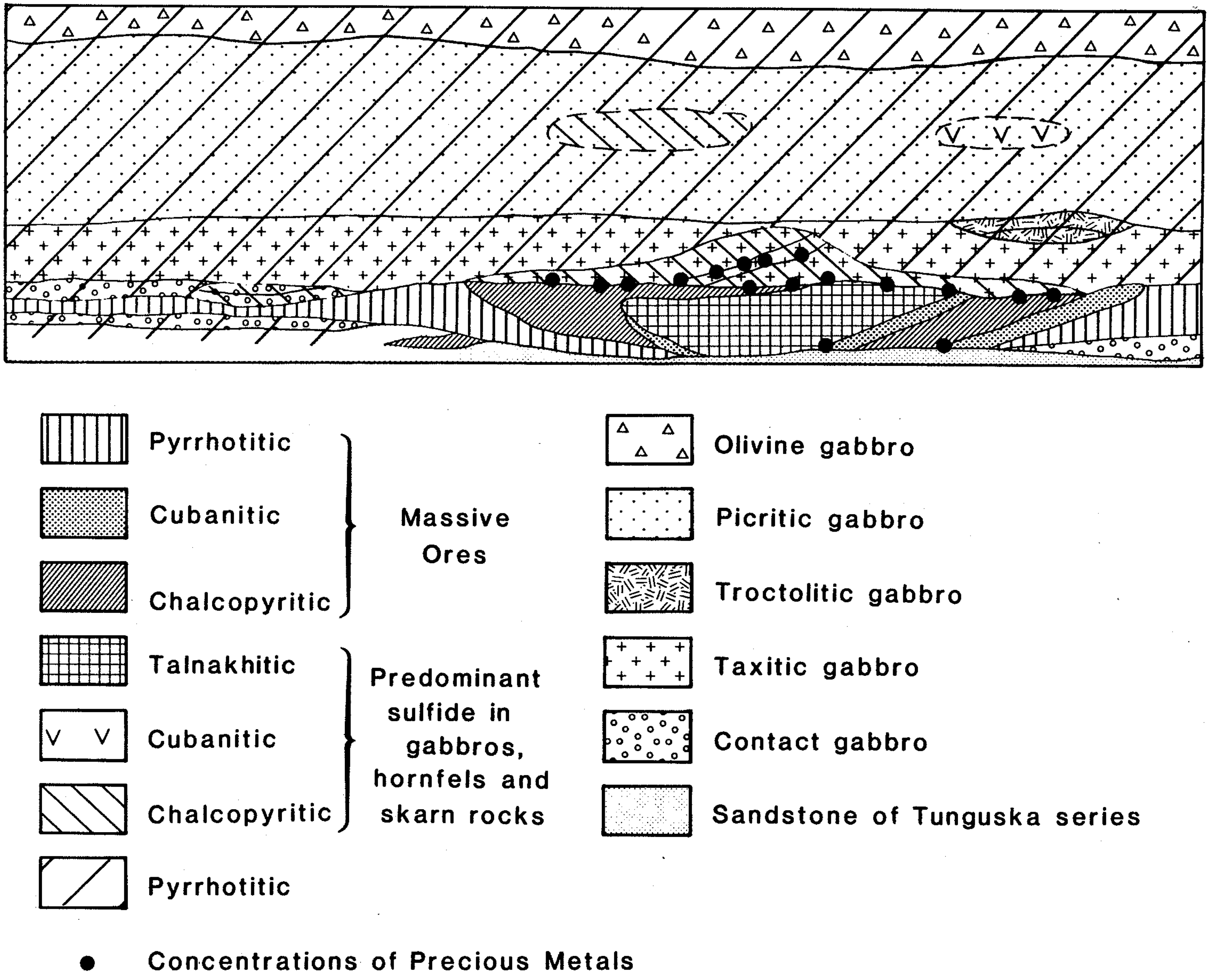


Figure 54. Transverse section of the southwestern Talnakh deposit (modified after Smirnov, 1977).

Table 13. Grades and Resources of Deposits of the Noril'sk - Talnakh District

	Noril'sk Deposits						
	Noril'sk I	Noril'sk I	Noril'sk II	Gora Chernaya	Gora Chernaya		
Ni (wb%)	0.5(7,3)	1.2 - 1.3(3)	0.28(3)				
Cu " "	0.8(3,7)	2.2(1,3)	0.65(1,3)	0.6(1)			
Co " "		0.1(3)	0.04(3)				
Ore, 10^6t	80(1)		10(1)	10(1)			
Pt	25%(4)					3.33ppm(6)	1.93ppm
Pd	71%(4)					9.10ppm(6)	5.79ppm(6)
Rh	-3%(4)					0.60ppm(6)	0.44ppm(6)
Ir	-(4)						
Ru	-1%(4)						0.10(6)
Os	-(4)					0.65ppm(6)	0.10(6)
Au	0.18ppm(6)						
PGE$_{(T)}$		up to 11 ppm(3)	3.8(3)	0.066-4.4ppm(5)	11.7ppm(5)		
Description	Deposit grade	Massive Ore	Deposit grade	Deposit grade	Massive lens	Cubanite Ore	Chalcopyrite Ore

	Talnakh Deposits			**Imanga**	**Others**
	Talnakh	Oktyabrisk	Tamyr		
Ni(wb%)	1.5(3)	3.65(3,7)	2.5(7)		
Cu" "	3.0(3,1)	4.7(3,1)		0.6(1)	0.5(1)
Co" "	0.1(3)	0.13(3)			
Ore, 10^6t	120(1)	130(7)		10	20
Pt	16%(4)	24.5%(4)			
Pd	67.8%(4)	64.5%(4)			
Rh	-11.2%(4)	4.0%(4)			
Ir	~1.5%(4)	2.7%(4)			
Ru	2.7%(4)	2.6%(6)			
Os	3.4%(6)	1.7%(6)			
Au	-0.36ppm(6)				
PGE$_{(T)}$ Description	Deposit grade	Deposit grade	Deposit grade	Deposit grade	Deposit grade

(1) Strishkov and Kimbell, 1984
(3) Obermiller, 1979
(4) Smirnov, 1977
(5) Quiring, 1962
(6) Ridge, 1984

disseminated and massive sulphides have been observed at the roofs of intrusions.

The Talnakh deposits (Figure 54) contain three types of ore (Ridge, 1984):

1. Massive ores which occur in picritic, taxitic and contact gabbro-dolerites provide about 70 percent of the total mineable ore. The thickness of the ore lenses is related to the total thickness of olivine-rich rocks in the intrusion. Interstitial ores with 10-20 percent disseminated sulphide are associated with the massive material. The massive ores are mainly of the pentlandite-chalcopyrite-pyrrhotite type whereas chalcopyrite and cubanite are both present in the disseminated sulphides.

2. Disseminated sulphides evenly distributed within picrite and taxite gabbro-dolerite layers make up about 10 percent of the ore at Talnakh. The upper part of the picrite gabbro-dolerite and, less often, the adjacent olivine-biotite gabbro-dolerites contain low concentrations of disseminated sulphides which gradually increase in quantity downwards. The middle and lower portions of the picrite gabbro-dolerites and the middle and upper portions of the taxite gabbro-dolerite units contain the highest concentrations of disseminated sulphides.

3. Massive-veinlet and "breccioid" exocontact ores: Veinlet segregations in the altered exocontact at the base and roof are widespread and account for 13 percent of the ores. The richest contain 30 to 50 percent sulphide and occur at the base of the intrusion where they form relatively thin, layer-like bodies which pinch out or break-up into en echelon lenses as they approach the main fault zone. Breccioid ores are the most widely distributed of the exocontact types in parts of the western Talnakh camp. These occur between apophyses of the intrusive body and stretch for considerable distances from the flange zones of the intrusions. The ores have a brecciated appearance with sulphides cementing and infilling between fragments of metasomatized or metamorphosed sedimentary rocks. The mineralogy of the exocontact ores is quite varied. Pyrrhotite is normally the main mineral although chalcopyrite is locally predominant and substantial amounts of millerite, pyrite, bornite and magnetite may be present. Cubanite- and talnakhite-rich zones are also present. In general, the exocontact ores are zoned downwards from pyrrhotite, to chalcopyrite, to millerite-bornite-chalcopyrite, and finally pyritic mineralization.

The distribution of PGE among the different ore types is variable with the highest concentrations occurring in the chalcopyrite-, cubanite- and talnakhite-rich ores and lesser amounts in the ores rich in pyrrhotite, millerite, bornite and chalcocite (Smirnov, 1977). In general the Pd:Pt ratio is about 3:1, however it may be as high as 5:1 in Cu-rich massive sulphides, segregations and veins. The absolute and relative abundances of PGE also vary considerably among deposits (Table 13).

At least 50 percent of the of the Pd and Pt in the Talnakh deposits occur in discrete PGM. The PGM tend to be concentrated with disseminated copper minerals, at the contacts of hangingwall segregations and in the talnakhite veinlets branching out from these, and in the selvages of veins. PGM, Au and Ag minerals occur along the outer margins of massive sulphide masses.

The Noril'sk-Talnakh deposits are characterized by an extraordinary variety of PGM including an abundance of rare species containing tin or lead. The most abundant PGM are Pt-Fe alloys, sperrylite and polarite [Pd,(Bi,Pb)], followed by stannopalladinite (Pd_5SN_2Cu), cabriite (Pd_2SnCu), taimyrite ($Pd_9Sn_4Cu_3$) and plumbopalladinite (Pd_3Pb_2). Less common, but not rare, are michenerite, moncheite, cooperite and vysotskite (PdS). Palladium reportedly occurs in solid solution in pentlandite and Rh in pyrrhotite.

SUDBURY, ONTARIO

Introduction

The many nickel-copper-PGE deposits of the Sudbury Igneous Complex (SIC) make it one of the great mining districts of the world. The nickel-copper sulphide ores occur at the basal contact of a funnel-shaped mafic layered intrusion, 60 km long by 23 km wide in surface dimensions. Discovered in 1856, the ores have been in production since 1886. During most of this time, Sudbury has been the world's largest producer of nickel. In addition, Sudbury was for many years Canada's largest producer of copper, as well as the world's largest producer of PGE (1934-1955). Other commoditites produced in significant amounts include gold, silver, cobalt, sulphur, selenium, tellurium and iron ore pellets.

Typical annual production of platinum and palladium at Sudbury in recent years is about 150,000 and 190,000 ounces, respectively. Total ore reserves stand at about 500 million tonnes averaging approximately 1.3% Ni, 1.0% Cu, and 1g/t total PGE, figures that have changed little in many years.

Tectonic Setting

The Sudbury Igneous Complex intrudes Archean and Proterozoic rocks close to the junction of the Superior, Southern and Grenville structural provinces (Fig. 55). Rocks of the Archean Superior province surround the west, north and east margins of the SIC. These rocks comprise mainly Levack Gneiss (2711 +/-7 Ma, Krogh et al., 1984) which consists of migmatitic tonalitic gneiss that contains mafic layers and xenoliths, and migmatitic paragneiss, all metamorphosed to upper amphibolite and lower granulite facies (Card et al., 1984). Rocks of the Proterozoic Southern province which form the footwall rocks along the south margin of the SIC comprise lower Huronian basalts and rhyolites (2450 +25/-10 Ma, Krogh et al., 1984) and turbiditic sediments (Dressler, 1984). These supracrustal rocks were intruded by the Creighton granite and Nipissing diabase (2223 Ma and 2160 Ma, respectively).

The oval basin of strata overlying the SIC begin with the Onaping Formation, a weakly stratified, heterolithic breccia unit up to 1600m thick, of apparent explosive origin (Muir and Peredery, 1984). This is overlain with gradational and conformable contact by the Onwatin Formation (about 600 m thick), mainly carbonaceous argillite and siltstone, and the Chelmsford Formation (about 850m thick), a proximal turbiditic greywacke of tonalitic derivation (Rousell, 1984a). No lateral equivalents to these formations are known outside the SIC.

All footwall rocks were cut by Sudbury breccia, which comprise irregular dykes and masses of pseudotachylite breccia. This was followed by emplacement of the Sudbury Intrusive Complex at 1850 +/-1 Ma (Krogh et al., 1984). Opinion is sharply divided as to whether the emplacement was an endogenic event associated with explosive volcanism or whether it was triggered by a meteoritic impact. The presence of certain shock features in footwall rocks and in the Onaping Formation is cited as evidence for the impact theory (Peredery and Morrison, 1984; French, 1972), and the postulated impact crater is interpreted to have been 80 to 100 km in largest dimension.

The Penokean orogeny (about 1850 +/-50, K.D. Card, personal communication) produced steepening of the South Range of the Sudbury basin, and south side-up displacement of the South Range along northeasterly oriented longitudinal faults (Rousell, 1984b).

Stratigraphy, Petrography

The SIC is a crudely phase-layered lopolithic body, and consists of the following four main units, in ascending stratigraphic order: Sublayer, Norite, Quartz Gabbro and Granophyre.

The Sublayer (Naldrett et al., 1984) is the basal unit, and occurs as discontinuous noritic lenses along the basal contact, and noritic to gabbroic dyke-like apophyses ("quartz diorite offsets") which penetrate subradially outward into the footwall rocks. The Sublayer contains most, and is associated with all, of the Ni-Cu ores. It is characterized by the presence of (1) nickeliferous sulphides and (2) a variety of xenoliths, including exotic ultramafic rocks. The texture ranges from intersertal to subophitic. The Sublayer appears to be an intrusion separate from the main SIC, though closely related to it.

The Norite (Naldrett and Hewins, 1984) is the lowermost unit of the main SIC. It is made up of several subunits which differ somewhat in the North and South Ranges of the intrusion (Fig. 56). The South Range norite consists mainly of cumulus plagioclase and hypersthene and intercumulus quartz, augite, titaniferous magnetite and ilmenite. It has a medium- to course-grained hypidiomorphic texture, and exhibits an igneous lamination parallel to layering. Toward the lower contact, the quartz content increases and the grain size becomes much finer. In the North Range the main norite is coarse-grained and richer in quartz and augite, and the lower part is much more mafic.

Norite grades upward into quartz gabbro through increase in quartz, augite and oxide minerals. Oxides are much more abundant in norite of the South Range than in that of the North.

Quartz and micrographic intergrowth of quartz and feldspar increase upward in the upper part of the quartz gabbro, thus grading into the overlying granophyre. Texture in the granophyre features tabular plagioclase grains dispersed in a matrix of micrographic intergrowth.

Silicate mineral compositions in the main norite and quartz gabbro (Fig. 56) show the normal upward increase in Fe/(Fe+Mg) of augite and hypersthene, and decrease in An content of plagioclase. The Fe/(Fe + Mg) trend of pyroxenes is reversed in the quartz rich norite of the south range, increasing downward toward the basal contact.

Sulphide Ore

The occurrence of Ni-Cu sulphide ore (pyrrhotite, pentlandite and chalcopyrite) along the base of the SIC is largely controlled by the distribution of the Sublayer, although in the North Range much of the ore overlaps downward into footwall breccias as well. In addition, the "offsets" also contain important sulphide ores. At least four main types of Ni-Cu sulphide deposits can be distinguished (Souch et al., 1969).

The South Range type of deposit (Fig. 57a) generally occurs in a depression in the base of the intrusion, and consists of the following sequence of textural types upward from the basal contact:

- massive sulphides with inclusions of footwall rocks ("inclusion massive sulphide"); the inclusions consist of gabbro, pyroxenite and peridotite, the latter two being exotic rock types,
- norite with abundant, mainly gabbroic inclusions and interclast sulphides ("ragged disseminated sulphide").

The North Range type of deposit (Fig. 57b) occurs partly in basal mafic inclusion-bearing norite and mainly in subjacent leucocratic footwall breccia, whose fragments include mainly footwall rocks and, in places, abundant ultramafic and mafic rocks. In addition to interstitial sulphide disseminated through the breccia matrix, and inclusion-bearing massive sulphide, there are commonly sulphide clasts in the breccia (Pattison, 1979).

Offset ores (Fig. 57c), hosted in the dyke-like "offsets", consist mostly of disseminated sulphides in inclusion-bearing gabbro-norite, and inclusion-bearing massive sulphide. The inclusion lithologies include gabbro, peridotite and pyroxenite.

The Falconbridge type of deposit (Fig. 57d) occurs within steep fault zones between basal norite and footwall supracrustal rocks. The ore consists of a near-massive sheet of inclusion-bearing sulphides in the main fault zone, and sulphide lenses in the footwall rocks.

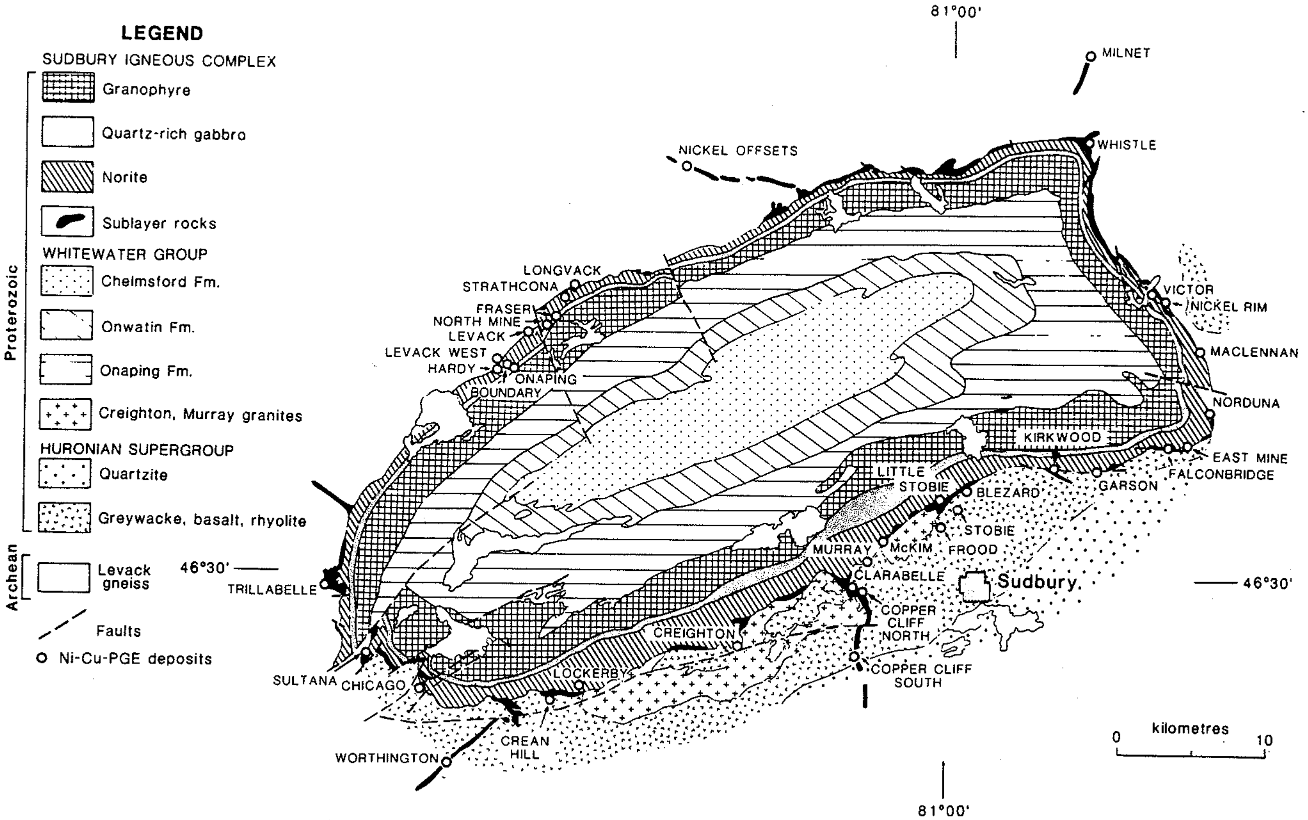


Figure 55. Geology and of the Sudbury structure (after INCO 1968 and Card et al., 1984), showing selected nickel-copper-PGE deposits.

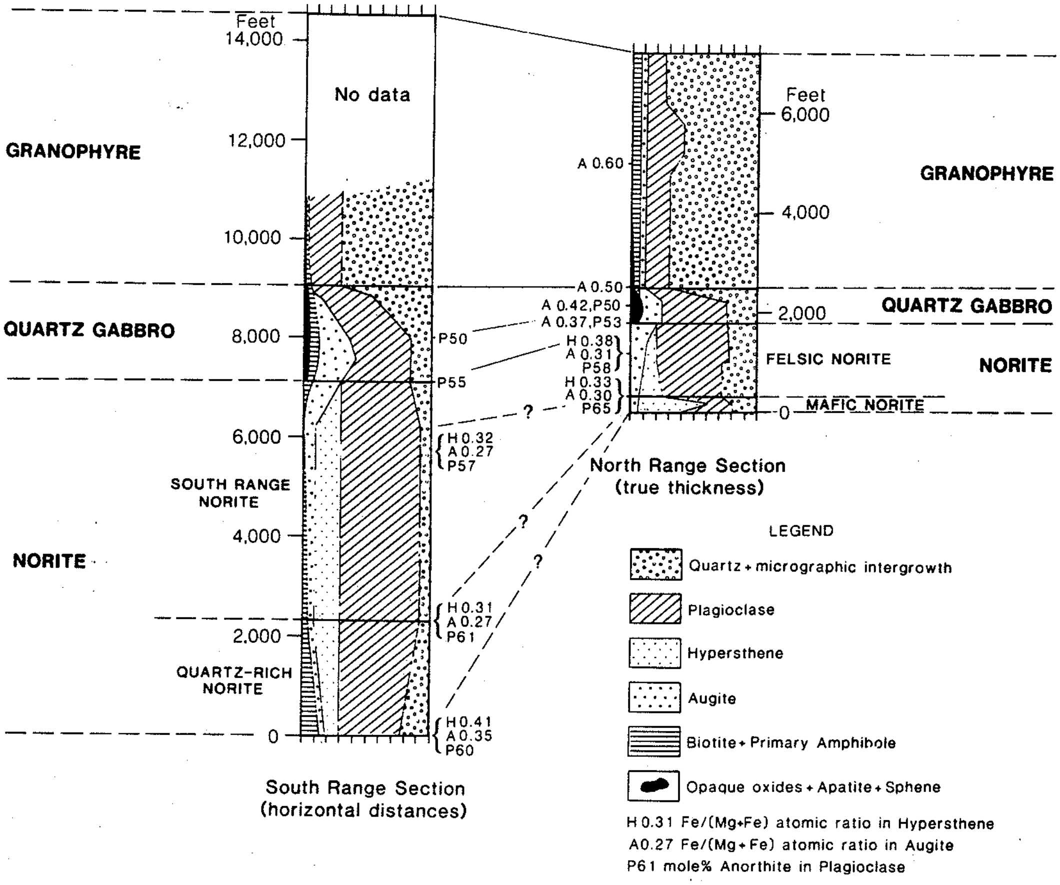


Figure 56. Sections showing modal compositions of rocks in the north and south ranges of the Sudbury structure (after Naldrett and Hewins 1984).

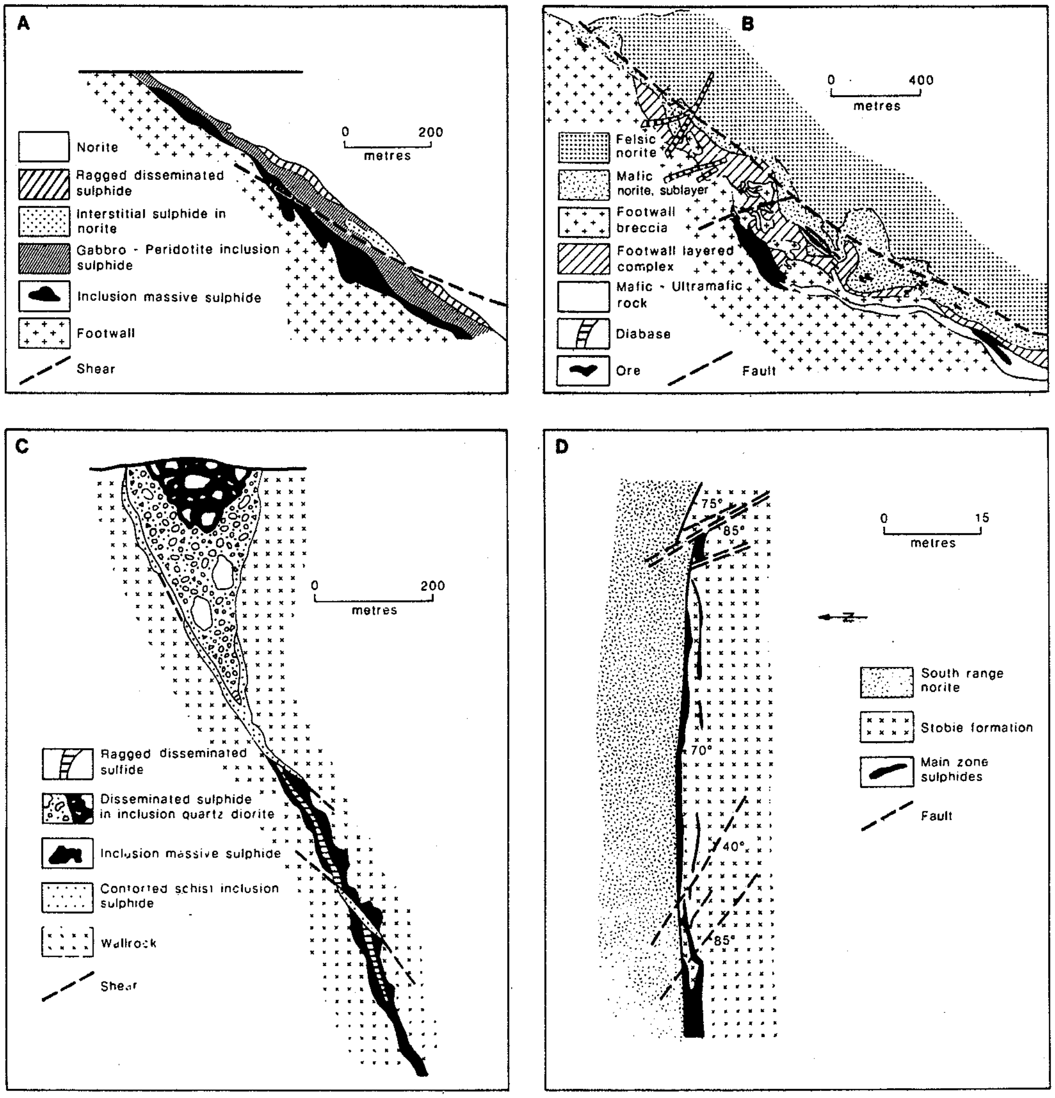


Figure 57. Typical geological sections of the four main types of ore deposits of the Sudbury structure. (a) South range: generalized section through the Murray mine looking west (after Souch et al., 1969). (b) North range: section looking east, Onaping-Levack area (after Coats and Snajdr 1984). (c) Offset: section through the Frood orebody looking southwest (after Souch et al., 1969). (d) Falconbridge type: plan of the 4525 level, Falconbridge mine (after Owen and Coats 1984).

Table 14: Metal content of Sudbury ores recalculated to 100% Sulphide (from Naldrett, 1984)

	Wt.%					ppb					ppm[1]		
	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Au	Zn	Pb	$\frac{Cu}{Cu + Ni}$	$\frac{Pt + Pd}{(Ru + Ir + Os)}$
LEVACK WEST														
Footwall Breccia Ore	5.6	3.3	0.17	1098	1223	228	73	62	26	166	153	28	0.37	14.4
Footwall Ore	5.8	5.3	0.11	1334	1350	53	22	17	10	97	529	39	0.48	54.8
Cu-rich Stringers	2.6	27.8	0.027	3370	5948	10	<3	0.3	<2	167	3716	258	0.91	1760
Average[2]	5.7	3.7	--	1150	1250	186	60	47	22	150	227	31	0.39	18.6
STRATHCONA														
Hanging Wall Ore	3.1	0.37	0.21	114	105	60	52	29	20	19	122	9	0.11	2.2
Footwall Breccia Ore	3.4	1.2	0.14	413	380	20	12	7	4	78	160	21	0.26	34.5
Footwall Ore	4.0	2.3	0.13	750	701	16	4	4	3	112	227	26	0.37	132
Cu Zone	0.51	32.3	0.087	137	40	4	3	0.2	2	13	2750	--	0.98	34
Average (i)[3]	3.63	1.23	0.15	420	372	30	21	12	8	54	233	26	0.25	19.3
Average (ii)	3.63	2.8	0.14	590	511	19	9	8	5	79	--	--	0.44	50
LITTLE STOBIE NUMBER 1														
Average	3.8	4.4	0.19	1930	2120	119	123	62	29	862	100	15	0.54	18.9
LITTLE STOBIE NUMBER 2														
Average	4.0	3.6	0.17	2130	3170	303	247	113	46	868	96	14	0.47	13
FALCONBRIDGE														
Average	5.35	1.52	0.22	546	381	287	225	144	40	174	120	14	0.22	2.3

1Zn, Pb, and As have not been recalculated to 100% sulphide.

[2] Does not include Cu-rich stringers.

[3] Average (i) is straight average of data. Average (ii) is a weighted average to give the Cu/(Cu + Ni) ratio of the ore reserves.

Table 15: Relative Abundance of Sudbury PGM

common	sperrylite	$PtAs_2$*	less-common	moncheite	$PtTe_2$
	michenerite	PdBiTe		merenskyite	$PdTe_2$
	froodite	$PdBi_2$		niggliite	PtSn
	insizwaite	$PtBi_2$		mertieite II	Pd_8Sb_3
rare	sudburyite	PdSb		ruthenium	Ru
	hollingworthite	RhAsS	very rare	hongshiite	PtCu
	irasite	IrAsS		sopcheite	$Ag_4Pd_3Te_4$
	kotulskite	PdTe		unnamed	Pd(Bi,Sb,Te)
				unnamed	Rh_2As
				unnamed	$RhTe_2$

*ideal formulas only

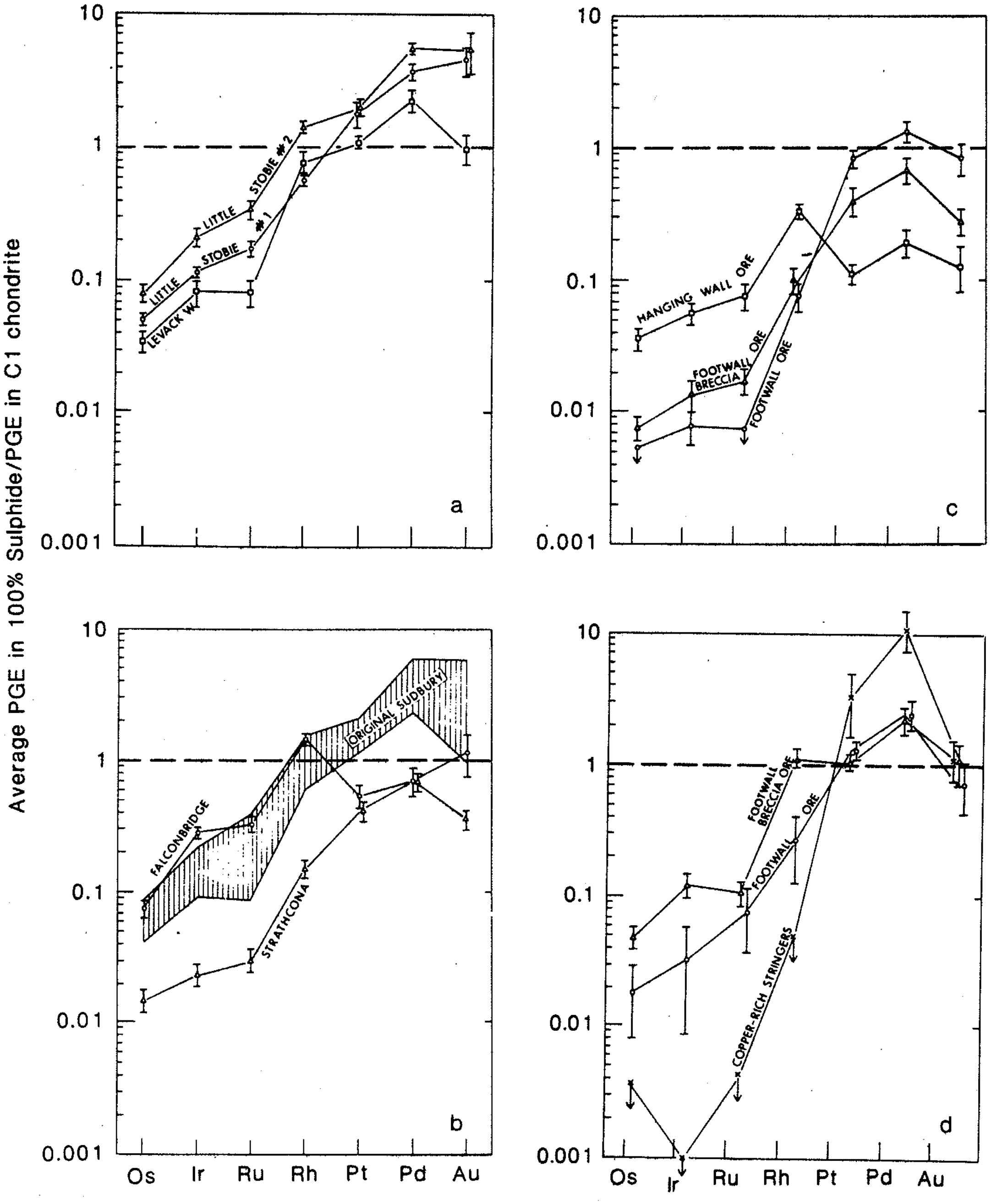


Figure 58. Average chondrite normalized concentrations of PGE in 100% sulphide in selected Sudbury mines and ore zones (after Naldrett 1984). (a) Little Stobie Numbers 1 and 2, and Levack West. (b) Falconbridge and Strathcona ("Original Sudbury" is the area occupied by the data in (a)). (c) Ore zones at Strathcona. (d) Ore zones at Levack West.

PGE Content, Distribution

Platinum group elements are distributed through all the Sudbury ores at low but economically significant levels (Table 14). Total PGE abundances differ from one mine to another, similar to variations in Cu. Levack West is probably typical of the camp, whereas Little Stobie numbers 1 and 2 are enriched in PGEs and Cu, and Strathcona and Falconbridge are depleted. PGE and Cu abundance also differ from one ore zone to another. The Cu-rich stringers at Levack West are greatly enriched in PGEs relative to the main ore zone.

Like Cu:Ni ratios, PGE ratios also show systematic differences from zone to zone (Table 14). In both Levack West and Strathcona, the ratio (Pt+Pd) / (Ru+Ir+Os) increases dramatically (in the same sense as the Cu/[Cu+Ni] ratio) from the hanging wall of the ore to the footwall. This zonation has been interpreted to be the result of fractional crystallization of monosulphide solid solution from a sulphide melt (Naldrett, 1984). PGE profiles (chondrite- and 100%sulphide-normalized) for these deposits and ore zones (Fig. 58) illustrate graphically the differences in amounts and proportions of PGEs among them.

Cabri and Laflamme (1984) list a total of 18 platinum group minerals (PGM) that have been identified in Sudbury ores (Table 15). In addition, measurable quantities of Pt, Pd, Rh and Ir occur in solid solution in sulfarsenides. Metallurgical balance calculations indicate that 91% of the Pt can be accounted for mineralogically, about 40% of the Pd, and most of the Rh and Ir. Little is known about the mineralogical occurrence of Ru and Os.

UNGAVA, QUEBEC

Introduction

The presence of significant magmatic Ni-Cu sulphide deposits in the Cape Smith-Wakeham Bay belt has been known since the 1950s. The period of exploration in the late '60s was based on interest in nickel and copper. These deposits are hosted in stratigraphically localized peridotitic sills within an Aphebian supracrustal sequence. Three main clusters of deposits (Donaldson, Katiniq and Cross Lake) totalling about 23 million tonnes averaging 2.3% Ni and 0.78% Cu (Lamothe, 1986) were demonstrated, but in 1971 after extensive development, a production decision by Falconbridge was eventually deferred. With the more recent interest in platinum, work by the Quebec government in 1986 (Lamothe et al., 1987) uncovered new anomalous PGE occurrences. In addition other studies reported significant levels of PGEs in the Katiniq (Barnes et al., 1982) and Donaldson (Dillon-Leitch and Watkinson, 1986) Ni-Cu deposits. These known occurrences suggest the possible presence of additional economically interesting PGE deposits.

Geological Setting

The Ni-Cu-PGE deposits of the Ungava peninsula of New Quebec occur in ultramafic/mafic sills within the Aphebian volcano- sedimentary Cape Smith-Wakeham Bay thrust-fold belt (Hynes and Francis, 1982), also known as the Ungava Trough (Fig. 59). The supracrustal sequence in this belt appears to represent in the main a stacking of allochthonous thrust slices forming a giant klippe derived from a root zone to the north of the presently exposed subjacent Archean basement gneisses (Hoffman, 1985, St-Onge et al., 1987).

The Ni-Cu-PGE-bearing supracrustal rocks of the belt comprise two main groups. The lower, Povungnituk Group (1960 Ma, zircon U-Pb, St-Onge and Lucas, 1986) consists in its lower part of marine slope-facies siliciclastic sediments including ironstones resting unconformably on Archean basement; and in its upper part of mixed siliciclastics, minor rhyolite, and both extrusive and intrusive Fe- and Ti-rich tholeiites that are considered to represent an episode of continental rifting (Hynes and Francis, 1982). The overlying Chukotat Group is almost entirely volcanic, of MORB-like chemistry. It comprises a lower cyclical sequence of olivine- and pyroxene-phyric basalts derived by fractionation of primitive magma (MgO > 15.5%); and an upper homogeneous sequence of evolved plagioclase-phyric basalts. These two groups, Povungnituk and Chukotat, are considered to represent rifting environments related respectively to a continental margin and the transition to an oceanic ridge setting (Hynes and Francis, 1982).

Two types of ultramafic/mafic quasi-conformable intrusions occur within the Povungnituk-Chukotat stratigraphy (Picard, 1986) but are confined to the eastern half of the belt (Baragar and Scoates, 1981). Both are considered comagmatic with the Chukotat volcanics, and contain the known Ni-Cu-PGE occurrences. (1) Peridotitic lenses with dunitic cores in the Povungnituk Group and at the southern margin of the Chukotat Group are thought to represent feeders to the Chukotat lavas. (2) Layered peridotite-gabbro sills occurring in both groups show varied degrees of differentiation. Within the Chukotat Group, peridotite-gabbro sills near the base give way upward to more gabbroic sills as a result of fractionation in the feeder system (Bedard et al., 1983).

Mineralization

Ni-Cu-PGE deposits in peridotitic lenses

The main Ni-Cu-PGE-bearing sulphide deposits of the Cape Smith-Wakeham Bay belt (Donaldson, Katiniq, Cross Lake) occur in a string of intrusions of the lenticular peridotite type which are localized in a single phyllitic sedimentary horizon at the contact of the Povungnituk and Chukotat Groups.

The KATINIQ deposits (Barnes et al., 1982) occur in a serpentinized olivine-rich sill which is up to 150 m thick and 2.5 km long (Fig. 60). It is a multiple intrusive unit consisting of several adjacent peridotitic lenses in each of which olivine increases from pyroxenitic margin to dunitic core. Sulphide concentrations occupy

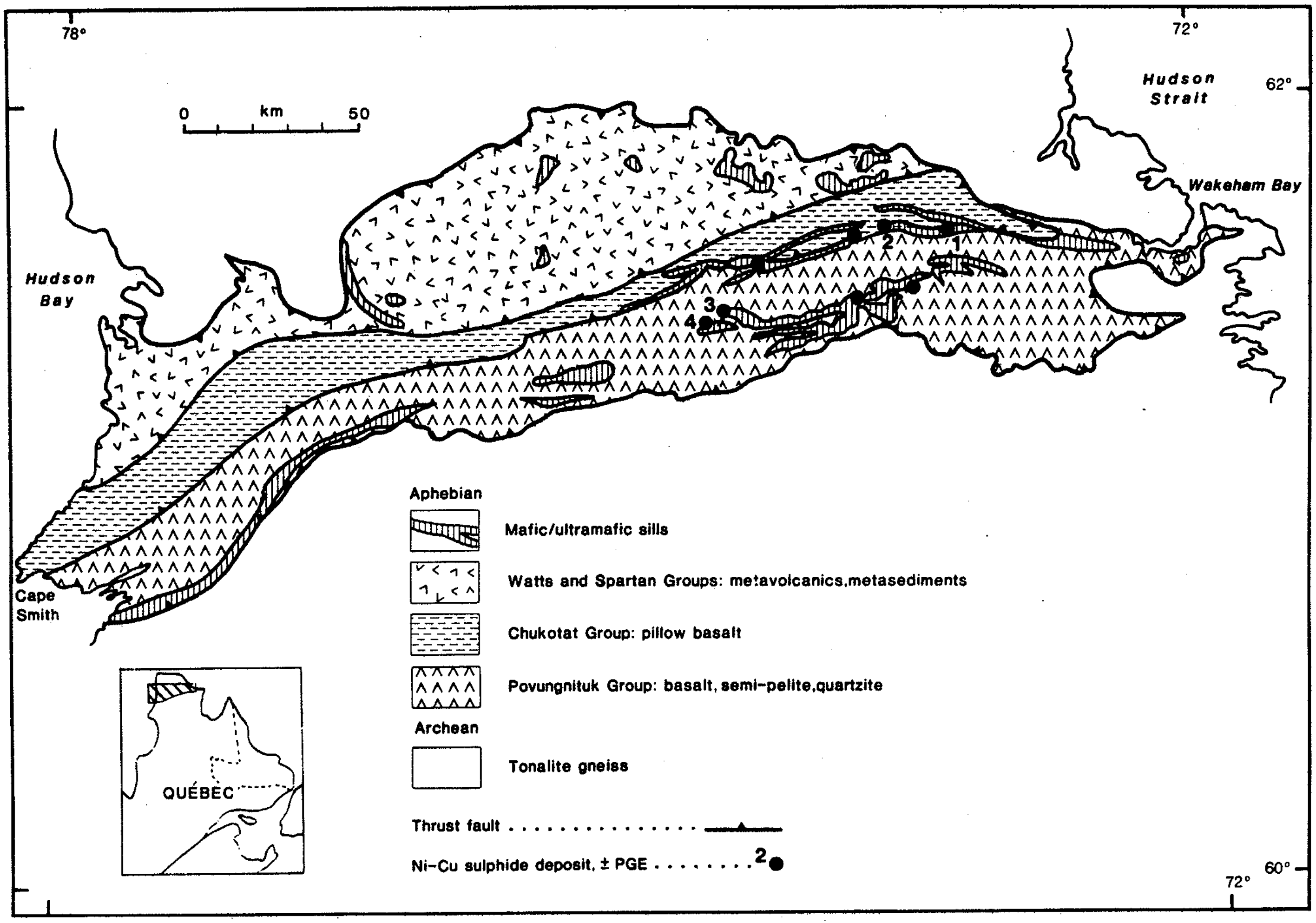


Figure 59. General geology of the Cape Smith-Wakeham Bay belt (modified after Lamothe, 1986 and St. Onge et al., 1987). Ni-Cu-PGE deposits: (1) Donaldson, (2) Katiniq, (3) Delta North, and (4) Bravo.

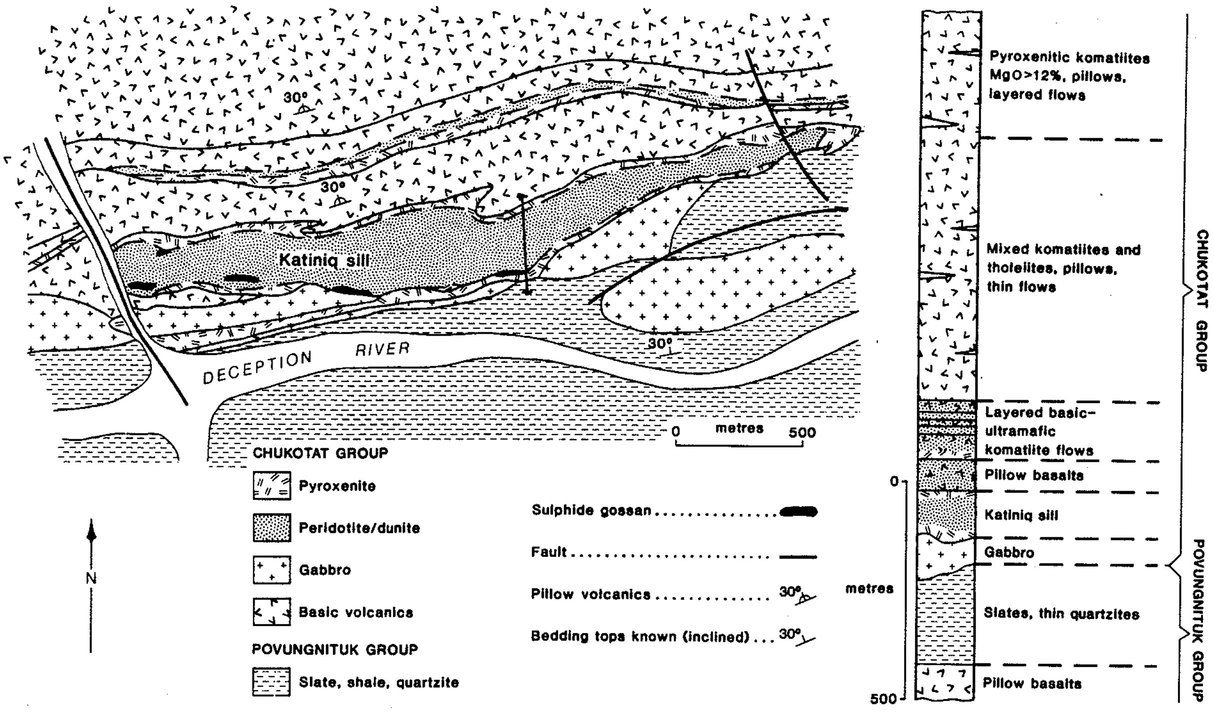


Figure 60. Geological plan and lithologic succession of the Katiniq deposit (after Barnes et al., 1982). Location of cross-section (Fig. 59) of the Katiniq Sill shown by the bar.

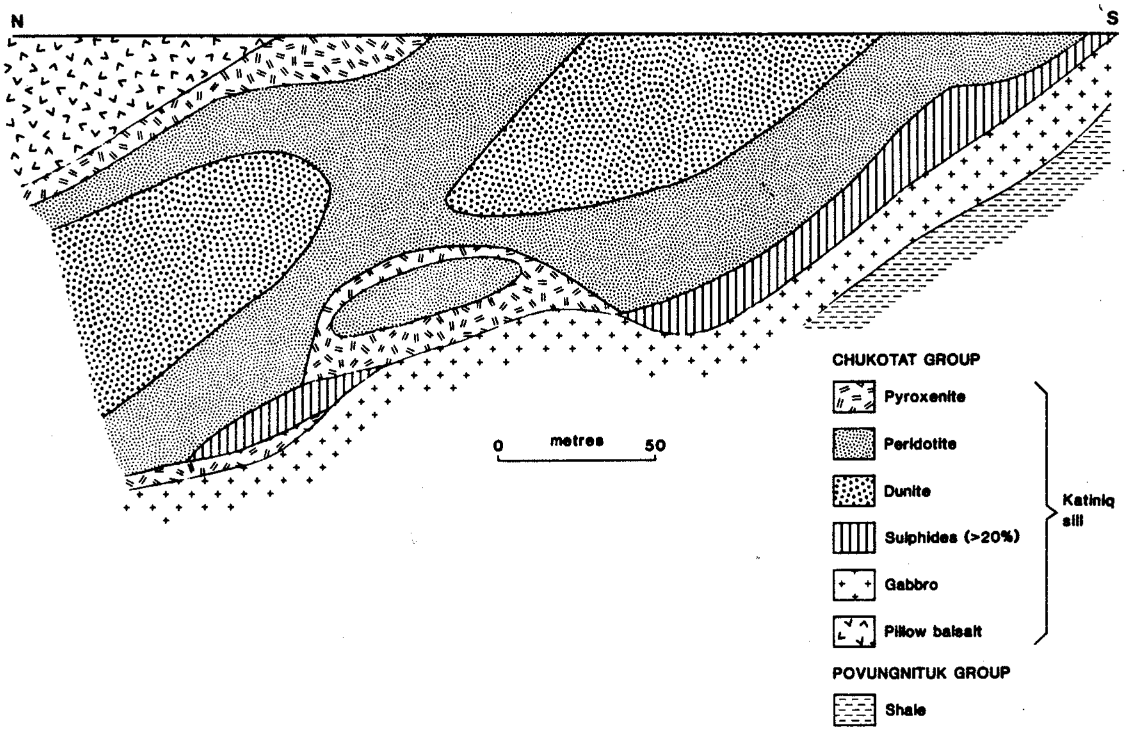


Figure 61. Geological cross section of the Katiniq deposit (after Barnes et al., 1982).

Table 16. Grades and resources of Donaldson W. and Katiniq deposits, Ungava

	Typical ore compositions*			
	Donaldson W.		Katiniq	
	Average	Maximum	Average	Maximum
Ni (wt%)	6.01	14.6	4.49	10.6
Cu " "	1.34	2.91	1.22	7.54
Co " "	0.094	0.29	0.087	0.188
S " "	14.5	37.2	16.1	32.8
Pt ppb	1326	4612	1409	5470
Pd " "	4626	24344	2895	8110
Rh " "	360	1747	253	594
Ru " "	967	6308	518	1560
Ir " "	154	985	90	252
Os " "	175	937	137	364
Au " "	151	592	96	409
No. samples	23		23	

Drill-indicated resources**	Donaldson	Katiniq
Ore tonnage (millions, tonnes	2.6	10.2
Grade - Ni (wt%)	4.4	2.4
- Cu (wt%)	1.0	0.7

* Calculated from the analytical data used to compute the sulphide-normalized averages given in Naldrett, 1981; through courtesy of A.J. Naldrett

** Lamothe, 1986.

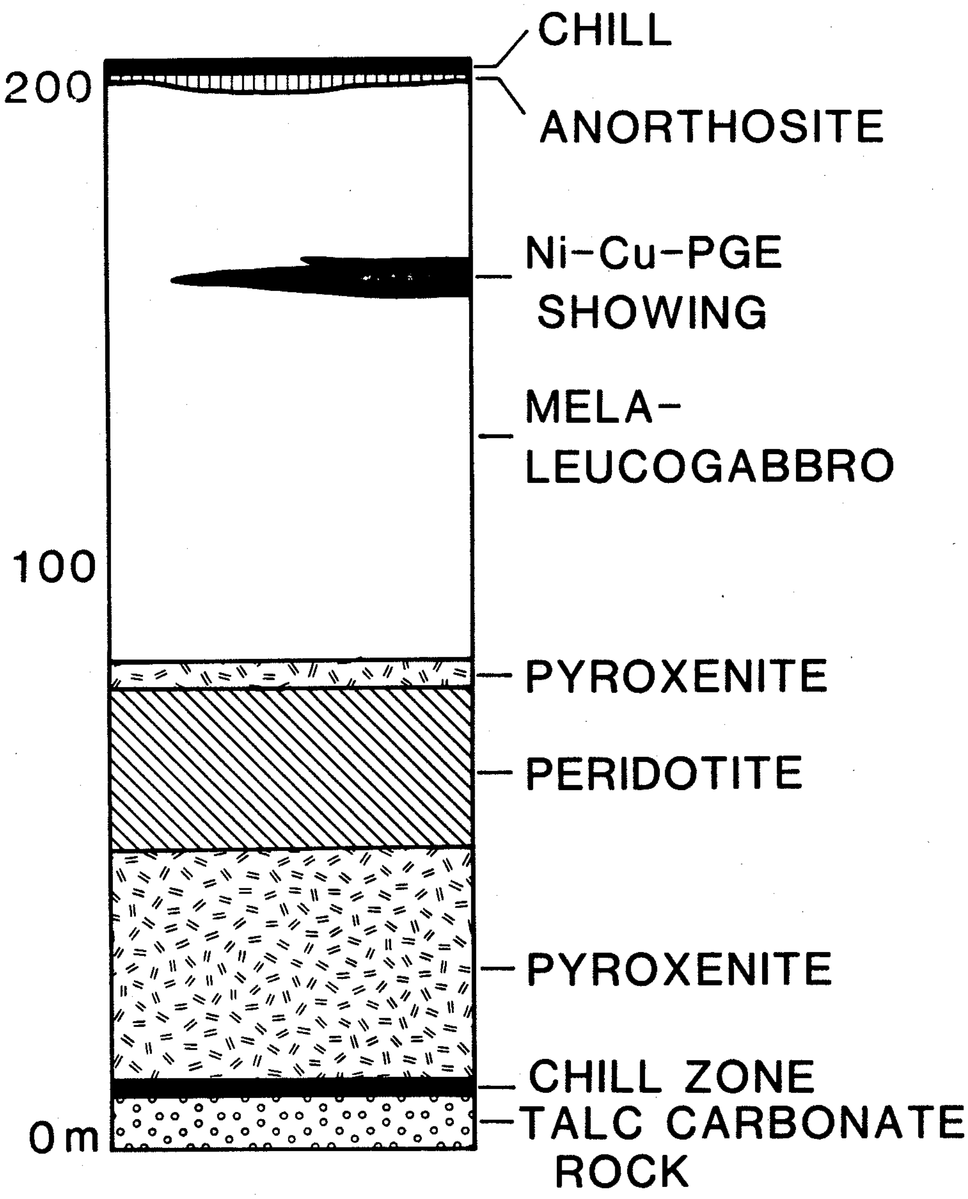


Figure 62. Stratigraphy of the Delta Sill (after Giovenazzo, 1986).

local depressions in the floor of the sill, at the base of the peridotitic lenses (Fig. 61). Massive sulphides at the base are overlain successively by net-textured and disseminated sulphides. The distribution of sulphides is thought due to the riffling out of suspended sulphide droplets from the flowing magma, and their accumulation as pools in basal depressions at the floor of the sill. Net-textured sulphides predominate and consist mainly of hexagonal pyrrhotite, pentlandite and chalcopyrite, with minor pyrite and trace sphalerite. Sulphide-silicate textures have been modified fairly extensively during serpentinization, resulting in complex intergrowths. PGE are clearly associated with the sulphides on the scale of assay intervals, but the identity and distribution of PGM are not known. Average grade for typical ore is about 3 to 5 g/T total PGE (Table 16). This is somewhat richer than most Archean komatiitic nickel sulphide ores, and about 5-10 times richer if only the sulphide fraction of the ores is considered.

The DONALDSON WEST deposit (Dillon-Leitch and Watkinson 1986) is one of three distinct Ni-Cu sulphide zones at the Donaldson site. It is similar to Katiniq in regard to inward increase of olivine content within the peridotitic intrusion, basal segregation of sulphides, and the upward sequence of massive, net-textured and disseminated sulphides. Opaque minerals include monoclinic pyrrhotite, pentlandite, chalcopyrite, minor pyrite, sphalerite, chromite, magnetite, ilmenite, titanomagnetite, traces of sulpharsenides and sulphantimonides, and rare PGMs and Au- and Ag-bearing minerals. The PGMs are mainly sperrylite ($PtAs_2$), sudburyite (PdSb), and testibiopalladite (PdSbTe), in addition to traces of several other Pd-bearing minerals. The PGMs are generally enclosed in sulphides, and are coarsest and most abundant in remobilized vein sulphides. Grades of total PGE in typical ore (see Table 16) average about 6 to 8 g/T, with higher Pd values in veins.

Numerous additional peridotite-hosted Ni-Cu deposits (Cross Lake, 2-3, Boundary and others) with similar characteristics occur along the same stratigraphic horizon (Dugas, 1971). The BOUNDARY deposits differ in that some of the hosting ultramafic lenses are believed to be extrusive (Albino, 1984). In the Cross Lake deposits values of about 1 g/T Pt and 1.4 - 5 g/T Pd have been obtained (Lamothe et al., 1987). Data on other deposits are lacking, but they are probably similar to those in the aforementioned deposits. Occurrences of this type are also known within the Povungnituk Group.

Ni-Cu-PGE deposits in gabbro-peridotite sills

PGE-bearing Ni-Cu sulphide occurrences of two other types are recognized in the Povungnituk Group (Lamothe et al., 1987). The DELTA NORTH occurrence consists of mineralized lenses in a thin pyroxenite horizon which is enclosed in a layered leucogabbro unit that forms part of the gabbroic upper portion of a gabbro- peridotite sill (Fig. 62). The lenses contain 20 to 60% net-textured and disseminated sulphides which include pyrrhotite, pentlandite, chalcopyrite, cobaltite, violarite and valleriite. Pt and Pd values of 0.7 to 5.3 g/T and 0.2 to 17.3 g/T respectively have been recorded.

The chlorite-hosted PGE-bearing sulphide occurrence in the margin of the ultramafic BRAVO intrusion appears to result from hydrothermal activity. Massive and disseminated sulphides comprise pyrrhotite, chalcopyrite, pentlandite, covellite and sphalerite. PGE values up to 1.7 g/T Pt and 1.0 g/T Pd have been encountered. Identified PGM include sperrylite ($PtAs_2$), sudburyite (PdSb) and a new complex Pd mineral. These occurrences indicate that in addition to the known deposits of the Donaldson-Katiniq type, possibly significant PGE mineralization exists in the gabbro-peridotite sills within the Povungnituk as well.

Source of sulphur

The small amount of published data on sulphur isotopes and Se/S ratios suggest a mantle source for sulphur in the Donaldson West deposit. This offers some encouragement for the PGE potential of these intrusions, though the typical anomalously Se-enriched values of major PGE deposits is not indicated.

LABRADOR TROUGH, QUEBEC - NEWFOUNDLAND

Introduction

The Labrador Trough of northeastern Quebec and adjacent Newfoundland is currently under active exploration for PGE as a result of several significant discoveries of PGE by La Fosse Platinum Group Inc. during the 1986 field season. These discoveries were made primarily by sampling known Cu-Ni deposits which occur through out the entire length of the Labrador Trough (Fig. 63). Table 17 summarizes, the analytical data obtained from the 1986 reconnaisance exploration program (Clark, 1987).

Southern Labrador Trough

A series of ultramafic-mafic sills can be traced over a strike length of about 250 km in the southern Labrador Trough. In the Retty Lake area, where the most significant discoveries of PGE have been made, three sills have been identified and characterized by Fournier, (1982, 1983) and Rohon, (1986):

(1) lower sill (>250 m of ultramafic rocks) intrudes turbidites of the Thompson Lake Formation.

(2) middle sill (30-50 m of ultramafic rocks) intrudes the Thompson Lake Formation turbidites, immediately below the Willbob lower contact.

(3) upper sill (>250 m of ultramafic rock) intrudes the Willbob Formation tholeiitic basalts.

Rohan (1986) concludes that the three sills are lithologically similar, consisting of a thin chilled gabbroic margin which is overlain by uralitized pyroxenites. A central zone of olivine-rich rocks including peridotite, mottled peridotite, feldspathic peridotite and possibly dunite, all displays cumulate textures, is a dominant feature of these sills. The peridotite zone is overlain by a pyroxenite similar to that found in the basal portion of the intrusion. The

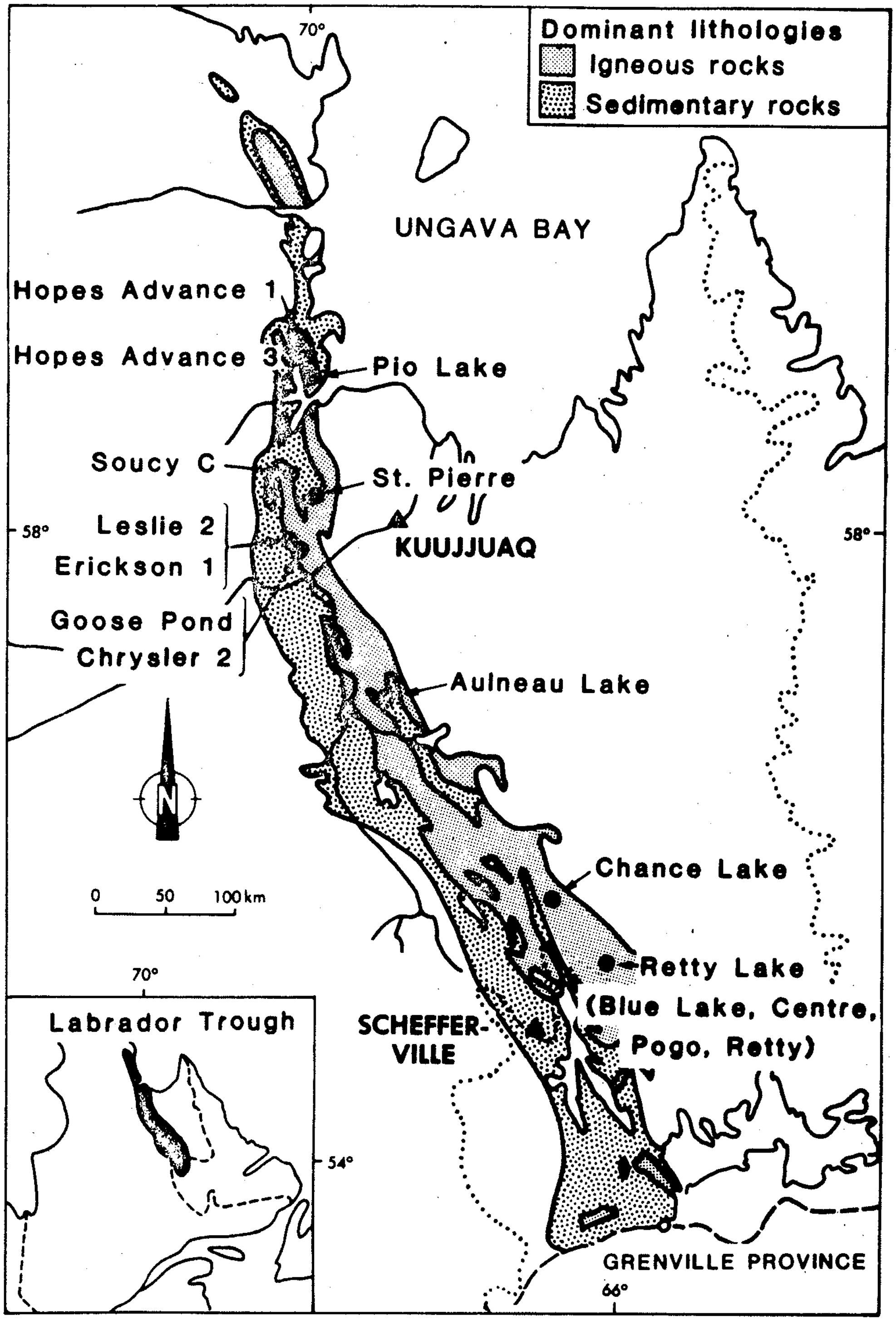


Figure 63. Location of principal Cu-Ni and Cu-Ni-PGE deposits in the Labrador Trough (after Clark 1987).

Table 17: Concentrations of PGE, Cu and Ni in PGE occurrences of the Labrador Trough.

Name	PGE results			Cu-Ni reserves		
	Pt (g/t)	Pd(g/t)	length	tonnes	Cu(%)	Ni(%)
Pogo (Retty L.)	1.4	13.0	0.6m (core)	692,600	1.00	0.65
Centre (Retty L.)	27.4	41.1	2.7m (core)	91,400	1.26	0.75
Blue Lake (Retty L.)	0.7	1.4	1.5m (chips)	506,400	0.66	0.50
	0.5	1.9	1.5m (core)	-----	--	--
Retty (Retty L.)	0.7	2.1	3.0m (chips)	-----	--	--
Lepage Zone (Aulneau L.)	1.0	3.1	14.0m (core)	1,088,000	2.02	0.45
Goose Pond (Gerido L.)	2.1	20.9	2.0m (chips)	-----	--	--
		(also 1.7 g/t Au, 7.4% Cu)				
St. Pierre (Thevenet L.)	0.3	1.0	1.0m (chips)	-----	--	--

Source: La Fosse Platinum Group Inc. The responsibility for the accuracy of the PGE data belongs entirely to La Fosse Platinum Group Inc.

Table 18. PGE in Werner Lake - Gordon Lake Ore
(Calculated from Scoates, 1963)

	Breccia Ore[1]	Disseminated Ore[1]
Rh	0.6 g/t	0.1 g/t
Pd	3.3	2.3
Pt	0.5	0.3

1) average of 14 assays
2) average of 6 assays

upper portions of the sills are made up of uralitized gabbroic rocks. The stratigraphic and lithological characteristics of these ultramafic-mafic sills are very similar to those described by Giovenazzo (1986) in the Ungava Belt.

PGE occurrences and nearly all Cu-Ni deposits in the Retty Lake area are confined to the middle sill. The sulphide mineralizations at the Blue Lake and Retty showings are believed to be confined to he base of the sill whereas at the Pogo and Centre showings, and the chance and Glance Lake showings further north, the sulphides occur in the central part of the peridotite zone. The pyrrhotite-chalcopyrite-pentlandite mineralization consist of immiscible sulphide droplets (1-10 mm in diameter) in the marginal zone, disseminated and net-textured sulphides and massive sulphides, in the ultramafic cumulates all of which clearly demonstrate that the Cu-Ni sulphide mineralization originated as a result of magmatic segregation. Features indicative of mino post magmatic sulphide remobilization are present. Significant concentrations of syn-sedimentary pyrrhotite-chalcopyrite +/- sphalerite mineralization occurs in the country rock adjacent and in contact with the middle sill. Field relationships of the marginal zone rocks with this environment suggest that crustal contamination of the magmas has taken place and this may account for the mineralization and the relatively high Cu/Ni ratios in these deposits. The carriers of the PGE in these ores are not well known, however sudburite (PdSb) has been tentatively identified (Clark, 1987).

Central Labrador Trough

In the Aulneau Lake area of the central portion of the Labrador Trough, seven individual Cu-Ni deposits are known. The most significant of these is the "Lépage Zone" which also contains PGE mineralization (Table 1). The seven deposits are associated with lenticular bodies of gabbro aligned in a highly deformed zone parallel to the regional structural trend (Lacroix, 1984, 1985). Minor amounts of glomeroporphyritic gabbro and pyroxenite are present within these bodies.

Primary magmatic and secondary mineralization of a hydrothermal origin are present (Lacroix, 1984). The primary pyrrhotite-chalcopyrite-pentlandite mineralization is associated with the pyroxenites whereas the secondary mineralization consists of pyrite and chalcopyrite along with traces of sphalerite and galena. The hydrothermal mineralization is associated with intense alteration (propylitization). Merenskeyite (Te, Bi) has been identified by Fournier (1982, 1983) at Aulneau Lake.

Northern Labrador Trough

In the northern portion of the Labrador Trough numerous Cu-Ni deposits are found in glomeroporphyritic gabbro sills (Fournier, 1981). The glomeroporphyritic gabbro commonly forms discontinuous leneses, with sharp or gradatidonal contacts, in the centre of a sill of average gabbroic composition and appearance. Discontinuous lenses of pyrrhotite-chalcopyrite-pentlandite mineralization up to 1 km in length and 50 m in thickness are located near the base of the glomeroporphyritic facies of these sills. Although no anomalous PGE values have been found in the Cu-Ni deposits in the glomeroporphyritic gabbro, important PGE concentrations have been discovered in the massive Cu-Ni sulphides in the pyroxenite horizon beneath mineralized glomeroporphyritic gabbro at the south end of Gerido Lake (Goose Pond). It is important to note that the glomeroporphyritic gabbro sills occur at the same stratigraphic position as that of the PGE-mineralized Retty Lake peridotites.

WERNER LAKE - GORDON LAKE, ONTARIO

The Consolidated Faraday Werner Lake-Gordon Lake mine is situated in northwestern Ontario, 13 km east of the Ontario-Manitoba provincial boundaries (Fig. 64). The deposit lies within the northwestern portion of the English River gneiss belt, approximately 19 km south of its north bounding fault. The mine produced 26,700,000 lbs of nickel plus copper, platinum and palladium during its 10 years of operation (1962-1972) (Canadian Mines Handbook, 1973/1974). Pre-production reserves were estimated at 1,017,846 tons averaging 1.62 percent nickel and 0.68 percent copper plus values in platinum metals (Canadian Mines Handbook, 1964).

Two distinct types of sulphide mineralization occurred in the deposits (Fig. 65); 1) disseminated copper-nickel sulphides in ultramafic rocks and 2) a breccia sulphide ore body hosted by amphibolite (Kilburn et al., 1969; Scoates, 1972). The former were represented by small peridotite pods distributed along an easterly-trending fault zone, the largest body measured 180 m in length, 45 m in width and 180 m in vertical dimension. The breccia ore body formed a continuous sinuous ore body hosted by amphibolitic gneisses. In longitudinal section, the breccia ore body had a crude wedge shape, the apex of the wedge pointing downward. It was approximately 600 m long on the upper levels, had a vertical dimension of 390 m and was 90 m long near its lower apex. It ranged in width from a few centimetres to 3 m. The sulphides contained numerous inclusions of subrounded plagioclase (sodic andesine), quartz and microcline in addition to blocks of amphibolite and pegmatite.

Six samples of disseminated ore and fourteen samples of breccia ore averaged 2.7 and 4.4 grams/ton combined Rh, Pt and Pd respectively (Table 18).

Sulphur isotopes for breccia ore sulphides have mantle values and range from +0.22% to -0.44% (Scoates, 1972).

ROTTENSTONE INTRUSION, SASKATCHEWAN

Introduction

The Rottenstone deposit in northern Saskatchewan is one of many Ni-Cu sulphide bodies in Canada known to contain significant concentrations of PGE. Although a relatively

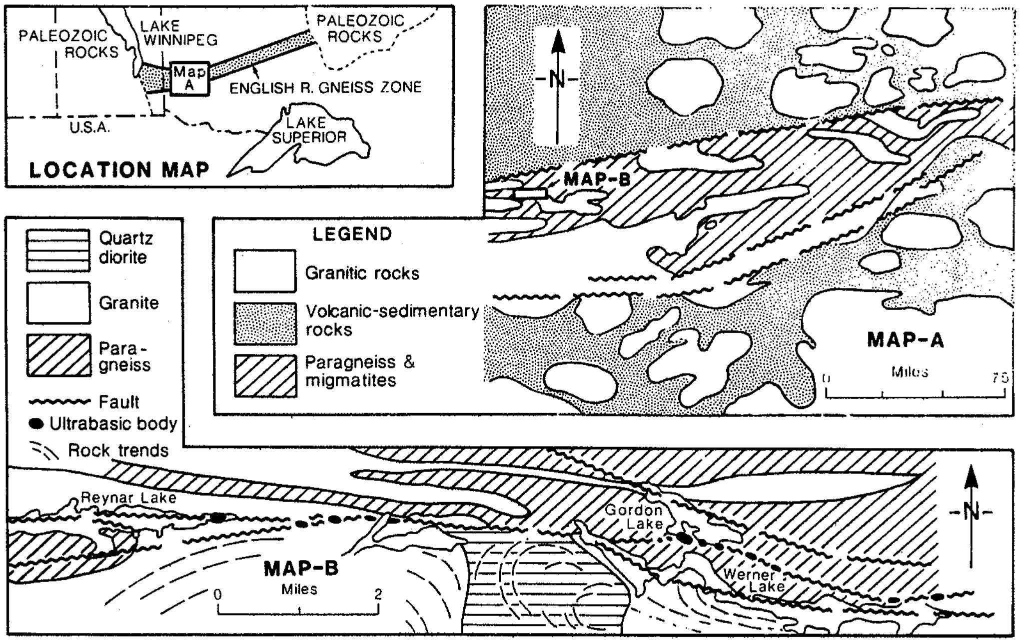


Figure 64. Generalized regional geology (after Scoates, 1972).

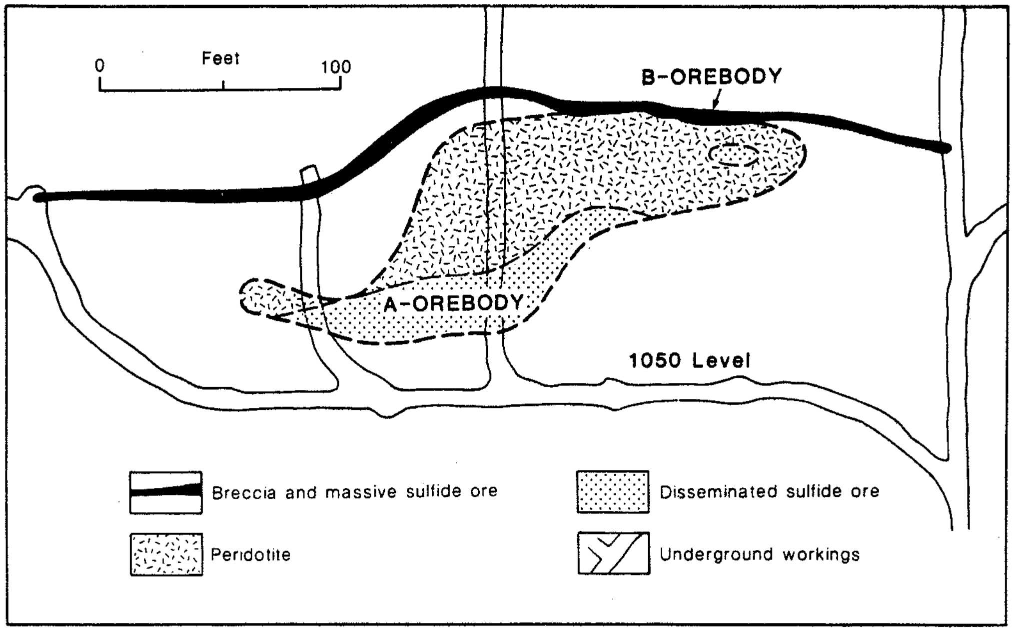


Figure 65. Breccia sulphide orebody (B-orebody) and disseminated ore (A-orebody) on the 1050 level. Blank area is predominantly amphibolitic gneiss.

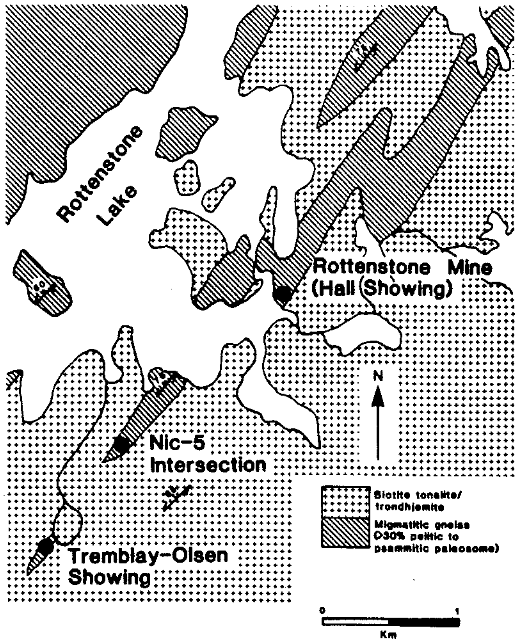


Figure 66. Geological setting of ultramafic intrusions at Rottenstone Lake.

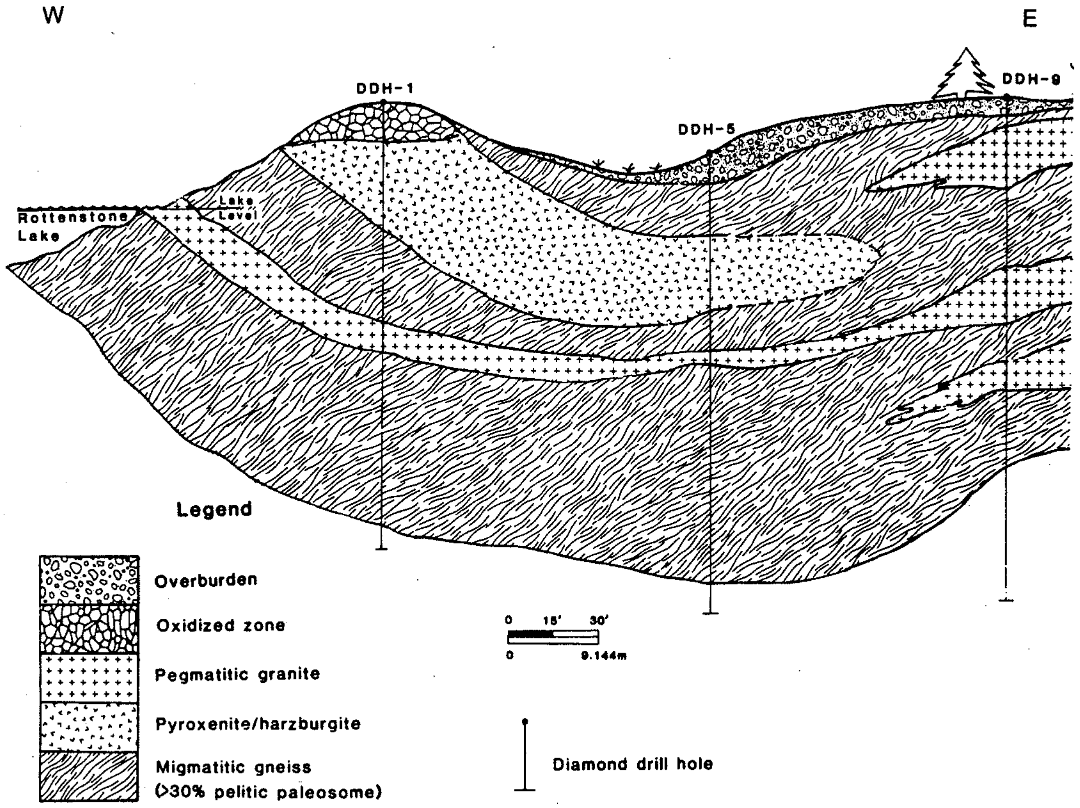


Figure 67. Simplified geological cross section of the Hall showing.

Table 19. Ore and Concentrate Compositions, Rottenstone Mine

	Ni[1]	Cu[1]	Pt[2]	Pd[2]	Au[2]	Ag[2]
Ore, preproduction average[3]	2.0	2.0	0.22	0.15	-	-
Ore, initial production[4]	3.23	1.63	0.14	0.10	0.03	0.02
Concentrate, initial run	10.83	5.74	0.33	0.53	0.01	1.25
assay check, 6/4/67	8.69	5.09	0.23	0.40	0.08	1.55
assay check, 1/5/67	7.10	4.46	0.22	0.45	0.06	0.92
assay check, 22/11/68	-	-	0.41	0.79	0.03	1.17

[1] percent; [2] oz/ton; [3] Northern Miner, April 15, 1965, p. 13; [4] September 5 - November 2, 1965, 5500 tons.

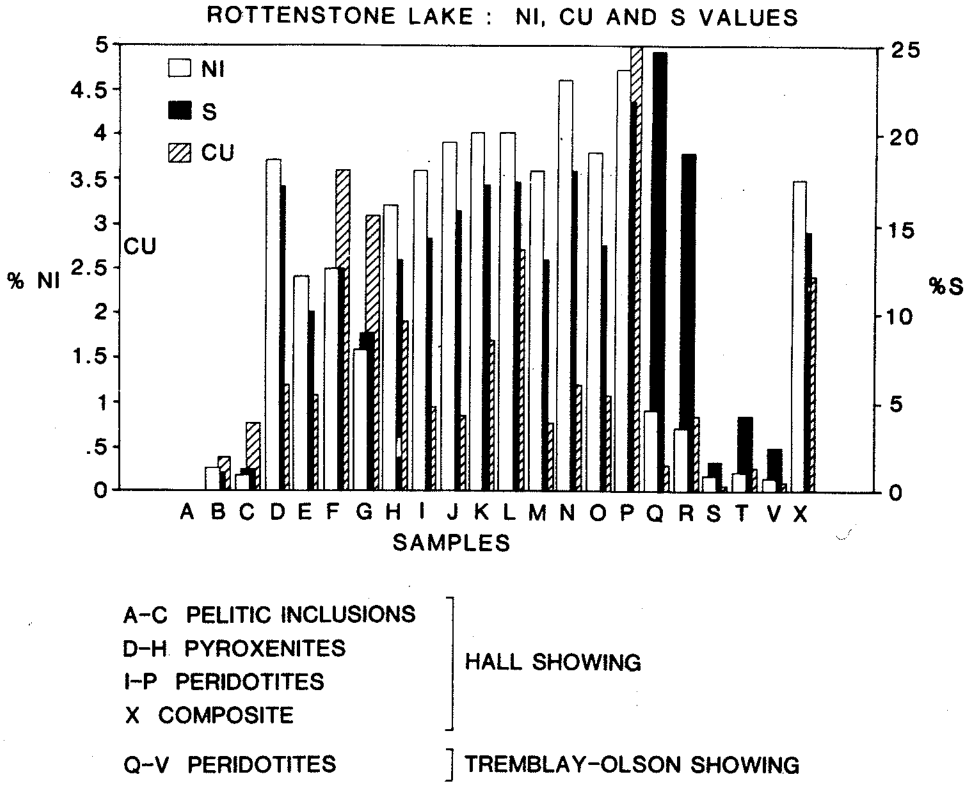


Figure 68. Ni, Cu and S contents of mineralized samples from Rottenstone Lake.

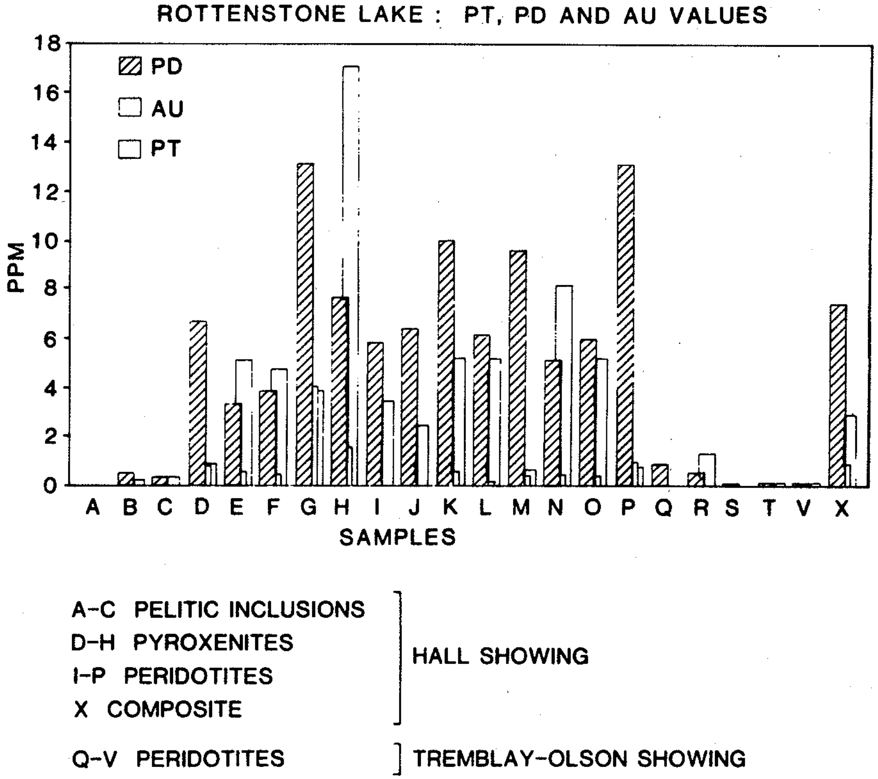


Figure 69. Pt, Pd and Au contents of mineralized samples from Rottenstone Lake.

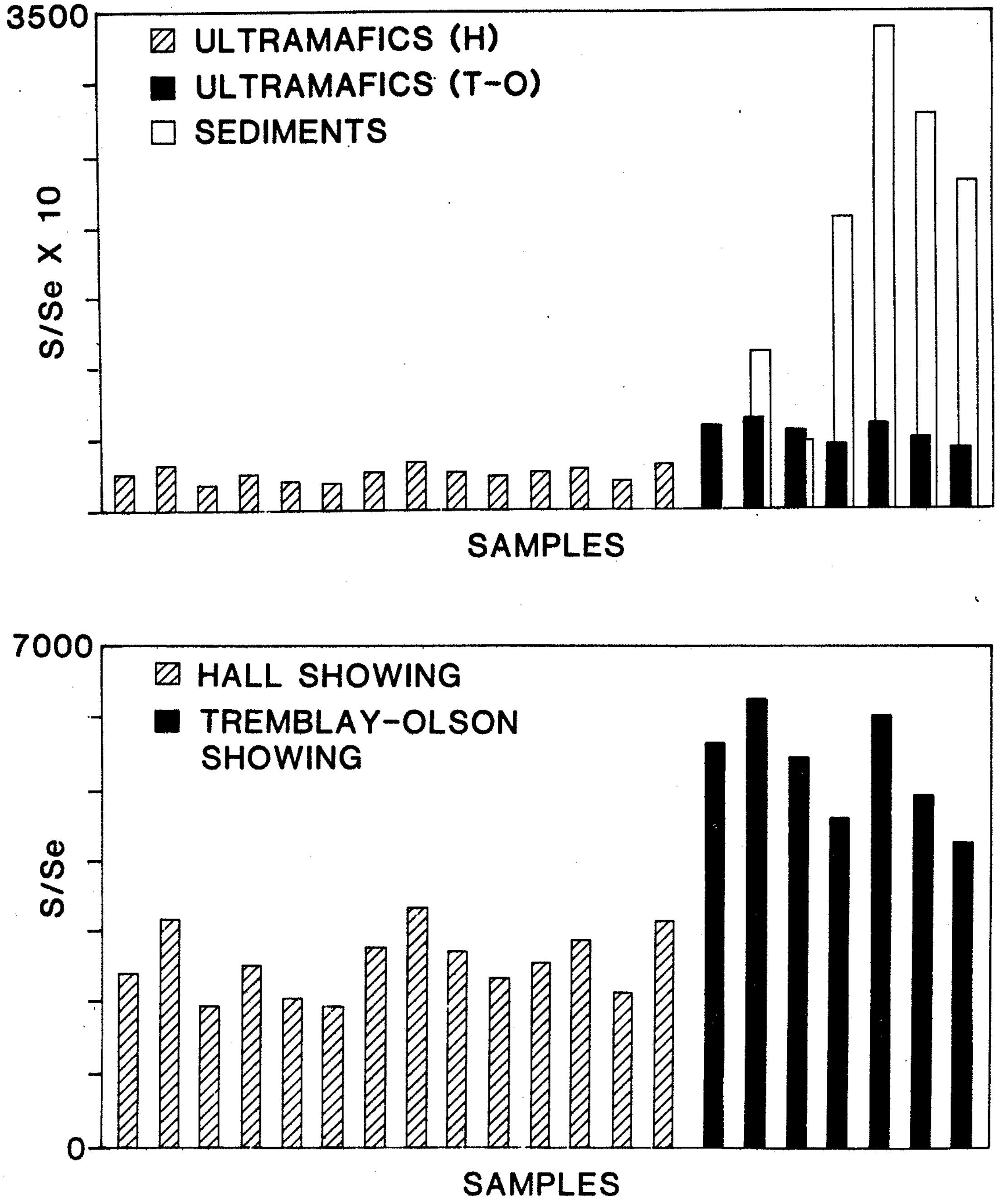


Figure 70. (A) S/Se ratios for ultramafic and sedimentary rocks at Rottenstone Lake. (B) S/Se ratios for ultramafic rocks from the Hall and Tremblay-Olson showing.

small deposit, Rottenstone is particularly noteworthy since it contained the richest concentrations of PGE + Au of any Ni-Cu ores in Canada.

Approximately 50,000 to 60,000 tons of ore were mined intermittantly from 1965-68 with an average grade of 2.0% Ni, 2.0% Cu, 7.5 ppm Pt and 5.1 ppm Pd (Northern Miner; April 15, 1965, p. 13). Richards and Robinson (1966) reported that between September 5 and November 7, 1965, 5,500 tons of ore averaging 3.23 % Ni, 1.83% Cu, 4.79 ppm Pt, 3.92 ppm Pd, 1.03 ppm Au and 6.85 ppm Ag were milled (Table 19).

Geological Setting

The ultramafic intrusion which hosts the Rottenstone deposit also known as the Hall showing occurs in a granitic migmatite terrane in the Rottenstone Domain within the Churchill Province of the Canadian Shield. It is one of three harzburgite-orthopyroxenite sills and plug-like bodies which occur within a migmatized pelite horizon along the east shore of Rottenstone Lake (Fig. 66).

The sill in which the Hall showing occurs has a strike length of approximately 50m, a width of 37 to 50m, a thickness that varies from 8 to 12m, and dips 30 degrees to the east. Although alternations of harzburgite and pyroxenite are noted in drill logs, no stratigraphic continuity of lithologies was observed within the intrusion. The surface expression of the intrusion was exposed along the east side of the lake where it occurred as a oxidized capping of pyroxenite and sulphide material rising 10-12m above the surrounding lake level (Fig. 67).

Most of the harzburgites and orthopyroxenites have been altered to serpentine and amphibole-rich rocks. However, compositional data on minerals from relatively fresh harzburgites reveal that the olivines range from $Fo_{83.4-85.9}$ and coexisting orthopyroxenes range from $En_{85.1-87.5}$. Orthopyroxene as iron-rich as En_{82} were found in the orthopyroxenites. Chromite occurs in some rocks in concentrations of 5 to 7 percent. Unlike chromite typical of most other ultramafic intrusions it has an unusual composition in that it has a very high ferrous/ferric iron ratio, high aluminum and relatively high ZnO (0.7 to 2.0%) contents. The Cr_2O_3 content varies from 17 to 43%. Another unusual feature of these rocks is the presence of graphite which occurs as inclusions in olivine and sulphide.

Sulphide and PGE Mineralization

Examination of mine records and mineralized samples around the open-pit at Rottensone Lake indicated that approximately 50% of the intrusion consisted of sulphides. Most of the mineralization occurs in the form of dense net-textured sulphides in the harzburgites, disseminated sulphides in the pyroxenites and occasionally massive sulphides were found in both lithologies.

A number of mineralized samples were obtained by one of us (LJH) from the vicinity of the open pit at the Hall showing as well as from the Tremblay-Olson showing, 2.5 km to the south. The Ni, Cu, S, Pt, Pd, and Au values for the various samples are shown in Figures 68 and 69. These data clearly substantiate the PGE and gold-rich character of the Rottenstone deposit. A composite sample revealed the following values: 3.3% Ni, 2.4% Cu, 7400 ppb Pd, 2900 ppb Pt, 75 ppb Ru, 190 ppb Rh, 120 ppb Os, 110 ppb Ir, and 940 ppb Au.

While the geology and mineralization at the Tremblay-Olson showing is superficially similar to that at the Hall showing, the Ni, PGE and Au grade are markedly lower. The Tremblay-Olson sulphides also have a much lower Se content than those of the Hall showing.

Genesis

The characteristics of sulphide mineralization at both the Hall and Tremblay-Olson showings are indicative of a magmatic segregation origin. The contrasting S/Se ratios of the two deposits also suggests an explanation for their very different Ni and precious metal contents.

In general, sulphides of a sedimentary origin have extremely low to negligible concentrations of selenium, whereas sulphides derived from a mantle source are known to be enriched in selenium. In the Rottenstone Lake area, the syn-sedimentary sulphides (Fig. 70) have very low contents of Se, and thus have high S/Se ratios (average 28,000). In contrast the sulphides and ores at the Hall showing have high contents of Se, and average S/Se ratio of 2,500 in similar to mantle values.

The Tremblay-Olson mineralization has a S/Se ratio of approximately 5,500; more than twice that found at the Hall showing (Fig. 70). When recalculated to 100 percent sulphide the Hall mineralization is approximately eight times as rich in Ni and precious metals as the Tremblay-Olson. The only plausible explanation for these differences is that a significant proportion of the sulphide mineralization at the Tremblay-Olson showing resulted from crustal contamination of the magma by the surrounding sulphur-rich migmatized sediments. The high proportion of sulphides at the Hall showing (approximately fifty percent) indicates that the bulk of the sulphides were derived from a much larger magma chamber at depth. Such an environment would have allowed the sulphides to equilibriate with a large volume of magma from which they can scavenge PGE and Ni. On the other hand, the patchy nature of the mineraliztion at the Tremblay-Olson showing suggests that the parent magma was not sulphide-saturated prior to emplacment but became saturated as a result of local contamination, as suggested by the S/Se ratios.

COLDWELL COMPLEX, ONTARIO

The Coldwell Complex, the largest alkaline complex in North America, lies on the north shore of Lake Superior. The Trans Canada Highway crosses the complex and the community of Marathon is situated on its east side. The 25 km diameter complex is crudely circular in outline (Fig. 71) and contains the products of oversaturated,

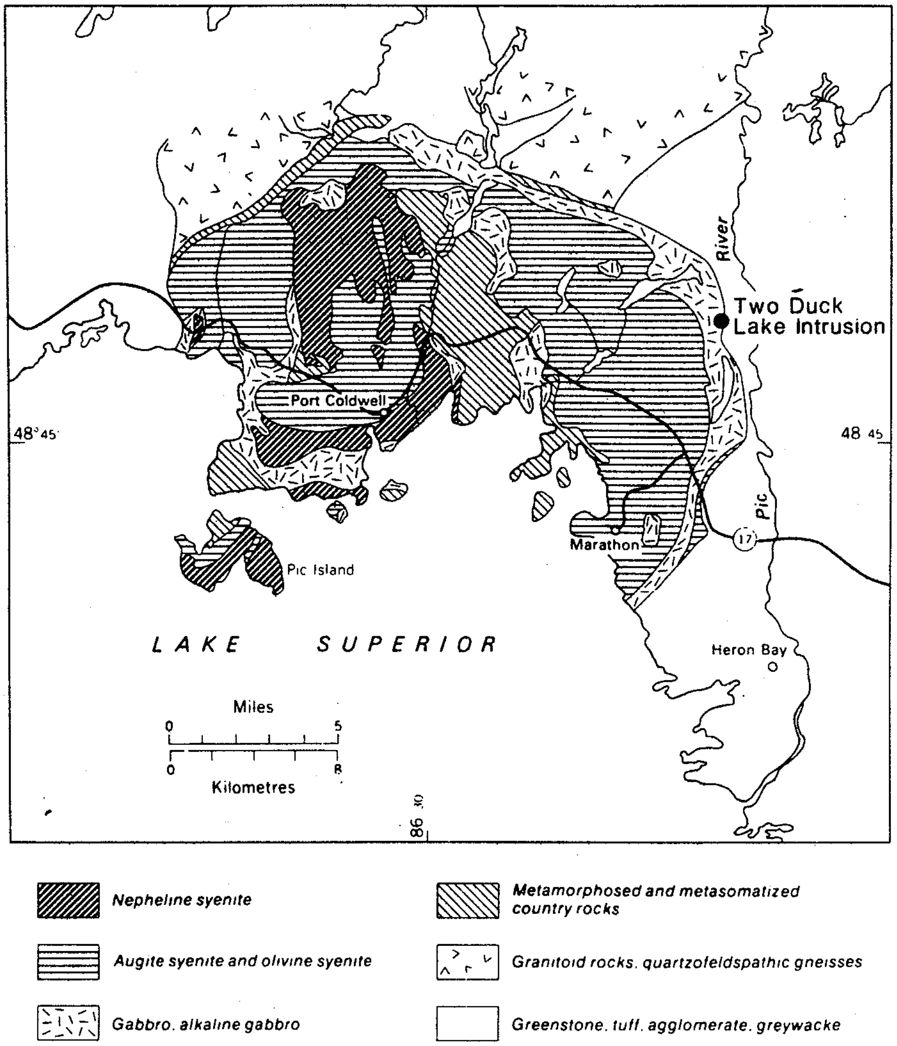


Figure 71. Generalized geology of the Coldwell Complex (after Wilkinson 1983).

saturated and undersaturated magmatism. The complex, which has a late Neohelikian age (1044 ± 6.2 Ma, Rb-Sr whole rock isochron, Platt and Mitchell, 1982) intruded mafic and felsic volcanic rocks, metasedimentary rocks and their derived gneisses and schists, and granitoid rocks, all of Archean age. Recently a U-Pb zircon/baddelyite age of 1108 ± 1 Ma has been determined on Centre 1 gabbro and Centre 2 syenite (Heaman and Machado, 1987).

The number of different intrusive lithologies and their complicated intrusive relationships have led to different schemes of petrographic subdivison. Currie (1980) identified four major divisions:

1) a marginal phase of metasomatized and reconstituted rocks,
2) an older, feebly alkaline phase of gabbro and augite-amphibole syenite,
3) a nepheline-bearing series ranging from gabbro to nepheline syenite, and
4) a complex but essentially bimodal suite of alkaline dykes.

Mitchell and Platt (1982), on the other hand, recognized three distinct intrusive magmatic episodes, each characterized by a distinct differentiation trend. In order of intrusion these are:

1) saturated alkaline rocks with peralkaline oversaturated residua,
2) miaskalic alkaline rocks with undersaturated residua, and
3) alkaline rocks with oversaturated residua.

The complex consists of a series of ring dykes, cone sheets and subsided blocks. It possesses three intrusive centres, the eastern part of the complex consisting of a massive central syenite surrounded by an older ring of gabbro (eastern gabbro), in which rhythmic, inch-scale and cryptic layering have been described (Puskas, 1967).

A currently subeconomic PGE deposit occurs near the eastern margin of the complex. The deposit contains an estimated 47 million tons, grading 0.02 oz Pt/ton, 0.054 oz Pd/ton, 0.42% Cu, plus minor Ni, Co, Rh, Au and Ag (The Northern Miner, March 2, 1987). The mineralization was previously described as being hosted by "heterogeneous gabbro", a variety of the eastern gabbro of the complex (Watkinson et al., 1983). However, Dahl et al., (1987) have described the PGE-bearing sulphide mineralization as being hosted by a separate intrusion, the Two Duck Lake intrusion. This body, composed of coarse grained to pegmatitic gabbro-monzonite, intruded the eastern gabbro of the Coldwell Complex and Archean metavolcanic rocks with which the complex is in contact.

Disseminated sulphides are interstitial to and intergrown with biotite, plagioclase, amphibole and ilmenomagnetite. Platinum group minerals occur mainly with chalcopyrite and bornite. Watkinson and Dahl (1987) have proposed that late stage fluid mobilized elements from the intruded rocks and that these elements were subsequently precipitated when this fluid reacted with pyrrhotite and magnetite. The fluid was either juvenile or derived through the breakdown of xenoliths.

WELLGREEN, YUKON TERRITORY

Introduction

The Wellgreen Ni-Cu-PGE deposit is situated in the southwest Yukon, approximately 300 km west of Whitehorse and 14 km southwest of km 1788 on the Alaska Highway. The deposit was discovered in 1952 and subsequent exploration delineated 669,150 tonnes grading 2.04% Ni, 1.42% Cu, 0.038 oz/ton Pt, 0.027 oz/ton Pd and and 0.005 oz/ton Au (National Mineral Inventory). The deposit was mined in 1972-73 with total production amounting to 189,211 tons of ore. The deposit is currently being re-evaluated due to the relatively high PGE content of the sulphides.

Geological Setting

The Wellgreen deposit occurs in the Quill Creek Complex, one of a number of Triassic intrusive, bodies emplaced in Permo-Triassic volcanic and sedimentary rocks of the Kluane Ranges (Campbell, 1960; Campbell, 1977). The Quill Creek Complex outcrops over a strike length of nearly 16 km and a width of up to 600 m. It intrudes volcaniclastic rocks of the lower Permain Station Creek Formation and is in fault contact at its southwest end with amygdaloidal basalts of the Upper Triassic Nikolai Formation (Campbell, 1977). The entire sequence has been intensely folded and faulted, and the ultramafic rocks of the Quill Creek Complex have been variably serpentinzed.

The thickness of the complex is estimated to range between 100 and 600 m although no complete section is exposed. The marginal member of the complex contains a thin (9.0 - 33.5 m) gabbroic facies consisting of a fine-grained chilled margin which grades upward into medium-grained leuco- and mesocratic mineralized gabbros. A thick zone of ultramafic cumulates, consisting of peridotite and dunite defines the overlying olivine-rich members. Olivine, olivine-chromite and olivine-sulfide cumulates predominate within this zone.

The sill has been intensely sheared and variably serpentinized as a result of numerous steeply-dipping ESE and ENE - trending normal faults. In the thicker, central part of the sill (Fig. 72), the faults juxtapose peridotite against peridotite while at the thinner east and west ends of the body hanging wall or footwall sedimentary rocks are faulted against ultramafic cumulates. A generalized cross-section of the Wellgreen Complex is illustrated in Fig. 73.

Ni-Cu-PGE Mineralization

Economic sulfide mineralization in the Wellgreen Complex, is associated with the gabbroic marginal member rocks. The three most prominent areas of mineralization are the East Zone, West Zone and North Zone (Fig. 72). A detailed cross-section of the East Zone is given on Figure 74.

At present four types of Ni-Cu-PGE mineralization are recognized in the Wellgreen Complex:

i) Massive Sulfide

Lenses of massive sulfide mineralization occur along the gabbro- quartzite contacts (Fig. 74). The distribution of these lenses is erratic and discontinuous with the largest occurring along moderately plunging "rolls" (mine terminology) at gabbro- quartzite contacts. The widths of these lenses vary rapidly from 1 to 18 m although they are generally less than 6 m wide. The sulfide-rich lenses are fine-grained and consist mainly of pyrrhotite with lesser amount of chalcopyprite, pentlandite and magnetite. Pentlandite occurs as fine grains rimming pyrrhotite and as feathery exsolution flames within pyrrhotite. In some samples the pronounced development of ribbon pentlandite (10 mm x 2 mm) imparts a strongly banded or gneissic fabric to the ores. Also, some of the massive sulfides lenses have a distinctive brecciated appearance and are best referred to as breccia ores. The structural position and fabric of the ore suggests that it originated as a magmatic segregation-type mineralization and has subsequently been remobilized to varying degrees.

Assays as high as 4.57% Ni, 1.58% Cu, 0.10% Co, 4.14 ppm Pt and 3.08 ppm Pd over 3.6 m have been recorded. In 1986, a 9.8 m chip sample (P27956) taken across the massive sulphide mineralization at the east zone (Fig. 74) gave a representative grade of 2.44% Ni, 2.07% Cu, 0.094% Co, 2400 ppb Pt, 2200 ppb Pd, 1020 ppb Au, 560 ppb Rh, 650 ppb Ru, 440 ppb Os, and 550 ppb Ir. The highest Pt, Pd, Au, Rh, Ru, Os and Ir values obtained from the massive sulfides is 6660, 7200, 1020, 750, 2000, 950, and 1200 ppb respectively. Fourteen grab and chip samples obtained from the massive sulfide mineralization in the Wellgreen Complex gave a mean value of 2.16% Ni, 1.97% Cu, 0.086% Co, 2781 ppb Pt and 1859 ppb Pd (Carne and Cathro, 1986).

ii) Mineralized Gabbro

Chalcopyrite, pyrrhotite and pentlandite occur as disseminations and/or narrow sulfide lenses within altered gabbro in proximity to the massive sulfide zones. The gabbro-hosted mineralization is distinct from that of the massive sulfides in that its sulfides are significantly coarse and chalcopyrite is the dominant sulfide species. Exploration by Hudson Bay Exploration and Development Company Limited during the 1950's and 1960's was not directed at the gabbro-hosted mineralization which was regarded as "waste rock" due to the prevailing technological and economic constraints (Carne and Cathro, 1986). As a result, many of the mineralized gabbro intersections were not assayed; i.e., a 20.0 m intersection from the west zone returned values of 0.44% Ni and 0.63% Cu. Assays of disseminated mineralization sampled in 1986 gave a mean value of 0.33% Ni, 0.56% Cu, 0.018% Co, 103 ppb Au, 800 ppb Pt and 833 ppb Pd. A 16.2 m chip sample (P27957-58) of the disseminated mineralization from the east zone (Fig. 72) gave a grade of 0.47% Ni, 1.10% Cu, 0.02% Co, 994 ppb Pt, 582 ppb Pd, 68 ppb Rh, 102 ppb Ru, 68 ppb Os, 68 ppb Ir and 308 ppb Au (Carne and Cathro, 1986).

iii) Disseminated Sulfides in Peridotite

A zone of disseminated nickeliferous pyrrhotite and chalcopyrite mineralization extends for over 100 m into the hanging wall peridotite from the gabbro contact. Patchy net-textured sulfides, with relict cumulus olivine, occur near the peridotite-gabbro contact in what appears to be the basal portion of the peridotite member. At higher stratigraphic levels in the peridotite the sulfide mineralization occurs in the form of scattered fine disseminations. Peridotites with disseminated sulfide mineralization contain a mean value of 0.20% Ni, 0.09% Cu, 0.013% Co, 200 ppb Pt, 230 ppb Pd and 24 ppb Au. Four chip samples (P27959-62) covering an interval of 24 m (Fig. 74) from the peridotite-gabbro contact recorded a systematic drop in Pt from 450 to 130 ppb, of Pd from 400 to 165 ppb and corresponding increase in Au from 10 to 24 ppb with increasing height in the peridotite.

iv) Mineralized Footwall Quartzite

Local concentrations of disseminated mineralization, erratic pods and stringer zones of sulfides occur along the gabbro contact zone in the footwall quartzite. The metal grades are similar to those found in the adjacent gabbro, however, continuity is poor and no attempt was made to mine the mineralized quartzite in the past. A mean grade for this type of mineralization is 0.35% Ni, 0.26% Cu, 0.017% Co, 519 ppb Pt, 338 ppb Pd and 468 ppb Au. High gold values, in the 1250-2350 ppb range, are found in association with anomalous concentrations of arsenides.

Two important features distinguish the Wellgreen Ni-Cu mineralization form nickel-copper deposits elsewhere:
(a) age of the intrusion and associated Ni-Cu mineralization and (b) absolute amounts of PGE in the ores and the nature of the chondrite-normalized PGE profiles for the 100% sulfides.

The Wellgreen Complex and associated mineralization is Triassic in age. This distinguishes it from most other Ni-Cu deposits in the world which are confined to the Precambrian. Apart from the age, it is distinct from most other deposits in that the sulfide ores are considerably enriched in platinum-group elements, especially the rarer elements Os, Ir, Ru, and Rh. The Wellgreen massive sulfide samples have been plotted on the chondrite-normalized PGE diagram in Figure 75. Comparison of the profiles reveal that the Wellgreen ores are similar to the flat profiles associated with Archean Komatiites than those of the steeper profiles related to the tholeiitic parental magmas that gave rise to the Sudbury, Lynn Lake, La Perouse, Great Lake Nickel, Okktyyab'sk-Talnakh type Ni-Cu ore deposits. The similarity in the profiles suggests a genetic link between PGE fractionation processes in both magmas.

CORYELL ALKALIC INTRUSIONS, BRITISH COLUMBIA

Introduction

Copper mineralization associated with the Coryell alkalic intrusions of southern British

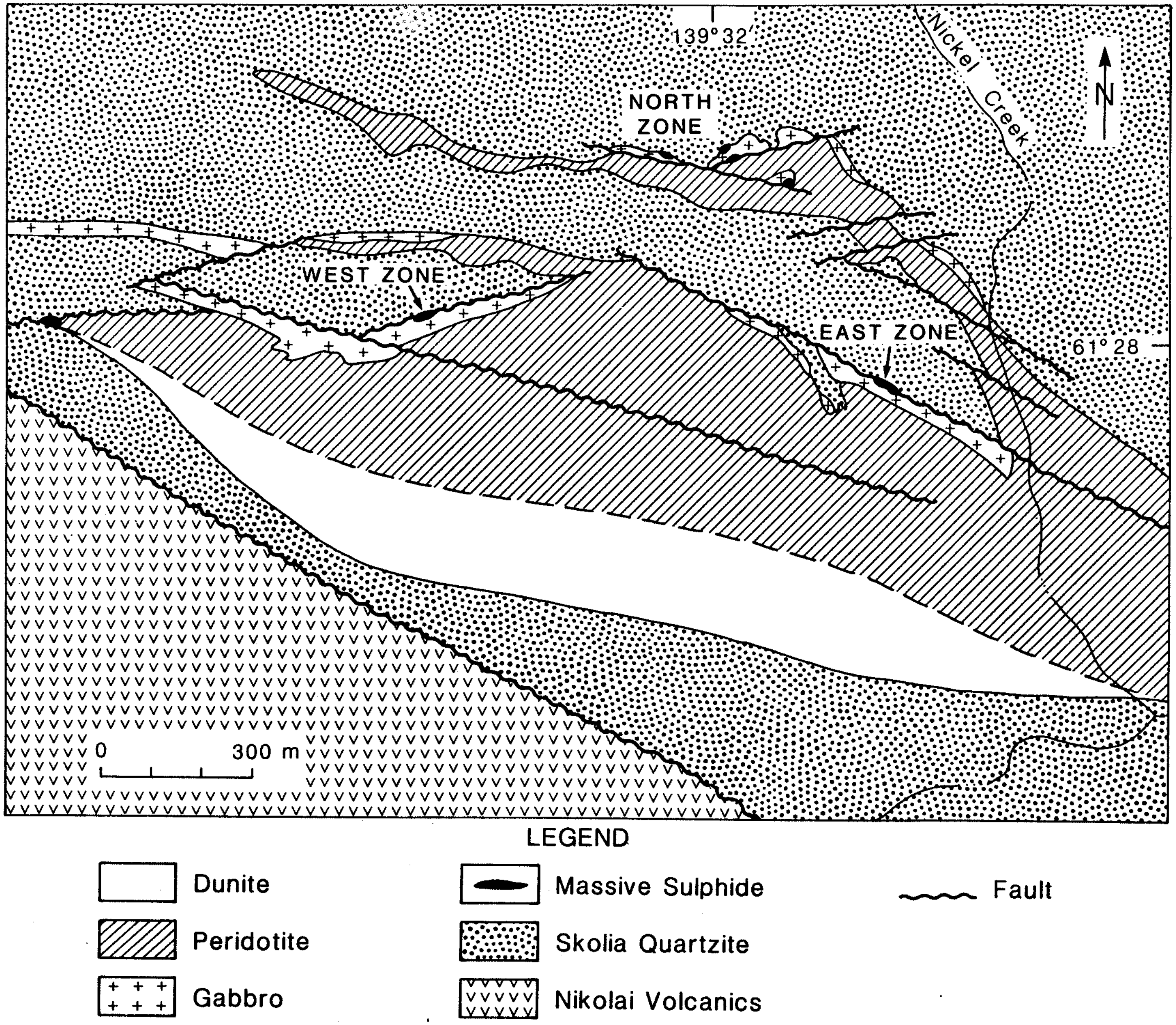


Figure 72. Generalized geology of the Central and Western portion of the Wellgreen Complex.

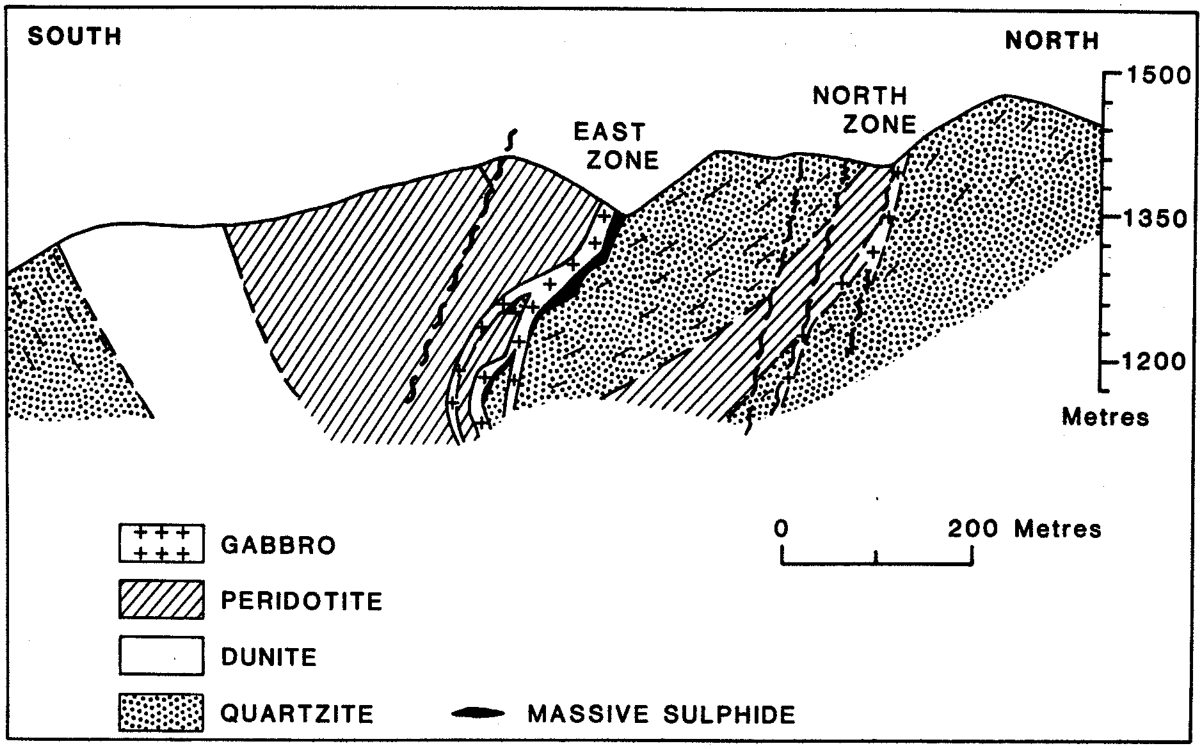


Figure 73. Generalized cross-section of the Wellgreen Complex.

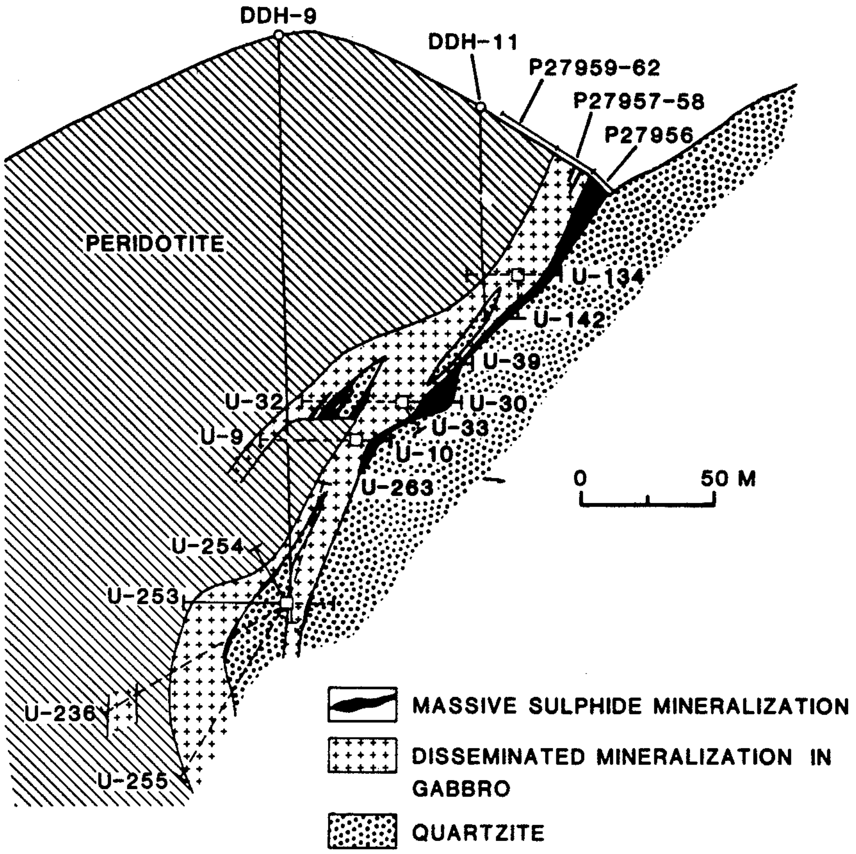


Figure 74. Cross-section through the East Zone of the Wellgreen Mine.

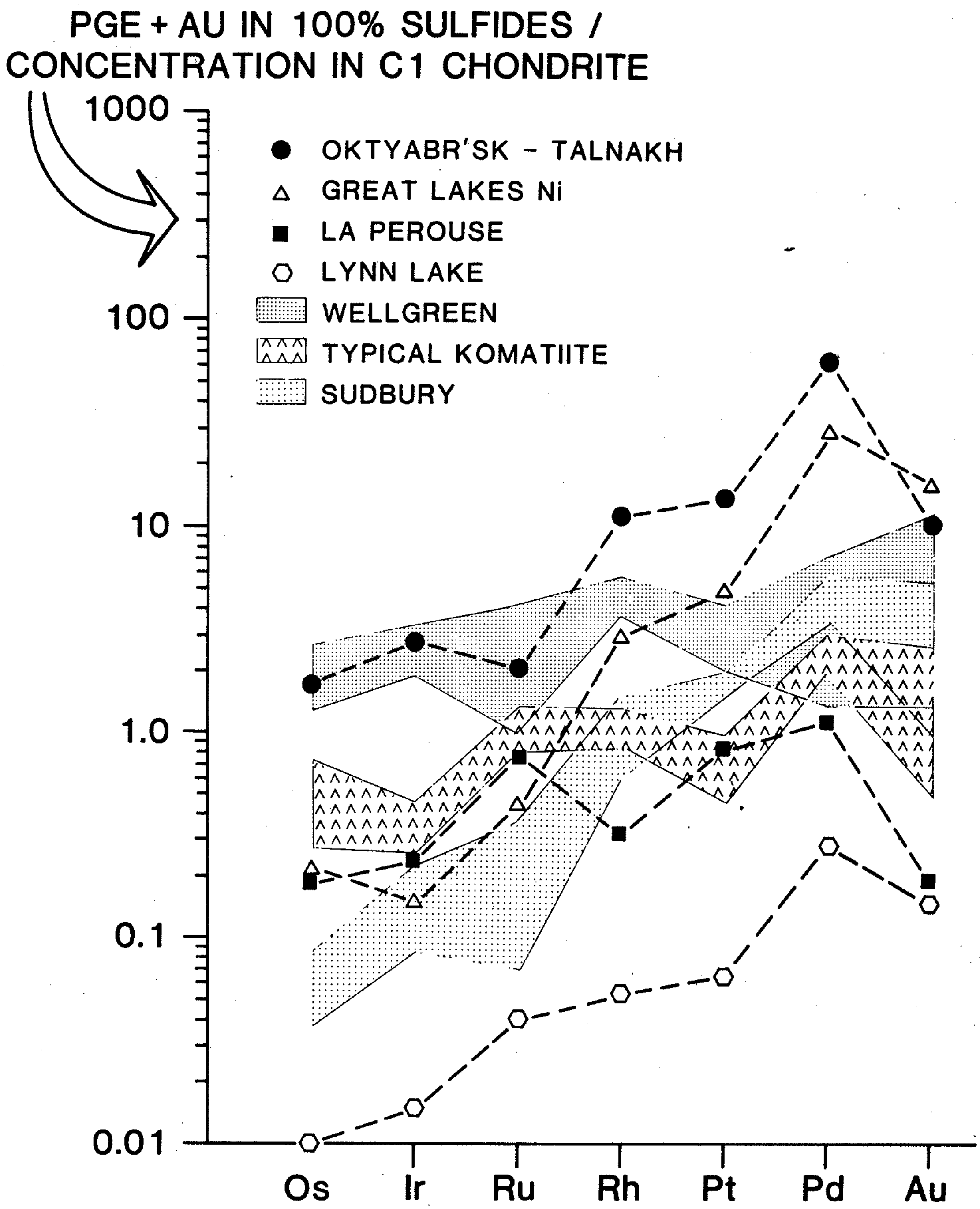


Figure 75. Chondrite normalized PGE profile for Wellgreen massive sulphide ores and ores from other deposits for comparison.

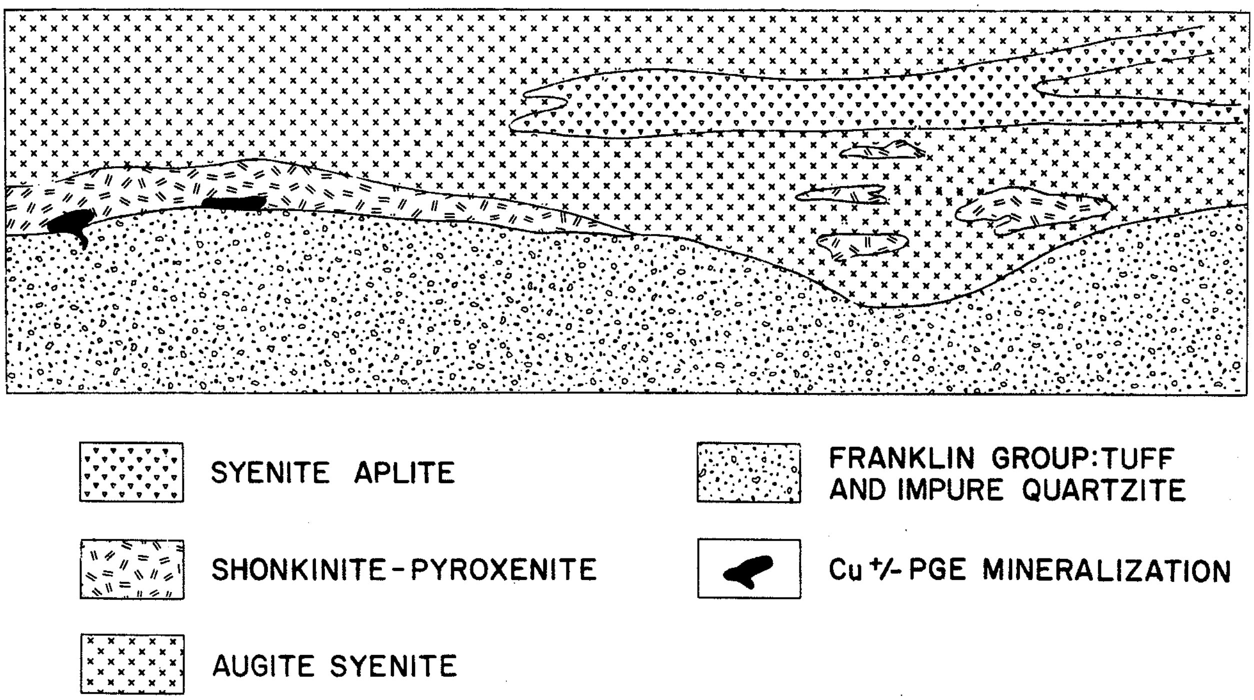


Figure 76. Cartoon of Coryell marginal facies and associated mineralization (after Drysdale, 1915).

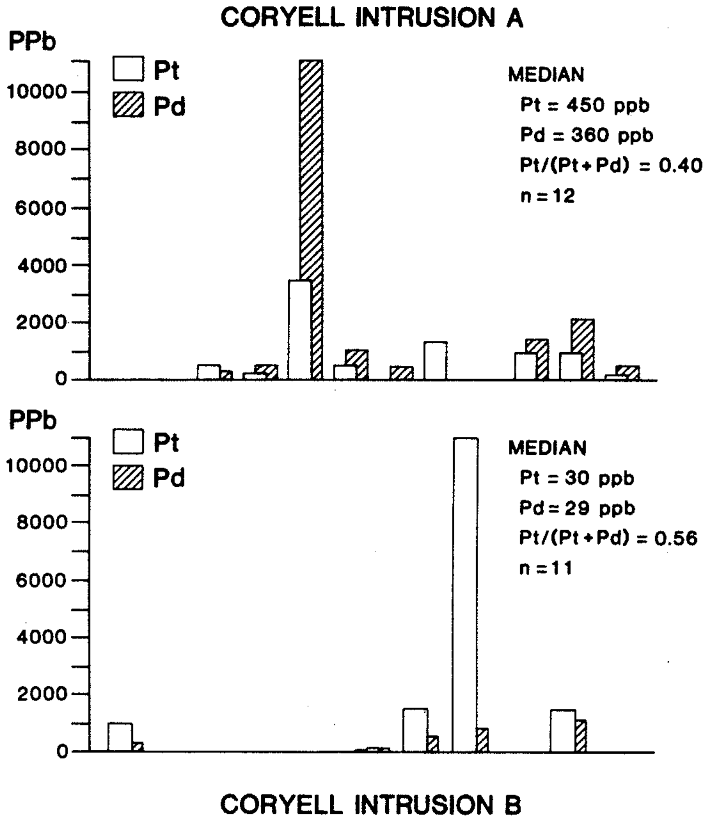


Figure 77. Pt and Pd values associated with copper mineralization at the Maple Leaf (A) and Sappho (B) properties.

Columbia have been known to contain anomalous levels of gold, silver and platinum group metals since 1915 (Drysdale, 1915). These bodies are well known in the area south and west of Nelson, B.C. and as far south as the international boundary. The most noteable occurrences of Cu-Ag-PGE-Au mineralization are at the Maple Leaf property in the Franklin Mining Camp and at the Sappho property in the Greenwood Mining Division.

Geological Setting

The Coryell intrusions comprise a series of alkalic batholiths, stocks and other intrusions of early Tertiary age which are believed to be coeval with the Eocene volcanics in the same area (Boyle, 1982). They consist of syenite, porpryritic augite monzonite, and rare shonkinite and granite. They occur mainly as necks, elongated bodies and dykes of a NE and NW orientation. The mineralization is generally associated with a marginal facies of the intrusion known as the "Black Lead". This facies is a black shonkinite-pyroxenite differentiate of the host augite-syenite intrusion. It consists of large augite phenocrysts (up to 2.5 cm in length) scattered through a groundmass of pyroxene and alkali feldspar. The shonkinite-pyroxenite generally occurs at the margins of the intrusion, however at some properties it is surrounded by augite-syenite (Fig. 76). In many places the trachytoid textured augite-syenite passes rapidly into the shonkinite-pyroxenite. Although irregular, the mineralization generally occurs near the outer margins of the shonkinite-pyroxenite as irregular segregations of chalcopyrite-pyrite +/- bornite in a shonkinite-pyroxenite gangue. The massive and semi-massive concentrations of sulphides tend to be surrounded by, or closely associated with orthoclase. Pyrite is disseminated in low concentrations in the host rock as inclusions within the mafic phases. In the Franklin camp intense thermal metamorphism of the country rock tuffs and impure quartzites occurs within a metre of the contact and secondary amphibole concentrations are abundant up to 3 metres from the contact. Significant concentrations of sulphides also occur in the contact aureole.

The Sappho property is centered 9.6 km south of Greenwood, B.C. and 0.6 km north of the international boundary. The principal rock types in the area of the claim are a microdiorite intrusion, exposed in the central and southeastern portion of the claim, and a younger cross cutting Coryell syenite, monzonite and shonkinite. The Coryell intrusion is poorly exposed but it is estimated to be approximately 350 m in length and from 50 to 170 m wide. These intrusions cut older volcanics and sediments and are best exposed in the south-central part of the area and along the eastern boundary (Church, 1986). The mineralization consists mainly of pyrite and chalcopyrite disseminated in shears, as blebs and pods of the same mineralogy in a biotite shonkinite and sericitized feldspathic pegmatoid phases of the Coryell intrusion. Sulphides are also found in epidote-chlorite-garnet- magnetite skarns near the intrusive contacts.

The Sappho property was worked from 1916 to 1918, and 112 tons of ore, grading approximately 6.06% Cu, was shipped to the Greenwood smelter. This ore contained 197 ppm of silver (O'Neill and Gunning, 1934). Unfortunately, no quantitative PGE assays were made. Recent analyses of samples, collected from this property, reveal Pt + Pd values up to 13 ppm with a median Pt/ (Pt + Pd) ratio of 0.56 (Fig. 77).

The Maple Leaf property is approximately 70 km NNE of the Sappho property and 80 km WNW of the city of Nelson, B.C. In 1915, a shipment of 23 tons of ore from the Maple Leaf property had an average grade of 9.6 percent Cu, 230 ppm Ag, 0.68 ppm Au and 8.9 ppm PGE, and a further shipment of 17 tons of ore in 1917 assayed 5.6 percent Cu, 89 ppm Ag, 4.5 ppm Au and 6.85 ppm PGE. The highest PGE assay recorded during this time was 13.7 ppm (O'Neill and Gunning, 1934). Recent assays on samples collected from this property gave values as high as 14 ppm Pt + Pd. Although the median Pt + Pd value is considerably higher than that for the Sappho samples, the Sappho samples have a much higher Pt/ (Pt + Pd) ratio (Fig. 77). The limited number of samples in Figure 77 are not intended to represent the median values for the deposits, but instead a range of values that can be expected and a confirmation of analytical data from the early part of the century.

A similar environment to the Coryell intrusions is the extensive Eocene alkaline provinces in the Highwood and Crazy Mountains of Montana. The Highwood Mountains of central Montana are well known for their distinctive suite of alkaline extrusive and intrusive rocks. The intrusive rocks occur as groups of laccoliths, stocks and dykes. Six small stocks occur in the central Highwood Mountains and are not much more than 1 sq. mile in area. Most consit of shonkinite and mafic feldspathoid syenites. Nine laccoliths, 1.7 sq. kilometres to 4 sq. kilometres in area occur here and consist primarily of shonkinite and syenite. Of these the Shonkin Sag laccolith is the most famous (Hyndman, 1972). Since this intrusion is the type area for the predominant lithology that makes up the "Black Lead" in the Coryell intrusions, and is the same age, one cannot overlook the possibility of Coryell-type Cu-Ag-Au-PGE mineralization. Although not widely known or appreciated alkaline rocks can contain high concentrations of PGE and have economically favourable ratios of Pt:Pd (> 1.0). This in conjunction with the presence of high concentrations of gold and silver and the need to find new types of geological environments to explore for platinum-group element mineralization renders this alkaline association an important new type of exploration target.

HYDROTHERMAL PGE DEPOSITS

NEW RAMBLER, WYOMING

Introduction

The most frequently cited example of a hydrothermal PGE-deposit is the New Rambler mine

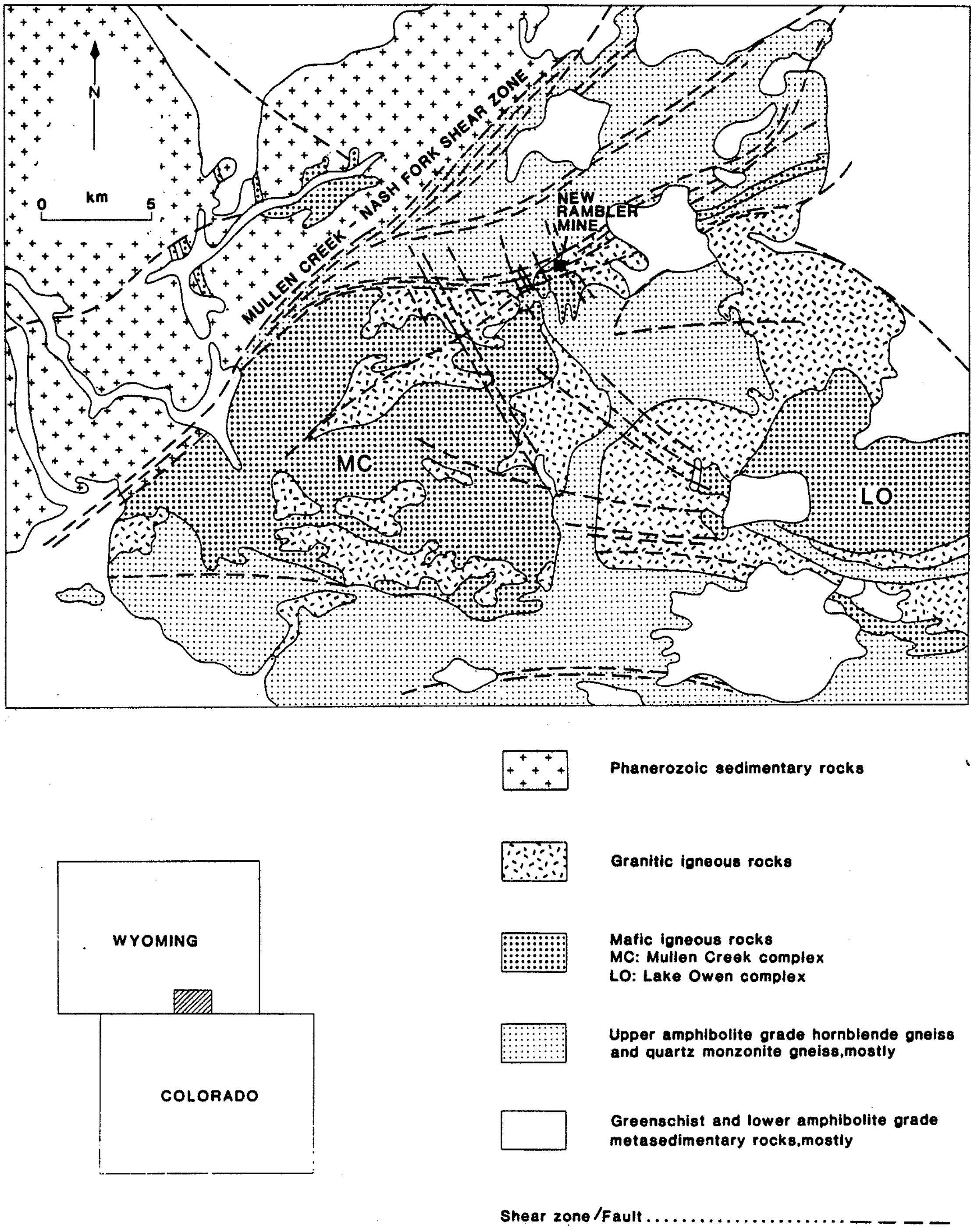


Figure 78. Generalized geological map of the Precambrian of the Medicine Bow Mountains, Wyoming, showing location of the New Rambler mine with respect to the Mullen Creek-Nash Fork shear zone and mafic intrusive complexes (after McCallum et al., 1976).

which is situated in the Medicine Bow Mountains in the Douglas Creek mining district of southeastern Wyoming, approximately 64 km WSW of Laramie. The mine was in operation during the early part of the century and produced ore until 1918 when a fire destroyed the operations and most of the records for this deposit. However, average grades of 75 ppm Pd and 4 ppm Pt were reported for this copper deposit.

A series of northeast trending shear zones dominates the structural fabric of the central part of the Medicine Bow Mountains. The Mullen Creek-Nash Fork shear zone is the most prominant of these and constitutes a major Precambrian lineament which splits the Medicine Bow Mountains into two distinct geological provinces. An east-trending branch of the Mullen Creek-Nash Fork shear zone is the dominant structural feature in the vicinity of the New Ramber mine. The Cu-PGE orebody was located at the intersection of this 1.6 km wide east-trending shear zone with a poorly defined NE-trending shear zone, and a set of four close-spaced NW-trending fractures (Fig. 78).

Cu-PGE Mineralization

The entire mine production came from three irregular pods of ore enclosed in decomposed metadiorite and metagabbro. The orebodies consisted essentially of massive sulphides, irregular nodules of massive sulphide in a jasperoid matrix derived from metagabbro and less abundant jasperoid disseminations in a sulphide matrix (matrix ore). Abundant disseminated fine-grained sulphides in jasperoid also occur in the vicinity of the orebodies (McCallum et al., 1976). All the mined material exhibits some degree (usually intense) of supergene alteration. The sulphide ore can be classified into three distinct associations:

1) An assemblage consisting mainly of pyrite with magnetite as a major accessory phase and traces of chalcopyrite, pyrrhotite and pentlandite. This association occurs as massive and disseminated sulphides in the quartz-sericite wall rock alteration.

2) An assemblage of chalcopyrite and pyrrhotite with minor pyrite and numerous trace accessories including sphalerite, mackinawite, pentlandite, electrum and five PGM occurs in massive sulphide, and as nodular and granular disseminations in the metagabbro. This assemblage makes up the bulk of the mineralization in the area.

3) An association identical to the above in major ore and matrix mineralogy but with a very distinctive base and precious mineral suite consisting of sphalerite, magnetite, pentlandite, electrum and seven PGM.

The evidence supporting the strictly hydrothermal origin for the New Rambler ores include the structural setting, the associated hydrothermal alteration, ore textures and matrix silicate relations. The predominance of the more soluble PGE (Pd and Pt) over the more chemically refractory Ir, Os, Ru and Rh is also significant. The ratio Pd:Pt: (Os + Ir + Rh + Ru) is 1800:100:1. The Pd:Pt ratios in mafic rocks in the vicinity of the New Rambler mine average about 1:1, and average abundances of Pd and Pt in the fresh metagabbros would require an enrichment factor of about 7,500 for Pd and 400 for Pt to generate the levels of Pd and Pt found in the copper ores (McCallum et al., 1976).

PETER LAKE COMPLEX, SASKATCHEWAN

Geological Setting

The Peter Lake Complex is a late Archean (Ray and Wanless, 1980) igneous complex made up of a suite of differentiated mafic plutonic rocks ranging in composition from gabbro to diorite with minor ultramafic and anorthositic components. The main mass of the complex is approximately 200 km long and has a width of 25 to 30 km, and consists of a number of individual intrusions (Fig. 79). Next to the Duluth Complex, the Peter Lake Complex is the largest mafic intrusion in North America. A significant portion of the western and eastern flanks of the complex are made up of sheared equivalents of these gabbros and diorites and are known as the Parker Lake Gneisses. These gneisses verge towards the south into the Needle Falls Shear Zone which is a major feature in the Precambrian of northern Saskatchewan. The axial planar nature of this major zone of shearing with the complex is most striking, and strongly suggests that the shear zone may have been a crustal line of weakness initiated during the late Archean and active through the Proterozoic. It is possible that the complex represents rift related magmatism during late Archean times, and is analogous to the late Proterozoic rift related magmatism that gave rise to the Duluth Complex.

PGE Mineralization

Two types of mineralization are present in the complex. The oldest is low grade magmatic Cu-Ni mineralization that occurs sporadically along the eastern margin. Much later hydrothermal mineralization is associated with a northerly trending set of faults coincident with the Tabbernor Lake system. This hydrothermal mineralization is much higher grade than the magmatic type. Both types of mineralization occur at Ant Lake, 4.2 km west of Patterson Island, Reindeer Lake. At this locality, disseminated magmatic mineralization seldom exceeds 300 ppb Pt + Pd, whereas values as high as 5162 ppb Pt + Pd have been found associated with the hydrothermal type (Fig. 80). The hydrothermal sulphides are typically Cu-rich and Ni-poor. For example, the most PGE-rich sample contained 5162 ppb Pt + Pd, 8060 ppm Cu and only 119 ppm Ni. These high Cu/Ni ratios are typical of PGE mineralization in gabbro hosted hydrothermal deposits such as New Rambler (McCallum et al., 1976) and Rathbun Lake (Rowell and Edgar, 1986). The presence of siginificant PGE mineralization and the immense size of the complex suggest that the Peter Lake Complex has excellent PGE potential.

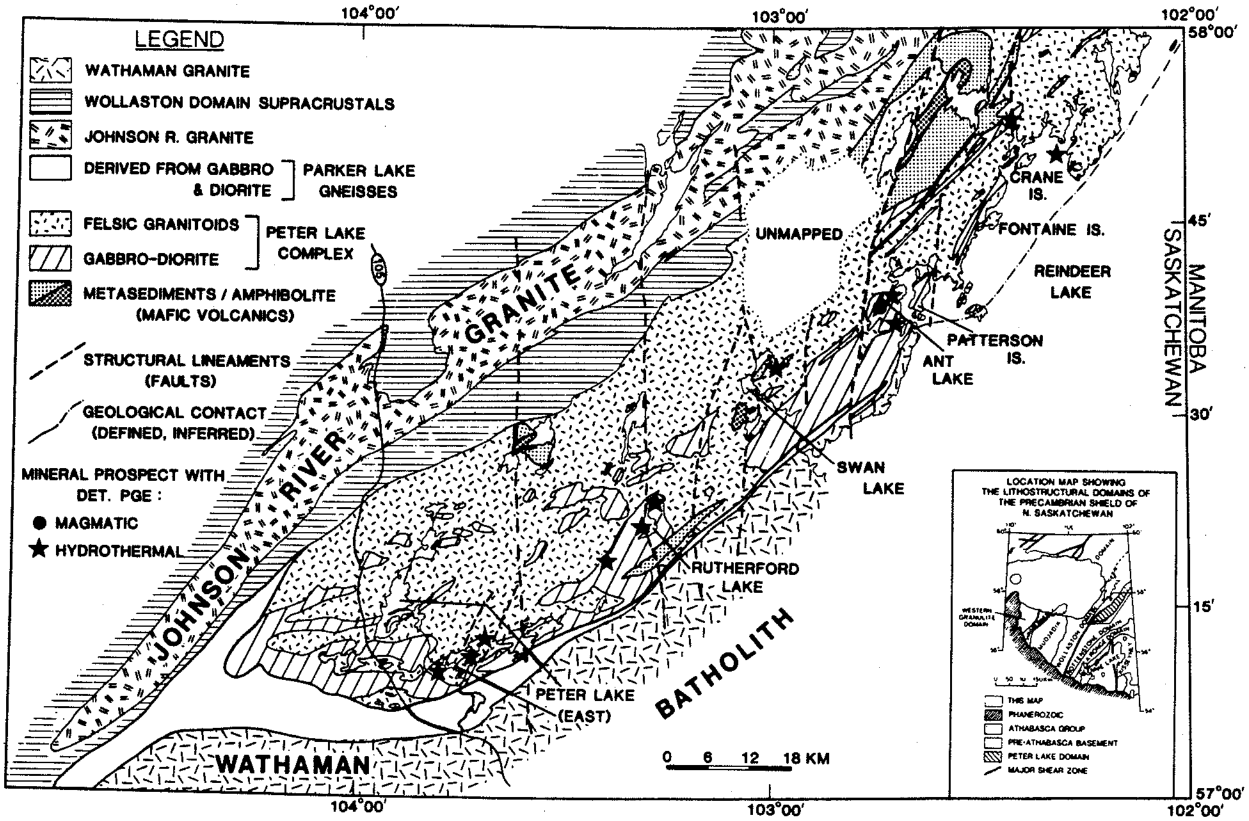


Figure 79. General geology of the Peter Lake Complex.

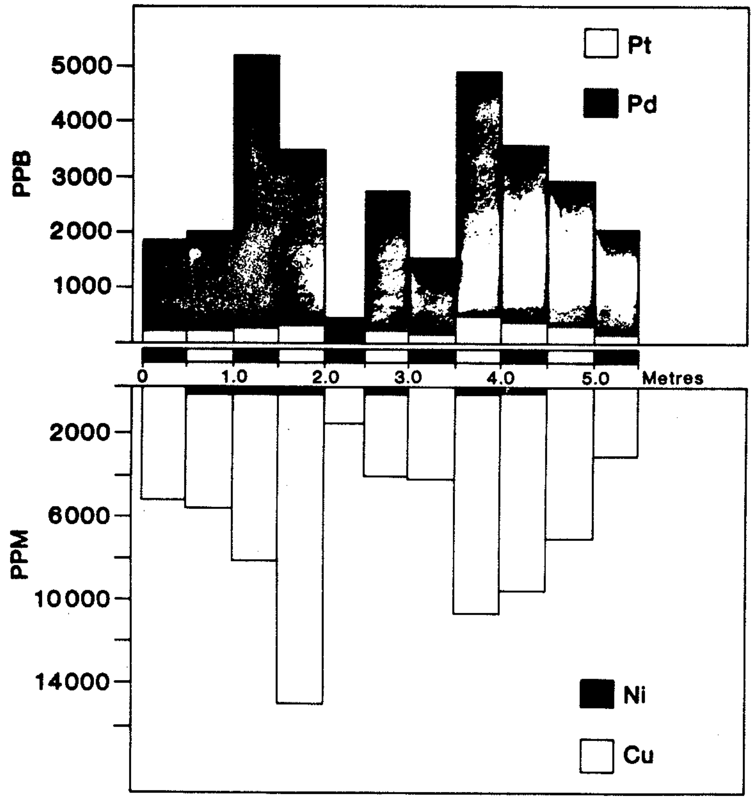


Figure 80. Pt, Pd, Ni and Cu contents of mineralized samples from the Ant Lake showing.

SHETLAND ISLANDS, UNITED KINGDOM

Introduction

Unusually high concentrations of PGE associated with podiform chromite have been reported from Unst, the northernmost of the Shetland Islands (Neary et al., 1984; Gunn et al., 1985; Prichard et al., 1986).

Geological Setting

The geology of Unst is depicted in Figure 81. The western and northern parts of the island are underlain by metasedimentary rocks which have been correlated with the Moinian and Dalradian of the Scottish mainland (Flinn et al., 1972). The ultramafic and mafic rocks which underlie much of eastern Unst and the adjacent island of Fetlar constitute the lower part of an incomplete ophiolite complex (Garson and Plant, 1973; Prichard 1982). Eastwards from the basal thrust, the succession comprises harzburgite tectonite, dunite, wehrlite, clinopyroxite and gabbro cumulates. Potassium-argon age determinations on four amphibole separates from the basal thrust ranged from 465 to 479 Ma, and presumably reflect the timing of ophiolite emplacement (Prichard and Neary, 1985).

PGE Mineralization

Numerous podiform chromite bodies occur within both the harzburgite tectonites and dunite cumulates, and some 52,000 tons of chromite were mined intermittently between 1827 and 1944 (Neary et al., 1984). Ophiolitic chromitites are characteristically enriched in Ru, Os and Ir as compared to most other rock types, and the absolute and relative abundances of PGE in the majority of the Shetland chromitite bodies appear to be typical in this respect. However, two of the chromitite occurrences within the tectonite part of the ultramafic succession are anomalously rich in PGE: these are the "Cliff" and "Harold's Grave" occurrences. In each of these localities, an series of small chromitite lenses ranging up to 1 by 10 metres in size occur en echelon within a dunite envelope in the harzburgite. However, the nature of the PGE mineralization in these occurrences is very different.

At Harold's Grave, the mineralogy and relative abundances of PGE are similar to those in other ophiolitic chromitites with Ru, Ir and Os more abundant than the other PGE and negatively sloping chondrite normalized profiles (Fig. 82). Laurite is the most abundant PGM, although its coarse grain size (up to 250 microns) is unusual (Prichard et al, 1986). What is noteworthy about Harold's Grave is the absolute abundance of PGE in the few published analyses. An average of three chromitites reported by Gunn et al. (1985) contained 4.0 g/t Ru, 1.8 g/t Ir, and 0.37 g/t Pt.

The Cliff occurrence is located within a zone of abundant talc carbonate alteration close to the basal thrust of the ophiolite (Fig. 81). The chromitite is not exposed but numerous samples from the dumps near the old workings returned analyses with tens of grams per tonne PGE, and ranging up to 26 g/t Pt, 46 g/t Pd and 5 g/t Au (Gunn et al, 1985). It is significant that that the dunite wall rocks to the chromitite are also enriched in PGE, although not to the same levels as the chromitites. The samples are atypical of ophiolitic rocks in terms of the relative abundances of PGE and define a steep positive slope on a chondrite normalized profile (Fig. 82). Mineralogically, the Cliff samples are also atypical in that sperrylite, stibiopalladinite, hollingworthite and laurite are the most common PGM (Prichard et al., 1986).

The PGE in the majority of Shetland chromitites is similar to that in ophiolitic environments which is generally regarded as magmatic in origin. The genesis of PGE enrichment at Harold's Grave and, more particularly, at Cliff is problematical. Prichard et al. (1986) favoured magmatic concentration in both localities. Indeed, there are sparsely disseminated magmatic sulphides in chromitite samples which we have collected from these occurrences. Nevertheless, we support the conclusion of Gunn et al. (1985) that the Cliff mineralization is hydrothermal in origin. They cited common occurrence of PGM with veins, and the unusual elemental association (e.g., As, Sb and Te). This conclusion is also consistent with our understanding, albeit incomplete, of the hydrothermal behavior of PGE (see below).

NICHOLSON BAY, SASKATCHEWAN

Introduction

A new type of hydrothermal U-Au-PGE association has been recognized in some of the pitchblende vein deposits in the Beaverlodge mining camp of northern Saskatchewan. This association was first recognized at the Nicholson #2 zone almost 40 years ago but until recently was treated merely as a geological curiosity. Similar U-PGE ores were mined at the Shinkolobwe mine in the Katanga province of Zaire and the ores were treated at Olen, Belgium, where U, Pt and Pd were recovered (Heinrich, 1958). Recent exploration in the Coronation Hill uranium mine area of Australia has revealed similar U-Au-PGE mineralization. The striking similarities in age, lithology, tectonic evolution and associated mineralization with that of the Nicholson Bay area strongly suggests a new type of Au-PGE deposit and metallogenic model.

Geological Setting

The oldest rocks in the vicinity of the Nicholson #2 zone are Proterozoic calcareous metasediments (dolomite) of the Tazin Group, and quartzites (white dolomitic quartzite and red quartzite/ quartzite breccia) of the Murmac Bay Formation (Fig. 83). Thin intercalations of basalt and tuff occur within the sedimentary sequence. These rocks are intruded by peridotite and gabbro which make up the Nicholson Bay Ultramafic Complex. Although there are no available age determinations for the intrusion, it is believed to be about 2100 Ma.

U-PGE-Au Mineralization

In the Nicholson Bay-Fish Hook Bay area there

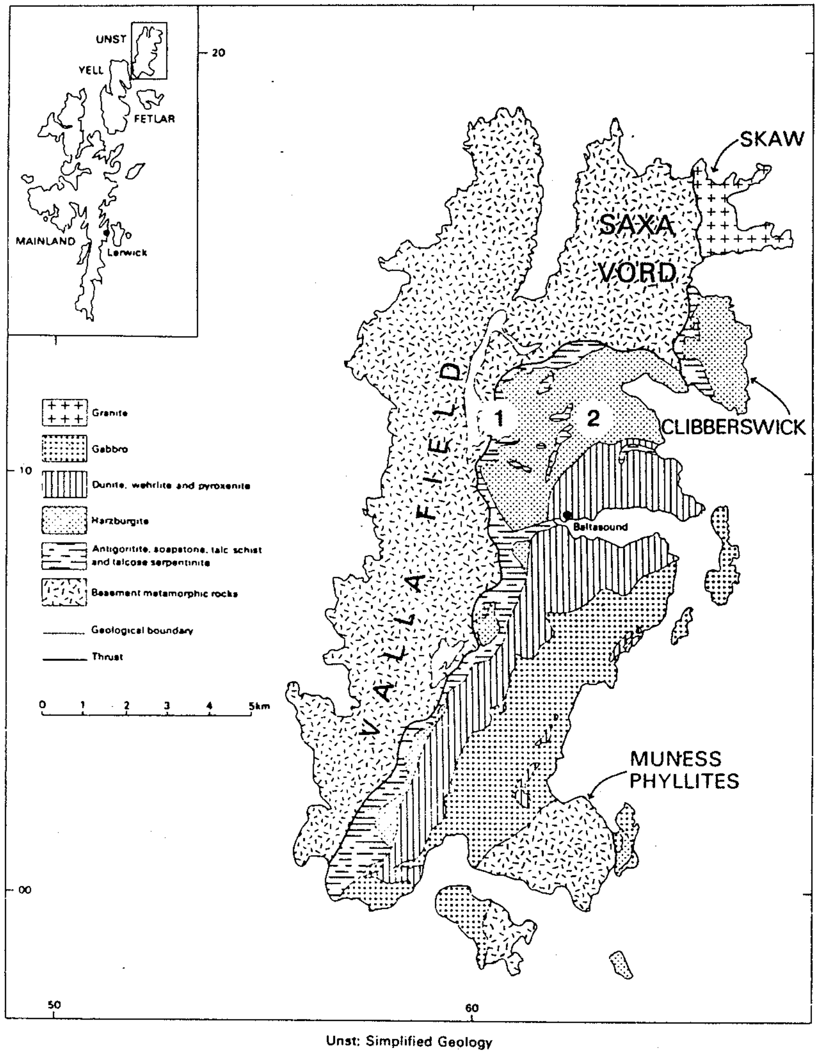


Figure 81. Geology of Unst, Shetland Islands showing the location of the Cliff (1) and Harold's Grave (2) PGE-enriched podiform chromite occurrences (after Gunn et al., 1985).

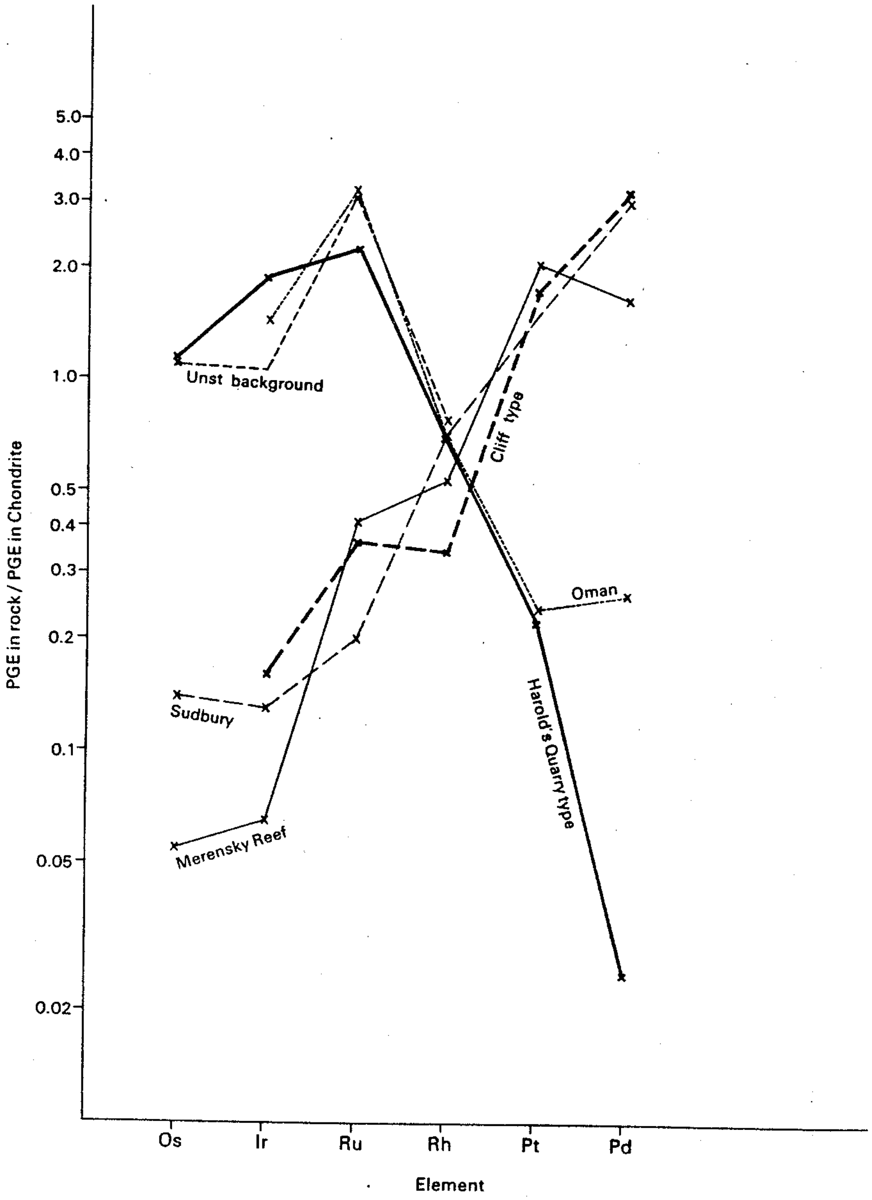


Figure 82. Chondrite-normalized PGE profiles of the Cliff and Harold's Grave chromitites, Unst, Shetland Islands (after Gunn et al., 1985).

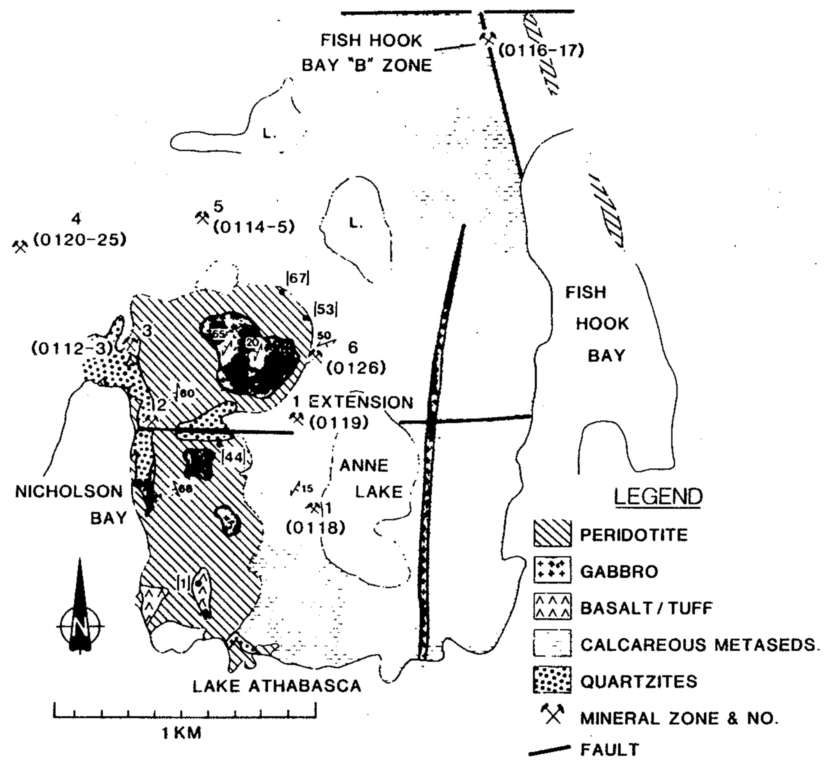


Figure 83. General geology and location of mineralized zones in the Nicholson-Fish Hook Bay area.

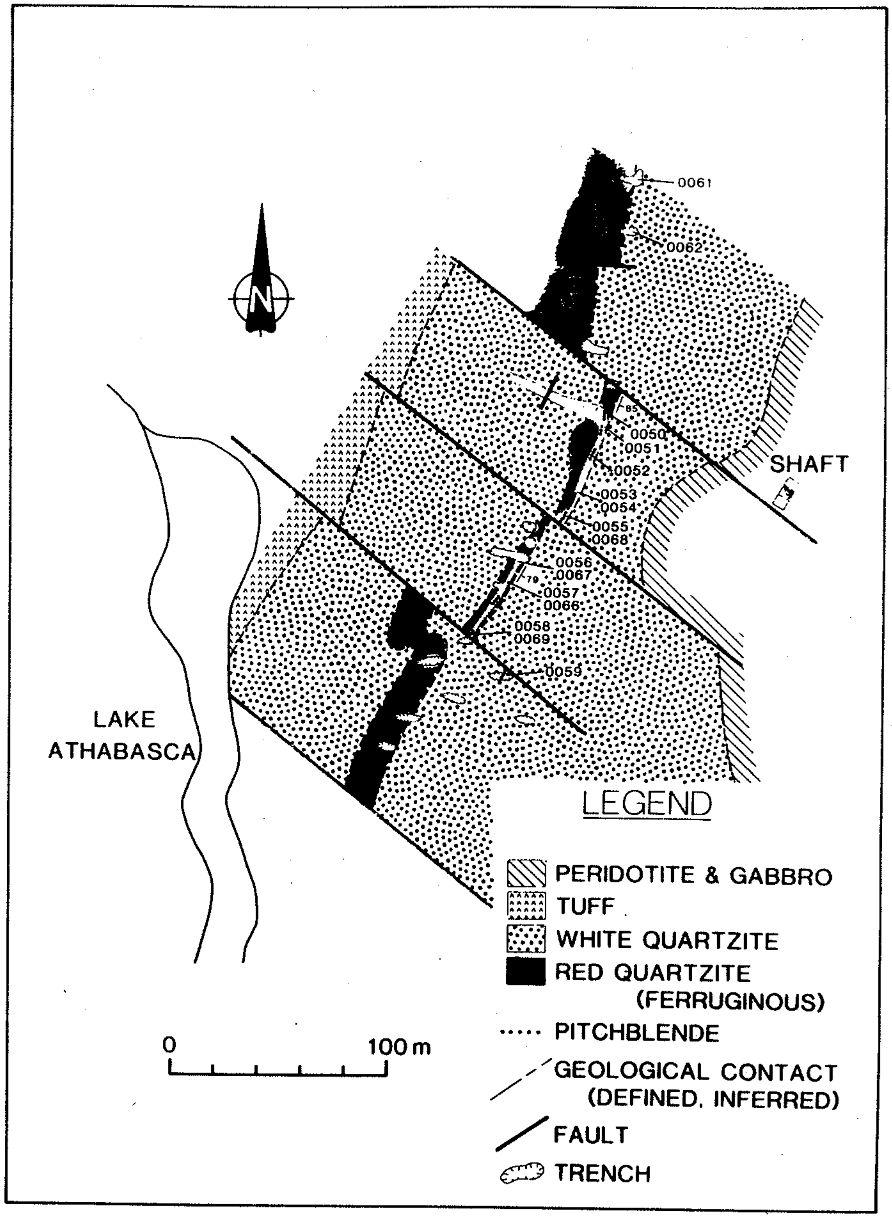


Figure 84. General geology of the Nicholson #2 zone.

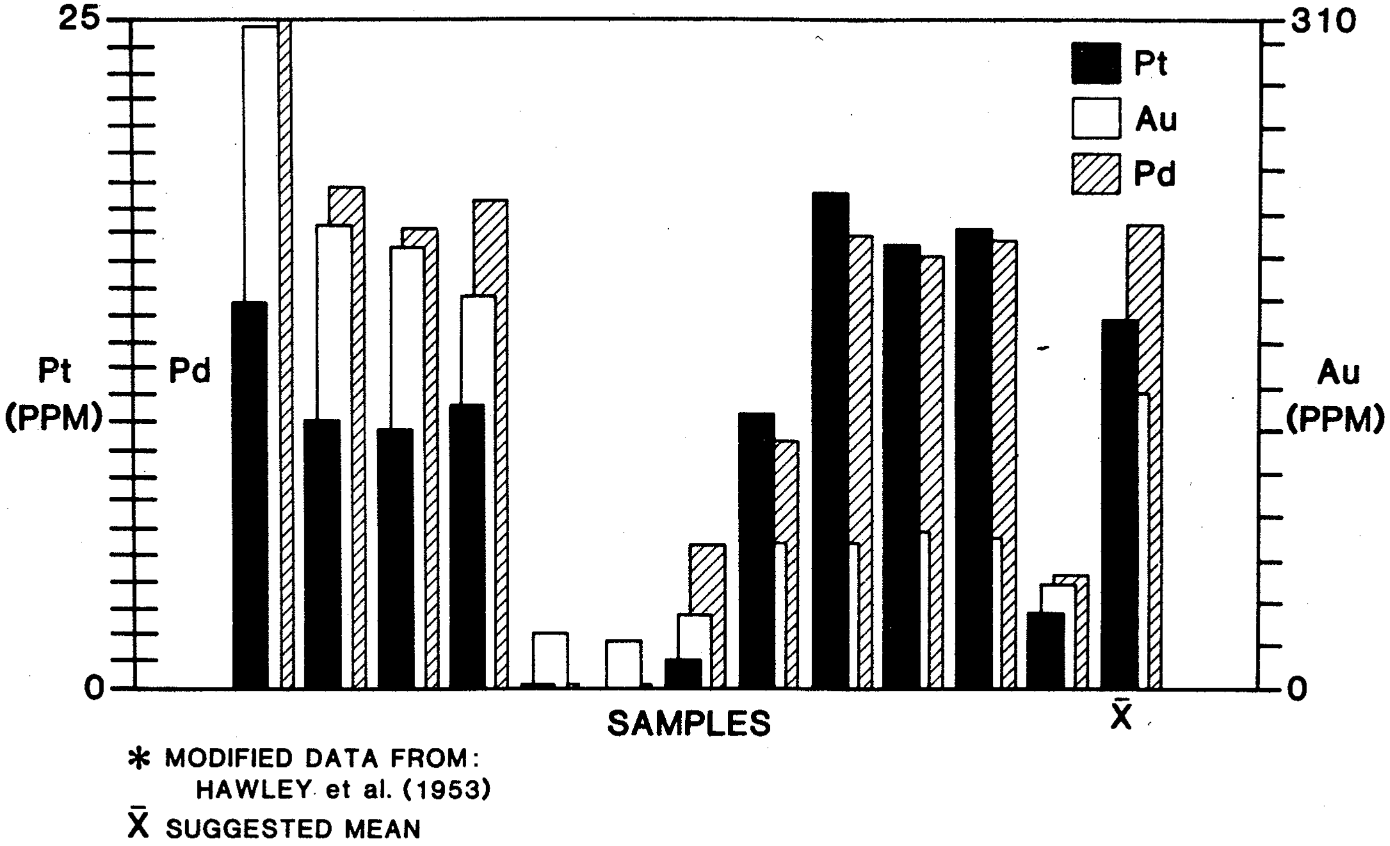


Figure 85. Pt, Pd and Au contents of ores from the Nicholson #2 zone (after Hawley et al., 1953).

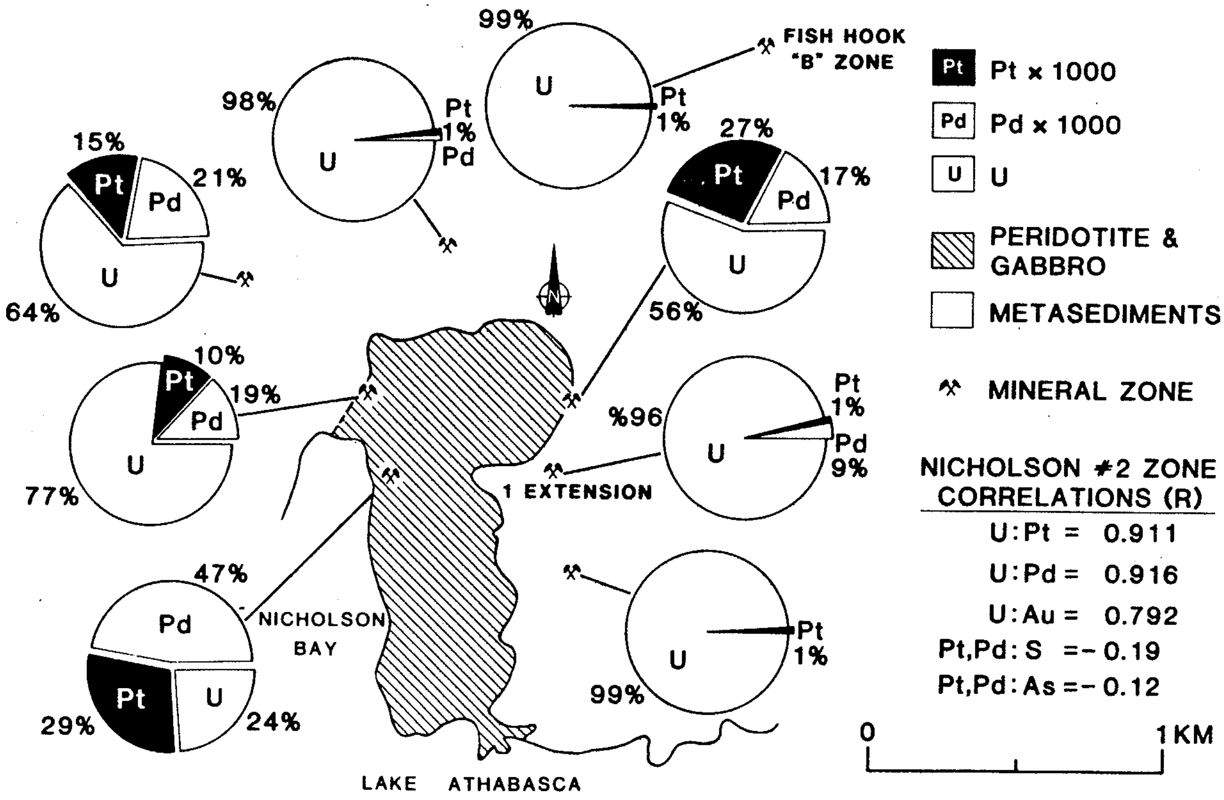


Figure 86. Proportion of Pt, Pd and U in the mineralized zones relative to the proximity of the Nicholson ultramafic complex.

are at least eight zones of pitchblende mineralization, six in the Nicholson Bay area (designated 1 to 6 in Fig. 83) and two in the Fish Hook Bay area. These were discovered as a result of extensive uranium exploration over the past forty years. Significant concentrations of PGE occur at the Nicholson #2 zone and along the east shore of Fish Hook Bay.

The U-Au-PGE mineralization in the Nicholson #2 zone is confined to a steeply dipping carbonate-hematite-pitchblende infilled shear and fracture zone at the contact between the white dolomitic quartzite and the red ferruginous quartzite breccia (Fig. 84). The shear zone trends 025° and dips 75-80° SE. The mineralized zone has a minimum strike length of 54 m and a width of 5 to 60 cm.

Although samples of the ore could not be obtained, Hawley et al. (1953) reported assays from which, with the exception of a few extreme values, a calculated mean grade for this zone is 136 ppm Au, 17.3 ppm Pd, 13.8 ppm Pt, and 0.4 ppm Rh (Fig. 85). Assay results on the Nicholson #2 zone collected in 1950 to access the uranium potential, showed spectacular Au values over narrow widths, for example, 2.85 oz/ton Au over 0.56 m. Recent surface sampling in the vicinity of the #2 zone by one of us (LJH) has confirmed exceptional Pt, Pd and Au values do exist at this locality. The best grab sample ran 5.4 oz/t Au and 2.59 oz/t Pt + Pd.

Significant levels of Au and PGM are also known from the Fish Hook Bay area. Two diamond drill holes cored in 1986 gave the following values: 1.60 m of 2.08 oz/t Au, 0.19 oz/t Pt and 0.41 oz/t Pd, and 0.90 m of 1.71 oz/t Au, 0.35 oz/t Pt and 0.41 oz/t Pd.

Hulbert (in progress) has shown that anomalous levels of PGE are found only where the uranium-bearing shear zones are in the immediate vicinity of the peridotites. Thus, it can be inferred that the PGE are derived locally from the peridotites. Mineralized zones as little as 100 metres from the peridotites are not significantly enriched in PGE like those near the contact. This is illustrated graphicaly in Figure 86 where it can be seen that the proportions of Pt and Pd relative to U are the highest at the Nicholson #2, 3 and 6 zones which are within, or at the contacts of the intrusion. Although peridotite does not outcrop at the Nicholson #4 zone, peridotite from underground workings were observed on surface dumps and thus could account for the relatively high Pt and Pd values at this locality.

Dating done on pitchblende samples from the Nicholson Bay area indicate the age of the mineralization at about 1115 Ma (Koeppel, 1968), about 1000 Ma younger than the inferred age of the intrusion. The inferred low levels of PGE in the source peridotites suggests that the hydrothermal fluids circulating through these rocks were very effective scavengers of PGE. Fluid inclusion studies of similar pitchblende veins in the Beaverlodge area (Sassano et al., 1972) as well as observations at the Nicholson #2 zone suggest that these hydrothermal fluids were very oxidizing and CO2-rich.

The association with uranium means that exploration for this type of deposit should endeavor to identify radiometric anomalies that coincide with mafic-ultramafic plutons and shear zones.

GENESIS OF PGE DEPOSITS

GENESIS OF MAGMATIC PGE DEPOSITS

Introduction

Magmatic PGE deposits form in a mafic or ultramafic silicate magma by the segregation of an immiscible sulphide melt that effectively concentrates the PGE from the parent silicate liquid. The common association of chromite suggests that this phase may also act as a "collector" of PGE, but its exact role remains to be resolved.

One fascinating aspect of magmatic sulphide deposits is that the relative proportions of the ore metals are extremely variable among different deposits (Naldrett et al., 1979; Naldrett and Duke, 1980; Naldrett, 1981). This is illustrated for the PGE in Fig. 87 where it can be seen, for example, that the extremes represented by the JM Reef of the Stillwater Complex and the Montcalm deposit near Timmins, Ontario differ by a factor of more than 10^4.

Several processes determine the size, grade and location of magmatic sulphide deposits, including:

1) generation of a mafic or ultramafic magma by partial melting of mantle peridotite,

2) ascent of the magma into the crust, possibly accompanied by fractional crystallization prior to final emplacement,

3) saturation of this magma with sulphide and the attendant formation of an immiscible sulphide melt,

4) the accumulation of the sulphide melt, and

5) possible modification of the magmatic sulphide by interaction with late magmatic fluids.

In this section, we describe the behavior of the PGE during these processes and then briefly review some of the genetic models which have been proposed for magmatic PGE deposits. A complete exploration of this topic would warrant a volume in its own right. The following is meant to provide merely a summary and an introduction to the literature.

Magmatic Geochemistry of PGE

Element Partitioning

The PGE are strongly partitioned among the various crystalline, molten and fluid phases present in magmas, and the various PGE exhibit different behavior. Abundance patterns of the

PGE in mafic rocks suggest that Pt and Pd behave as incompatible elements during crystallization of silicate and oxide minerals whereas Os, Ir, Ru and Rh are moderately compatible with olivine, pyroxene and spinel (Naldrett and Duke, 1980). That is, the concentrations of Pt and Pd will be higher in the silicate melt than in the co-existing silicate and oxide minerals but the concentrations of Os, Ir, Ru and Rh will be higher in the crystalline phases. All the PGE are extremely chalcophile and siderophile, and will partition strongly into a molten sulphide or metal phase if one is present.

The distribution of elements may be expressed quantitatively in terms of the Nernst partition coefficient:

$$D^{x/y} = c^{x}/c^{y}$$

where c^{x} and c^{y} are the concentrations of an element in phases x and y. The precise value of the partition coefficient will be a function of temperature, pressure, the concentrations of other elements in each phase, and so on. However, approximate values are sufficient to demonstrate general principles. Typical values of partition coefficients for some chalcophile elements are presented in Table 20. It is important to note that whereas the coefficients for Ni, Cu, and Co are based upon experimental observations, those for the PGE are inferred from the compositions of natural phases. In particular, while there is wide agreement that the partition coefficients for PGE between sulphide and silicate melts are very large, estimates range over 4 orders of magnitude: that is, from 200 (Ross and Keays, 1979), through 1500 (Naldrett et al., 1979) to 100,000 (Campbell and Barnes, 1984).

Magma Generation

The mafic and ultramafic magmas from which magmatic PGE deposits are derived are generated by partial melting of mantle peridotite. The relatively few available analyses of spinel and garnet lherzolite nodules which reflect the composition of upper mantle contain 0.005 to 0.01 chondritic abundances and are essentially unfractionated. The strong depletion relative to chrondrite presumably reflects the partitioning of PGE into the earth's metallic core. The mantle is believed to be inhomogeneous but unfortunately there are insufficient data to indicate the extent of variation in PGE abundances.

The concentration of a trace element (c^{L}) in a partial melt may be calculated from the following equation derived by Shaw (1970):

$$\frac{c^{L}}{c_{o}} = \frac{1}{D_{o} + F(1-D_{o})}$$

where c^{L} is the concentration in the liquid after melting of a fraction F of a solid in which the initial concentration was c_0, and D_0 is the bulk residuum/silicate liquid partition coefficient weighted according to the relative masses of the phases in the residuum.

Naldrett and Barnes (1986) have modelled the partial melting of a typical spinel lherzolite initially containing 60 percent olivine, 25.2 percent orthopyroxene, 12 percent clinopyroxene, 2.8 percent spinel,and from 0 to 0.2 percent sulphide. In the model, the bulk partition coefficients (Table 20) were adjusted to account for the change of the proportions of phases in the residuum and also the liquid composition as melting proceeded. The modelled concentrations of Pd and Ir are illustrated in Figure 88. (The behavior of Pt would be similar to that of Pd, whereas the behavior of Ru, Os and Rh would be similar to that of Ir.)

When no sulphide remains in the residuum, Pd is incompatible throughout melting and its concentration is highest in the initial melts and declines as melting proceeds. The concentration of Ir, which is a compatible element, increases as the percentage of melting increases. Accordingly, the concentration of Pd and the Pd/Ir ratio are expected to be highest in melts generated by smaller degrees of partial melting.

The patterns are very different when even a small amount of sulphide is present in the residuum, however, with the concentrations of both Pd and Ir being extremely low in the partial melts until virtually all the sulphide is consumed. The amount of melting required to consume the sulphide depends upon the amount initially present but it does not seem likely that any sulphide would remain once the mantle has undergone as much as 25 percent melting. The Pd/Ir ratio in the melt remains near unity so long as sulphide is present which is very different from melting in the absence of a sulphide phase.

Most basaltic magmas probably represent from 10 to 25 percent partial melting of mantle peridotite whereas the extremely magnesian komatiite liquids would require up to 60 percent melting. The available data for PGE abundances in rocks believed to reflect the compositions of mantle melts vary over a wide range (Table 21). The average concentrations in komatiitic melts agree reasonably well with a simple model involving 60 percent partial melting. Similarly, the concentrations in marginal rocks of the Bushveld and Stillwater Complexes and in continental tholeiites are consistent with 10 to 25 percent partial melting with no sulphide in the residuum. Mid-ocean ridge basalts on the other hand are strongly depleted in PGE which might indicate that sulphide was present in the residual mantle. However, the Pd/Ir ratio is not consistent with this.

Fractional Crystallization

Mafic and ultramafic magmas may be expected to undergo at least some fractional crystallization during their ascent from the mantle and emplacement in the crustal magma chamber in which they ultimately come to rest, and the fractional crystallizatiuon process will alter the absolute and relative abundances of PGE in the magma. The effects of fractional crystallization may be calculated using the Rayleigh Fractionation Law

$$c^L = c_o^L F^{(D-1)}$$

where c^L is the concentration of the element in the derivative melt, c_o^L is its concentration in the parent melt, F is the mass fraction of the parent melt represented by the derivative melt, and D is the bulk partition coefficient.

The calculated concentrations of Pd and Ir in a sulphide undersaturated magma undergoing fractional crystallization of olivine are illustrated in Figure 89. Since Pd is considered to be completely incompatible with olivine, its concentration in the melt increases as crystallization proceeds. In fact the enrichment is by a factor of 2 after 50 percent crystallization and a factor of 10 after 90 percent. The pattern would be the same if crystallizing phases were pyroxenes or plagioclase since Pd is incompatible with these as well. The concentrations of compatible PGE, on the other hand, decrease rapidly. The net effect of fractional crystallization of olivine alone is to rapidly increase the Pd/Ir ratio. By analogy with Ni, it is assumed that Ir is less strongly partitioned into the pyroxenes than olivine and the depletion of Ir due to removal of pyroxene or mixtures of pyroxene and olivine would be less severe than for olivine alone. Similarly, because Ir is incompatible with plagioclase, and plagioclase fractionation would enrich the liquid in Ir.

The trends are very different for fractional crystallization of sulphide-saturated magma. The crystallization of silcate or oxide minerals from sulphide-saturated magma will cause the segregation of an immiscible sulphide liquid (e.g., Duke and Naldrett, 1978; Duke, 1979). Even though the proportion of immiscible sulphide will be small relative to that of crystalline silicate, because the sulphide melt/silicate liquid partition coefficients are so large, the resultant bulk partition coefficient is also large. The consequence of this is that fractional crystallization of a sulphide-saturated magma will bring about rapid depletion of all the PGE.

Sulphide Segregation

The fundamental requirement for the generation of a magmatic sulphide deposit is that the magma becomes saturated with sulphide at some point during its crystallization history so that an immiscible sulphide phase may form. Some magmas may be sulphide saturated from the time of generation in the mantle. There is some evidence, for example, that this was the case for mid-ocean ridge basalts (e.g., Czamanske and Moore, 1977; Duke, 1979). Such early saturation is not favourable for the generation of magmatic ores because early separation of sulphide would leave the magma depleted in chalcophile elements. Alternatively, an initially undersaturated magma may become saturated due to any of several factors acting alone or in combination. These include cooling and crystallization, contamination by siliceous material (Irvine, 1975), assimilation of country rock sulphur (e.g., Mainwaring and Naldrett, 1977), oxidation (MacLean, 1969), increase in pressure (Wendlandt, 1982), and magma mixing (Irvine, 1977).

Once a magma becomes saturated and an immiscible sulphide melt segregates from the silicate liquid, the chalcophile elements including the PGE are strongly partitioned into the sulphide melt. Whereas the relative concentrations in the two immiscible liquids are given by the partition coefficients (Table 1), the absolute concentrations are a function of the relative masses of sulphide and silicate.

This is demonstrated by the relationship derived by Campbell and Naldrett (1979)

$$c^s = \frac{c_o^L D^{s/L}(R+1)}{(R+D^{s/L})}$$

where c^S is the final concentration of an element in the sulphide melt, c_o^L is the initial concentration in the silicate liquid prior to sulphide segregation, R is the ratio of the mass of silicate liquid to the mass of sulphide liquid, and $D^S/^L$ is the sulphide/silicate liquid partition coefficient as defined above.

The value of R which obtains in any given situation in nature is not readily determined but will depend in part on the cause of sulphide segregation. Perhaps the simplest case is that of a cooling sulphide-saturated magma in which sulphide is forced out of solution due to crystallization of silicate minerals and the attendant decrease in the mass of silicate liquid. In this case, the R value is a function of the sulphide solubility and the amount of crystallization. For example, if the sulphide solubility is 1 wt. percent (i.e. about 0.33 percent S), the R value would be about 10^4 for 1 percent crystallization or about 10^3 for 10 percent crystallization. Much lower R values are possible when sulphide saturation occurs as a result of local assimilation of country rock sulphur.

The variation of the concentrations of Cu, Co, Ni, and Pd in sulphide melt as a function of R is illustrated in Figure 90. The highest concentrations of chalcophile elements are achieved at the highest R values. More importantly, the higher the partition coefficient, the more sensitive the concentration of the element in the sulphide will be to the value of R. Thus the concentration of Co (D=60) only sensitive to R where the latter is about 10^2 or less, and the concentration of Ni (D=275) only decreases significantly as R drops below 10^3. The concentrations of Pd and the other PGE, on the other hand, are strongly dependent upon the R value throughout the magmatic range.

The concentrations of major metals and PGE in most magmatic Ni-Cu ores can be successfully modelled on the basis of R-values of the order of 10^4 or less. (e.g. Naldrett and Duke, 1980; Naldrett, 1981). However, the PGE tenor of sulphide of the major stratabound deposits including the Merensky Reef, the J-M Reef and the UG-2 chromitite are less readily explained. Naldrett and Duke (1980) pointed out that the high PGE tenor implied that either the PGE concentration in the parent magma or the PGE partition coefficient was 10 to 1000 times greater than the generally accepted values. Subsequently, Campbell et al. (1983) have argued that to form the very PGE-rich magmatic sulphides in the Merensky Reef and JM Reef, R-values of the order of 10^5 to 10^6 and PGE partition coefficients of 10^5 were required.

Genetic Models - A Brief Review

Stratabound Magmatic Deposits

The most important examples of this type are the Merensky Reef and UG-2 chromitite of the Bushveld Complex and the J-M Reef of the Stillwater Complex. There are a number of striking similarities among these deposits, including their occurrence at clearly defined horizons in the igneous stratigraphy over tens or hundreds of kilometres, their position at or near the base of cyclic units, the association of PGE with ostensibly magmatic sulphides, the presence of pegmatoidal or coarse grained textures within or immediately below the mineralized units, the presence of hydrous minerals such as biotite and apatite, and the presence of graphite.

However, there are also important differences. The Merensky Reef and the UG-2 chromitite correspond to lithological layers and, apart from the irregularities represented by the potholes in the Merensky, are essentially stratiform as well as stratabound. The J-M Reef, on the other hand, is a stratigraphic interval defined by the presence of PGE-bearing sulphides and is locally discordant. The Merensky Reef is made up mainly of a pegmatoidal bronzite layer with thin chromitite layers at its base and top. The UG-2 is mainly chromitite with minor pyroxenite layers. The J-M Reef "package" includes peridotite, troctolite and anorthosite, and only minor amounts of cumulus chromite occur.

While there can be little doubt that these deposits are of magmatic origin (sensu lato), the precise nature of the processes which led to the concentration of PGE within them remains highly controversial. Many of the early genetic hypotheses concerning the Merensky Reef were summarized by Vermaak (1976) whereas some more recent models were reviewed by Naldrett et al. (1987). Perhaps the most fundamental question concerns whether the enrichment of PGE was synchronous with accumulation of the cumulate pile or occurred somewhat later through transport and deposition by late magmatic or hydrothermal fluids.

Magma Mixing

There is now abundant evidence that in the case of both the Bushveld and Stillwater Complexes, inputs of two or more chemically distinct magmas were involved (e.g., Sharp, 1981; Todd et al., 1983). These two magmas were designated as "U-type" and "A-type" by Irvine et al. (1983) because they give rise to cumulates dominated by mafic minerals and plagioclase respectively. Moreover, the Merensky Reef and the J-M Reef each occur at or near the stratigraphic level marking the transition between cumulates derived from the contrasting magmas (Sharp, 1985; Todd et al., 1983). It is not unreasonable, therefore, to appeal to mixing of the two magmas to give rise to PGE reefs, especially since it has been shown that magma mixing can bring about saturation in both sulphide and chromite (Irvine, 1977).

Two models for magma mixing have been proposed, both of which incorporate the concept of compositionally and density stratified magma chambers. The turbulent plume model (Campbell et al., 1983; Naldrett et al., 1987) is illustrated in Figure 91. This involves injection of a pulse of buoyant primitive magma into a density stratified magma chamber. The plume convects turbulently as it rises, entraining and mixing with host magma. The plume rises until it reaches the level of its own density where it spreads out to form a layer. The mixing and attendant cooling cause sulphide saturation, and the turbulent convection ensures that the sulphide melt which segregates remains in suspension and mixes with a large volume of magma, thus attaining a high R-value and maximizing the tenor of PGE. Eventually, the hybrid layer cools to the point where turbulent convection subsides, allowing suspended crystals and sulphide droplets to settle or be carried to the floor of the chamber by convective overturn.

The second mechanism is the double diffusive convective magma mixing, proposed by Irvine et al. (1983) and illustrated in Figure 92. This model incorporates a novel concept of the formation of igneous layering whereby gently inclined layers are not deposited sequentially but rather form concurrently by downdip accretion with each rock layer crystallizing from a corresponding liquid layer. In the case of the J-M Reef, Irvine et al. (1983) envisaged that the intrusion had evolved to the stage where the resident U-type magma consisted of three major liquid layers which, from the base upward, were crystallizing bronzite, plagioclase+bronzite, and plagioclase+bronzite+augite. An influx of A-type liquid, then entered the chamber and, being denser than the resident U-type liquid spread out underneath it. Double-diffusive finger mixing of the two liquids would have occurred along their interface. Whereas the U-type liquid was initially saturated with bronzite and the A-type with plagioclase, the resulting hybrid liquids were initially unsaturated and capable of resorbing cumulates in adjacent layers. Irvine et al. (1983) suggested such resorbtion may explain the enigmatic potholes and the dimpled lower contacts which are characteristic particularly of the Merensky Reef. A second consequence of mixing was that the U-type hybrids became saturated with olivine rather than bronzite. The initial mixing of the U- and A-type liquids did not bring about sulphide saturation. The fractionated liquid produced at the face of accreting plagioclase cumulates was denser than the adjacent liquid layer and moved downward. The fractionated liquid at the face of accreting olivine cumulates, on the other hand, was less dense than that in the adjacent liquid layer and flowed upward. Irvine et al. (1983) postulated that precipitation of sulphide to form the J-M Reef occurred where this fractionated liquid mixed with liquid in an overlying layer precipitating olivine+plagioclase cumulates.

Filter Pressing

A model proposed initially by Vermaak (1976) and supported by von Gruenewaldt (1979) involved formation of the Merensky Reef from intercumulus liquid expelled from the underlying partially consolidated cumulates which became trapped under a relatively impermeable anorthositic mat. The intercumulus liquid would be enriched in incompatible elements including PGE, sulphur and volatiles by postcumulus fractional crystallization. For example, 50 percent crystallization of the intercumulus melt would double the concentration of Pt and Pd (e.g., Fig. 89).

Variations of this model have been proposed by Gain (1985) for PGE in the UG-2 chromitite and by Scoates et al. (1986) for PGE enrichment in the Lower Chromitites of the Bird River Sill. According to Gain's model, illustrated in Figure 93, magmatic sulphides accumulate initially with the chromite from the main body of magma but are further enriched in PGE through equilibration with upward migrating intercumulus liquids. This is an alternative mechanism for achieving a high R-value.

Naldrett et al. (1987) have argued against this mechanism in the case of the Merensky Reef because the upward migrating intercumulus liquid would have been stripped of its PGE as it passed through the sulphide-bearing Pseudoreef and UG-2. Also, if the Merensky pegmatoid crystallized from or reacted with ascending intercumulus liquid, the bronzite might be expected to have a lower Mg-number than the adjacent units, which is not the case (Naldrett et al., 1986).

Deuteric Enrichment

Jackson (1961) suggested that pegmatitic patches underneath certain chromitite layers in the Stillwater Complex resulted from the trapping of hydrothermal fluids beneath relatively impermeable chromite cumulates. Lauder (1970) extended this proposal to explain the laterally continuous Merensky pegmatoids and suggested further that the PGE were introduced into the Reef by hydrothermal fluids which moved upward through the cumulate succession and became trapped upon encountering the impermeable pyroxenite cumulates which immediately overlie the Reef. Subsequent studies have revealed the presence in both the Merensky Reef and J-M Reef of chlorine-rich hydrous minerals, fluid inclusions in postcumulus quartz and feldspar, and other features indicative of the presence of aqueous fluids (Ballhaus and Stumpfl, 1986; Stumpfl and Ballhaus, 1986; Johan and Watkinson, 1985; Boudreau and McCallum, 1985; Mathez et al., 1985).

Perhaps the most convincing case for the magmatic hydrothermal origin of stratabound mineralization has been made by Boudreau and McCallum (1986) for the Picket Pin deposit in the Stillwater Complex. They argue that high temperature fluids migrated upwards during solidification of interstitial melt in the underlying cumulates and were effectively trapped when they encountered the relatively impermeable overlying adcumulates. Several lines of evidence support this model including the presence of discordant, pipe-like zones of sulphide mineralization in the footwall, the association of PGE-bearing sulphides, arsenides and antimonides with quartz and apatite, and the enrichment of the mineralized horizon in incompatible elements. Calculations by Boudreau and McCallum (1986) indicate that the fluids were rich in silica, alkalis, HCl and HF.

Discordant PGE Mineralization

The best examples of discordant PGE mineralization in layered intrusions are the dunite pipes of the Bushveld Complex. Early models for their formation involved intrusion of a ultramafic magma (Wagner, 1929; Heckroodt, 1959). Cameron and Desborough (1964) argued convincingly that the dunite formed by replacement of anorthosites, norites and bronzitites of the adjoining Critical Zone by high temperature aqueous fluids. Schiffries (1982) developed this model further in terms of a process of infiltration metasomatism. He proposed that fluids flowing through irregular channelways near the pipe axis gave rise to reaction fronts which moved outward at different rates and resulted in the characteristic metasomatic zonation. Schiffries believed that PGE and base metals were transported in the fluid as aqueous chloride complexes. He noted also that the large decrease in volume associated with the metasomatic reaction could account for the collapse structures in the Critical Zone rocks adjacent to the Driekop Pipe.

Marginal Sulphide Accumulations

The majority of the world's economic Ni-Cu-PGE deposits may be characterized as massive to heavily disseminated accumulations of sulphide at or near the floor or walls of intrusions, or at the base of komatiitic lava flows. Duke and Naldrett (1983) have argued that during the normal evolution of a sulphide-saturated mafic magma, sulphide segregation will accompany precipitation of a relatively large proportion of silicate crystals. The presence of numerous crystals impedes the coalescence of sulphide droplets and their accumulation into high grade pools. Duke and Naldrett (1983) envisaged two circumstances that would favour the formation of massive accumulations. In one case, if the magma becomes sulphide saturated prior to or during emplacement, sulphide droplets could become mechanically segregated from the silicate crystals during flow of the magma and accumulate, for example, in footwall depressions or other structural traps. Alternatively, massive sulphides could readily accumulate if the magma was saturated in sulphide but undersaturated in silicate minerals. The most direct means to achieve this condition would be to add sulphur directly to the magma through the assimilation of country rock. Alternatively, under certain circumstances it is possible for a magma composition to move into the primary phase field of sulphide by mixing with less primitive magma or contamination with felsic material (Irvine, 1975, 1977). There is a growing body of

Table 20. Nernst Partition Coefficients of the Chalcophile Elements

Element	olivine / liquid	orthopyroxene / liquid	clinopyroxene / liquid	spinel / liquid	sulphide / liquid
Pd	0	0	0	0	10^5
Ir	10	4	2	12	10^5
Ni	10	4	2	12	275
Cu	0	0	2	4	250
Co	4	1.5	1	3	60

Table 21. Concentrations of Pd and Ir in Mafic and Ultramafic Magmas (in parts per billion)

	Pd (Range)	Pd (Avg)	Ir (Range)	Ir (Avg)	Pd/Ir (Avg)
Mid-Ocean Ridge Basalts[1]	<0.1-6.9	1.0	0.0011-0.116	0.01	50
Continental Tholeiites					
Average[2]		8.3		0.092	100
Logan Sills[3]	<5 - 24	15.2		0.52	30
MacKenzie Dykes[4]	22 - 30	24.3			
Bushveld Marginal Rocks[5]	10 - 30	20	0.2 - 0.6		
Stillwater Marginal Rocks[6]		55	0.2 - 0.3	0.25	220
Spinifex Texture Komatiites[7]		8.6		1.2	7.2

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[1] Hertogen et al. (1980); [2] Crocket (1981); [3,4] GSC Unpublished Data; [5] Sharpe (1982);
[6] Page (1976); [7] Crocket (1981)

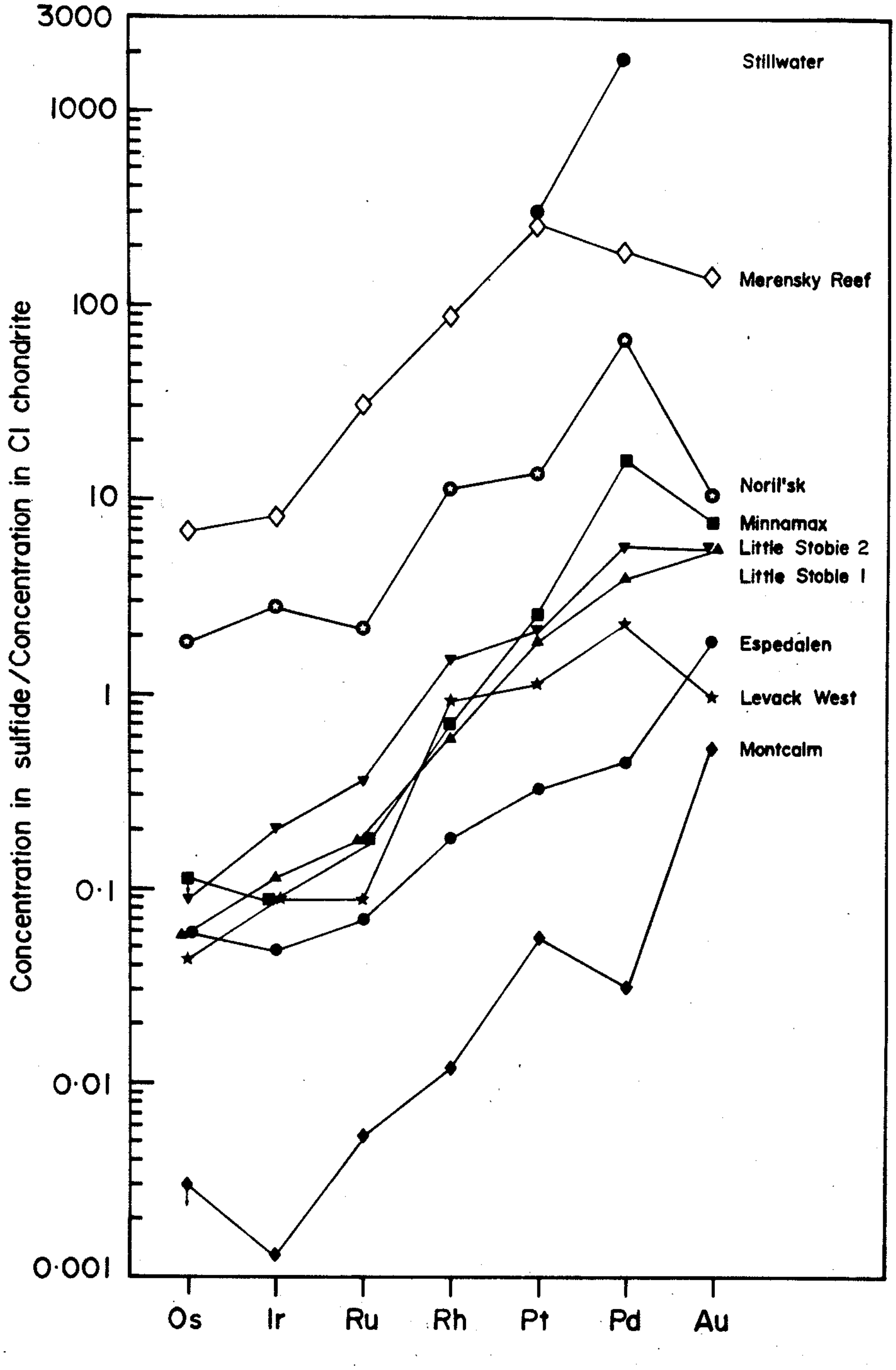

Figure 87. Tenor of PGE in some magmatic sulphide deposits, normalized to C1 chondrite (after Naldrett and Duke, 1980).

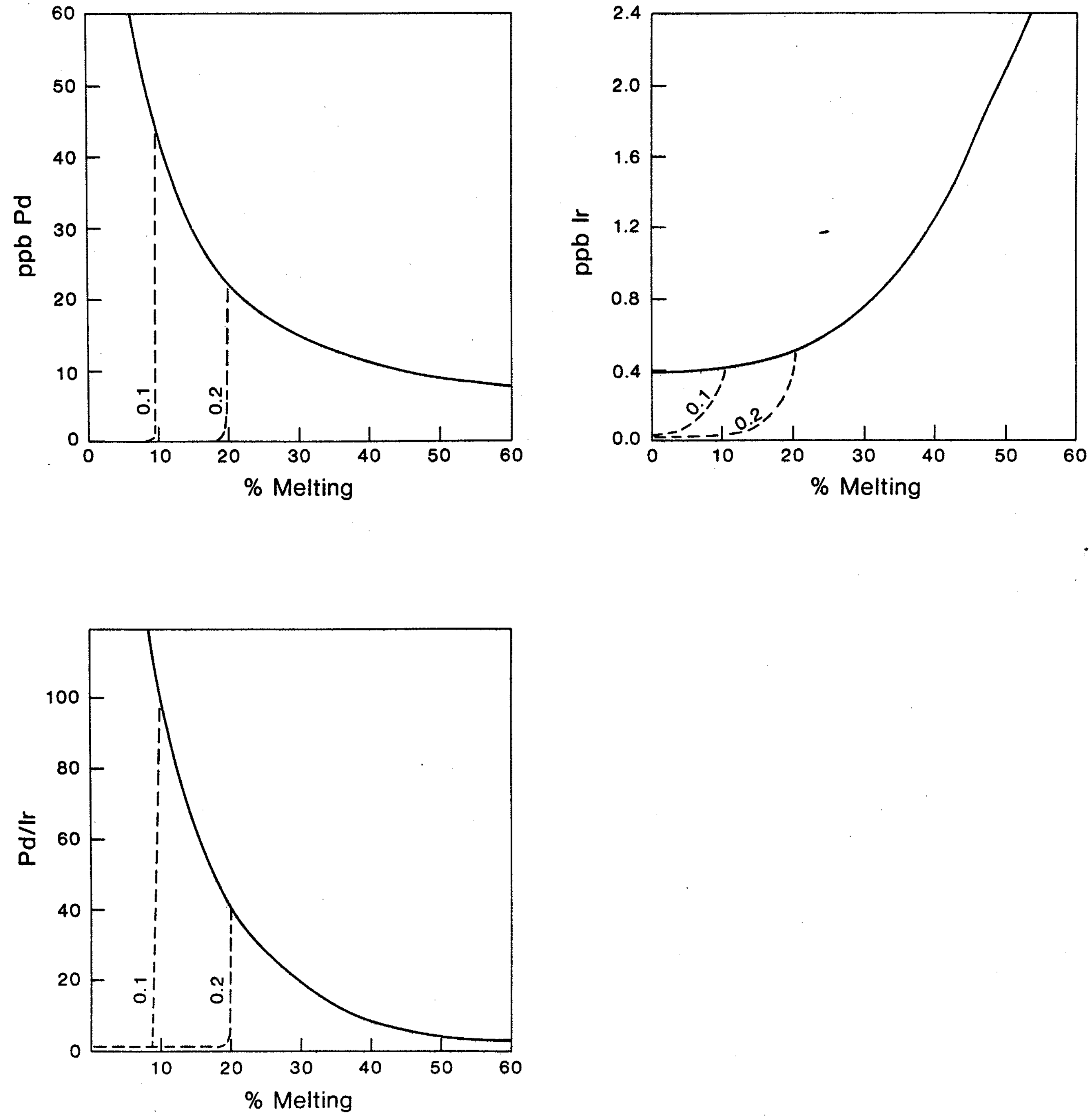

Figure 88. Variation of Pd, Ir and Pd/Ir in partial melts of mantle peridotite as a function of the percent of melting (after Naldrett and Barnes, 1986). Their model assumes that the melt can dissolve 1.0 percent sulphide. The solid lines reflect melting where the initial sulphide content of the mantle is low enough that no sulphide remains in the residua. The dashed lines apply where the mantle initially contains 0.1 or 0.2 percent sulphide so that some sulphide remains in the residua during the early stages of melting. The behavior of Pt would be similar to that of Pd whereas the behavior of Rh, Ru, and Os will be similar to that of Ir.

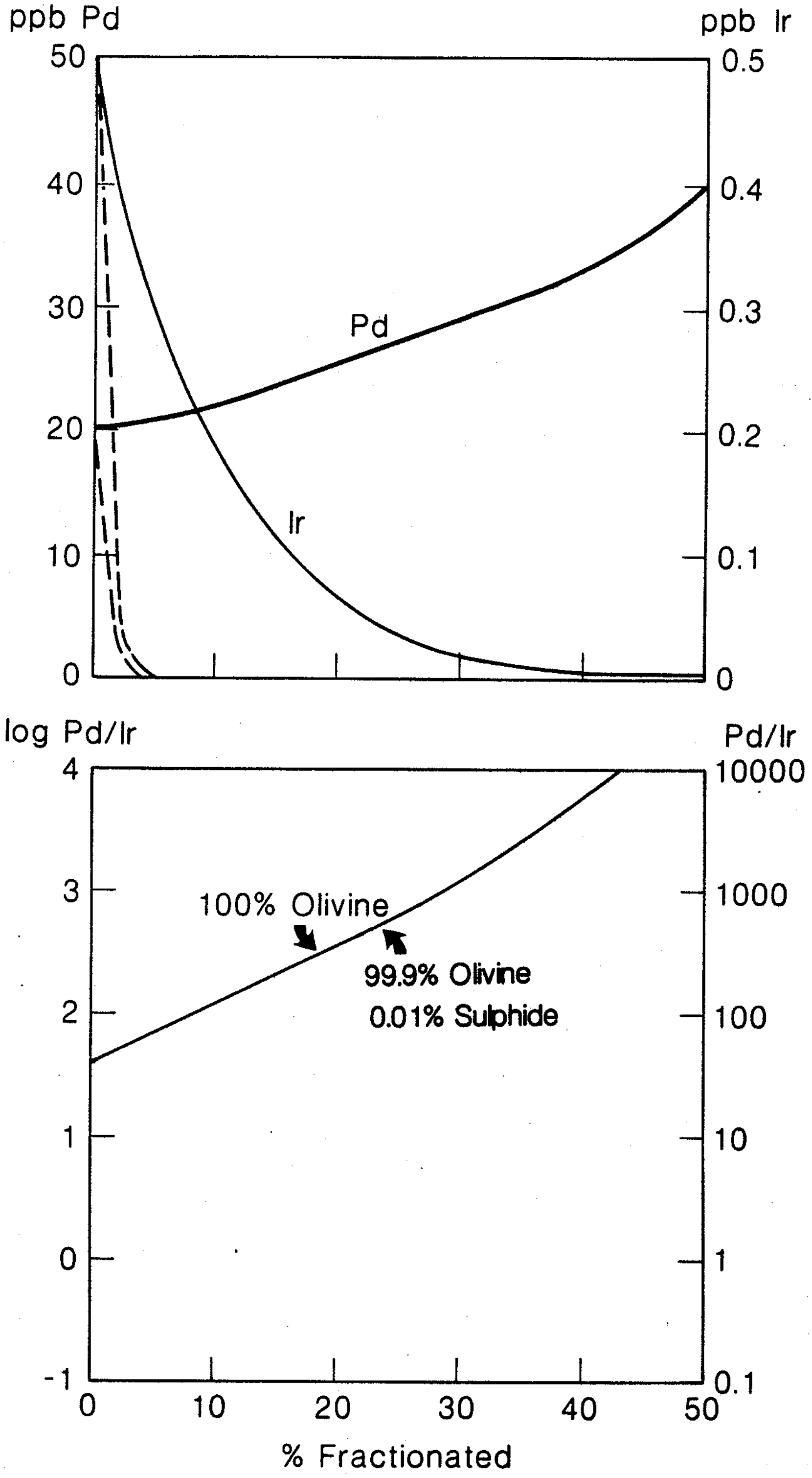

Figure 89. Variation of Pd, Ir and Pd/Ir during fractional crystallization of olivine from a basaltic magma (solid lines) and fractional segregation of olivine and sulphide in a 1000:1 ratio. Note that the segregation of even this small amount of sulphide drastically depletes the magma in PGE. The behavior of Pt would be similar to that af Pd whereas the behavior of Rh, Ru and Os would be similar to that of Ir.

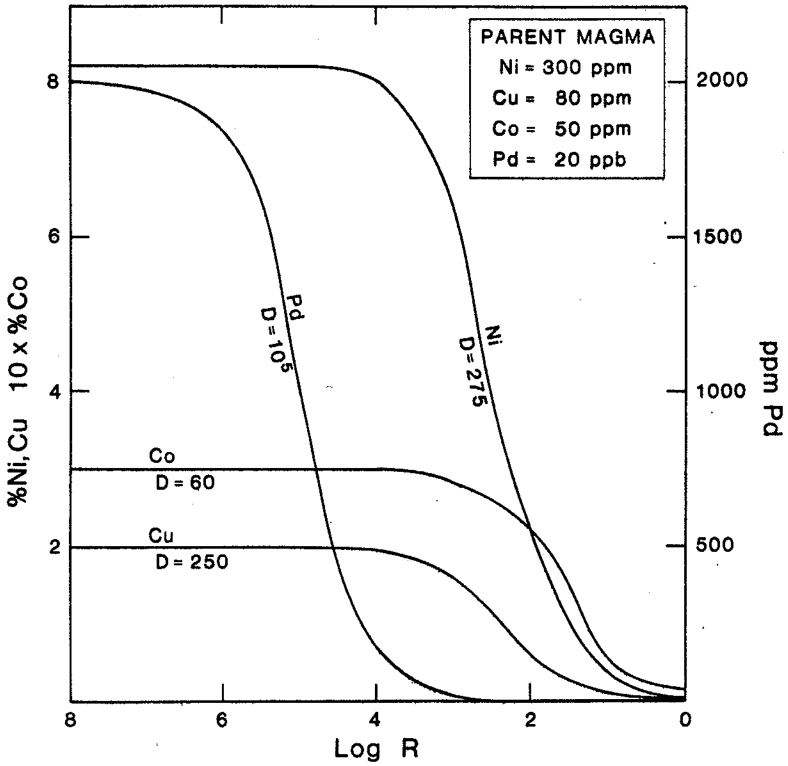

Figure 90. Variation of the concentration of metals in immiscible sulphide melt that segregates from a silicate liquid as a function of the mass ratio of silicate liquid to sulphide melt. The range of R-values typical of normal magmatic evolution is indicated by the shaded bar.

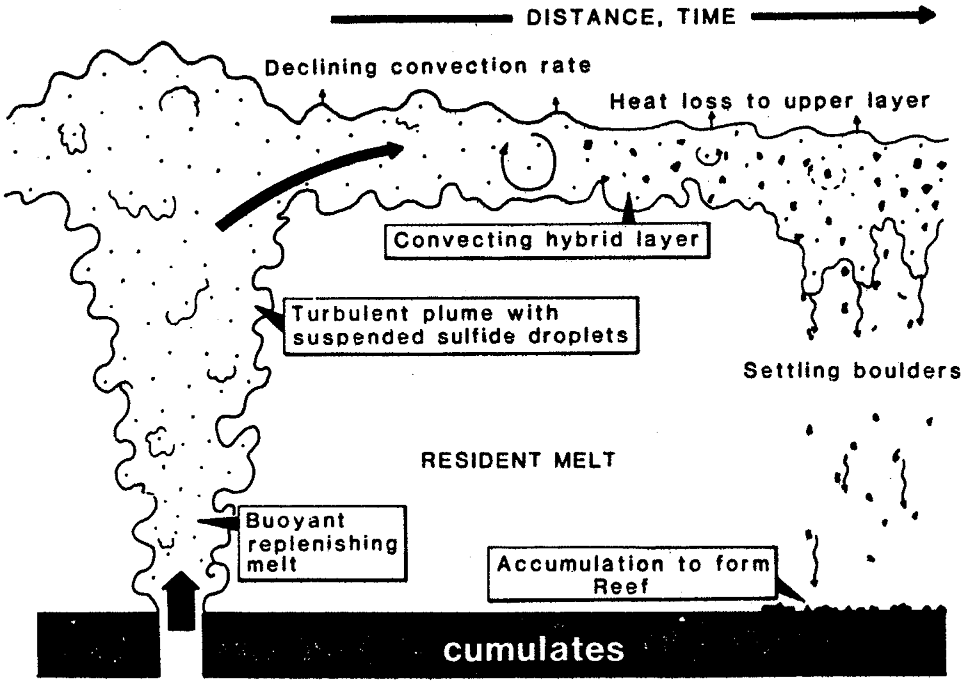

Figure 91. The turbulent plume - magma mixing model for the origin of PGE "reefs" (after Campbell et al., 1983).

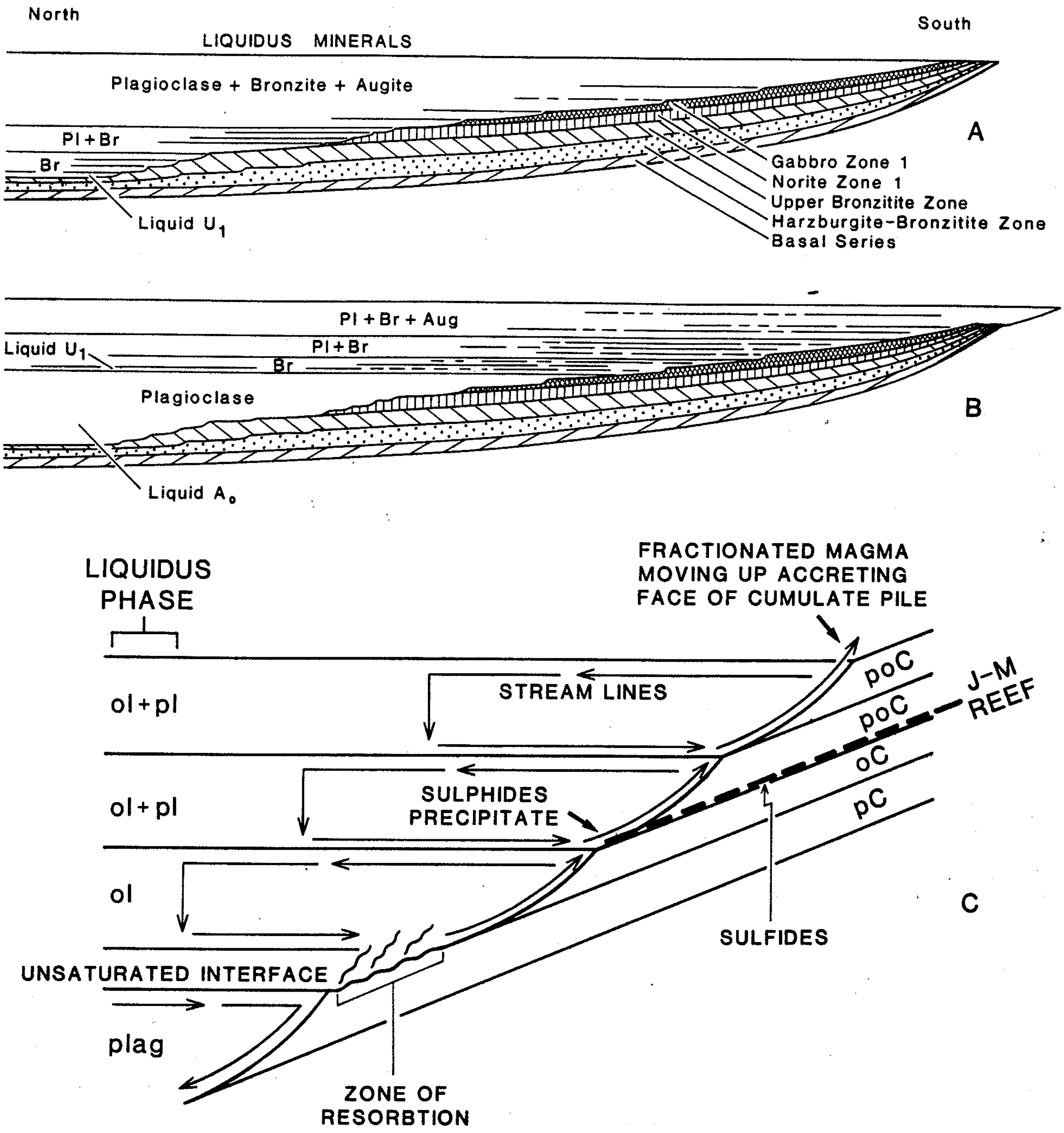

Figure 92. The formation of the J-M Reef by double diffusive convection - magma mixing. (a) The U-type magma resident in the Stillwater chamber evolved to the point that it consisted of three major liquid layers with bronzite, plagioclase + bronzite, and plagioclase + bronzite + augite as liquidus phases. (b) A-type magma entered the chamber and spread out underneath the U-type liquid. The interface was at the top of Gabbro Zone I where Troctolite-Anorthosite Zone I (with the J-M Reef) ultimately formed. (c) Finger mixing at the interface initially produces unsaturated hybrids which can resorb the adjacent cumulates. The U-type hybrids become saturated in olivine, and olivine + plagioclase. Residual liquid from the crystallization of olivine migrated up the face of the accreting cumulates and mixed with liquids crystallizing olivine and plagioclase, causing sulphide saturation and the formation of the J-M Reef. Figures 90a and 90b after Irvine et al. (1983), figure 90c after Naldrett et al. (1987).

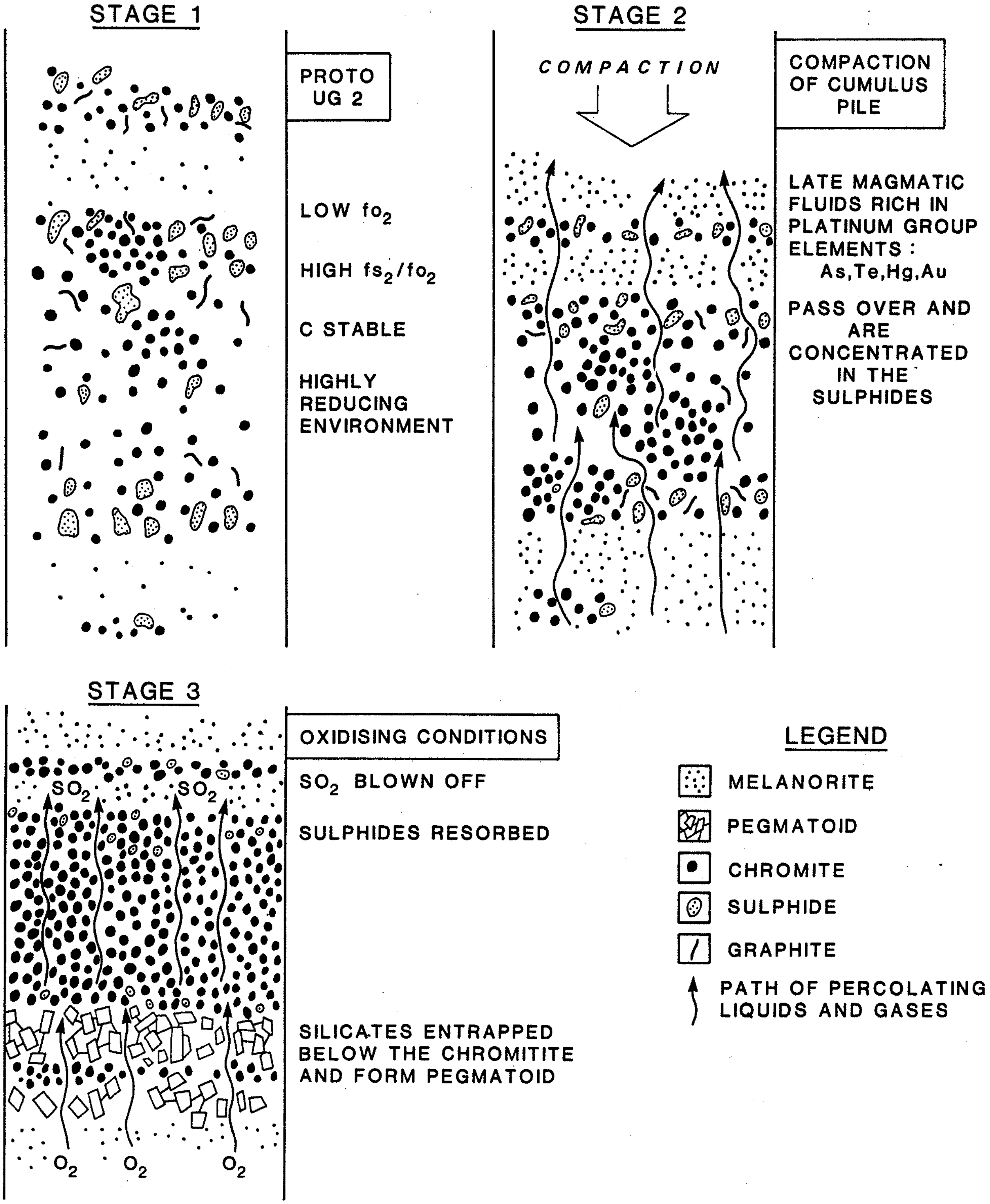

Figure 93. Model for the origin of PGE enrichment of the UG-2 chromitite by the upward migration of intercumulus liquid (after Gain, 1985). Stage 1 involves the formation of a crystal mush with immiscible sulphide droplets. Compaction of the cumulus pile during Stage 2 causes intercumulus liquid to migrate through the UG-2 and the sulphides already present in the layer scavenge PGE from this liquid. During Stage 3, oxidizing fluids stream through the layer, remove sulphur (SO2), and reduce the modal proportion of sulphide. The remaining sulphide would be anomalously rich in PGE.

evidence that indicates that such contamination plays an important role in the segregation of marginal accumulations of sulphides.

The rocks of the Sudbury Igneous Complex, for example, are unusually quartz-rich, and isotopic, major and trace element data suggest that the magma assimilated about 50 percent crustal material (Naldrett et al., 1986). There is general agreement that emplacement of the complex was preceded by either meteorite impact or explosive volcanism which led to the formation of the complex suite of breccias observed at Sudbury. The presence of these breccias at the locus of intrusion would have promoted assimilation. The sulphur isotope and Se/S ratios in the Sudbury ores in general are indicative of a mantle source although there is evidence of a crustal sulphur component in certain deposits (e.g., Strathcona). The Sudbury sulphides are closely associated with xenoliths of cumulate ultramafic and mafic rocks which crystallized within the crust (Scribbins et al., 1984) but are not present in exposed portion of the complex. The gravity and magnetic data of Gupta et al. (1984) indicate the existence of a mafic-ultramafic mass underlying the complex at a depth of 5 to 8 km that may be the source of the xenoliths. It is possible that the sulphides segregated in a magma chamber at depth and were subsequently emplaced along with the xenoliths.

The prevalent genetic model for the Noril'sk-Talnakh ores also involves contamination by crustal rocks. In particular, it is commonly believed that the sulphur in the ores was derived by assimilation of Devonian evaporites. The mean ^{34}S ratio of sulphides is 12.0 per mil for the Oktyabr'sk deposit and 8.1 per mil for the Talnakh and Noril'sk I deposits, whereas the mean ratio in middle Devonian anhydrite is 15.2 per mil (Gorbachev and Grinenko, 1973). Vinogradov and Grinenko (1966) estimated that 30-50 percent of the sulphur in the Noril'sk intrusions was assimilated from sedimentary anhydrite and that this amounted to 1.5 percent of the total mass of the intrusions.

There is some evidence to indicate that within a number of marginal massive sulphide deposits, higher Pt and Pd grades are associated with copper-rich sulphide segregations. Examples include Cu-rich stringers in the footwall at Sudbury, cubanite ores at Noril'sk-Talnakh and Cu-rich portions of the marginal sulphides of the Muskox Intrusion. This association may be explained by fractional crystallization of the molten sulphide whereby Pt and Pd would be concentrated along with Cu in the residual liquid (e.g., see discussion of Naldrett, 1981), or may result from secondary redistribution of metals during metamorphism or hydrothermal activity.

The most important example of a marginal sulphide accumulation in which the PGE predominate over nickel and copper is the Platreef of the Bushveld Complex. There is a consensus that generation of magmatic sulphides in the Platreef resulted from the contamination of the magma with country rock material but the exact nature of the contaminant remains to be resolved. The association of magmatic sulphides with mainly dolomitic, metasedimentary xenoliths within the Platreef led Liebenburg (1970, p.180) to suggest that the magma became sulphide saturated when it assimilated sulphur from the footwall sediments. De Waal (1977) also attributed the sulphide segregation to reaction with the sediments, but suggested that it was due to an increase in oxygen fugacity accompanying the addition of H_2O and CO_2 to the magma rather than sulphur assimilation. Buchanan et al. (1981) found that ^{34}S values in Platreef sulphides ranged from 6.3 to 9.2 per mil, significantly different from the -0.6 to 3.5 per mil range characteristic of "primary magmatic" sulphides of the Bushveld (Liebenburg, 1968), and concluded that sulphur was added to the magma through reaction with the dolomite xenoliths. Similarly, Gain and Mostert (1982) concluded that the breakdown of xenolithic material released H_2O, CO_2 and S which simultaneously the sulphide solubility and increased the sulphur content of the magma. However, Hulbert (in preparation) has analysed a more extensive suite of Platreef sulphides and found an average ^{34}S value of 2.7 per mil, which falls within the magmatic range. Cawthorn et al. (1985) have presented Sr-isotope and trace element data which indicate substantial contamination of the Platreef magma by siliceous material and seem to preclude significant assimilation of sediments. They suggest that the contaminant was partial melt or fluid derived from an adjacent granite.

GENESIS OF HYDROTHERMAL PGE DEPOSITS

Introduction

As Stumpfl (1986) pointed out, the concept that only magmatic crystallization-segregation processes concentrate platinum group elements has been increasingly questioned in recent years in the light of evidence that volatile fluids are implicated in the mobilization and deposition of PGE in a variety of geological environments. The temperatures at which this mobilization are thought to have taken place ranges from over 600°C, where the PGE-concentrating hydrothermal effects are an intimate part of the magmatic process, to as low as about 5°C, where PGE concentration takes place on the seafloor.

PGE concentration at the higher temperatures by fluids of magmatic affiliation are dealt with in the preceeding article. This article will deal only with mobilization and precipitation of PGE over the lower part of this temperature range and thus restrict discussion to those mineral deposits to which the term "hydrothermal" is conventionally applied. An obvious characteristic of these hydrothermal platinum deposits (see below), is that palladium is often more abundant that platinum but that other PGE tend to occur at much lower concentrations than either. This appears to be a reflection of the greater tendency of Pt and Pd to form aqueous complexes (and hence their greater solubilities in aqueous solutions) compared to the other PGE. In order to limit the scope of this article, attention will be focussed on platinum rather than the entire PGE group, but it should be borne in mind that the arguments are equally applicable to palladium.

Hydrothermal platinum deposits

As summarized by Mertie (1969) and Cabri (1981), and as indicated in Table 22, anomalous concentrations of platinum occurs in a wide variety of hydrothermal mineral deposit types. These occurrences of hydrothermal platinum demonstrate that platinum can be mobilized and concentrated by relatively low temperature hydrothermal processes. However, in the majority of hydrothermal deposit types the concentration of platinum is so low that at the best it can be economically recovered only as a byproduct from mining operations for the primary ore metal. Of the hydrothermal deposit types in which platinum has been reported, the two that appear to offer the most economic potential based primarily on platinum content is the U-Au-Pd-Pt type, for which Coronation Hill and Nicholson Bay are taken to be examples, and the Pt-Pd-Au type, for which Rathbun Lake, deposits of the New Rambler and Centennial Ridge District (Wyoming) and the Cliff showing of the Shetland (Unst) ophiolite are likewise taken to be examples. Some of these examples have been described in preceeding articles.

So few examples of these platiniferous deposits are known, or their discovery has been so recent, that the typical features of the "types" have not yet been characterized. Consequently, not only is any classification of them is highly tenuous at the present time but also there is insufficient information on which generalized genetic models can be knowledgeably based. The attempt here to rationalize the little that is known about the two "types" must therefore be considered to be highly speculative.

The starting point to the deductive process used here is the observation that gold is also enriched in both "types" of hydrothermal platinum deposits. A comparison of the chemical behaviour of platinum with that of gold in aqueous solutions therefore should offer some constraints on the mode of genesis of hydrothermal platinum deposits.

Comparison of the Aqueous Chemistry of Platinum and Gold

Compared to that of platinum, the aqueous chemistry of gold is relatively well known. The most important inorganic ligands that are known to complex with gold and significantly enhance its solubility in aqueous solutions are the chloride, bisulphide and hydroxyl anions (Seward, 1984). The fields of dominance of the chloro-, thio- and hydroxy-complexes respectively are shown in Fig. 94. Since the hydroxycomplexes require a combination of high pH and high pO^2, their importance in natural hydrothermal systems is minimal (Seward, 1984). As chloride complexes, the solubility of gold increases with increasing temperature, increasing chloride activity, decreasing pH and increasing pO^2. A minimum of 1 molal chloride concentration is required to give Au solubilities greater than 1 ppb at 250°C and pH 4 in a solution in equilibrium with pyrite and hematite (Fig. 94). Thio-complexes are stable only at relatively low pO^2 within the stability fields of sulphide minerals, but give rise to high Au solubilities (Seward, 1973). A concentration of only about 30 ppm sulphur in solution gives 1 ppb Au concentration at the point of maximum gold solubility near neutral pH (Fig. 94). The solubility of gold as thio-complexes increases with increasing temperature and sulphur content of solution, but decreases rapidly on oxidation of aqueous sulphide species to sulphate species.

In order to simplify the graphical representation of metal solubilities, only the solubilities attributable to thio-complexes are shown in Fig. 95A and Fig. 95B. The shaded areas indicate maximum solubilities of the metals over a range of three orders of magnitude. For gold, the perimeter of the shaded area represents a solubility contour of about 0.1 ppb in Fig. 95A and about 20 ppm in Fig. 95B. That area of dramatic decrease of metal solubility (see Fig. 94) with increasing pO^2 is designated the area of most efficient metal precipitation. This is a reasonable designation for a natural hydrothermal solution because ore deposition from reduced ore solutions usually involves oxidation. Pyrite, for example, requires such an oxidation for its precipitation from a sulphurous solution.

The aqueous chemistry of platinum is not so well known as that of gold, but of the inorganic ligands considered above, platinum forms aqueous chloroplatinates and the sulphides of platinum are known to be soluble in alkaline sulphide solutions (Westland, 1981). Under very oxidizing and acidic conditions, platinum is more soluble than gold as chloro-complexes, but the Pt:Au ratio of solutions saturated with both metals decreases with decreasing pO^2 (see Fig. 96). Within the stability fields of sulphides, gold is at least five orders of magnitude more soluble than platinum as chloride complexes.

There are no thermodynamic data for platinum thio-complexes, although preliminary experimental data (S.A.Wood, pers.com.) suggest the solubility of platinum in bisulphide solutions at 25°C is of the same order of magnitude as that for gold. The fields of maximum solubities of platinum thio-complexes shown in Fig. 95A and Fig. 95B were calculated assuming a range of possible stoichiometries comprising H^+, HS^- and OH^- ligands to a mononuclear complex and selecting those that are compatable with the pattern of maximum solubility of platinum sulphides in alkaline sulphide solutions reported by Westland (1981). Platinum thio-complexes contributing to the platinum solubility foeds indicated in Fig. 95 include $Pt(HS)_2(OH)_2^{--}$, $Pt(HS)_2S^{--}$, and $Pt(HS)_3^{-}$. At relatively low concentrations of sulphur in solution (Fig. 95A), the field of maximum solubility of platinum and the field of most efficient platinum precipitation are almost identical to the corresponding fields for gold (though of course the relative solubilities of the two metals are not known). With increasing sulphur content (Fig. 95B), the field of most efficient platinum precipitation occurs at an increasingly lower pO^2 than that for gold ay neutral pH.

The geological implications for these patterns of relative solubility of platinum and gold as thio-complexes are two fold. Firstly, the calculations, as also indicated by the preliminary experimental data of S.A.Wood, suggest that if significant quantities of gold are mobilized as thio-complexes then significant quantities of platinum will be mobilized as well. Secondly, as the metal-carrying capacity of the solution increases (i.e. the greater the sulphur content) the greater the probability of fractionation of gold from platinum during dissolution from the source area and the greater the probability of spatial separation of gold from platinum during ore deposition. These effects may explain the wide range of Pt:Au ratios in deposits of hydrothermal affinity.

Genetic models.

Restricting arguments concerning platinum and gold solubilities in aqueous solutions to the solubility patterns outlined above, attention will now be turned to possible explanations of some of the known features of the two most promising "types" of hydrothermal platinum deposits.

U-Au-Pd-Pt Type.

Using the Nicholson Bay and Coronation Hill deposits as being representatives of the Type, features which appear significant and must be explained by a plausible genetic model include:

1. The metal association of platinum (and palladium) with uranium and gold.

2. The spatial association of the examples of the Type with deposits of the Unconformity-related Uranium Type. The Nicholson Bay deposit is in the same ore district as the Athabasca Basin uranium deposits and the Coronation Hill deposit is in the South Alligator River ore district.

3. The high concentration of selenium associated with the platiniferous mineralization.

4. The elemental and mineralogical association of the Type also occur in Unconformity-related or redox front-related deposits.

For example, the uranium deposits of the South Alligator River, typically contain minor amounts of iron, copper and nickel sulphides together with selenides, and the genesis of the deposits is ascribed to the reduction of oxidized metalliferous groundwaters near a litholgical redox front (Foy,1975; Needham and Stuart-Smith, 1987). Similarly, basal parts of the Musonoi deposit and the Shinkolobwe deposit of the Zairean Copper Belt contains a U-Pt-Pd-Au-Se association (Theo Verbeek, pers.comm). Again, the classical redox-front genetic models for uranium (e.g. Robertson et al., 1978) and red-bed copper deposits (e.g. Rose, 1976) are applicable.

Fig. 97 shows the calculated solubilities of gold as platinum in a chloride solution as a function of pO^2. In order to carry more than 1 ppb Pt or Au, the solution must be oxidized and acidic, and even more so than indicated in Fig. 96 at lower temperatures. The reduction of this fluid to the stability of iron sulphides (Fig. 94 and Fig.96) would precipitate essentially all the platinum and gold in solution. Even if the ratio of S:Se in the oxidized solution was 10,000:1, the platinum would precipitate as selenides rather than sulphides upon reduction of the solution (note that other metals transported in the oxidized solution, including iron and lead, would also tend to precipitate as a selenide rather than a sulphide upon reduction). The elemental associations can thus be explained if all the ore components were carried in an oxidized chloride solution, and the reduction of this solution was the main cause of ore deposition.

The mineral zonation pattern marking progressive reduction is very sensitive to pH and the concentrations of the ore elements, chloride, carbonate and sulphur in the oxidized solution. If under the conditions illustrated in the diagram the concentration of all ore components in the oxidized solution were greater that 1 ppm then the mineralogical zonation from oxidized to reducing conditions across the redox front would be Pt+Au+selenides (+nickel sulphides) to uranium oxides to copper sulphides. Since the topology of the diagram does not substantially change for lower temperatures, the above observations are applicable to temperatures as low as 25°C. However, because the solubility of both platinum and gold as chloride complexes decreases with decreasing temperatures, the probability of significant quantities of the precious metals being associated with uranium mineralization is correspondingly lower at lower temperatures. At more alkaline pH, uranium oxides tend to precipitate at higher pO^2, and hence the Pt-Au-selenide assemblage may spatially coincide with the uranium oxide assemblage, but again the probability of significant platinum and gold concentration significantly decreases with increasing pH (see gold chloride solubilities, Fig. 94). A schematic illustration of mineral zonation in a deposit produced by this process is shown in Fig. 97, noting that the zonation is also dependant upon mass balance considerations as well as mineral solubilities.

The elemental association could also be explained if the platinum, gold and selenium (?) were mobilized by reduced sulphurous groundwaters and the uranium, copper, nickel and selenium (?) by oxidized groundwaters, with ore precipitation taking place in the zone of mixing between the two groundwater types. In this case, the platinum, gold and selenides might be expected to show a closer spatial relationship to sulphides than uranium oxides (Fig. 98). Because in a dynamic situation, involving the supply of a relatively small quantity of reduced fluids to a replenishing large reservoir of oxidized solutions, the supply of reduced sulphur may be totally consumed by the precipitation of pyrite and copper sulphides, leaving the more soluble nickel in solution. However, as is the case of all hydrothermal mineral deposits, because during ore deposition mineral zone boundaries tend to oscillate and migrate with time, the complexities of natural mineral assemblages cannot be accurately predicted without a detailed knowledge of the actual genetic processes involved.

At this stage of knowledge on the U-Au-Pd-Pt "type" the only conclusions that can be drawn is that the elemental association is explicable by hydrothermal precipitation due to redox reactions.

If all ore components are supplied by the one solution, then that solution must be highly oxidized (i.e. the source rocks can contain no iron mineral except hematite or an iron-bearing carbonate) and chloride-rich (>1 molal chloride), with the probability of platinum and gold in the precipitate increasing with increasing temperature, salinity and acidity of the solution. If ore precipitation is due to the mixing of two groundwater types and the platinum and gold are transported as thio-complexes, then the reduced solution must contain >30 ppm sulphur at approximately neutral pH and may be permissibly cool. Since this type of groundwater has the highest probability of being developed within carbonaceous/pyritic shales, and shales are characteristically impermeable, perhaps the most viable siting for deposits formed by these means is where fractures have permitted the focussed discharge of such groundwaters into a an oxidized lithology (Fig. 98).

Pt-Pd-Au Type

If the platiniferous deposits of Rathbun Lake (Rowell and Edgar, 1986), Cliff, Unst ophiolite (Prichard et al., 1981; Gunn et al., 1985; Leake and Gunn, 1986; Prichard et al., 1986) and the New Rambler (McCullum et al., 1976) and Centennial Ridge area of Wyoming (McCallum, 1968) are representatives of the same genetic type, then perhaps the most significant feature that they have in common is the mineralization occurs along structurally controlled zones in mafic-ultramafic bodies. Investigators of all three localities ascribe the concentration of PGE to hydrothermal process on the basis of the association of platiniferous minerals with hydrothermal sulphides and the presence of hydrothermal alteration. However, there is no consensus as to the source of the metals and the process by which the platiniferous minerals were accumulated.

McCallum et al. (1976) favour the interpretation that the New Rambler deposit was formed at a temperature of around 335oC from hydrothermal solutions that leached the ore metals from the surrounding mafic rocks rather than by alteration or remobilization of a magmatic sulphide deposit. Similarly, Rowell and Edgar (1986) report that they observed no textural evidence for magmatic sulphides in the Rathbun Lake deposit. Although Gunn et al. (1985) suggest that the platiniferous mineralization is entirely of hydrothermal alteration and most probably associated with the process of serpentinization of the ultramafic rocks of the Shetland ophiolite, the possibility of the PGE having been pre-concentrated by magmatic processes can not as yet be ruled out (Prichard et al., 1986; Prichard and Lord, in press). If the latter is the case, then the Cliff occurrence in the Shetland ophiolite may be more analogous to PGE enrichments in, for example, the Lac-des-Isles Complex, which have been ascribed to redistribution from magmatic sulphide concentrations by hydrothermal fluids (Talkington and Watkinson, 1984).

In all cases, the platiniferous minerals are assocaited with sulphides of copper and nickel which in the case of Rathbun Lake and Cliff, at least, are also accompanied by various phases containing arsenic, antimony and bismuth. Assuming that the genesis of these deposits is primarily the result of the interaction between a hydrothermal solution and a ultramafic-mafic rock, the genetic problem therefore appears to be primarily the identification of the constraints that will allow the mobilization and concentration of Pt (and Pd) and Au along with sulphides of copper and nickel solely as a result of this process.

The interaction of aqueous solutions with ultramafic rocks has been studied experimentally by Janecky and Seyfried (1986) who concluded that the reaction paths depended on initial solution composition and rock texture, the latter affecting the relative reaction rates of the primary mineral phases. All other factors being equal, olivine reacts faster than enstatite with water below 400^{o} (Martin and Fyfe, 1970), but the reverse is true at 300^{o}C if the water initially contains seawater concentrations of magnesium (Janecky and Seyfried, 1986).

Fig. 99 schematically illustrates the changes in concentration of some components of a low salinity pore fluid as the result of the progressive serepentinization of a rock containing olivine and enstatite. Initial reactions may be exemplified as being dominantly Reaction 1 and to some extent Reaction 2 (Fig. 100). The net effect of these reactions is to cause the pore fluid to become alkaline and increase the concentration of magnesium and silica in the pore fluid. With reference to Fig. 95, it can be seen that a forsterite-serpentine assemblage (at low activities of Mg^{++}) will buffer the pore fluid to alkaline pH, and at this pH pyrrhotite is stable only at a high concentration of sulphur in the co-existing pore-fluid. In arriving at these high equilibrium concentrations of sulphur, the quantity of sulphide that can be dissolved (>>30 ppm, see Fig. 95) is so great that the alkaline pore fluids would be capable of dissolving the entire sulphide component of a normal ultramafic or mafic rock. At alkaline pH the sulphur will be present in solution dominantly as HS-, and therefore the pore fluid will have the capacity to dissolve significant quantities of platinum and gold as thio-complexes (Fig. 99).

The maximum concentration levels of HS^{-} , and consequently maximum concentrations of platinum and gold, in the pore fluid is confined to just the initial stages of the reaction progress (Fig. 99A) because of several inter-related factors. As the process of serpentinization continues, the progressive release of nickel through the dissolution of olivine causes the pore fluid to become saturated with respect to heazlewood, which continuously precipitates and thus progressively removes sulphur from solution. This decrease in sulphur concentration in the fluid allows the iron released by dissolution of olivine and pyroxene (as well as that small amount released by the dissolution of pyrrhotite) to precipitate as magnetite. The continuation of the serpentinization process also increasingly involves reactions of the types 3 to 6 (Fig. 100), which consume the Mg^{++} and SiO^{2}(aq) produced by reactions of types 1 and 2 (Fig. 100) and which eventually cause the pore fluid to become more acidic (Fig. 99A). As can be seen from Fig. 95, a serpentine + magnetite ncentrations of the pore fluid at neutral pH to <<0.001 molal, which will not allow significant gold and presumably platinum solubility as thio-complexes.

The conclusion to be drawn from this examination of the process of serpentinization by a low salinity pore fluid is that it is only during the very initial stages of serpentinization does the pore fluid develop the capacity to transport gold and platinum. Extraction of this fluid before its reaction with the olivine-enstatite assemblage proceeds beyond the point of diminishing platinum-leaching capacity therefore provides a potent ore-fluid for hydrothermal Pt-Pd-Au deposits. Since the zone of high platinum mobility moves with the serpentinization front and serpentinization involves a volume expansion of the rock, and furthermore because serpentinite deforms in a ductile fashion even under low stress, the most viable escape paths for the fluid would seem to be brittle fractures developed in the fresh ultramafic rock at the serpentinization and rock expansion front (Fig. 101).

Because platinum arsenide is much more insoluble than the platinum sulphides, introduction of arsenic into the chemical system would provide an efficient mechanism for fixing platinum as the arsenide (sperrylite). The introduction of arsenic into the system may be effected by the exchange and mixing of pore fluids from the partially serpentinized ultramafic-mafic body with pore fluid from a surrounding arsenic-bearing source such as sedimentary rocks (Fig. 101).

In the case of the Cliff occurence, the reason for preferential platinum and gold concentration in chromite pods (Prichard et al, 1981; 1986) could be that the chromite pods acted as structurally competent bodies that deformed by brittle fracture during serpentinization of surrounding ultramafic rocks, allowing the ingress of pore fluids from the serpentinization front along dilatant micro-fractures in the chromitite. Not enough is known of the geology and geological history of the New Rambler deposit to speculate on an actual mechanism for Pt-Pd-Au concentration, but it is worthwhile to note that McCallum et al. (1976) commented on the reporting of "peridotite" and "pyroxenite" in drill holes beneath the deposit. Again at Rathbun Lake, the timing and cause of the shear zones and fractures with which the platiniferous mineralization is associated (Rowell and Edgar, 1986) would be essential to a full explanation as to the genesis of the deposit.

Discussion

The cosmic and mantle abundance of platinum is about ten times that of gold (Naldrett and Duke, 1980). Current mine production of platinum is about fifteen times less than that of gold. The discrepancy is due to the amount of gold produced from hydrothermal (sensuo lato) ore deposits. Considering the general chemical similarities of platinum and gold, the question that might be asked is whether these differences in the primary sources for the two metals is more an artifact of exploration concepts (i.e. platinum occurs in significant concentrations only in magmatic deposits) rather than differences in the geochemical behaviour of the two metals.

On the other hand, as would be predicted from their positions in the Periodic Table, platinum (and palladium) also has chemical affinities with nickel. The association of both gold and nickel with platinum and palladium in hydrothermal ore deposits therefore does not provide an empirical indication as to the most appropriate analogy on which to base a speculation of the behaviour of platinum in hydrothermal fluids.

Thiocomplexes have been ascribed an important role in the genesis of gold deposits (Seward, 1984). Therefore, if platinum is also significantly soluble as thiocomplexes, an association of platinum with gold deposits would be expected. However, the limited data on platinum in lode gold deposits suggest that this is not commonly the case (Boyle, 1979; see Table 22). This may indicate that either the solubility of platinum as thiocomplexes is in reality very low compared to that for gold, or, more probably, that for lode gold deposits gold is transported mainly as other species, such as halide complexes (e.g. Helgeson and Garrels, 1968; Kerrich and Hodder, 1982) or, noting the association of lode gold deposits with carbonates, as unidentified species in a CO^2-H^{2}O fluid. Whether the reverse is also true and that some types of natural fluids can mobilize and concentrate platinum without concentrating gold, remains of course merely a matter of speculation.

For a metal to be commonly concentrated by natural hydrothermal processes, not only must it be sufficiently soluble under conditions commonly encountered in nature so that it can be mobilized at significant concentration in the ore fluid, but it must also possess a sufficient range of solubility so that it can be efficiently precipitated at the site of ore deposition. Most hydrothermal fluids are in a reduced state. Oxidized hydrothermal fluids must be generated in hydrothermal reservoirs in which hematite is the only iron-bearing mineral. If the range of solubility of platinum in natural hydrothermal solutions is dependant mainly on the reduced sulphur content of the solution, the limitation to the number of circumstances under which a sudden desulphurization of an ore fluid can take place in the subsurface severely limits the number of environments in which hydrothermal platinum deposits can form.

In this respect, the behaviour of platinum in hydrothermals fluids may be more analogous to that of nickel rather than that of gold. The exploration inference to be drawn from this analogy is that whereas hydrothermal deposits of both nickel and platinum are known, they both are so rare (because of the rarity of the combination of circumstances required for their formation) that their overall contribution to total metal resources and their importance as explorations targets is very small compared to the major ore deposit types.

Table 22: Concentration of platinum in various hydrothermal ore deposit types. The average concentration in magmatic sulphide deposits is shown for comparison.

Deposit type	Pt concentration	Reference
Porphyry Coppers	1 mg per tonne Cu	Cabri, 1981
Cu-Mo porphyries	Mo-conc 12-500 ppb Cu-conc 0-440 ppb	I.R. Jonasson (unpub. data)
Carbonatite (Palabora)	654 g per tonne Cu	Cabri, 1981
Lode Au quartz veins	<5 ppb	Boyle, 1979
Kupferschiefer	up to 340,000 ppb	Kucha, 1982
U-Au Nicholson Bay	average 14,000 ppb	Hawley et al., 1953
U-Au Coronation Hill	average 700 ppb	Northern Miner
Volcanogenic sulphides		
Weedon	Cpy 400 ppb	Hawley et al., 1953
Aldermac	Cpy 90 ppb	Hawley et al., 1953
Modern ocean floor		
Near-ridge Mn nodules	average 97 ppb	Haynes et al., 1985
Mn crusts	average 420 ppb	Clark et al., 1985
Salton Sea Brine	51 ppb	Harrar & Raber, 1984
(Magmatic sulphides	100 mg per tonne Cu	Naldrett, 1981)

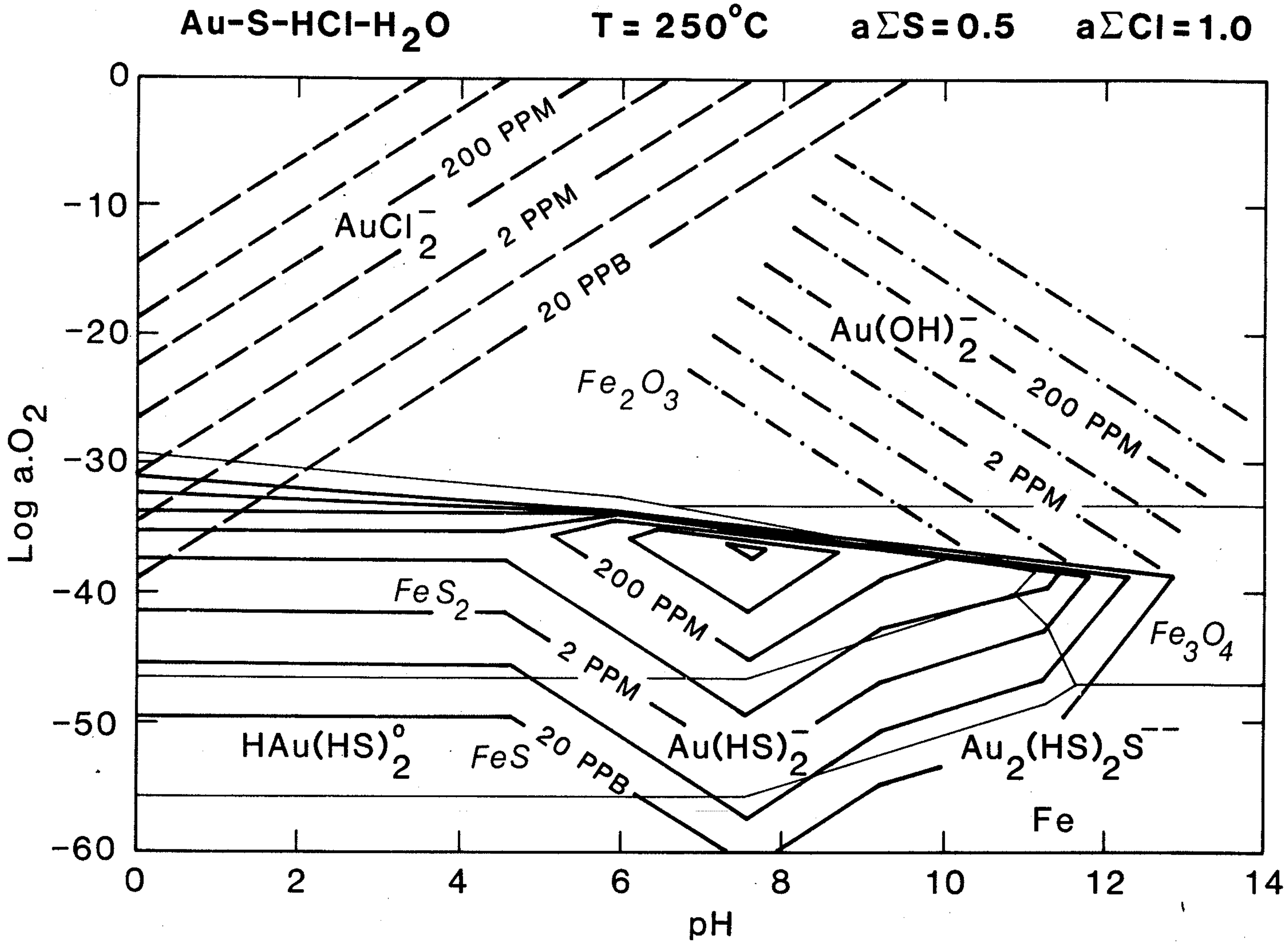

Figure 94. Calculated gold solubility in aqueous solution as a function of pO_2 and pH at 250°C and 0.5 m total sulphur. Fields of dominance and gold solubility contours (in ppm) for the major aqueous complexes of gold superimposed upon the stability field of iron minerals in the Fe-S-O system. Stoichiometries and thermodynamic data for gold complexes as listed by Seward (1984). Thermodynamic data for aqueous species in the S-H system from Ellis and Giggenbach (1971); other thermodynamic data from F.A.C.T. data base.

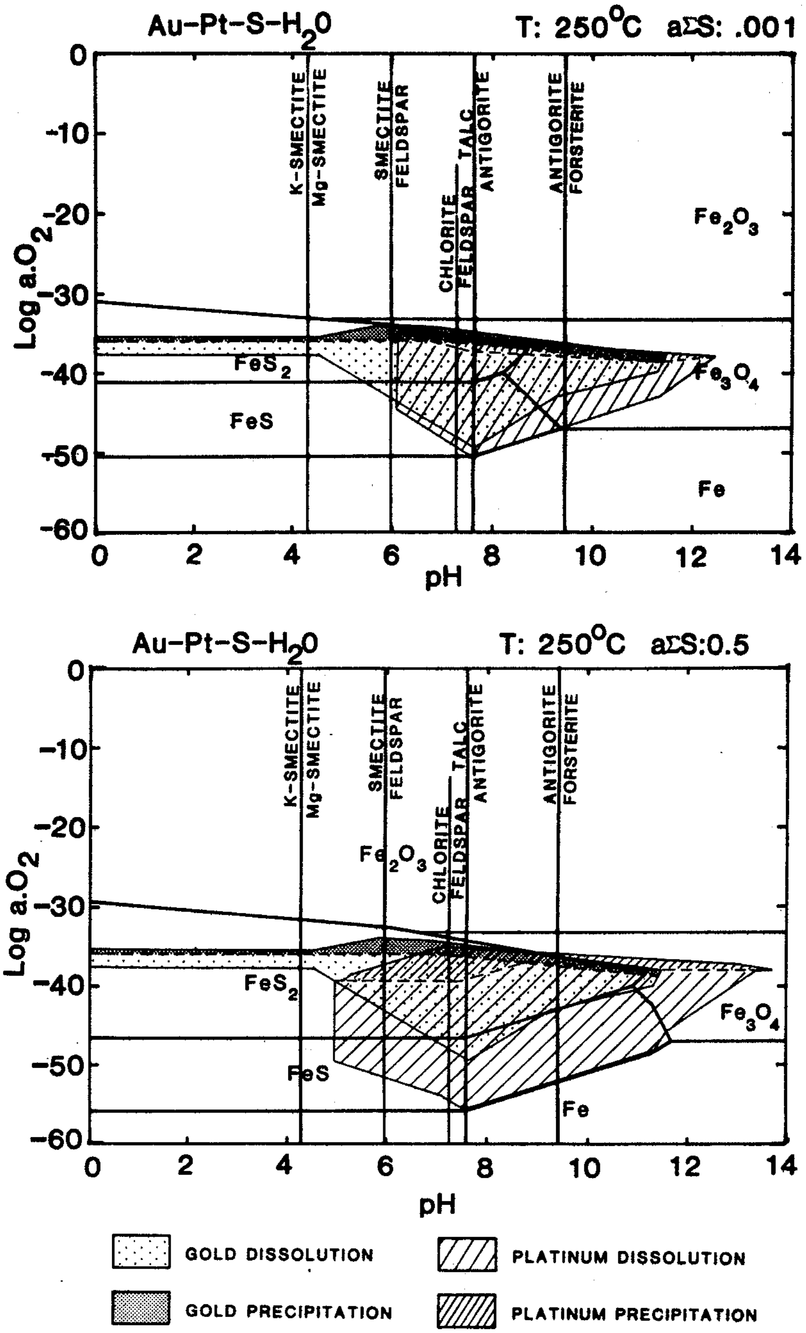

Figure 95. Calculated field of maximum solubilities of platinum and gold as thio-complexes as a function of pO_2 and pH at 250°C. The shaded areas represent a range of three orders of magnitude of metal concentration in solution. Also shown are the pH values buffered by the indicated silicate reactions at a.Mg^{++} = 10^{-8}. See text for further explanation. A. 0.001 molal total sulphur concentration. The perimeter of the shaded area for gold represents about 0.1 ppb gold concentration in solution. B. 0.5 molal total sulphur concentration. The perimeter of the shaded area for gold represents about 20 ppb gold concentration in solution.

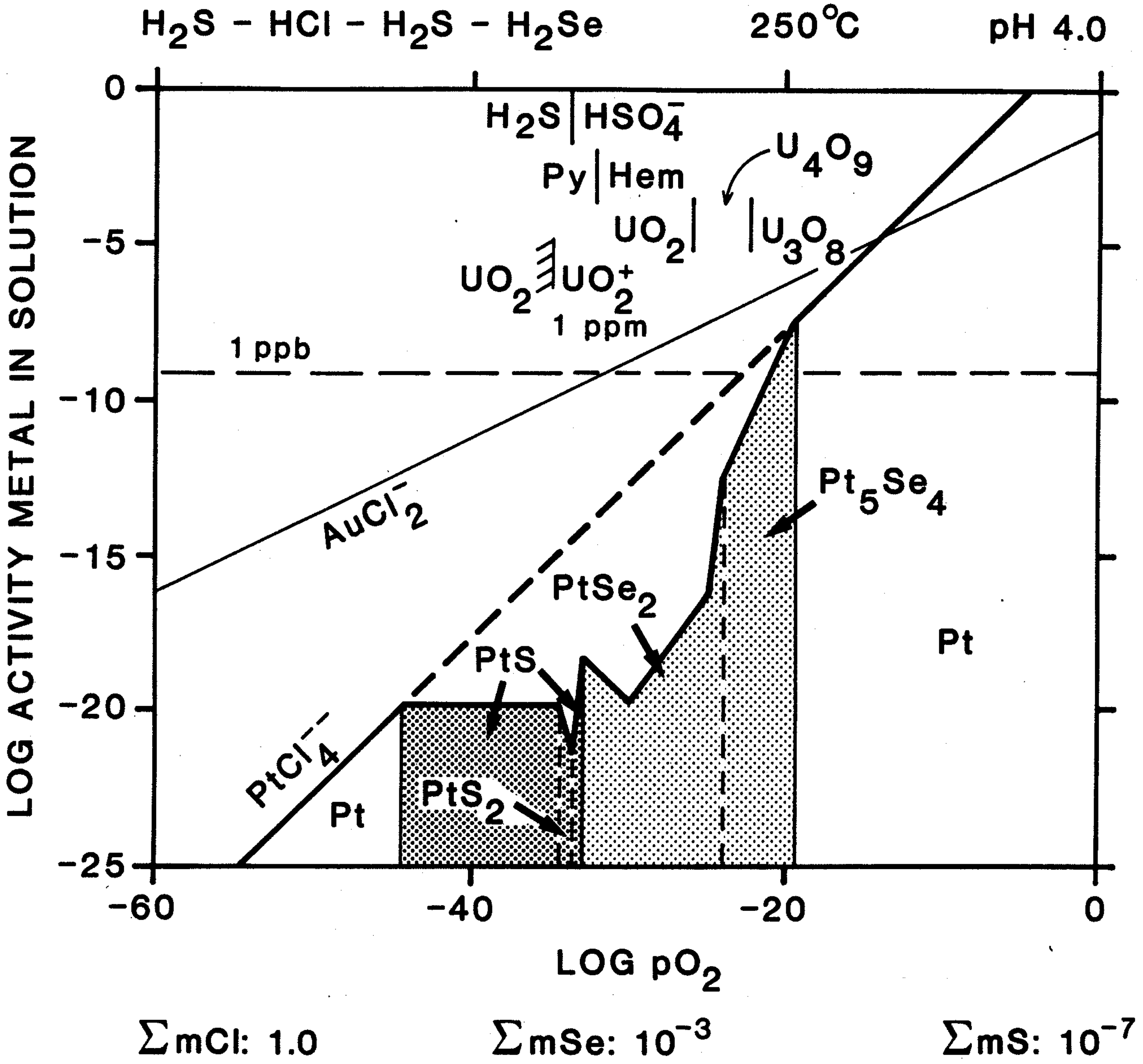

Figure 96. Solubility of platinum and gold as a function of pO_2 at 250°C and pH 4 in a 1 m NaCl solution containing 0.001 m total sulphur and 10^{-7} moles total selenium concentration. The top centre of the diagram indicates the pO_2 of some phase boundaries and 1 ppm solubility of UO_2 for reference. Gold solubility is for the metal. Platinum solubility for the phases indicated. The broken heavy line represents the solubility of platinum metal (i.e. in a 1 m NaCl solution with no sulphur or selenium).

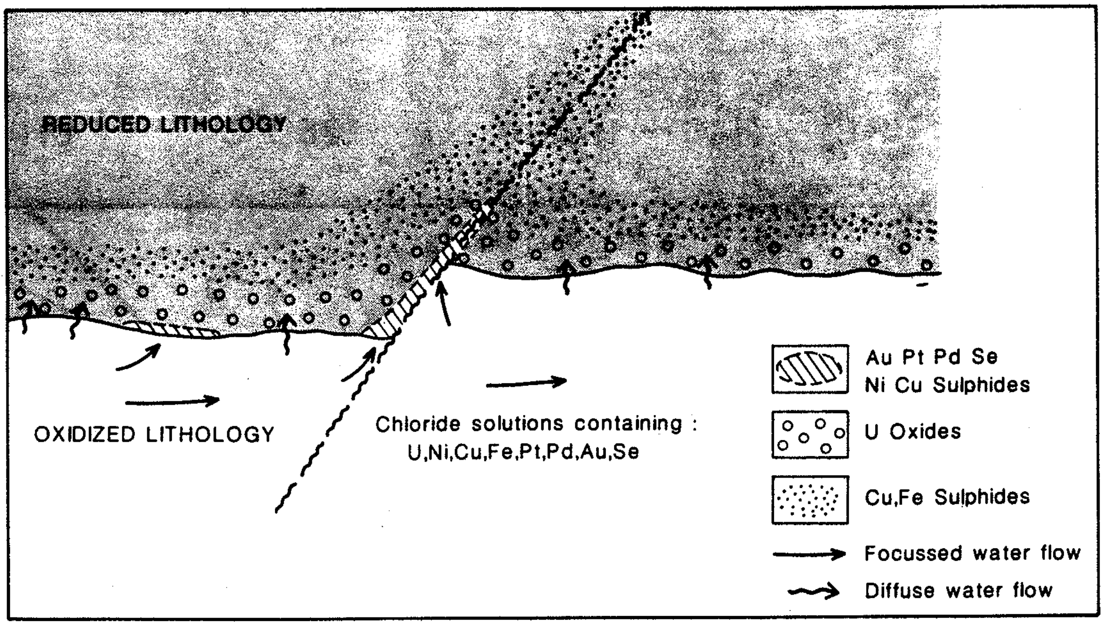

Figure 97. Schematic representation of ore element zonation as the result of the progressive reduction of an oxidized acidic chloride solution containing dissolved U-Cu-Ni-Pt-Pd-Au at a redox front.

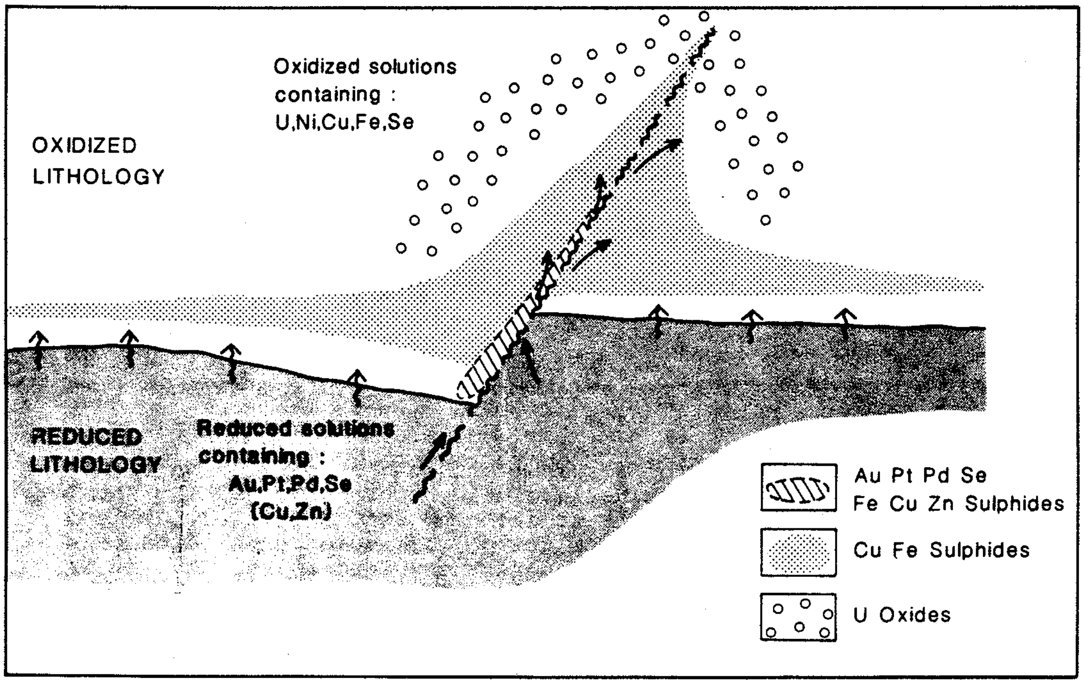

Figure 98. Schematic representation of ore element zonation as the result of the progressive interaction of an oxidized acidic solution containing dissolved U-Ni-Cu-Pt-Pd-Au and a neutral reduced sulphurous solution containing Pt-Pd-Au-Se-Cu-Zn at a redox front.

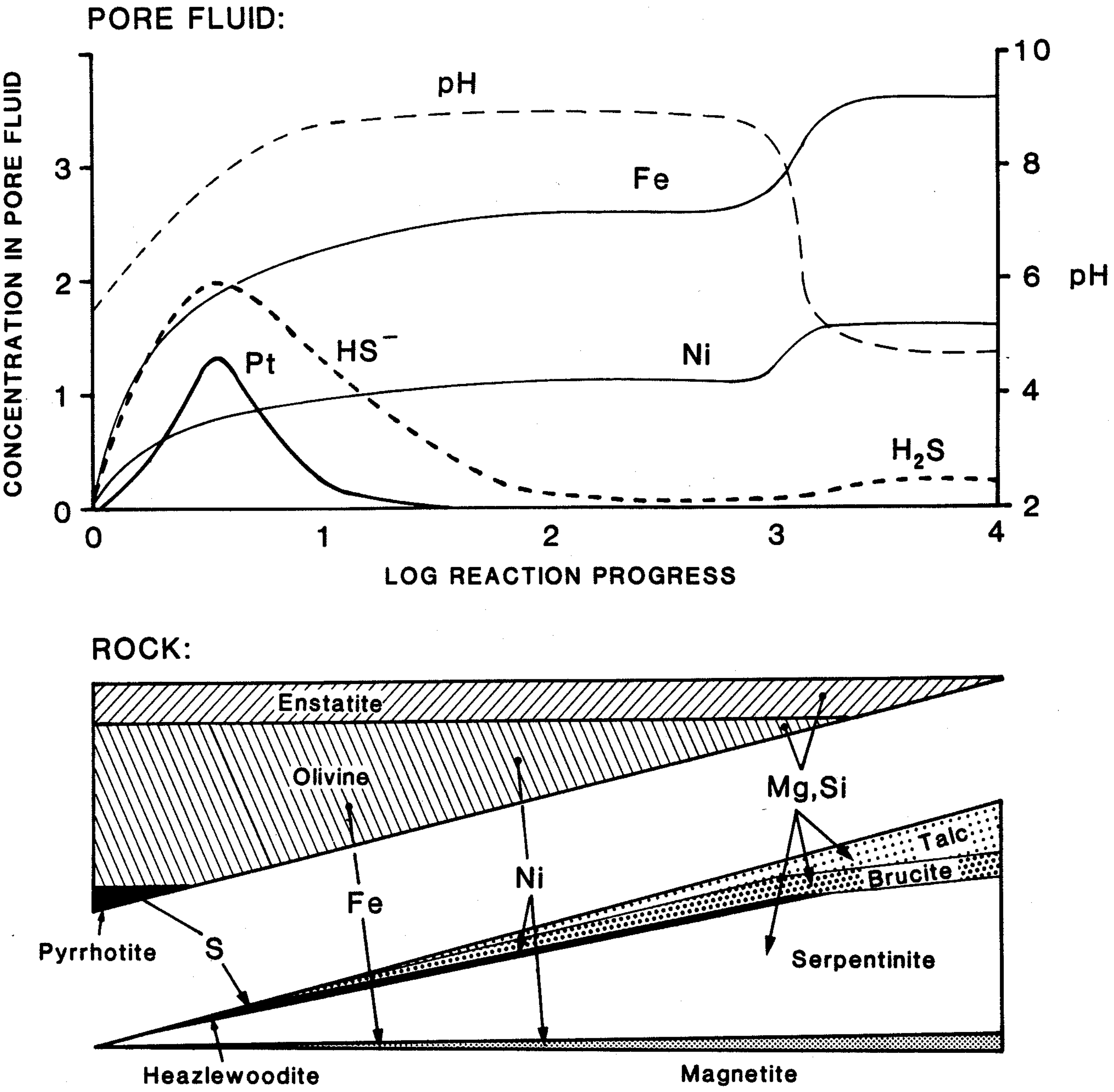

Figure 99. Semi-schematic representation of the progressive serpentinization of a harzburgite by low salinity aqueous fluids. A. Progressive change (from left to right) of some components of the pore fluid. B. Progressive change in the relative proportion of solid phases. The relative length of vertical line through the fields of the solid phases is an indication of the relative proportion of that solid phase at that point in the reaction progress.

INITIAL REACTIONS:

1) $$\underset{\text{Forsterite}}{Mg_2SiO_4} + 2H^+ + H_2O = \underset{\text{Serpentine}}{Mg_3Si_2O_5(OH)_4} + Mg^{++}$$

2) $$\underset{\text{Enstatite}}{3MgSiO_3} + 2H_2O = \underset{\text{Serpentine}}{Mg_3Si_2O_5(OH)_4} + SiO_2(aq)$$

SUBSEQUENT REACTIONS:

3) $$\underset{\text{Forsterite}}{Mg_2SiO_4} + SiO_2(aq) + 4H_2O = \underset{\text{Serpentine}}{2Mg_3Si_2O_5(OH)_4}$$

4) $$\underset{\text{Enstatite}}{3MgSiO_3} + Mg^{++} + 3H_2O = \underset{\text{Serpentine}}{Mg_3Si_2O_5(OH)_4} + 2H^+$$

5) $$Mg^{++} + 2H_2O = \underset{\text{Brucite}}{Mg(OH)_2} + 2H^+$$

6) $$3Mg^{++} + 4SiO_2(aq) + 4H_2O = \underset{\text{Talc}}{Mg_3Si_4O_{10}(OH)_2} + Mg^{++}$$

Figure 100. Some mineral-solution reactions during serpentinization of harzburgite.

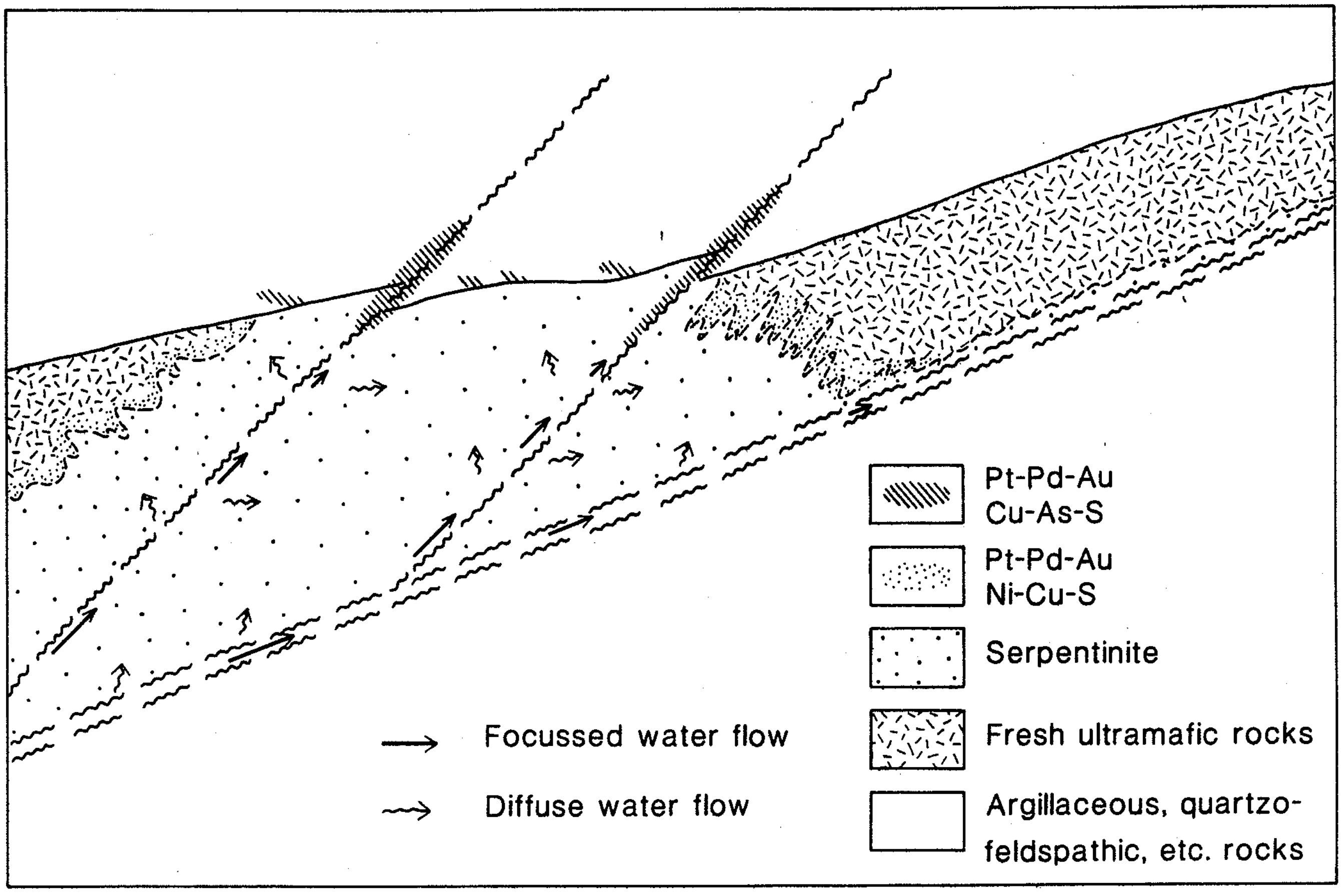

Figure 101. Schematic representation of the concentration of platinum by the process of serpentinization of an olivine-bearing ultramafic or mafic rock. The zone of platinum concentration can be visualized as a roll front that migrates along brittle fractures induced by differential volume expansion at the serpentinization front. Precipitation of platinum is induced by desulphurization (due to the precipitation of heazlewoodite) or oxidation and/or reaction with arsenic-bearing groundwaters of surrounding rocks.

Conclusions

As illustrated by the examples discussed above, there is no doubt that platinum and palladium can be mobilized and concentrated in significant quantities by hydrothermal processes. The available geological data and thermochemical models of the metal associations are compatable with hydrothermal platinum being deposited in two geological environments: 1. At redox fronts, with the platinum being mobilized as chloride complexes by oxidized fluids or as thio-complexes by reduced fluids. 2. In structurally controlled sites spatially associated with ultramafic-mafic rocks, where platinum precipitation is controlled by desulphidization of pore fluids produced by the initial hydrothermal alteration of olivine-bearing assemblages.

At the present time, considerations on the genesis of hydrothermal platinum deposits are severely constrained not only by a lack of data on the deposits themselves but by an incomplete knowledge of the behaviour of platinum in hydrothermal fluids.

EXPLORATION GUIDELINES

Introduction

In conclusion, we propose the following list of exploration guidelines for magmatic and hydrothermal PGE deposits. Some of these are suggested on basis of our understanding of deposit genesis whereas others are simply empirical observations for which the genetic significance is not fully appreciated. These guidelines are generalizations and we can point to exceptions in virtually every case.

Magmatic Deposits

1. Magmatic Affinity

There are surprisingly few data from which we can determine the concentrations of PGE in magmas but those that are available indicate that all magmas are not equally endowed. As noted above, for example, MORB's (Mid-Ocean Ridge Basalts) are extremely depleted in PGE and so it is perhaps not surprising that there are relatively few magmatic PGE deposits in ophiolitic rocks. Similarly, whereas PGE mineralization is known in the synvolcanic tholeiitic intrusions characteristic of Archean greenstone belts (e.g., Bird River Sill, Big Trout Lake), they are not of high grade. Magmas of CFB (continental flood basalt) affinity, on the other hand, commonly have relatively high concentrations of Pd and Pt and so PGE-rich magmatic sulphides might be expected in this association. Where feasible, it would be useful to analyse the chilled margins of differentiated intrusions to obtain an indication of the PGE content of the parent magma.

2. Differentiated Mafic/Ultramafic Intrusions

Magmatic sulphide deposits are, by definition, the product of differentiation processes, and so the fact that a given intrusion is differentiated is in itself a positive indication. More particularly, the presence of laterally extensive igneous layering is a requisite for stratabound mineralization. The most significant stratabound deposits occur in large intrusions (e.g., Bushveld, Stillwater, Great Dyke): however, it should be noted that the intrusions which host some of the very PGE-rich marginal sulphide deposits such as Noril'sk and Rottenstone are not particularly large.

3. Presence of Magmatic Sulphides

The presence of magmatic sulphides in an igneous body indicates that one of the prerequisites for the formation of a magmatic segregation deposit has been met: that is, that the magma has been sulphide-saturated during at least part of its history. An important point with respect to the PGE-rich stratabound deposits, including the Merensky and J-M Reefs, is that the quantity of sulphide is generally less than 2 to 3 percent. Such small amounts of sulphide will not necessarily be apparent from casual examination of the rock. Magmatic sulphides are typically polymineralic, with pyrrhotite, chalcopyrite and pentlandite as the most common phases. (Monomineralic pyrite grains in mafic rocks, for example, are almost certainly not magmatic because pyrite melts incongruently to pyrrhotite + liquid sulphur at 743°C.) Texturally, magmatic sulphides typically appear interstitial and molded around cumulus silicate and oxide crystals because the sulphide liquidus temperature is usually lower than that of the silicate melt.

4. Presence of Chromite or Chrome Spinel

Magmatic PGE deposits may occur in either mafic (Merensky, UG-2, J-M Reef) or ultramafic (Great Dyke MSZ, Stillwater and Bird River chromitites) differentiates, but the associated spinel phase is invariably chromite or chrome spinel rather than magnetite. Moreover, chromitite layers are present in many but not all cases. Compositionally, the chromites in mafic differentiates are iron-rich. An intriguing observation we have made is that the chrome spinels from a number of magmatic PGE deposits are anomalously rich in TiO_2, with concentrations up to 12 percent or more. Examples include Noril'sk, Crystal Lake, Fox River and Wellgreen.

5. Coarse-grained or Pegmatitic Textures

Pegmatitic texture has long been recognized as one of the diagnostic characteristics of the Merensky Reef. However, pegmatitic or coarse-grained textures also occur within or immediately below the J-M Reef, the UG-2 chromitite, the Crystal Lake Gabbro, the Stillwater and Bird River chromitites, and the Roby Zone at Lac des Iles, among others. Such textures are usually interpreted to reflect the presence of late-stage, volatile-rich magmatic fluids.

6. Synmagmatic Layer Disruption

Plastic and brittle deformation of various kinds affects igneous layers (commonly chromitites) hosting PGE concentrations in a number of intrusions (e.g., Bird River Sill, Crystal Lake Gabbro, J-M Reef). This deformation is thought to have been synmagmatic and may be related to the migration of intercumulus melt or volatiles prior to complete solidification of the cumulate pile. The "potholes" which characterize the Merensky Reef are another type of layer disruption but these probably formed during the initial accumulation of the layers.

7. Presence of Graphite, Chlorine-rich Hydrous Phases

Graphite occurs in stratabound deposits such as the Merensky and J-M Reefs, the discordant dunite pipes of the Bushveld, and marginal sulphide deposits such as Rottenstone. The presence of Cl-rich mica and apatite in some stratabound deposits including Merensky, J-M Reef and Picket Pin is also intriguing. While the significance of these minerals is hotly debated, their presence nevertheless constitutes a useful empirical guideline.

8. Elevated Se/S Ratios

The Se/S ratios of PGE-rich magmatic sulphide deposits are generally greater than inferred mantle values. Examples include the Merensky Reef, the J-M Reef, the Lower Chromitites of the Bird River Sill, Rottenstone, and Crystal Lake Gabbro. This enrichment of Se in PGE-rich deposits is not well understood, but the resulting high Se/S ratios are emerging as a valuable exploration guideline. By contrast, magmatic sulphides with relatively low PGE have Se/S ratios below the mantle range which is usually indicative of a crustal source of sulphur.

9. Massive/Breccia Contact or Vein Sulphides

Copper-rich sulphide segregations at intrusive contacts (Muskox, Noril'sk) or in footwall veins (Levack West - Sudbury) are enriched in PGE and also in Se. At Levack West these may represent the last residual sulphide melt separated from the main ore zone. However, such Cu- and PGE-rich segregations may also form by secondary remobilization.

Hydrothermal Deposits

1. Redox Fronts

It is predicted on theoretical grounds that deposition of PGE from hydrothermal fluids will occur at redox boundaries. This may occur as the fluid passes from more oxidized to more reduced rocks, or vice versa, depending on whether the PGE are present in th fluid as chloride or thio-complexes. Most natural redox boundaries occur in sedimentary sequences, and both uranium and copper mineralization are known to form in such environments. PGE, together with Au and Se, appear to be preferentially associated with uranium (e.g., Coronation Hill, Shinkolobwe) rather than copper enrichment. U-Au-PGE veins at Nicholson Bay are associated with hematitic alteration which may reflect a redox control in this environment as well.

2. Serpentinization Fronts

In theory, at least, the pore fluids of a serpentinization front have the ability to mobilize Pt, Pd and Au in significant concentrations. Hydrothermal PGE enrichment in the Unst ophiolite may have originated by this mechanism, though this has not been proven.

3. Faults and Shear Zones in Mafic/Ultramafic Rocks

The PGE enrichment in deposits such as New Rambler and Peter Lake appear to represent remobilization of PGE from magmatic magmatic sulphides and redeposition in fracture controlled veins in mafic rocks. The PGE-rich portions of the U-Au-PGE veins at Nicholson Bay within or close to the ultramafic body.

4. Selenium Enrichment

As in the case of magmatic deposits, certain hydrothermal PGE mineralization is characterized by anomalous levels of Se and the presence of Se minerals (e.g., Nicholson Bay)

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MUSKOX INTRUSION (Footnote added in proof - GSC)

PGE in the Footwall Marginal Zone

As was indicated under "Distribution of Sulphides", the footwall marginal zone of the Muskox intrusion contains many Ni-Cu occurrences (Fig. 18). These are currently being evaluated for their PGE potential by Equinox Resources Ltd. The most significant PGE values found to date occur in Cu-rich sulphides along the eastern margin of the intrusion. Values as high as 4.3 oz/t Pd, 0.37 oz/t Pt, 0.19 oz/t Au, 0.013 oz/t Rh and 4.4 oz/t Ag have been reported. The Cu- and PGE-rich sulphides occur some 15-20 m below the gabbro-metasediment contact, and form lenses of unknown dimensions of massive sulphides containing fragments of metasediments. These lenses are enclosed in metasediments and associated hybrid rocks which consist of hornfels and contaminated siliceous bronzite gabbros.

Sulphides also occur in the marginal zone of the intrusion, in gabbroic rocks and adjacent ultramafic cumulates. These consist of up to 5% disseminated pyrrhotite, pentlandite and chalcopyrite, but PGE concentrations are generally less than 200 ppb.

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