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MINES AND MINERALS DIVISION

ONTARIO GEOLOGICAL SURVEY

Open File Report 5681

The Platinum Group of Elements in Ontario

by

A.J. Macdonald and M.E. Cherry

1988

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Macdonald, A.J., and Cherry, M.E.

1988: The Platinum Group of Elements in Ontario; Ontario Geological Survey, Open File Report 5681, 279p., 74 figures, 28 tables, 1 appendix, and 1 map in back pocket.



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V.G. Milne, Director
Ontario Geological Survey

0.1 Foreword

This report has been assembled to meet a steadily increasing demand from explorationists for information about platinum group elements (PGE) in Ontario. It comprises contributions from a number of authors, identified at the beginning of each section, on the geochemistry and mineralogy of the PGE, the geology of PGE deposits and hypotheses of their formation, and descriptions of known and potential PGE occurrences in Ontario.

In the interest of quick dissemination of the information, no attempt has been made to maintain one style of presentation among the different authors. For the same reason, some repetition of ideas occurs throughout the text. The emphasis of the report is upon field-identifiable characteristics of platinum group minerals (PGM) and deposits of PGE; discussions of genesis, microscopic and chemical characteristics, and other topics are intended as brief summaries, and not extensive reviews.



V.G. Milne
Director, Ontario Geological Survey

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ACKNOWLEDGEMENTS

GCW : T. Eagles (X-Ray Assay Laboratories), M.P. Gorton and C. Cermignani (University of Toronto) discussed whole-rock and microprobe analytical methods. D. Conrod (University of Toronto), and A.J. Macdonald (Ontario Geological Survey) and P.J. Whittaker (Ontario Geological Survey, now with Noramco Ltd.) contributed valuable discussion of geological topics. Amongst others, J.T. Arengi, C.W. Graf and J.C. Rucklidge assisted with recent fieldwork relevant to this project. S. Azuma wrote the software for plotting the Grenville geochemical data. Dr B.W. Murck kindly supplied the excellent line drawings of the Stillwater rock textures (Figure 2.2). J. Van Kralingen and J.M. Wybourn provided the Grenville Province map (Figure 3.50) and the Mafic/Ultramafic Rock Tetrahedron (Figure 2.1) respectively. F. Neub (University of Toronto) took the SEM photos. W.B. Hicks provided photomicrographic facilities. Others too numerous to mention provided help in the collection of the assembled data.

AJM : I would like to acknowledge A.C. (Sandy) Colvine, who initiated this project in 1986 and gave me the opportunity to contribute to the compilation in early 1987. Iva Sherrett is thanked for the task of typing the bulk of this report. Geri Atkinson and Patricia Taylor are thanked for drafting some of the diagrams; Patricia also proofread the manuscript. Certain portions of Section 5.0 were greatly improved following careful readings by Drs. H.R. Williams, J.M. Duke, A.J. Naldrett, J.F.H. Thompson and R.G. Roberts, to whom I am most grateful.

GCP : Umex Incorporated provided financial support and freedom of access to the geological data at the Thierry Mines; T. Uerbeek and R. Dehenne were particularly helpful, as well as J.-J. Lefebvre who provided assays of sulphide concentrates; R. Kennedy and B. Zuckerandal, Mine Geologists, helped in mapping and producing mine sections. Thanks are extended to R. Eckstrand (Geological Survey of Canada) and G.B. Skippen (Carleton University) for their guidance with petrological interpretations. Financial support was provided through NSERC Grant A7874 to D.H. Watkinson.

PJW : I wish to thank my colleagues for their contribution to this work. A.C. Colvine (Chief Scientist, Ontario Geological Survey) proposed the review and helped coordinate its progress together with A.J. Macdonald (Ontario Geological Survey). Valuable discussions with G.C. Wilson (Turnstone Geological Services Ltd.), D.H. Watkinson (Carleton University) and R.S. James (Laurentian University) are appreciated. Drafting was provided by G. Atkinson and J. Van Kralingen (Ontario Geological Survey); the manuscript was typed by I. Sherrett.

ADM : I would like to acknowledge Ken Fenwick (Manager, Northwestern Region, Ministry of Northern Development and Mines) who initiated my portion of this project in 1984, George Patterson (Resident Geologist for the Thunder Bay-Atikokan District), James Macdonald and Richard Sutcliffe (Ontario Geological Survey), and Dick James (Laurentian University) who all provided valuable discussion; and especially my co-author, Rick Dutka (now with Ovaltex Inc.) whose mapping and drafting skills were invaluable throughout the project.

THE PLATINUM GROUP OF ELEMENTS IN ONTARIO

An Ontario Geological Survey Open File Report,

edited by

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Manuscript approved for publication by V.G. Milne, Director, Ontario Geological Survey, January 31, 1988.

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THE PLATINUM GROUP OF ELEMENTS IN ONTARIO

1.0 INTRODUCTION (A.J. Macdonald)

This report commences with an overview of the chemistry (Section 1.1) and mineralogy (Section 1.2) of the platinum group of elements (PGE). Section 1.3 gives a brief overview of mafic and ultramafic rocks in Ontario, to provide an introduction to subsequent descriptions. Section 2 outlines the hypotheses for different styles of platinum group mineralisation, considering the magmatic (Section 2.1) and hydrothermal (Section 2.2) environments. Section 3, by far the most voluminous component of this report, considers potential host rocks for PGE mineralisation throughout Ontario, commencing with Archean rocks, mainly in northwestern Ontario (Section 3.1), and continues with Proterozoic suites (Section 3.2). Section 4 deals with analytical procedures for platinum (Section 4.1) and a consideration of methods of treating PGE data. Section 5 summarises our understanding of PGE mineralisation, and provides exploration guidelines. References for this report and an annotated bibliography of the PGE in Ontario are in Sections 6 and 7, respectively.

A 1:2 000 000 scale geological map is inserted in the back pocket, giving the locations of intrusions and mineral occurrences described in this report.

For additional information, the interested reader is referred to Mertie (1969), Mohide (1979) and Cabri (1981) for more exhaustive reviews of the geology, supply and mineralogy, respectively, of the PGE. Wilson (1985) has recently published an indexed bibliography of the PGE, and Postle et al. (1986) have reviewed platinum group element deposits in Ontario.

1.1 GEOCHEMISTRY OF THE PLATINUM GROUP ELEMENTS (G.C. Wilson)

The six platinum group elements (PGE) are ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). They are Group VIII transition metals (atomic numbers 44-46 and 76-78), and as such share chemical characteristics with iron (Fe), cobalt (Co) and nickel (Ni), the more abundant Group VIII elements. The average concentrations in chondrite meteorites of the 6 PGE are given in Table 1.1, along with their mean crustal concentrations and melting temperatures. The low levels of abundance in most rocks, and scarcity of analyses for PGE in certain meteorite groups, limit precision in these values. The generally very low abundances and heterogeneous distribution also result in incomplete data: the author knows of no explicitly derived, mean crustal concentrations for the PGE.

In most geological situations, Pt and Pd are far more abundant than the other 4 PGE; accordingly, it is convenient when considering assays to look at concentrations of these 2 elements as first indicators of PGE enrichment. Mining grades of ore in which PGE yield the bulk of smelter revenue are in the order of 5 g/t (0.15 troy oz/short ton), similar to ore grades in Ontario's lode gold mines. Given that probable mean crustal abundances are in the part per billion (ppb) range, these ore grades represent an enrichment of 3 orders of magnitude over background.

The PGE generally exhibit siderophile characteristics in chondrites (Mason 1979); their behaviour is, however, more complex in terrestrial samples. Naldrett (1981a) calculated the PGE content of a sulphide liquid which might have solidified to form ore at the Levack West Mine in Sudbury. These calculated contents, shown in Table 1.1 as LWL (Levack West Liquid), illustrate a strong fractionation in comparison to chondritic abundances. When normalized to the given mean chondritic values, Pd shows a relative enrichment two orders of magnitude greater than that of Os. This difference is nearer 4 orders of magnitude in the richest ore from the Levack West Mine, containing several thousand ppb (0.1 oz/ton) of both Pt and Pd, and only a few ppb at most of the other four PGE. Note that the calculated liquid composition and the ore both exhibit major relative enrichment in the least refractory PGE. This fractionated behaviour within a group of elements of generally similar properties is the basis of a powerful petrological tool, analogous to the use of rare earth element (REE) abundances in igneous petrology, in which chondrite normalization is also employed. Due to the inherent difficulty of osmium analysis the Pd/Ir ratio of a magma provides a more convenient measure of the behaviour of the least refractory metal relative to the most (see e.g. Keays 1982); this ratio varies in analysed samples from 0.1 in Pd-depleted chromitites in ophiolites, to 865 in the J-M Reef of the Stillwater (Barnes et al. 1985) to >10,000 at Lac des Iles (Macdonald et al. 1987). Spinifex-textured komatiites seem to be derived from the most primitive magmas, with ratios as low as 6.3 (Keays 1982). Flat patterns are associated with a high degree of partial melt, as with komatiite-related deposits. Depending on the host mineralogy, PGE values may be recalculated to 100 percent sulphide or chromite (e.g. Borthwick and Naldrett 1984), to better approximate the levels in the carrier phases without dilution from the bulk rock (i.e., essentially barren silicates). This approach is discussed in greater detail in Secton 4.2, and is illustrated in Figure 1.1A and B. A combination of normalized PGE abundance and steepness of graphs has been used by some authors to classify various types of PGE deposit (e.g. Naldrett 1981b; Rowell and Edgar 1986).

1.2 Mineralogy of the PGE (G.C. Wilson)

Like silver, the PGE occur in a large number of minerals, in contrast with the simple mineralogy of gold. The PGE can occur as (a) native metals, (b) alloys, (c) as discrete minerals, combining with sulphur, tellurium, arsenic, antimony, mercury and bismuth, (d) in solid solution, at much lower concentrations in common sulphides such as chalcopyrite ($CuFeS_2$) and pentlandite ($(Fe,Ni)_9S_8$). The compositions of some of the more abundant platinum group minerals (PGM), mentioned throughout this report, are listed in Table 1.2. Cabri (1981) reports that sperrylite, the platinum arsenide, is the most ubiquitous of the PGE minerals. It is, however, exceedingly rare for any PGE mineral to be visible in hand specimen, in contrast to gold, as the minerals generally occur as opaque inclusions with a maximum dimension of about 200 microns (Cabri 1981), with only rare exceptions, such as sperrylite crystals from the Sudbury area (Figure 1.2).

The detailed PGE mineralogy of the Sudbury Igneous Complex (Section 3.2.3) has been described by Cabri and Laflamme (1976), who found that deposits on the North Range differed from those in the South Range: North Range PGE minerals also carry tin and little antimony, while those on the south range are tin-free and antimony-bearing.

Watkinson and Dunning (1979) noted that vysotskite (PdS) is the most common PGE mineral at the Lac des Iles deposit, described further in section 3.1.4.2, reflecting the palladium-rich nature of the mineralisation.

The application of the electron microprobe to mineralogy led to the discovery of many PGM; some of the earliest work involved Ontario deposits (Rucklidge 1969). PGM are treated at length by Cabri (1981), who has also provided a very useful glossary of some 74 species (Cabri 1976). The analysis of PGE in common sulphides is gradually maturing with the development of suitable analytical techniques (see e.g. Cabri et al. 1984). Examples of the complex mineralogy associated with PGE are given in Figures 1.3 and 1.4.

Detailed information regarding the PGE mineralogy and mineral chemistry for deposits in Ontario, and elsewhere, is summarized in CIM Special Volume 23, "Platinum-Group Elements: Mineralogy, Geology, Recovery", edited by L.J. Cabri (1981).

1.3 Geology of PGE Deposits (G.C. Wilson)

Tectonic setting can be used as a framework for classifying the major Ni-Cu-(PGE) deposits (e.g. Naldrett and Cabri 1976, Naldrett and Macdonald 1980, Naldrett 1981a,b, Cabri and Naldrett 1984). DeYoung et al (1985) provide a major tabulation of data on Ni deposits. Guilbert and Park (1986, pp.307-340) provide a synopsis of layered mafic intrusions and PGE deposits. Recently, Macdonald (1987b) has presented a classification of PGE deposits that places emphasis upon the process by which mineralisation occurred.

Table 1.1 : Platinum Group Element and Gold Abundances

Element	Chondrites		Clarke	LWL	MP (°C)
(1)	(2)	(3)	(4)	(5)	(6)
Os	517	514	1	22	3045
Ir	480	540	1	47	2410
Ru	690	690	1	60	2310
Rh	134	200	1	186	1966
Pt	1010	1020	5	1154	1772
Pd	560	545	15	1253	1552
Au	139	152	3	150	1064

All values in ppb. Notes on columns in table;

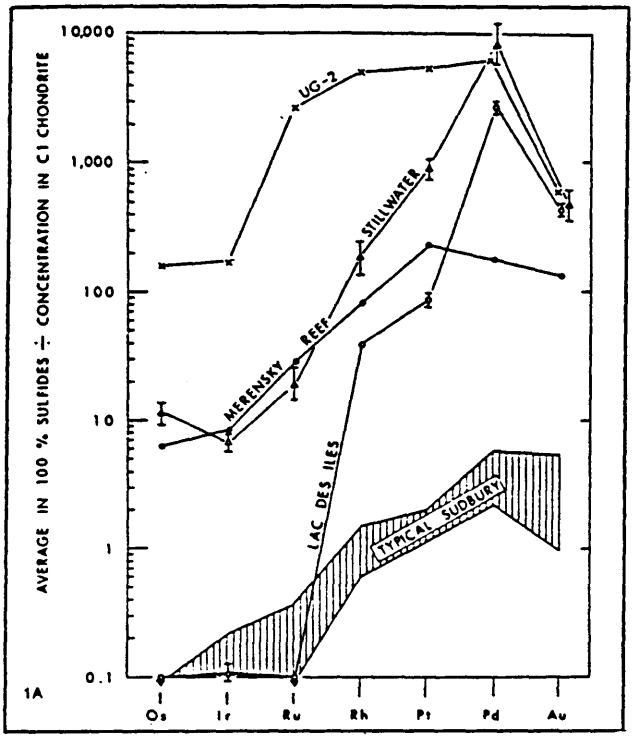
1) Chemical symbols (for chemical and physical data on the metals see e.g. Weast (1980) and Walker et al (1983)),

2-3) Meteorite data in column (2) refer to analyses of C1 chondrites (Ru,Pt; Mason 1979 - updated for Pd,Ir,Os,Au by Anders and Ebihara 1982), except for Rh (C1 estimate of Anders and Ebihara (1982), as no C1 data available). Column (3) gives compilation of Naldrett and Duke (1980), an oft-cited set of values and so useful for preparing comparative plots. The C1 class of meteorite is chosen as a reference standard as it is thought to represent the most primitive form of solar system material.

4) Clarke of concentration; estimated mean crustal abundance for each PGE. Pd from Ronov and Naroshevsky (1972), the others from McBryde (1972), except for Au (Taylor and McLennan 1985, p.67). Accurate values are extremely hard to derive, and at least the first four should be considered as working approximations only, possibly at least an order of magnitude too high. Taylor and McLennan (1985) propose mean Pd abundances for bulk continental crust and lower crust of 1.0 / 1 ppb respectively, and equivalent mean values for Ir of 0.1 and 0.13 ppb. Greenland et al (1974) estimate the crustal abundance of Ir at only 0.03 ppb (Os is probably of similar rarity). In comparison, Morgan (1986) derived the following estimates for pristine upper mantle material; 3.0 ppb Os, 3.4 ppb Ir, 4.5 ppb Pd, 1.01 ppb Au, and 200 ppm S.

5) 'LWL' is a calculated average composition for sulphide liquid responsible for ore at Levack West Mine, Sudbury (Naldrett 1981a, p.675). Note inverse trend of PGE values to melting points. See text for discussion.

6) Melting points in degrees Celsius (taken from Weast 1980).



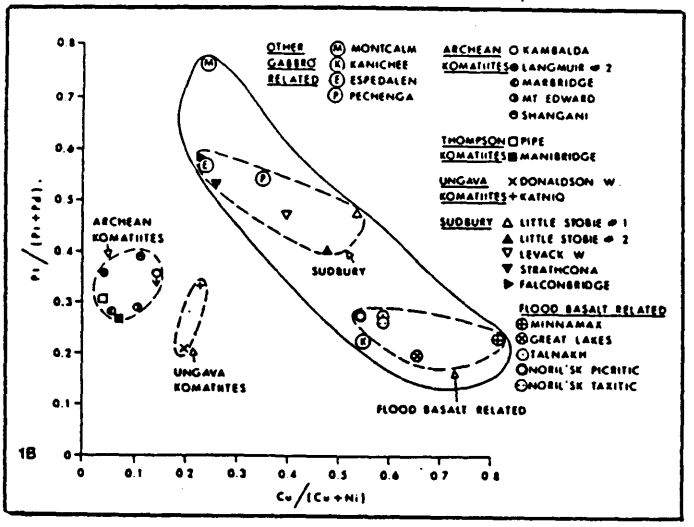


Figure 1A : A representation of the distribution of the six PGE plus gold, recalculated as if the rock were 100 percent sulphide, and normalized to mean chondritic abundances. After Naldrett (1981b).

Figure 1B : Plot of Cu/(Cu+Ni) against Pt/(Pt+Pd) for a number of deposits, principally of tholeiitic affinity (major enclosed area on plot). After Naldrett (1981b).



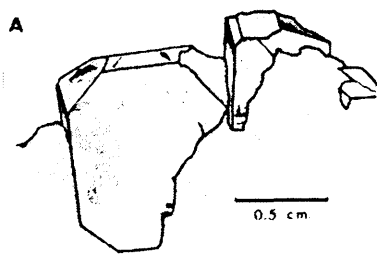




Figure 1.2 : A dramatic exception to the general case, in which PGM occur as occult phases 'buried' in common sulphide species or in chromite. Centimetre-sized euhedral crystals of sperrylite (platinum diarsenide) in Ni-Cu sulphide ore from the Vermilion Mine, Sudbury.

Specimens in collection of Royal Ontario Museum, from the area of the 'Offset Dyke' in Denison Township, on the S.W. side of the 'South Range'.

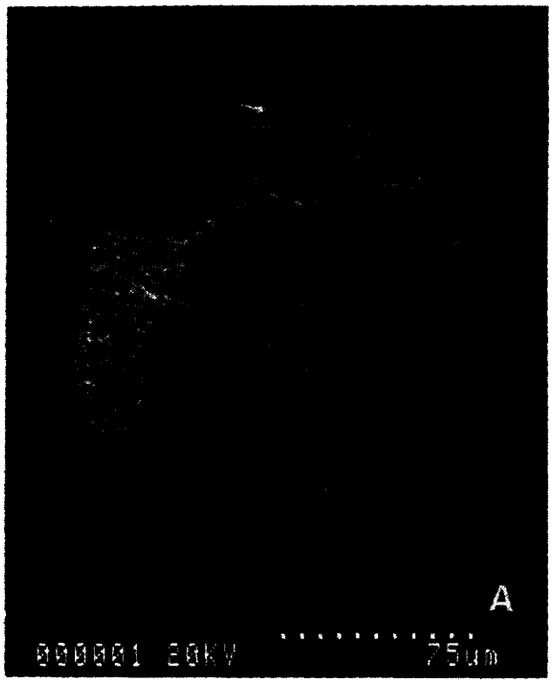
Figure 1.2A. M 31066 (upper), Photograph by Vi Anderson. **Figure** 1.2B. M 31065 (lower), Photograph by Bob Gait.

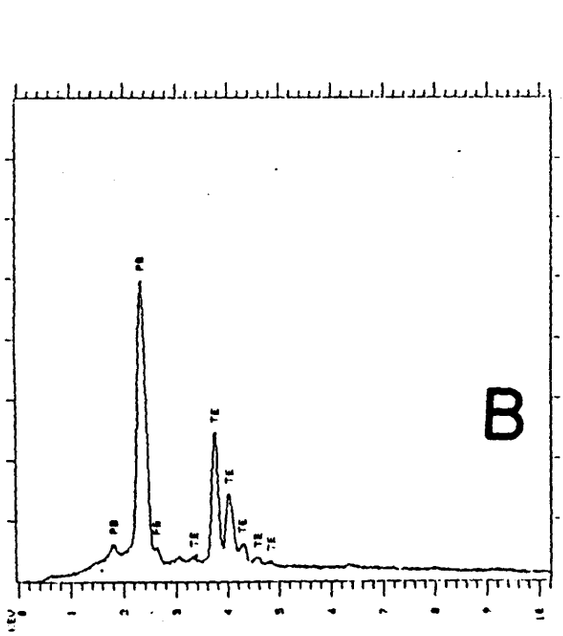
Table 1.2 : Condensed Classification of PGE-bearing Deposits

Type	Metals	Description	Examples
1.	PGE-dominant		
1A	PGE	Stratiform reefs in major layered intrusions	Merensky Reef, Bushveld, and J-M Reef, Stillwater
1B	PGE	Ultramafic breccias	Bushveld dunite pipes
1C	PGE	Placer	Goodnews Bay, Alaska
2.	PGE-Ni-Cu		
2A	PGE-Ni-Cu	Large sulphide-rich deposits	Noril'sk-Talnakh, USSR and Sudbury, Ontario
2B	PGE-Cu-(Ni)	Smaller deposits	New Rambler, Wyoming, and Cuniptau, Ontario
3.	PGE-other metals		
3A	PGE-Cr	Chromitites in major layered intrusions	UG-2 Reef, Bushveld
3B	PGE-Cr	Chromite pods in ophiolites	Bay of Islands, Newfoundland
3C	PGE-Cr	Chromite pods in Alaskan ultramafics	Urals, USSR
3D	PGE-Au-V	Black shales	Kupferschiefer, Poland

The above classification is simplistic, serving mainly to highlight the mineralogical affinity of the deposits (with sulphides or chromite, except for 1C and 3D). There is an inherent economic bias; the Merensky Reef would not be mineable solely for base metals, nor Sudbury for PGE alone. The examples include the largest known PGE deposits (1A, 2A, 3A) as well as smaller, now exhausted deposits (1B, 2B), some of which were however of locally extremely high-grade (1B). Refining of refractory chromite-rich ore is more complex than for ordinary sulphide ores, and depends on the chromite chemistry. This influences the viability of Cr-rich deposits for PGE recovery, whether they are very large (3A) or smaller and lower-grade or subeconomic (3B, (?) 3C).

See text for amplification. For more detailed classifications, see Naldrett and Cabri (1976) and Naldrett (1981b).





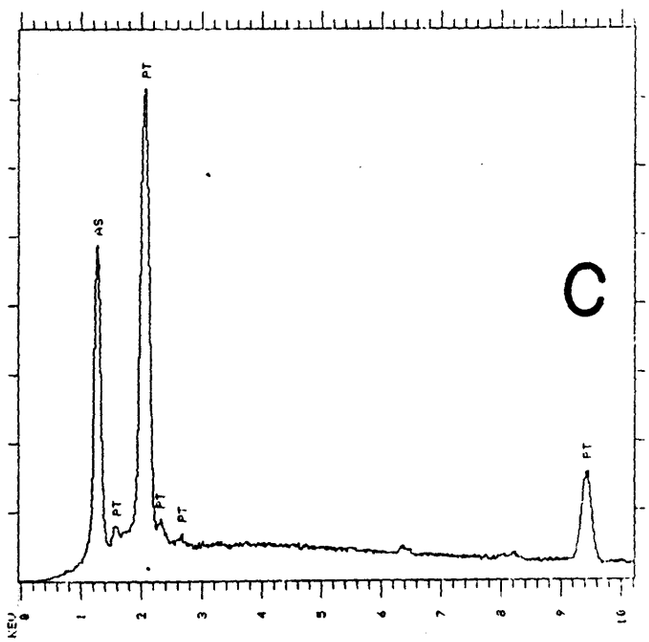


Figure 1.3A. Scanning electron micrograph of a small (0.15 mm diameter) rounded inclusion within a large sperrylite of the form shown in Fig. 1.2. The central grey grain is the mineral altaite (PbTe). The two dark grains are the common sulphide pyrrhotite. The bright arcuate rim is native bismuth, and the small grain at the upper right is native gold. The host phase, sperrylite, is one of the most common and distinctive PGM. The simple formula is $PtAs_2$, i.e. this ore mineral ideally contains 56.6 wt.% platinum. R.O.M. sample R355, from Sudbury. Long axis of photo; 250 μm, scanning electron micrograph.

Figure 1.3B, C. Energy-dispersive spectra reveal the chemistry of altaite and sperrylite. The bismuth is quite pure (no minor elements detected), whereas the gold contains a proportion of silver.

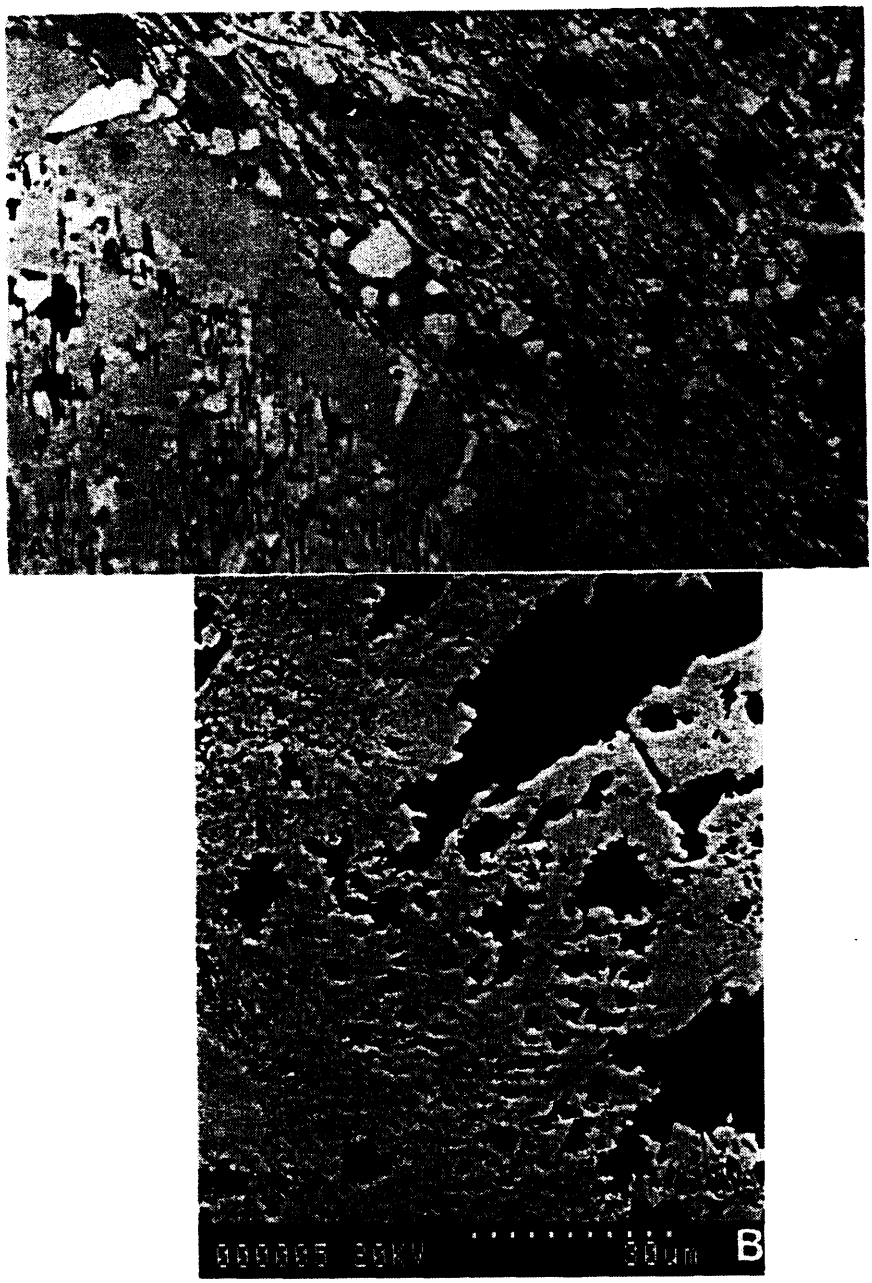


Figure 1.4 : Complexities of sulphide ore and gangue are illustrated elsewhere in this report. Two examples follow;

Figure 1.4A. Sample from the Frood Mine, Sudbury. The white euhedral phase in the chalcopyrite veinlet was submitted as (?) sperrylite, but is actually 'pure' pyrite (Fe,S alone detected by electron probe). The pyrrhotite host consists of domains whose variable orientation is visible in the alignment of (pale) exsolved marcasite. A fifth phase, small white euhedra in the pyrrhotite, is nickeliferous pyrite (about 5 wt.% Ni). Long axis of photo; 0.6 mm. Crossed polars, slightly offset.

Figure 1.4B : . Apparent reaction rims are often visible between sulphide ore minerals and their rock-forming silicate hosts. These are most often seen against plagioclase, and are typically a mixture of ferromagnesian silicates (amphibole, chlorite, sometimes with epidote minerals) and opaque phases (oxides and silicates). The opaque phases may be very fine-grained, as in this example from the Mountain Grove intrusion, where the fine 'porous' rim abuts plagioclase in uralitized metagabbro. Qualitative x-ray microanalysis of a point within this secondary electron image reveals only Fe and S, in proportions suggesting pyrite. Long axis of photo; 100 μm, scanning electron micrograph.

Table 1.3 : Simplified Compositions for 16 Platinum Group Minerals

Mineral	Simple formula	Additional elements
Braggite	(Pt,Pd,Ni)S	
Cooperite	PtS	Pd, Ni
Hollingworthite	RhAsS	Ru, Pt, Pd, Co, Ni
Irarsite	IrAsS	All PGE, Ni, Co
Iridosmine	Os,Ir	All PGE, Fe, Cu, Ni
Kotulskite	PdTe	Ni, Bi, Sb, Pb
Laurite	RuS2	Ir, Os
Merenskyite	$PdTe_2$	Pt, Ni, Bi, Sb
Michenerite	PdBiTe	Pt, Ni, Sb
Moncheite	$PtTe_2$	Pd, Ni, Bi, Sb
Sperrylite	$PtAs_2$	Rh, Ir, Sb, S
Stillwaterite	Pd_8As_3	Sb, Te, Sn, Bi
Sudburyite	PdSb	Ni, Bi, Te, As
Temagamite	Pd_3HgTe_3	Bi, Sb
Testibiopalladite	PdSbTe	Ni, Bi
Vysotskite	PdS	Ni, Pt

Note that solid solution is extensive within groups of PGM. Refer to literature for details, e.g. glossary of Cabri (1976, 1981), PGM references in Fleischer (1983), or Wilson (1985a).

Table 1.4 : PGE Reserves in some Deposits

	BUSHVELD COMPLEX			GREAT DYKE*	SUDBURY	NORIL'SK	STILLWATER
	Merensky Reef*	UG2*	Platreef*				J-M Reef*
Million Tonnes	2160	3700	1700	1679	310	1640	49
Grade (Total PGE+Au, g/t)	8.1	8.71	7.27	4.7	0.9	3.8	22.3
Contained PGE +Au (tonnes)	17496	32227	12360	7890	279	6232	1093
Percentage of total	22.6	41.5	15.9	10.2	0.4	8.0	1.4

* : Primary Product

Data from Buchanan (1979), Naldrett (1981), Robson (1985) and Naldrett et al. (1987).

The majority of known occurrences of PGE are related to basic igneous rocks, occurring within them, or as placer deposits derived from them. Accordingly, one approach to classification of PGE deposits is based upon the associated igneous rock type. Furthermore, concentrations of the PGE are closely linked to occurrences of Ni-Cu sulphides, and fall naturally into two distinct associations with the sulphides: those in which PGE dominate, and are the primary commodities recovered from the ore, and those in which the PGE are by-products of Ni-Cu and Cr ores. A classification of major PGE deposits, based upon these two main characteristics (igneous rock type and ore composition), is given in Table 1.3. Ore compositions, grades and reserves from a number of the more important PGE deposits are given in Table 1.4.

The PGE deposits of the Bushveld and Stillwater Complexes account for the overwhelming bulk of the world production plus reserves. A description of the geology of these deposits is, therefore, an appropriate basis for discussion of the geology of other PGE deposits, which invariably are compared with those of the Bushveld and Stillwater Complexes. A number of recent publications have described mineralisation in these two complexes: Naldrett (1981a,b), Czamanske and Zientek (1985), the Bushveld Issue of Economic Geology (1985, volume 80, number 4) and several articles in the recently published Mineral Deposits of South Africa, edited by Anhaeusser and Maske (1986), from which the following brief descriptions are synthesized.

The Bushveld and Stillwater complexes show some remarkable similarities, both on the gross and small scales. At the exposed base, both complexes contain a 1.2 to 1.5 km thick, ultramafic zone (cumulus olivine and pyroxene) containing significant chromite deposits (Figure 1.5). Above the ultramafic zone, plagioclase is a cumulus phase, which together with bronzite (orthopyroxene) gives rise to a suite of norite rocks, with associated anorthosite and bronzitites. In both intrusions PGE mineralisation is concentrated approximately 1 to 1.2 km stratigraphically above the ultramafic suite; in the Bushveld Complex, the PGE are concentrated within an average 1 metre wide, pegmatoidal feldspathic pyroxenite, known as the "Merensky Reef" (Vermaak 1976); at the Stillwater Complex, the "JM Reef" (formerly the "HP Reef") meanders within a complex assembly of norite, gabbro, anorthosite, troctolite, olivine cumulate and pegmatoidal gabbro. For a full description of the host rocks for the JM reef, refer to Turner et al. (1985). Naldrett (1984b) observes that *"while there are some important differences between the two major PGE deposits .... a number of striking similarities are present, the most important of which are listed here:*

1) Stratigraphic position: both the Merensky and JM reefs occur a few hundred metres above the first appearance of cumulus plagioclase in the host intrusion.

2) Mineralisation in both reefs takes the form of interstitial magmatic Fe-Ni-Cu sulphides, carrying exceptionally high concentration of PGE.

3) Both are characterized by the reappearance of cumulus phases which were dominant in the early crystallization history of both intrusions: olivine and chromite in the Stillwater Complex, bronzite and chromite (and locally olivine) in the Bushveld.

4) Very coarse grained pegmatoidal gabbroic rocks are common in both reefs.

These similarities leave little doubt that the two reefs share a common origin, and provide important constraints upon genetic models".

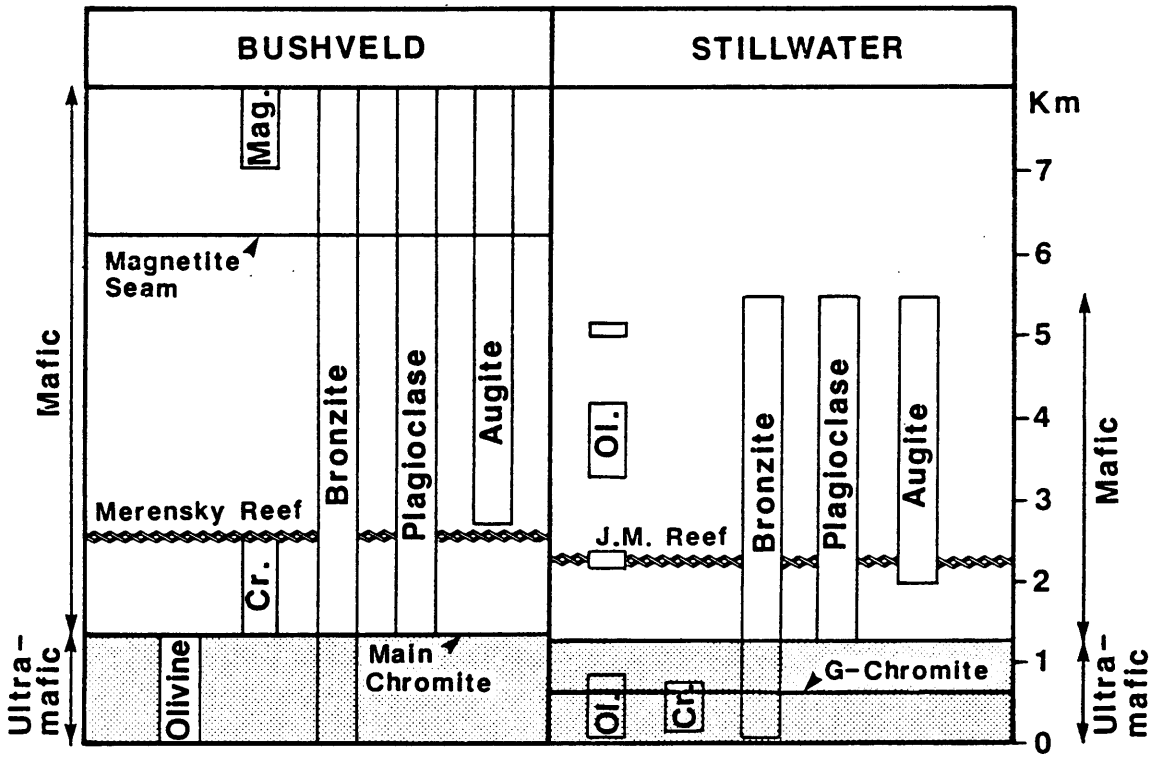


Figure 1.5 : Stratigraphic sections for the Bushveld and Stillwater Intrusive Complexes (Campbell et al. 1983). Note the relative positions of the J-M and Merensky Reefs with respect to the mafic/ultramafic contacts.

A review of proposed genetic processes for the formation of PGE deposits is presented in Section 2. Much controversy still exists regarding the origin of Merensky and JM reef mineralisation. On the one hand, the re-appearance of olivine and chromite (Stillwater), bronzite and chromite with local olivine (Bushveld) as cumulus phases, combined with detailed lithogeochemical and radiogenic isotopic analyses (e.g. Campbell et al. 1983; Sharpe et al. 1986) has provided the basis for a model involving the replenishment of the magma chamber with a more primitive, ultramafic magma at the Merensky and JM reef stratigraphic levels, respectively. On the other hand, the orthomagmatic hypothesis, outlined above, does not necessarily account for the spatial association between the PGE-bearing reefs and postcumulus hydrosilicates, pegmatitic textures and abnormal concentrations of graphite. Some authors suggest that as upward crystallization in the magma chamber proceeded, intercumulus melt and volatiles gradually evolved into a significant component of the magmatic system, culminating with mineralisation at the stratigraphic levels of the Merensky and JM reefs (see Stumpfl and Ballhaus 1986; Ballhaus and Stumpfl 1985a).

The Bushveld Complex also contains three other significant PGE-bearing deposits: (1) the UG2 chromitite layer, (2) the Platreef and (3) dunite pipes. The UG2 chromitite is found 30-400 m below the Merensky reef, again within the mafic portion of the Bushveld complex. PGE are associated with minor base metal sulphides and laurite (RuS_2), generally enclosed by chromite (von Gruenewaldt et al. 1986b). The UG2 is reported to have an overall grade of PGE + Au that is similar to that of the Merensky Reef, with a slightly lower platinum tenor, although this is compensated by a higher rhodium grade (Naldrett 1981b) and the additional reserve of 41% Cr_2O_3 over an 80 cm thickness (de Kun 1987). Metallurgical problems associated with testing this ore have recently been resolved, and the UG2 PGE deposit must now be regarded as the world's largest single PGE reserve: 32.27 tonnes of total PGE + Au metal, at an average mining grade of 8.712 g/tonne (data in Naldrett 1981a), implying a tonnage in the UG2 orebody of approximately 3.7 billion tonnes, calculated to a depth of 1200 m.

The Platreef mineralisation has not been described in such detail as the Merensky or UG2 mineralisation, several differences exist between typical Merensky Reef and the Platreef (as summarized in Cawthorn et al. 1985).

1. The Merensky Reef is a stratabound deposit; the Platreef appears to be discordant.

2. The Merensky Reef occurs toward the middle of the layered sequence; the Platreef is a marginal facies.

3. The Merensky Reef is generally no more than 1 m thick, although it does thicken in places to 8 m. The Platreef is distributed over a zone up to 200 m thick with irregularly distributed mineralisation.

4. The Platreef contains numerous xenoliths of floor rocks and shows extensive interaction with floor rocks. The Merensky Reef is free of such megascopically observable effects.

Naldrett (1981b) notes that mineralisation in the Platreef is never far from the floor of the intrusion and that much of the better ore occurs where dolostone and banded ironstone of the country rock form the floor to the

intrusion. Naldrett (1981a) gives Platreef reserves of 11.78 tonnes of PGE + Au at a grade of between 7 and 27 g/tonne, suggesting a total tonnage between 430 million and 1.7 billion tonnes.

The Dunite Pipes constitute the final Bushveld PGE ore type, and contained the highest grades reported for the complex: 2,050 ppm PGE (Wagner 1929). The Dunite Pipes are typically cored by an hortonolite dunite (olivine composition, Fo_{22}) which tapers downward, and is encased within an olivine dunite envelope (Fo_{80-92}). The total width of the pipe may be approximately 100 m (Wagner 1929; Cameron and Desborough 1964). Based upon textural evidence, Cameron and Desborough (1964) suggest that the original bronzitite host rock was metasomatised by fluids of unspecified origin, converting bronzite to olivine, by the leaching of SiO_2, Al_2O_3 and Na_2O, and the introduction of FeO, TiO2, U and the PGE. These subsolidus, deuteric reactions exemplify the complexities that can occur within a complex, heterogeneous, volatile-bearing igneous complex.

1.4 PGE and Mafic/Ultramafic Rocks in Ontario (G.C. Wilson)

Historically, Ontario's PGE production has been an important but secondary product of the Sudbury Ni-Cu mines. During the 1940's, Canada supplied 40% of the world's platinum (Robson 1986). A combination of economic and academic geological interest has ensured that both the ores (Naldrett 1984a) and their surroundings (Pye et al. 1984) are now very well documented, although not yet free from controversy. The development of Sudbury and Canadian nickel mining has been reviewed by Smith (1986, chapters 4,7,14) and by Howard-White (1963). Other, lesser-known Ni mining operations have also yielded Pt, although none are currently operational. These include the Shebandowan Mine (Section 3.1.6.2), and the Kanichee layered intrusion (Section 3.1.7.8) near Temagami (Bennett 1978, James and Hawke 1984).

Table 1.5 is a listing of selected mafic-ultramafic intrusions in Ontario, arranged in order of radiometric ages. Figure 1.6 is a simplified geological map of the province, indicating areas discussed in this report; the relevant Section numbers are also given in Figure 1.6. The locations of specific intrusions throughout the Province, described in Section 3, are given on Map 1 (back pocket).

Exposed surface areas of four Ontario mafic-ultramafic intrusions are compared with other layered mafic intrusives in Table 1.6. It may be more than coincidence that the largest known PGE reserve is hosted by one of the largest known mafic/ultramafic complexes (compare Tables 1.4 and 1.6).

Field prospecting for PGE must necessarily proceed with a different set of criteria from those applied in the search for gold, which most commonly occurs in the native state, and which, when alloyed with its most common associate, silver, is still sufficiently distinctive that an experienced individual can readily detect the 'colour' in a coarse, high grade sample. Even when it is of microscopic size, or 'locked into' sulphides, a prospector can still recognize favourable ground in terms of a combination of favourable circumstances. The features concerned vary from one occurrence to another, but typically combine evidence for increased permeability (deformation, such as fracturing, veining etc.), the passage of potentially auriferous fluids (e.g. alteration), potential fluid sources or 'heat pumps' (felsic intrusions) and a favourable lithology for deposition (host rocks susceptible to fracturing and/or replacement).

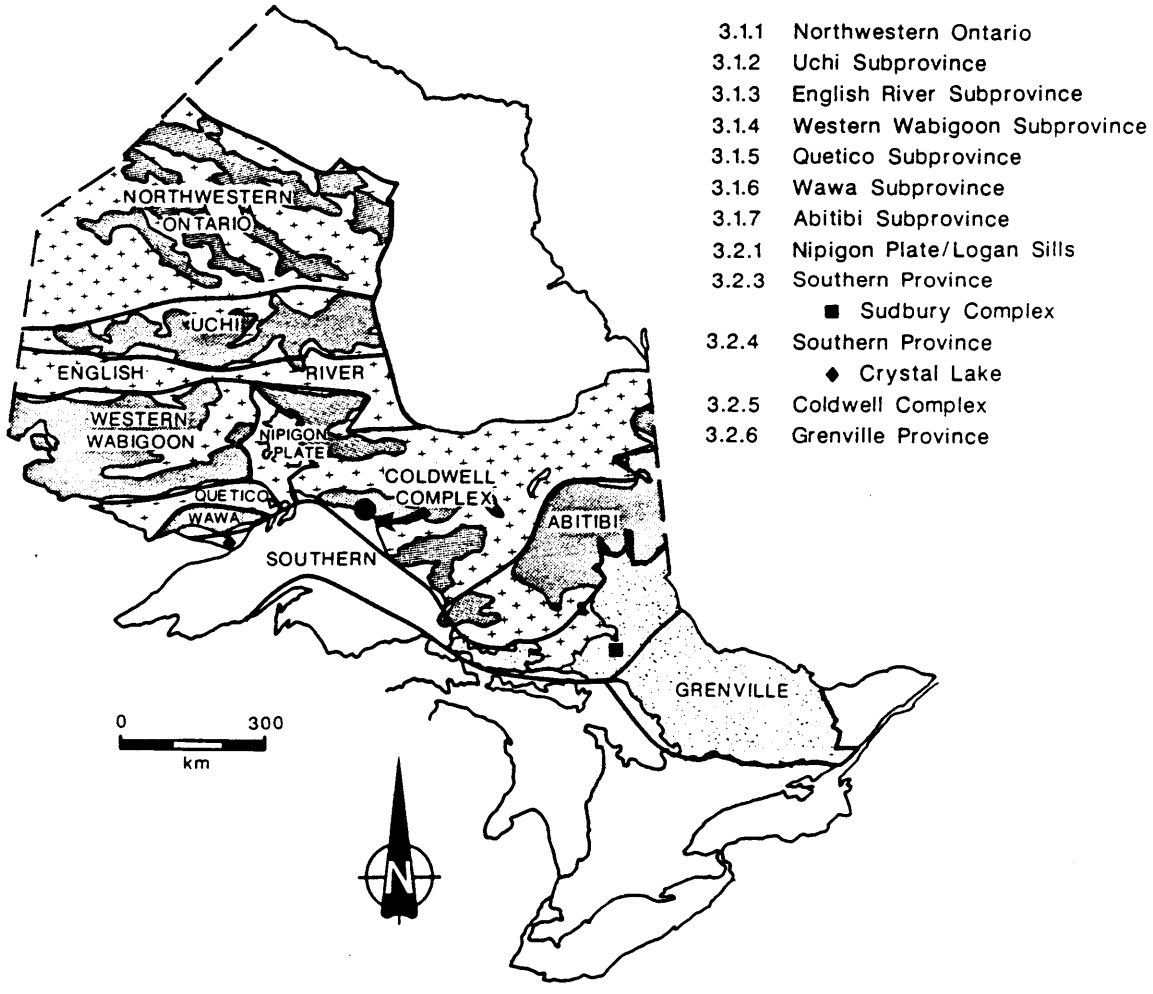


Figure 1.6 : Geological Sketch Map of the Province of Ontario showing the location of major Geological Provinces and mafic/ultramafic intrusive complexes. Numbers (e.g. 3.2.1) refer to sections in this report.

Table 1.5 : Summary of Selected Radiometric Ages In Ontario

Unit dated	Date (Ma)	Reference	Notes	Technique(s)
Archean				
Bad Vermilion anorthosite	2747±58	Ashwal et al 1985	Rainy Lake	Sm-Nd isochron
Mulcahy gabbro	2732± 1	Morrison et al 1986	Crystallization	U-Pb zircon
Early Proterozoic				
Nipissing diabase	2162±27	Fairbairn et al 1969	Crystallization	Whole rock Rb-Sr
	2150±50	Van Schmus 1965	Blind River area	Whole rock Rb-Sr
	2219± 4	Andrews et al 1986, Corfu and Andrews 1986	Crystallization (Castle Mine)	U-Pb baddeleyite
Sudbury igneous complex	1840±21	Faggart et al 1985	Crystallization	Sm-Nd
	1850± 1	Krogh et al 1984	Norite intrusion	U-Pb zircon
Late Proterozoic				
Coldwell complex	1189±40	Turek et al 1986		U-Pb zircon
	1088±10	Thorpe 1986		U-Pb zircon
	1044± 6	Platt and Mitchell	17-point isochron	Whole-rock Rb-Sr
Grenville Province				
Umfraville gabbro	1180±20	Symons 1978	Emplacement	U-Pb zircon

This only a small selection of all published dates relevant to mafic intrusions in Ontario. Where possible, unambiguous emplacement ages have been selected. When comparing the latest results with analyses made 20 years or more ago that the decay constants employed may have been slightly different. For a geographically -indexed catalogue of age dates in Ontario, see Easton (1986). For simplicity, values are rounded to ±1 Ma. N.B. Coldwell complex age in dispute (see references).

Table 1.6 : Area of Selected Intrusive Complexes in Ontario

Intrusive Complex	Area (km^2)	Major/minor axes (km)	Map(s)
Sudbury Basin	1243	58 x 24	2361
Coldwell complex	278	27.4 x 15.5	2220 / 2232
Lac des Iles	32.2	11.9 x 4.4	2135
Kanichee intrusion	0.6	1.0 x 0.6	2323
Comparative Data, Worldwide;			
Bushveld Complex, South Africa	67340		
Duluth Complex, USA	4715		
Great Dyke, Zimbabwe	3265		
Dore Lake complex, Quebec	470		
Muskox intrusion, N.W.T.	350		
Stillwater complex, Montana	194		
Skaergaard complex, Greenland	104		
Skye, Scotland	73		
Ardnamurchan, Scotland	62		
Rhum, Scotland	30		

Approximate surface dimensions of various structures / intrusions hosting mafic rocks in Ontario. Note that in each case the major contiguous structure revealed by or inferred from surface mapping is considered; satellite intrusions are excluded. Areas estimated by the 'trace, cut, and weigh' method. N.B. areal estimates are easy to derive from maps, but for that more meaningful quantity, the volume of magma intruded and currently preserved, a combination of mapping and geophysics may be required.

Map references (mostly 4-digit numbers) refer to maps published by the Ontario Department of Mines / Ontario Geological Survey, on five scales from 1:253,440 to 1:31,680 (1 inch:4 miles to 1 inch:0.5 miles).

N.B.; Coldwell complex estimate excludes that portion of the plutonic mass beneath Lake Superior; a simple geometric estimate of the remainder could add 232 km^2, for an overall area of 510 km^2.

Comparative data worldwide taken from Guilbert and Park (1986, p.314). They quote a value of 1342 km^2 for the Sudbury complex.

Can similar guidelines be laid down for PGE prospecting? Available evidence suggests the following approaches, although more field experience in Ontario will be required to refine a methodology for local application. The awareness of the possible environments of PGE concentration is crucial, as well as the processes which may effect the 3 to 4 orders of magnitude local enrichment required to form ore grades (Section 2). It is well to remember the obvious, namely the known association of most PGE deposits with Ni-Cu sulphides and with chromite deposits (see Section 1.3). Most Ni deposits in Ontario are associated with ultramafic rocks, both intrusive and extrusive, although exceptions such as Montcalm have gabbroic hosts (Franklin and Thorpe 1982). The geology of Ontario nickel deposits is well-documented, both in the Sudbury area (e.g. Pye et al. 1984) and in the Abitibi belt, where the komatiitic petrologic association has been described extensively (e.g. Naldrett and Mason 1968, Green 1978, Coad 1979, Barnes et al 1981, Barnes and Naldrett 1986).

Broadly, two kinds of PGE targets may be identified, based on the 'orthomagmatic' and 'hydrothermal' hypotheses for PGE concentration. The first kind of target includes stratiform concentrations of sulphides and oxides (chromite in particular) within intrusions showing evidence in outcrop or drill core for igneous layering and/or sulphide-silicate, oxide-silicate liquid immiscibility. Substantial experimental data are now available concerning chromium solubility in ultrabasic melts and the circumstances of chromite formation (e.g. Murck and Campbell 1986, Barnes 1986).

The second kind of target includes pegmatitic segregations, mineralogy consistent with late volatile activity (such as biotite, secondary amphibole, carbonate or graphite) and channelways for volatile movement and concentration, such as shears, fracture intersections or pipe-like structures. Occurrence of PGM and bornite in mylonite at the Thierry Mine, near Pickle Lake, northwest Ontario, is an indicator of possible PGE enrichment along shear zones (Patterson and Watkinson 1984a). Ni-PGE ore is also concentrated along a shear zone at the Cuniptau Mine (Sandefur 1942) within the Kanichee layered complex (James and Hawke 1984). Pegmatoids often occur in association with oxide segregations or layers in prospective intrusions; examples include the Stillwater, Bushveld, and Coldwell Complexes and the Bird River Sill.

Discussion amongst those involved in PGE research has been increasing steadily concerning the relative importance of 'magmatic' versus 'hydrothermal' processes in PGE ore formation. Almost all researchers would concede that the elegant propositions developed for orthomagmatic genesis of the world's greatest known PGE resources, historically focussed on the Bushveld Complex, and more recently on the Stillwater Complex are grossly correct, even if experts differ on the precise mechanisms responsible. In the immediate future, argument is likely to revolve around the capacity of late fluids to carry (or at least accumulate) high PGE values, on their ability to remobilize pre-existing magmatic deposits, and, in particular, on the extent and scale on which such processes can operate. The occurrence of mafic pegmatoids and complex platinum-group mineral assemblages (Merensky Reef; Vermaak and Hendriks 1976), and complex volatile-rich mineralogy (summarized in Sections 2.1 and 2.2) has sustained a measure of support for late magmatic or hydrothermal modifications within magmatically-precipitated deposits. Even those few PGE-rich ores generally thought to have formed hydrothermally (such as the New Rambler Cu-PGE deposit in Wyoming; McCallum et al. 1976) are not fully characterized in terms of their tectonic setting and spatial relation to possible metal sources (A.J. Macdonald, Geologist, Ontario Geological Survey,

Toronto, personal communication, 1985). The great variation in the chemical properties of PGE dictates that Pd and, to a somewhat lesser extent, Pt are those elements most likely to concentrate in the hydrothermal environment.

Appropriate exploration targets for PGE mineralisation in Ontario include the diversity of plutons, stocks and sill-like intrusions described in Section 3, as well as overburden-covered areas with geophysical indications of high-density rock near-surface. The majority of all these intrusions, which occur widely throughout the province, have been prospected repeatedly, for Ni and Cu, but not necessarily in detail for PGE. They range from the Grenville Province in southeastern Ontario to the far northwest, where such Ni-Cu deposits as that at Gordon Lake occur in fault bounded mafic/ultramafic bodies (Carlson 1958). Within a mafic-ultramafic body, zones of suitable mineralogy (sulphide or oxide concentrations), texture (variable-textured or pegmatitic) and structural setting (evidence of shearing or alteration) should be examined and possibly assayed. Large numbers of Ni-Cu prospects have been documented in Ontario (Shklanka 1969). Detailed PGE data (e.g. Naldrett et al. 1980, Barnes et al. 1981, Naldrett 1982, Borthwick and Naldrett 1984) are available for a number of intrusions in Ontario, including some outside the Sudbury area.

Regional mapping within Ontario has advanced to the point where major near-surface bodies of mafic-ultramafic bodies are all recognized, and large-scale remote sensing (e.g. for serpentine mineral traces, by Sultan et al. 1986) are in any case hard to apply because of overburden and vegetation problems. On a more local scale, it should be noted that PGE deposits typically contain a low (0.5 to 5%) sulphide content, so that chemical factors are likely to provide more sensitive discriminants than bulk geophysical properties. Much current PGE exploration in fact consists of re-examination of old Cu-Ni prospects. Two practical factors (expense, and the trend for most PGE deposits to be dominated by Pt and Pd) dictate the use of a 3-element package of {Pt+Pd+Au} in basic exploration programs. The costlier precious metal assay (six PGE plus Re and Au) is a worthwhile addition in chromite-rich showings with significant Pt values.

Analysis of PGE is not simple; because of the extremely low concentrations in most rocks, researchers have had to devise sophisticated analytical methods, often coupled with complex pre-concentrations of the material to be analysed. Commercially-available techniques include instrumental neutron activation (INAA), emission spectrography and atomic absorption spectrography, and the recently-developed method of inductively-coupled plasma spectrography. Pre-concentration may be effected by the fire-assay method, where the precious metals are extracted into a nickel sulphide 'button' which can then be ground or dissolved in acid for the actual analysis. As with gold, heterogeneous distribution of tiny PGM grains in a rock can introduce a complex 'nugget' effect, adding to the expense of assay by requiring greater sample weights and/or a larger number of assays. The analysis of PGE-bearing rocks is addressed in further detail in Section 4.

Recent developments, due to an anticipated upturn in PGE demand and buoyed by the recent rising price, has resulted in a marked increase in exploration for these metals and may, in turn, result in an increase in the number of producers in the province; recently, a production decision was announced for the Pd-Pt-Au (Cu, Ni) deposit in the Lac des Iles intrusion (Northern Miner, July 27, 1987). Current reserves are quoted at 20.4 million tons with an average total PGE grade of 5.75 ppm and a Pd:Pt ratio of approximately 7:1 (Tintor 1986; Sutcliffe 1986).

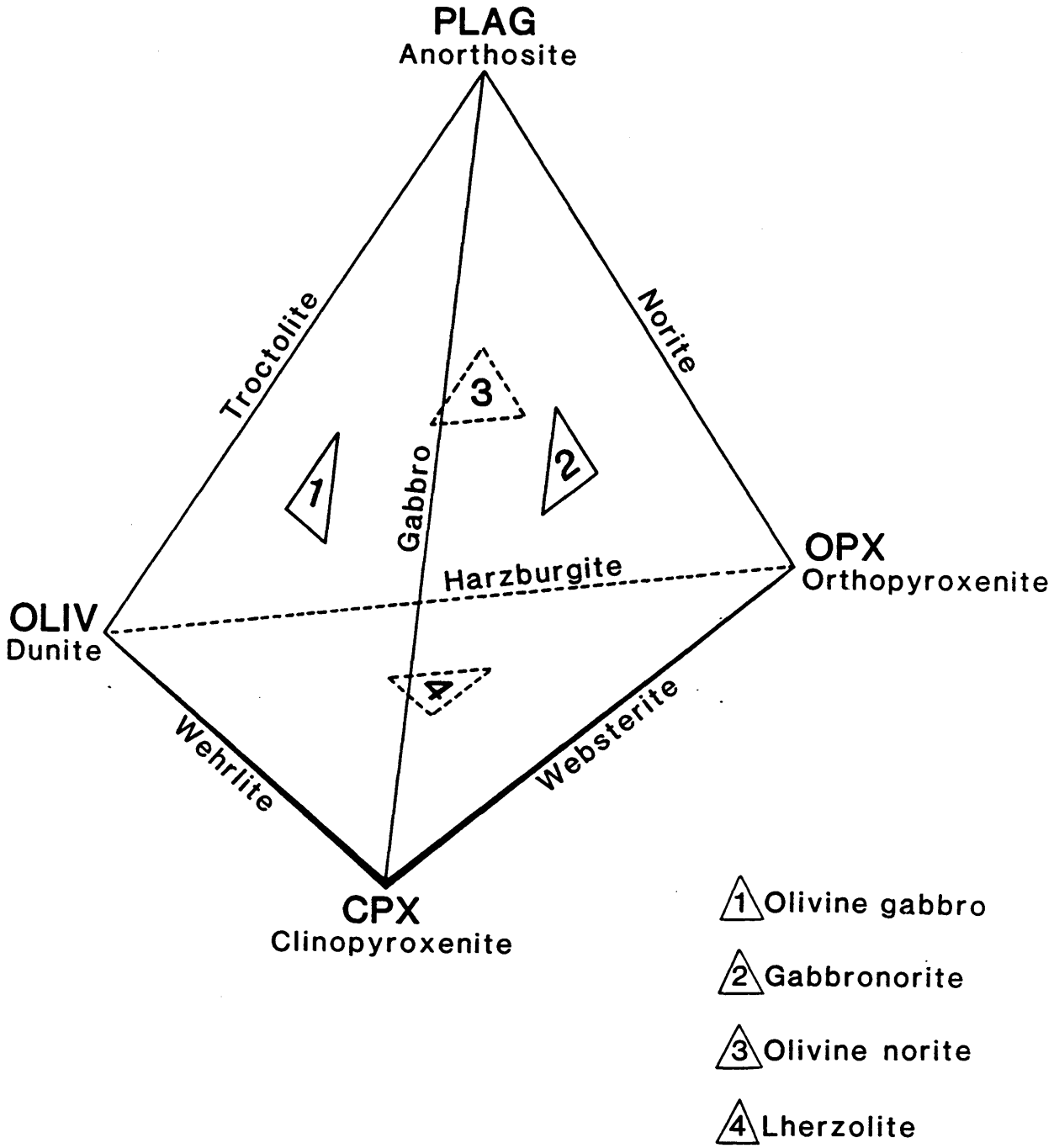


Figure 2.1 : Generalized nomenclature for mafic and ultramafic rocks composed of varying proportions of PLAGioclase feldspar, OLIVine and 1-2 pyroxenes (OPX, CPX). See Streckeisen (1976) for details, and for ultramafic rocks rich in hornblende.

2.0 PLATINUM GROUP ELEMENT MINERALIZATION

2.1 PGE in the Magmatic Environment (G.C. Wilson)

A generalized overview of physical processes in magma chambers, and their influence on the disposition, texture and composition of the resulting rocks, is a prerequisite for interpreting features of gabbroic and related intrusions. Relevant factors include:

-initial composition and temperature of magma
-rates of heat loss from chamber walls
-aspect ratios (length: breadth: depth) of chamber
-viscosity of magma of a given temperature and composition
-nucleation rate of crystals in magma
-crystal-liquid density contrasts; sinking and floating
-convection currents and crystal dispersal
-effect of new magma pulses of same or different starting composition
-local variations due to wallrock assimilation.

It is impossible to understand these processes without a working knowledge of their supposed products, the rocks. With the exception of hornblendites, the majority of mafic and ultramafic rocks are essentially composed of variable proportions of plagioclase feldspar, clinopyroxene, orthopyroxene and olivine. If these four components are arranged at the apices of a tetrahedron (Figure 2.1) then the apices represent monomineralic rocks (example: olivine alone constitutes a dunite); the six edges, rocks with two essential minerals (example; plagioclase and orthopyroxene comprise norite); and the four faces indicate rocks with three essential phases (example; olivine gabbro). More exact nomenclature is based on estimates of modal proportions of the different minerals; this may be possible in slabbed sections in some coarse-grained rocks, but requires microscopic examination in others. Many subdivisions are given in the glossary of Johannsen (1938), but the systematic method of assigning rock names given by Streckeisen (1976) is recommended for modern studies.

A brief synthesis of current understanding of magma chamber processes follows; as a useful addition, Cox et al. (1979) offers an introduction to modern igneous petrology.

a) The heat transfer within, and the outward loss from, a cooling magma chamber is a primary control on the form and distribution of lithologies within an intrusion. Layering may develop on the wall, roof and sides of a magma chamber. In a chamber of adequate dimensions, the initial composition and intrusion temperature of the magma determine whether large-scale convection is initiated, and hence whether transport by convective plumes supplements crystal settling in the build-up of a basal crystal 'mush' (Brandeis and Jaupart 1986). Sampling of a chilled margin may approximate the initial composition of the incoming magma.

b) The mechanism of crystal settling, with first-formed crystals slowly sinking (travelling along convection currents to accumulate toward the base of the magma chamber) can generate the class of rocks known as cumulates (see e.g. Wager et al. 1960, Wager and Brown 1968). Such processes, reviewed by Irvine (1979), will also produce layering, slumping and other features more familiar in sedimentary rocks. The development of the concept of cumulate rocks, first developed in the classic studies of Wager and co-workers on the Skaergaard and other basic layered intrusions of the Atlantic-bounding

Tertiary Volcanic District, has undergone revision as more field and experimental data became available (Campbell 1978). For instance, the evidence that plagioclase crystals cannot sink in Fe-rich tholeiitic liquid necessitates some modification to (or replacement of) the theory. Heterogeneous nucleation, whereby feldspar, pyroxene, spinel and other phases grow in the magma as crystal composites, provides one solution to this problem, with the denser minerals overcoming the buoyancy of the lighter ones (Campbell 1978). Expulsion of the 'intercumulus liquid' between the crystals in the pile will promote formation of an 'adcumulate', which may be essentially monomineralic, such as anorthosite, dunite, etc. Highly viscous melts, high thermal gradients and stagnant conditions will tend toward the opposite textural extreme, with a high proportion of trapped liquid crystallizing around the cumulus phase(s), forming an 'orthocumulate' (Campbell 1986a, 1987). Some examples of cumulate textures are shown in Figures 2.2 and 2.3. Squeezing trapped intercumulus fluid may generate dikelets of rock-forming silicates within the crystal pile (e.g. Bell and Harris 1986, p.51). As the residual intercumulus liquid crystallises further, modifications to the mineral compositions occur within the cumulate pile (Tait 1985). There is a very extensive literature on cumulate rocks, and on the layered intrusions in which they are best developed; see e.g. Jackson (1961, 1967), Wager and Brown (1968) and Irvine (1980a). Descriptions of outcropping layered intrusions in Ontario include those of the Lac des Iles Complex (Sutcliffe and Sweeney 1985) and the Mulcahy gabbro (Sutcliffe 1986).

The sinking of early-formed crystals in a magma chamber may itself bring about sulphide (plus PGE) segregation by the mechanism of filter pressing. This is discussed by Duke (1986) for the case of the layered Dumont sill in the Abitibi greenstone belt in Quebec. Upward expulsion of sulphur-rich intercumulus liquid from the crystal pile may lead to localized sulphur saturation and the development of a zone rich in magmatic sulphide. Olivine cumulates below the sulphide zone may be sufficiently depleted in nickel (due to partitioning of the metal into the sulphide phase) that whole rock analyses of such rocks from different heights in a layered intrusion may be of value in exploration (Duke 1986). Duke (*ibid.*, p.47-48) suggests that 'the presence of even trace amounts of magmatic sulphides may be significant' in exploration for Ni sulphide deposits in ultramafic, synvolcanic sills of the Dumont type. A caveat for whole system modelling of a magma chamber, particularly a relatively small one, is the possibility that a stagnant layer may form near the base, such that even with a single magma pulse crystallization may proceed differently in basal and central regions of the chamber (Jaupart and Brandeis 1986).

c) Incoming magma pulses may replenish the chamber, creating local thermal instabilities and chemical inhomogeneities, and via magma mixing, which may promote overturn, layering and PGE enrichment. Many such pulses may have entered a chamber, as in the case of the Rhum igneous complex, Scotland. James and Hawke (1984) identified five cycles (pulses) in the Kanichee complex near Temagami. Apart from the large-scale features such as cyclic units, mixing may, by changing physicochemical processes on a local scale, generate new textures or mineralogical features visible in hand specimen or thin section. Thus a new magma influx may be recorded on thin-section scale by embayment and resorption of previously crystallized silicates such as olivine (Barnes 1983, Borthwick 1984).

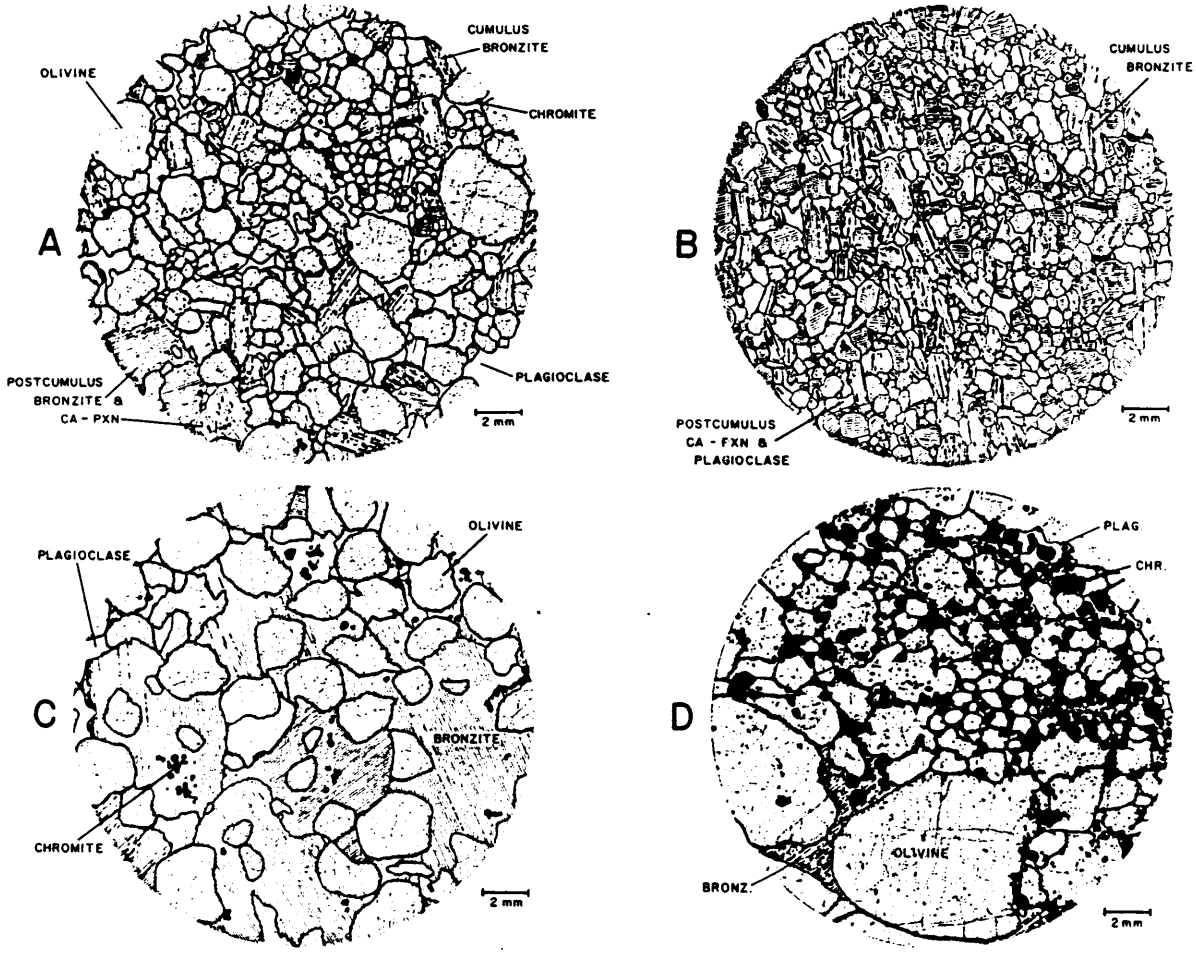


Figure 2.2 : Line Drawings of Rock Textures -

Samples from the Ultramafic Zone of the Archean Stillwater layered intrusion, Montana. From Murck (1985).
2.2A. Olivine-bronzite cumulate with intercumulus plagioclase and two intercumulus pyroxenes.
2.2B. Bronzite cumulate (bronzitite) with minor intercumulus clinopyroxene and plagioclase.
2.2C. Olivine cumulate, illustrating resorption of olivine crystals by intercumulus bronzite. Bronzite oikocrysts surround cumulus olivine.
2.2D. Coarse olivine cumulate / gabbro pegmatite, at basal contact of G chromitite. Massive chromite subunit (immediately above basal contact) has adcumulus texture, with intercumulus silicate effectively expelled.

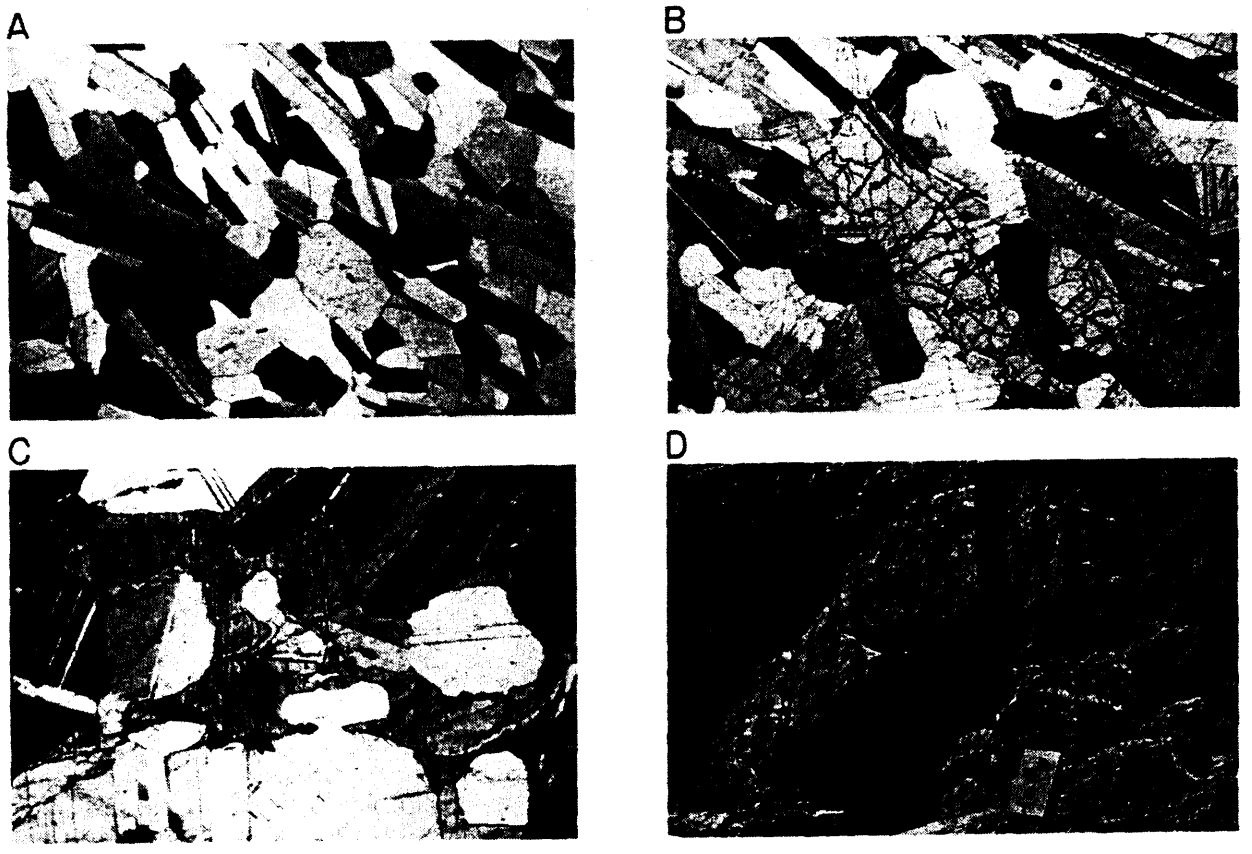


Figure 2.3; Cumulates and Layered Rocks -

A. Extreme plagioclase adcumulate, Unit 15, Rhum layered complex, Scotland. Long axis of photo; 5.7 mm, crossed polars.
B. Troctolite, displaying pervasive fractures in plagioclase, and wider-spaced fracturing in olivine. Unit 13, Rhum. Long axis of photo; 5.7 mm, crossed polars.
C. Intercumulus clinopyroxene between cumulus plagioclase in anorthosite, Frog Pond area of the Stillwater complex. Long axis of photo; 3.8 mm, crossed polars.
D. Classic example of modal fluctuations on outcrop scale, the 'inch-scale layering' in the Banded Zone of the Stillwater intrusion reflects the proportions of plagioclase and pyroxene in the rock. Individual layers generally 1-4 cm in thickness.

Double-diffusive convection (see e.g. Irvine 1980a, Irvine et al. 1983, Huppert and Sparks 1984; Turner and Campbell 1986) may result from mixing of two magmas of differing composition and temperature. The concept is applicable to development of layering; the 'double' diffusion of heat and chemical components between two magmas is important in the present context in that the process may strongly partition trace elements into one liquid rather than another. Mixing of ultramafic and anorthositic magmas is invoked to explain the onset of PGE mineralization in the Bushveld complex (e.g. Von Gruenewaldt 1979, Sharpe 1985).

d) Liquid immiscibility, as manifested by the separation of sulphide and silicate liquids in an igneous melt, can provide an elegant explanation for stratiform concentrations of PGE in large layered intrusions. Roedder (1979) reviews the basis for liquid immiscibility in magmas, including a variety of spheroidal textures as displayed in some variolitic basic lavas. As applied to the Pd-Pt-bearing J-M Reef of the Stillwater Complex (Bow et al. 1982), the occurrence of PGE with the sulphide phases becomes a natural consequence of such processes. The 'R-factor' (see e.g. Keays and Campbell 1981, Barnes 1983, Campbell and Barnes 1984, Barnes and Naldrett 1985), or ratio of the quantity of a sulphide melt divided into the amount of silicate melt with which it can equilibrate, gives a measure of the likely concentration of PGE from an initial influx of magma into a magma chamber. Due to high partition coefficients, extreme relative enrichment of PGE in the sulphide phase is predicted. Equilibration of sulphide with a very large volume of magma will promote concentration of available PGE into the former (see e.g. Barnes et al. 1982). Comparison of enriched material with a chilled marginal phase may allow an estimate of the total in-chamber enrichment. The use of R-factor modelling may be invalidated in chromite-rich deposits, such as the UG2 reef in the Bushveld Complex, by the additional partitioning of PGE into Cr spinels, as noted by Von Gruenewaldt et al. (1986a,b).

Textural evidence for such sulphide 'collectors' of precious metals includes interstitial, apparently primary sulphide between cumulate silicate grains, and inclusion of sulphide blebs in the centres of such clearly magmatic silicates (see e.g. Barnes and Naldrett 1985, 1986a).

Careful petrography may be needed in order to differentiate between magmatic co-precipitation of silicate and sulphide, and the replacement of the former by the latter (cf. Barnes and Naldrett 1986a,b and Fleet 1986). A variety of igneous processes are illustrated in Figures 2.3 and 2.4. The aforementioned authors assign different interpretations to petrographic observations, but although this choice is a common dilemma, both arguments may have some validity. Co-precipitation is one tenet of the immiscibility modelling applied in particular to the Stillwater Complex, while replacement has been documented elsewhere such as in the Adirondack Mountains (e.g. Morrison and Valley 1986). Descriptions of the Renzy mine in the Grenville of Quebec (Forrester 1957; Johnson 1972) indicate both sulphide liquid immiscibility and subsequent remobilization of sulphides. Net-textured sulphides provide persuasive evidence of immiscibility phenomena (Figures 2.4a,c,d), while pervasive fracturing and silicate alteration illustrate fluid phase transfer processes. Net textures occur in rocks of all ages, and thus reflects a fundamental igneous process; examples include Archean ultramafic rocks in the Abitibi Belt (Coad 1979), Grenville examples (see Section 3.2.6), and the Cenozoic ores of the Pacific Nickel deposit (McLeod 1975, Figure 2.4a). In the Cape Smith belt in Quebec upper greenschist facies metamorphism in the Donaldson West ultramafic sill caused sulphide remobilization, replacement of altered silicate by sulphide ('reverse net-texture'), and

fracturing which facilitated development of carbonate-rich veinlets with chalcopyrite and PGM (Dillon-Leitch et al. 1986). In the case of highly deformed and metamorphosed deposits, a more immediately useful question might be the relative importance of local sulphide mobility induced by dissolution versus ductile shear.

e) Development of mafic pegmatoids resulting from volatile concentration late in the crystallization history is considered in Section 2.2.

f) Assimilation of wallrocks may produce locally anomalous conditions, e.g. strong reduction by inclusion of carbonaceous sediments, as in the well-known native iron occurrence of Disko Island in West Greenland (Ulff-Moller 1985). It is also possible that vital ore-forming components such as sulphur might be to some extent derived by assimilation of host rocks (e.g. Mainwaring and Naldrett 1977, Ripley 1986). Assimilation of magmas en route to the surface provides a mechanism for contamination of, for instance, continental tholeiites (Campbell 1985) and komatiitic melts (Huppert and Sparks 1985). Substantial volumes of felsic material may be assimilated by mafic-ultramafic melts, according to, e.g. studies on the Sudbury intrusives (Naldrett et al. 1986). A check on contamination levels may be provided by Se/S ratios (Duke et al. 1987). Primitive upper mantle material is estimated to have an Se/S value of around 0.000285 (Morgan 1986).

A related phenomenon in ultramafic rocks is metasomatism, particularly the development of reaction zones at the contact between peridotitic intrusions and siliceous country rocks. Such reaction zones provide good examples of the operation of diffusion processes in metamorphism (Evans 1977). In some instances, such as the Pacific Nickel deposit in southern British Columbia, there is some debate as to the metamorphic or magmatic origin of such zones, which are often monomineralic. Aho (1956) favoured a late magmatic (deuteric) origin for coarse marginal hornblendites, formed by replacement of ultramafic rocks, rather than by magmatic crystallization. McLeod (1975) and Vining (1977) attributed this unusual rim to later metasomatism by reaction with younger, dioritic to tonalitic intrusions. Limited field observations suggest that at least two hornblendites are present, one coarse and essentially monomineralic, the other with minor interstitial feldspar and of a more convincingly igneous texture; this is in accord with occurrence of these enigmatic rocks as both rim facies and as dykes, as noted by Clarke (1969).

The Lake Renzy ultramafic intrusion in Quebec displays a border zone up to 15 metres wide against the paragneiss country rock; the zone is a coarse hornblendite poikilitically enclosing minor olivine and pyroxene, and the coarsest hornblende occurs in areas of brecciation and country rock assimilation. At one outcrop (Johnson 1972, pp.21-22) 'hornblende appears as scattered clots, which appear to be incipient crystals'. Faint foliations in the border zone may be due to near-total assimilation of gneiss inclusions.

Discriminants for the above mentioned processes include:
-igneous layering and related structures
-cumulate and other igneous textures
-varied macroscopic textures suggestive of magma mixing
-modal and cryptic variations
-disseminated sulphides, net-veined textures
-whole rock analyses
-normalized PGE patterns

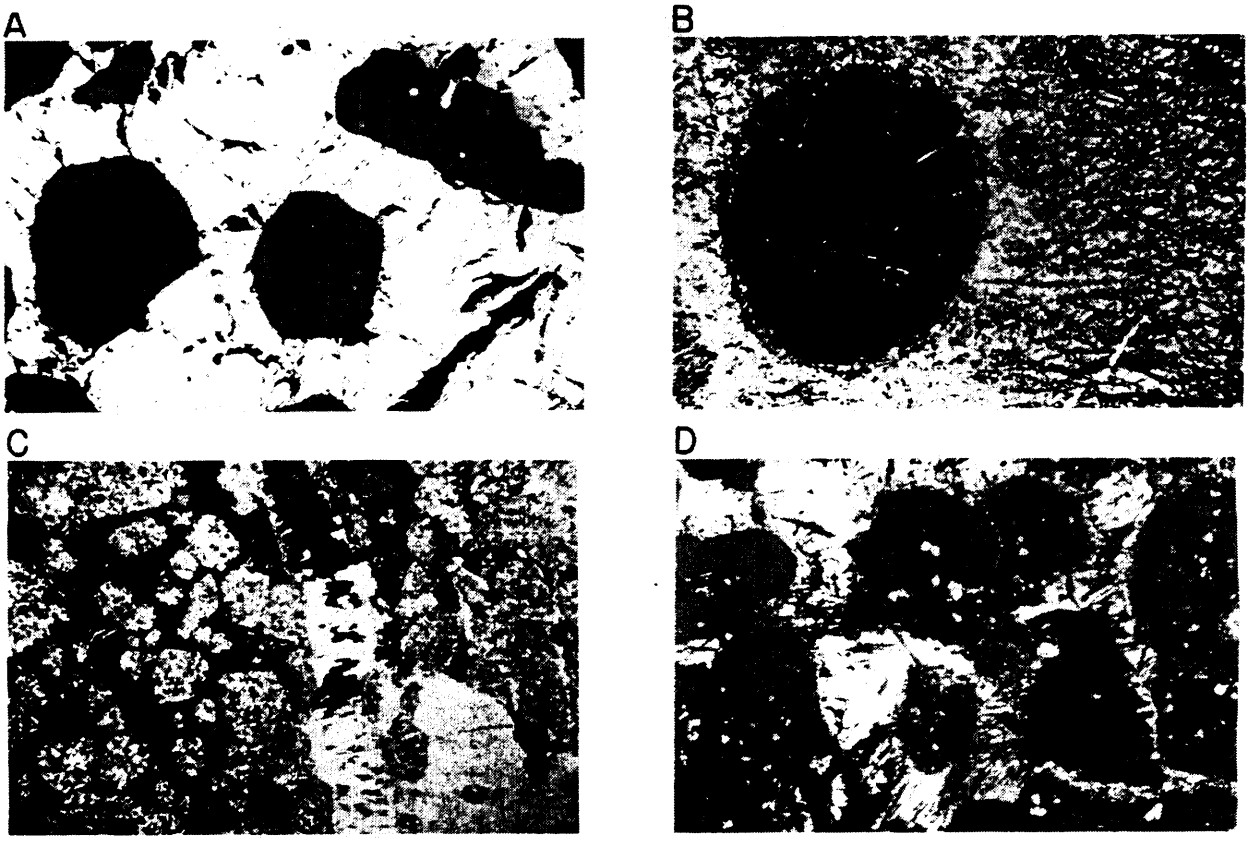


Figure 2.4 : Net Textured Sulphide Ores -

A. Rounded olivine in net textured sulphide (largely pyrrhotite) in harzburgite. Pacific Nickel Mine, B.C. Long axis of photo; 3.0 mm, reflected light.
B. Rounded bleb of coarse sulphide in silicate (serpentinized olivine) matrix. Troctolite, Frog Pond area, Stillwater. Long axis of photo; 4.7 mm, crossed polars.
C. Pyrrhotite and chalcopyrite dominate opaque assemblage in mineralized, altered peridotite. Minor chromite also present. Late sulphide-carbonate veining shows coarser, angular grain outlines. Cuniptau Mine, Kanichee intrusion, Temagami, Ontario. Long axis of photo; 5.7 mm, crossed polars.
D. Sulphide defines the rims of former cumulus olivine grains, now pseudomorphed by hydrous silicates. Cuniptau Mine. Long axis of photo; 3.0 mm, reflected light.

Details of the discriminants outlined above are given in the references sited in individual sections. Note that cryptic variations generally require extensive petrography or electron microprobe analysis, and so are not ideal for general exploration purposes.

Apart from photomicrographs (e.g. Figures 2.3, 2.4, 2.5), good line drawings can be very instructive and can give a clearer impression of rock textures. The examples in Figure 2.2 are from the Stillwater complex (Murck 1985). Further examples of textures produced by crystallisation and subsequent alteration are shown in Figure 2.5, and are discussed in Section 2.2.

As mentioned earlier, the ratio of {Pt+Pd}/{Os+Ir+Ru} is an important diagnostic for the processes, chemistry and tectonics of different PGE deposits. Rowell and Edgar (1986) note that the values of this ratio for the Rathbun Lake occurrence and for the New Rambler Mine in Wyoming (McCallum et al. 1976) are 1120 and 1100 respectively, and that such high ratios are probably characteristic of hydrothermal PGE deposits, and of the relative solubility of the PGE themselves.

Finally, the likelihood of some parental magmas being especially good PGE carriers (for transport from their siderophile origins at depth up into the crust) must be considered. It has recently been proposed (Hamlyn et al. 1985, Sharpe and Hulbert 1985, Hamlyn and Keays 1986) that magnesian, Ti-poor magmas of a composition similar to boninite lavas may be essential precursors of PGE deposits in layered intrusions, although the details of this are still in debate. The current thinking considers boninites to be 'second-stage melts', derived from comparatively refractory residues of an initial partial melt of mantle material; fusion of this residue generates magma which is likely to be relatively PGE-rich, yet S-poor (Hamlyn and Keays, 1986). Komatiitic magmas are well-established 'parents' to Ni sulphide deposits and PGE concentrations may also be found in intrusions of Mg tholeiitic affinity, perhaps through the agency of post-magmatic hydrothermal processes (James and Hawke 1984). It is important to note that repeated fractionation of a single initial mantle composition will modify the observed PGE distributions in the resultant melts, a concept developed to explain, for example, the difference between the Alexo deposit and other komatiitic nickel occurrences in the Abitibi (Barnes et al. 1981). The initial compositions may be hard to estimate, due to commonly pervasive serpentinization, carbonatization or other post-magmatic processes which may greatly alter whole-rock chemistry while sometimes preserving the original igneous textures.

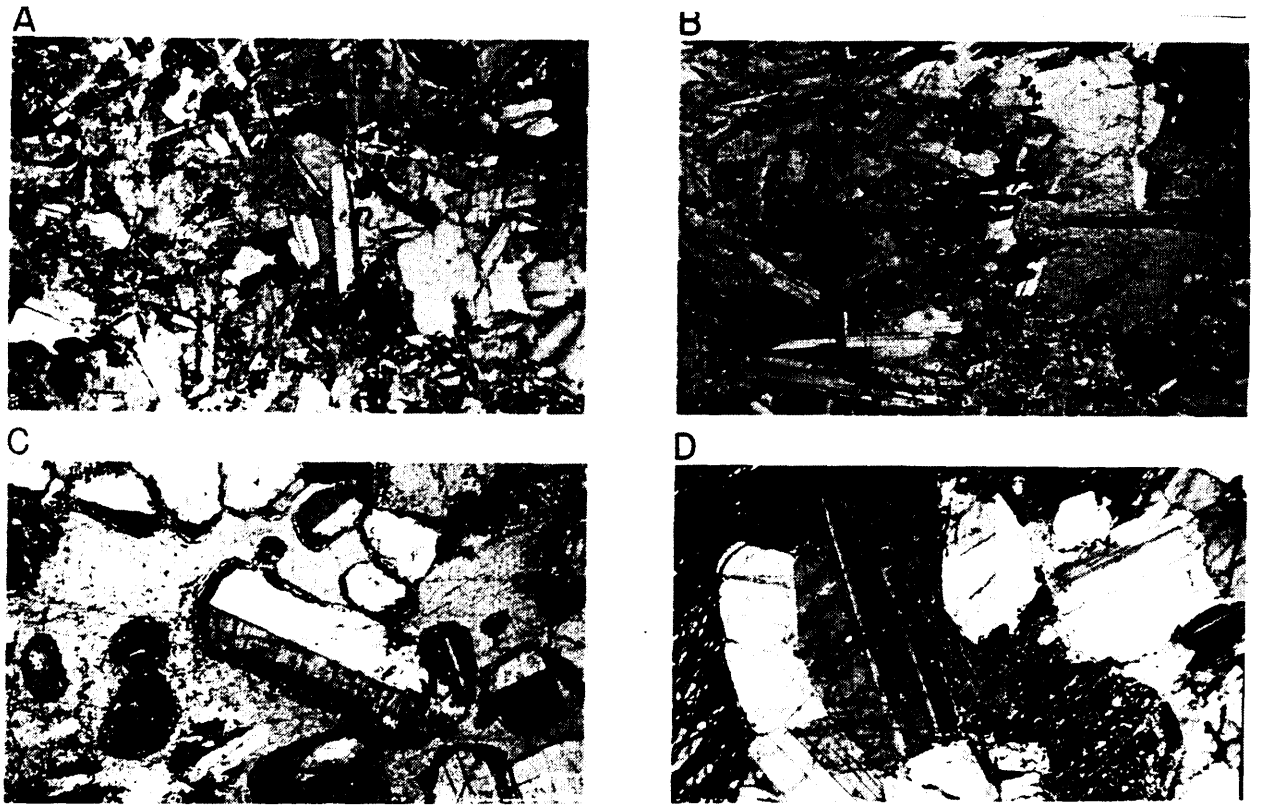


Figure 2.5 : Igneous Textures and variable degrees of Alteration

A. Subophitic texture in Nipissing diabase from the Cobalt district, Ontario. Plagioclase partially enveloped by clinopyroxene. Long axis of photo; 5.7 mm, crossed polars.
B. Coarser subophitic texture in olivine gabbro from Rhum. Minor biotite in fine-grained matrix of altered plagioclase and olivine. Long axis of photo; 5.7 mm, crossed polars.
C. Highly altered gabbroic troctolite, with twinned plagioclase in fine-grained talc-rich matrix. Frog Pond area, Stillwater. Long axis of photo; 5.7 mm, crossed polars.
D. 'Amoeboid' olivine in contact with anorthositic host rock. Serpentine, with talc, magnetite, iddingsite and carbonate replace the olivine, while sericite and epidote are developed in the feldspar. Frog Pond area, Stillwater. Long axis of photo; 6.0 mm, crossed polars.

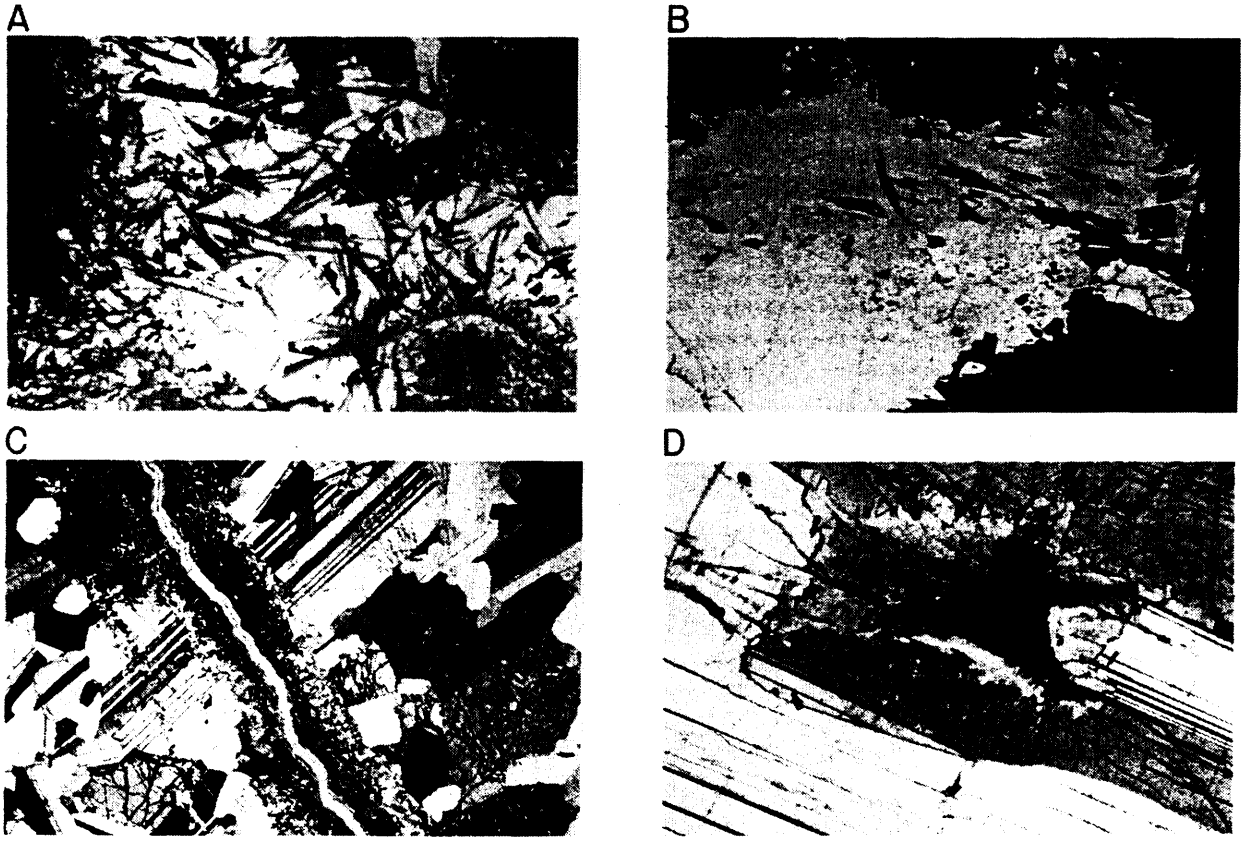


Figure 2.6 : Late (Deuteric / Hydrothermal) Assemblages-

A. Pyrrhotite and chalcopyrite intergrown with feathery hydrous silicates, of which the most abundant is serpentine. Talc, chlorite and carbonate are also major rock components in this altered peridotite. Cuniptau Mine. Long axis of photo; 0.8 mm, reflected light.

B. Uralitized gabbro, with amphibole enclosed within chalcopyrite-dominated sulphide (pyrrhotite is the most abundant sulphide in the rock as a whole). Lac des Iles, Ontario. Long axis of photo; 3.0 mm, reflected light.

C. Serpentine-filled veinlet cuts fractured plagioclase. Olivine is only altered to iddingsite in the vicinity of this major fracture; thinner fractures in plagioclase presumably did not support late fluid flow. Troctolite from Unit 13, Rhum. Long axis of photo; 5.7 mm, crossed polars.

D. A 'web' of epidote replacing plagioclase adjacent to interstitial sulphide. Such epidote is also common along fractures. Frog Pond area, Stillwater. Long axis of photo; 1.4 mm, crossed polars.

2.2. PGE in the Hydrothermal Environment (G.C. Wilson)

Late volatiles concentrated in the waning stages of mafic magmatism are responsible for coarse grained pegmatoids analogous to the more familiar pegmatites in granitic terrains. Hydrous minerals may become stable at temperatures ranging from the magmatic domain downward. They include pargasite (below 1100°C), the chlorite-talc-tremolite assemblage (below 800°C) and serpentines (600°C and below, antigorite first, lizardite last), as noted by Nicolas (1986). Volatile phases may include halogens, water, sulphur, and (in one form or another) carbon (Wilson 1985b). These may be manifested by coarse-grained graphite (Volborth and Housley 1984, Ballhaus and Stumpfl 1985a, Stumpfl 1986), and as apatite and biotite with elevated halogen contents (Ballhaus and Stumpfl 1985a, Mathez et al. 1985, Boudreau et al. 1986, Volborth et al. 1986). The carbon may, at least in some intrusions, be derived largely by assimilation of country rock sediments (as implied by some C isotope data; Touysinhthiphonexay et al. 1984, Taib and Ripley 1986), although it is too early to accept this as a universal result. Some of the graphite from the Bushveld and Stillwater is enriched in Cl and F and may be associated with other 'incompatible' elements such as As and Re (Volborth and Housley 1984, Rucklidge et al. 1985). Within the Bushveld Reefs, productive (Merensky Reef) and barren (Bastard Reef) may be distinguishable in terms of fluid inclusion populations (Ballhaus and Stumpfl 1985b, 1986) and mineral chemistry. Structural and lithological discontinuities in the layering of the Bushveld reefs, known as 'potholes' (Elliot et al. 1982, Buntin et al. 1985) display some of the most striking evidence of late volatile enrichments, including phase separation between silicate (H_2O, SiO_2) and sulphide (CO_2, CH_4, H_2S)-dominated fluids (Ballhaus and Stumpfl 1985a). In addition, crystalline graphite occurs in mafic phases within the Rottenstone Ni-Cu-PGE deposit in Saskatchewan (L.J. Hulbert, Geological Survey of Canada, personal communication, 1987; Sabina 1987).

It appears from the above data that there is ample evidence of spatial relationships between sulphides, PGE and late volatile-rich mineralogy in mafic intrusions. Ontario examples are the Cuniptau Mine within the Kanichee intrusion (Section 3.1.7.8, and James and Hawke 1984, Figure 2.6A) and the Lac des Iles intrusion (Section 3.1.4.2., and Figure 2.6B).

Pyroxene-poor anorthositic rocks from the Stillwater show signs of plagioclase alteration, and may contain a few percent quartz and minor apatite. Salpas and Haskin (1985) determined these features to be consistent with interaction between silicates and deuteric fluids; lack of REE anomalies negates the likelihood of an external source for such fluids (assuming that REE, commonly concentrated in apatite, were mobile in the fluids). Schiffries (1986) has described hydrothermal silicate vein assemblages from the Bushveld. These contain calcic amphibole with up to 5 weight % chlorine, calcic plagioclase which is more Ca-rich than wallrock feldspar by up to 25 weight percent anorthite, and clinopyroxene which is Ca-rich and (Al, Ti, Cr)-poor relative to wallrock clinopyroxene, and lacks the usually characteristic (magmatic) twinning and exsolution features. Sulphide-silicate intergrowths provide evidence of intermixture of their respective components under late hydrous conditions. Other samples, mineralized or barren, may display extensive fracturing and alteration, of both feldspars and ferromagnesian minerals (Figure 2.6).

The mean, normalized modal composition for the Merensky Reef (Vermaak and Hendriks 1976, p.1246) is orthopyroxene: 64.9%, plagioclase: 25% and clinopyroxene 10.1%, so that the rock is a clinopyroxene norite, after

Streckeisen (1976). The reef has a pegmatoidal texture and may contain a small amount of either quartz or olivine. Interstitial sulphide content appears to be very variable, but in general is in the 1-3 weight % range, with pyrrhotite, pentlandite and chalcopyrite as principal sulphides (Vermaak and Hendricks 1976, p.1251). There is also a complex assemblage of PGM and other rare ore minerals. The reef is very narrow, averaging 75cm, although variable, from several metres to 30 cm (Guilbert and Park 1986, p.313-328), and is laterally continuous for tens of kilometres. This remarkable continuity is noted in other layers in the complex, suggesting the possibility of 'a layered magma chamber with liquid layers approximately 100 metres thick and extending horizontally for over 100 km' (Hatton 1986), and is one of the arguments used in support of an orthomagmatic (specifically, magma mixing) origin for the Reef (e.g. Naldrett et al. 1986). The hypothesis explaining reef formation in terms of the mixing of plagioclase- and olivine-saturated (anorthositic and ultramafic, i.e. 'A' and 'U'-type) magmas is reviewed in terms of fluid dynamics and deposit geology by Campbell and Turner (1986), and for the general distribution of magnetite and chromite layers by Irvine and Sharpe 1986). The occurrence of magnetite layers near the bases of geochemical cycles is consistent with their generation by magma mixing, although mixing need not always form such a layer (Merkle and Von Gruenewaldt 1986). Ballhaus and Stumpfl (1986) present detailed fluid inclusion and mineralogical evidence implying an additional role for hydrothermal (deuteric) processes in the evolution of the reef.

Little information is available on the stability and possible efficiency of complexes capable of transporting the more mobile PGE (Pd, Pt) in hydrothermal solutions; sulphide and perhaps chloride complexing may be significant (Mountain and Wood 1986), although organometallic complexes may be unstable in the relevant temperature range. The importance of Cl has been suggested in platiniferous occurrences such as the Driekop pipe on the Transvaal (Schiffries 1982), at other locations within the Bushveld, as mentioned earlier, and in the Stillwater (Volborth et al. 1986). High Cl contents in fluid inclusions in the Merensky Reef, but not in the PGE-poor Bastard Reef, are compatible with transport of PGE by Cl complexes (Stumpfl 1986).

Within the Stillwater podiform and pipe-like structures cutting across the layered igneous stratigraphy have recently been explained in terms of 'feeder channels' along which late magmatic-hydrothermal fluids conducted the components of a volatile- and PGE-rich late sulphide paragenesis (Boudreau and McCallum 1985 a,b, 1986). Such fluids may have migrated through large volumes of the Banded Zone; inclusions in quartz associated with altered oxides high in the zone were identified as Cl-rich by Maze and Carlson (1981). The occurrence of ultrabasic (hortonolite dunite) breccia pipes in the eastern Bushveld (Stumpfl 1962, 1974: Stumpfl and Rucklidge 1982) is notable both for high grades and for the complex exploration target such a 'bonanza' presents. These features are not necessarily confined to major intrusions. Pipelike orebodies occur at the Pacific Nickel property in British Columbia (Aho 1956). Here, as at the Renzy mine in Quebec, hornblendite rims may surround ultramafic bodies. Close analogues of the Bushveld pipes have yet to be described from other intrusions.

Ultramafic pegmatites in the Bushveld are reviewed by Viljoen and Scoon (1985). They make an important distinction between the platiniferous composite ultramafic pipes such as Dreikop (Stumpfl and Rucklidge 1982) which are more primitive than the host cumulate sequence that they replace, and iron-rich ultramafic pegmatites, which are more fractionated than their

cumulate host, and normally non-platiniferous. As a point of nomenclature, such transgressive lithologies can be described as 'pegmatites' whereas others which are not obviously discordant and may therefore be part of the igneous stratigraphy, are known as 'pegmatoids'.

Discriminants for hydrothermal deposits appear to include cross-cutting field relations (other than those generated by movements within the still-mobile crystal pile in the magma chamber), sulphide-bearing pegmatites with an abundance of hydrous phases (coarse biotite is generally the easiest to identify; graphite is also an excellent indicator, but seems very limited in occurrence), and elevated Pd:Pt ratios (as the most easily obtainable and at the same time economically relevant index amongst the PGE). For reconnaissance work analysis of sulphide-bearing grab samples for Pt, Pd and Au is to be recommended; this costs a fraction of a complete PGE determination, and the latter should be reserved for assay of high-grade and otherwise important samples as part of a more detailed program of property assessment.

Certain textures and alteration styles are encountered repeatedly in mafic rock suites. In plagioclase-rich rocks it is especially common to find numerous parallel, evenly-spaced fractures, most prominent in the feldspar, and less common or absent in coexisting olivine and pyroxene. Incipient alteration to epidote or sericite may occur along these fractures, which in extreme cases present a 'lined' appearance in hand specimen, appearing similar to a coarse perthite. Foster and Hudleston (1986) report an unusual cleavage in troctolitic rocks of the Duluth Complex. Microscopic extensional fracturing with serpentinization along the fracture surfaces was noted. A lack of shear fracturing or ductile deformation suggested 'that cleavage formation involved crack propagation at high fluid pressures'. A sample from the Isle of Rhum displays close-spaced fracturing (Figure 2.6C), and epidote is commonly encountered along fractures and grain boundaries within Stillwater feldspars (Figure 2.6D).

How important a role do hydrothermal fluids play with respect to magmatic processes? Do they represent only a local reworking of magmatically-derived PGM, or do they generate a distinctive class of PGE deposits? At this stage, the data are equivocal. Renewed interest in the PGE due to economic factors has resulted in the initiation of considerable research into PGE mineralization; the results of this work are expected to shed light on the respective importance of the orthomagmatic versus hydrothermal hypotheses.

Already, within Ontario, data from a number of localities point to the significance of hydrothermal processing. Quartz and quartz-carbonate veins cutting the Wanapitei intrusions are enriched in Au and PGE (Finn et al. 1982), and a case has been presented for hydrothermal PGE in this intrusion (Rowell and Edgar 1984, 1985). The gabbronorite host rock has been extensively altered in the Rathbun Lake deposit of the Wanapitei intrusion, and the small ore body is adjacent to, but not within, the metasedimentary country rock (Rowell 1984, p.67). Discrete PGM in this deposit occur in gangue phases or within chalcopyrite, suggesting concentration at a late stage. Talkington and Watkinson (1984, p.130) provide a further illustration of the association between hydrous phases, sulphides and PGE at the Lac des Iles deposit: a grain of the palladium telluride kotulskite occurring in chalcopyrite which has invaded a cleavage plane in secondary amphibole. Recent work on the Coldwell complex (Watkinson et al. 1986) reveals many features indicative of late volatile activity. Note that metamorphism and strong deformation (as in shear zones) may alter the distribution of PGE between the existing PGM (Hak et al. 1985).

Section 3: PGE PROSPECTIVE AREAS IN ONTARIO

3.1 ARCHEAN MAFIC INTRUSIONS

3.1.1. NORTHWESTERN ONTARIO

3.1.1.1. General Discussion (P.J. Whittaker)

Layered ultramafic to mafic intrusions and homogeneous mafic intrusions comprise a substantial portion of the easterly trending, greenstone belts of northwestern Ontario (Figure 3.1); layered intrusions form approximately 12% of the Sandy Lake belt (OGS Map 2178) and 60% of the Big Trout Lake belt (OGS Map 2292). These intrusions are regionally conformable, and may be pre-or syn-tectonic, since many show regional deformation patterns similar to those of the host greenstones (e.g. the Big Trout Lake belt, Map 2292; and the Severn River belt, Maps 2292 and 2178). The intrusions are predominantly gabbroic sills, which are locally discordant. Stock-like intrusions occur in batholithic terrains, and as isolated exposures in areas of drift cover, where their relationships with the surrounding rocks have not been discerned.

These mafic rocks are generally massive, medium grained, and equigranular; some display preserved ophitic textures. The larger sills, such as those at Big Trout Lake and at Muskrat Dam Lake (Figure 3.1), have fractionated to anorthositic compositions. These larger complexes, which are the most fractionated of the mafic intrusive suites, offer the greatest variety of environments with potential to host PGE mineralization. PGE might be associated with sulphide and/or chromite accumulations in the ultramafic parts of intrusions; or with sulphides in gabbroic to anorthositic pegmatites and in mafic layers in anorthositic phases of a fractionated intrusion. For example, the layered intrusive complex at Big Trout lake contains chromite as layers in peridotite (Whittaker 1980); PGE are associated with chromite (Talkington et al. 1984) and with net-textured sulphides (Borthwick and Naldrett 1982, 1983).

All of these mafic intrusions (Figure 3.1, Table 3.1) deserve examination for PGE. The intrusion at Big Trout Lake, about which more is currently known, is described below. The Rottenfish Lake - Muskrat Dam Lake intrusive complex is also described. Information sources for other mafic intrusions in northwestern Ontario are summarized in Table 3.1. Regional geological maps at 1:253,400 scale are available for Mameigweiss Lake (Map 2287), Big Trout Lake and Severn River (Ayres 1969, Map 2292), Stull Lake, Sachigo Lake, Lingman Lake and Rottenfish Lake (Ayres 1969) and the Severn River and Sandy Lake (Map 2178) greenstone belts, all of which have ultramafic and mafic intrusive complexes (Thurston et al. 1979).

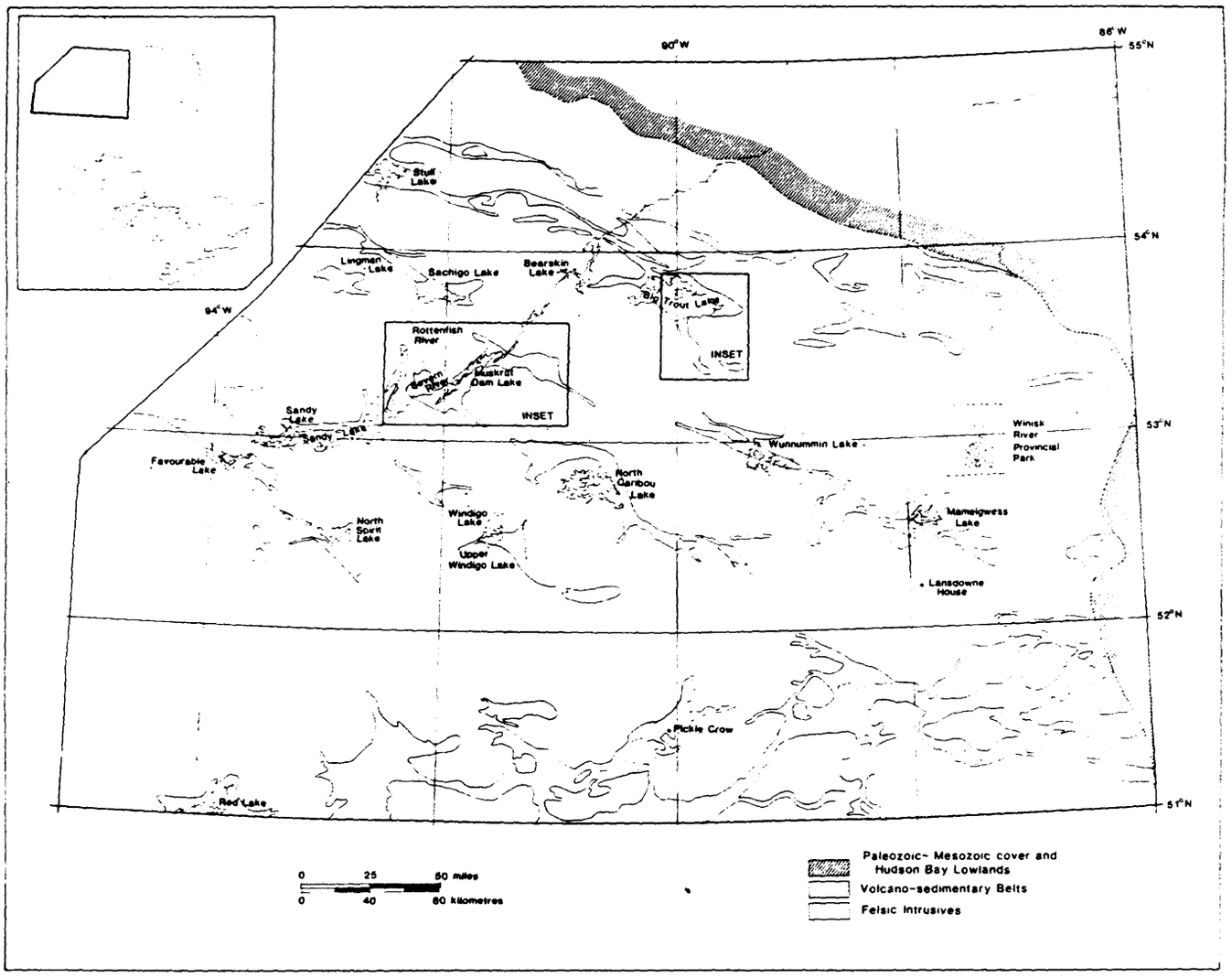


Figure 3.1 : Northwest trending greenstone belts of northwestern Ontario, emphasising mafic and ultramafic components. See insets for details.

Table 3:1 Lithologies, locations and references to ultramafic and mafic intrusions in northwestern Ontario

Area	Lithology	Reference(s)	Lat.	Long.
Abbott Lake	diorite, quartz diorite	OGS compilation map 2287	52°41'	88°13'
Bend Rapids	gabbro	OGS compilation map 2287	53°45'	86°58'
Big Trout Lake	dunite, peridotite, gabbro, anorthosite	Hudec, 1964; Thurston et al., 1979; Whittaker 1980	53°45'	90°00'
Caulkin Lake	diorite, quartz diorite	OGS compilation map 2287	52°34	82°12'
Croal Lake	pyroxenite, gabbro	Thurston et al., 1979, p.58	53°03'	87°37'
Foster Lake	gabbro, diorite	Bennett and Riley, 1969, p.30; Satterly, 1937	54°31'	91°25'
Gilleran Lake	gabbro, diorite	Bennett and Riley, 1969, p.22; Satterly 1937	54°22'	92°25'
Goods Lake	gabbro	OGS compilation map 2287	52°36'	86°41'
Goose River Arm	peridotite	Thurston et al., 1979, p.52,53	53°58'	89°52'
Hilton Lake	diorite, quartz diorite	Bennett and Riley, 1969, p.37	53°36'	93°45'
Kasabonika Lake	gabbro	Thurston et al., 1979, p.58	53°33'	88°34'
Lingman Lake	diabase, anorthosite	Bennett and Riley, 1969, p.15	53°52'	92°55'
Matthews Lake	gabbro, anorthosite	Bennett and Riley, 1969, p.28	54°17'	91°42'
Misikeyask Lake	serpentinite	Bennett and Riley, 1969, p.29	53°53'	90°17'
Mucnmore Lake	diorite, quartz diorite	OGS compilation map 2287	52°55'	88°34'
Muketei River	diorite, quartz diorite	OGS compilation map 2287	53°49	86°15'
Munekun Lake	gabbro, diorite	Ayres, 1969, p.30	53°25'	91°13'
Muskrat Dam Lake	gabbro, diorite	Ayres, 1969, p.30	53°22'	91°45'
Northern Stock	gabbro, diorite	Bennett and Riley, 1969, p.34	54°50'	91°35'
Ponask Lake	dunite, pyroxenite, gabbro	Bennett and Riley, 1969, p.19; Satterly, 1937	54°03'	92°45'
Portage Lake	gabbro, anorthositic gabbro, hornblende diorite	Bennett and Riley, 1969, p.28; Hudec, 1964, p.24; Thurston et al., 1979, p.51	53°57'	90°12'
Rottenfish Lake	diorite	Ayres, 1969, p.34	53°11'	92°28'
Rottenfish River	gabbro	Ayres, 1969, p.41,61	53°22'	92°22'
Rowlandson Lake	gabbro, anorthositic gabbro	Prest, 1940, Thurston and Carter, 1970, Thurston et al., 1979	52°30'	87°55'
Sandy Lake	gabbro	Bennett and Riley, 1969, p.7 Satterly, 1938	53°05'	93°00'
Seeber Lake	gabbro	Bennett and Riley, 1969, p.15	53°52'	93°05'
Stanley Lake	gabbro, diorite	Thurston et al., 1979, p.71	52°58'	90°54'
Swan Lake	gabbro	OGS compilation map 2177	54°10'	91°07'
Weagamow Lake	dunite	Thurston et al., 1979, p.71	52°56'	91°21'
Winiskiss Channel	gabbro	OGS compilation map 2287	53°35'	86°48'
Wunnummin Lake	peridotite[1], gabbro[2], diorite[3]	Thurston et al., 1979, p.87,94,95	1. 52°48'	88°35'
			2. 52°45'	88°30'
			3. 52°46'	88°27'

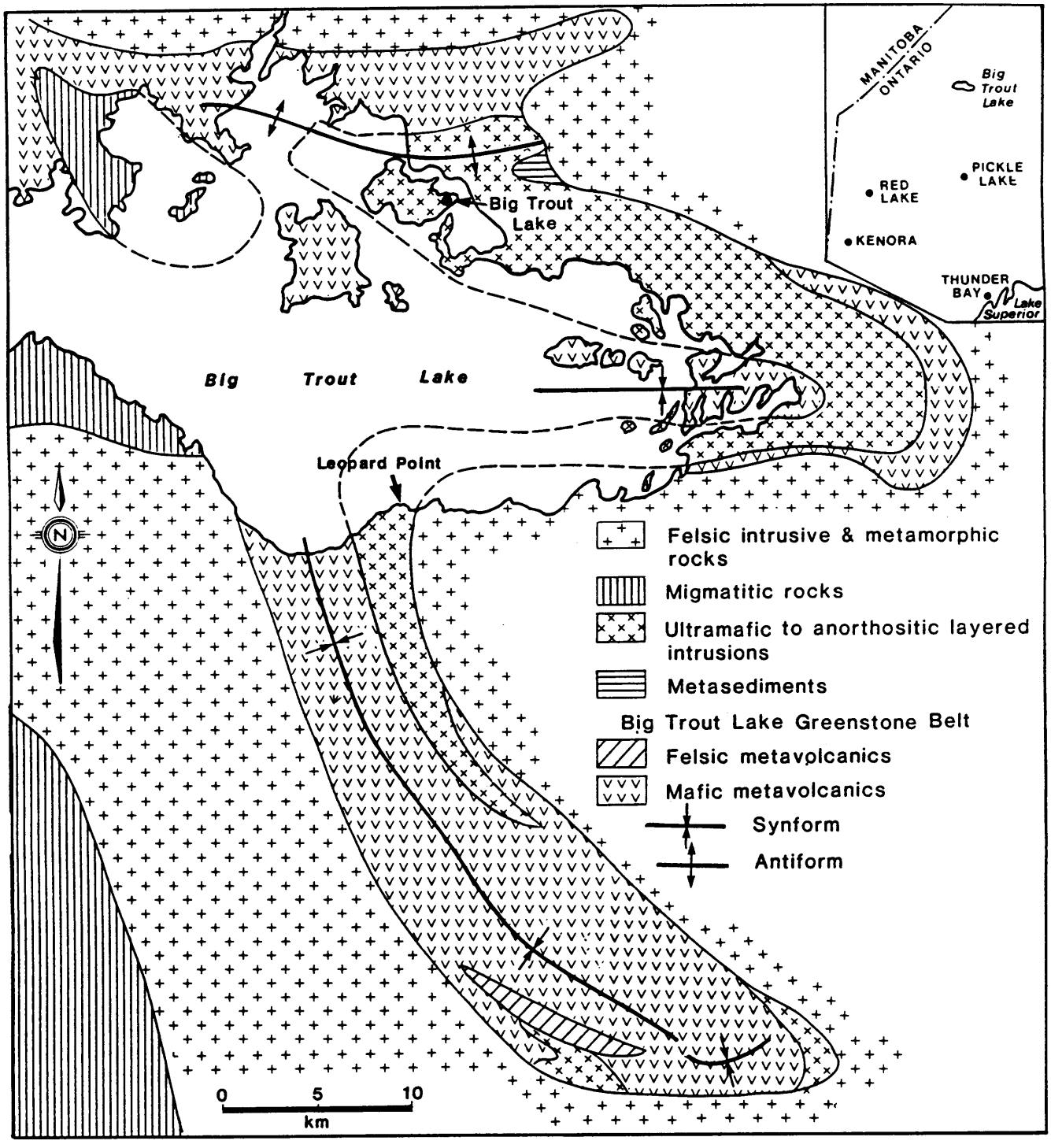


Figure 3.2 : Geology of the Eastern part of Big Trout Lake Complex, after Thurston et al. 1979).

3.1.1.2. Big Trout Lake Intrusive Complex (P.J. Whittaker)

3.1.1.2.1. Location and Access

Big Trout Lake is 420 km northeast of Red Lake and is accessible by float-equipped aircraft from Red Lake and Pickle Lake. A landing strip on Post Island at the community of Big Trout Lake accommodates wheel-equipped aircraft (Figures 3.1, 3.2).

3.1.1.2.2. Previous Work

Early geological mapping of the Big Trout Lake area was by Tyrrell (1913), who briefly described the major rock types. Hudec (1964) conducted reconnaissance geological mapping in the area, and Thurston (Thurston et al. 1971, 1979) carried out regional geological mapping.

Information from prospecting activity is available in the Resident Geologist's Files, Ontario Ministry of Northern Development and Mines, Sioux Lookout. Whittaker (1980) examined chromite at Big Trout Lake, and noted the PGE potential of intercumulus sulphides. The occurrence of PGM in the chromite has been confirmed by electron microprobe studies (Talkington et al. 1984).

3.1.1.2.3. Geology of the Big Trout Lake Intrusive Complex

The Big Trout Lake area is underlain by a succession of Early Precambrian sedimentary, volcanic and intrusive rocks (Figure 3.2, Thurston et al. 1979). Much of the area is covered by till, and outcrops are widely scattered.

The Big Trout Lake Intrusive Complex (BTLIC) is a fractionated, layered sill composed of a lower ultramafic and an upper mafic sequence. The ultramafic portion of the sill includes a lower peridotite with dunite, chromite and chromite-rich layers, and an upper, homogeneous peridotite. The ultramafic portion of the sill is overlain by a succession of gabbro, anorthositic gabbro, gabbroic anorthosite and minor lenses of anorthosite.

Anorthositic gabbro and gabbroic anorthosite crop out on the northeastern and southeastern shores, respectively, of Big Trout Lake. These rocks outline the limbs of an eastward plunging anticline (Figure 3.2; Hudec 1964, Thurston et al. 1971). The anorthositic succession is intrusive into a metamorphosed Archean basalt-andesite sequence. South of the gabbroic anorthosite at Leopard Point (Figure 3.2), diamond drill information indicates a sheet-like serpentinite consisting of minor dunite and chromitiferous layers in peridotite. The intrusion dips steeply to the east, is up to 500 m thick, and is in fault contact with quartz diorite and diorite to the east. Shearing within the serpentinite becomes more intense towards Leopard Point, where a fault contact is postulated between serpentinite and the gabbroic anorthosite. Because the contact between the gabbro-anorthosite succession and the underlying ultramafic rocks is obscured by overburden and complicated by several fault zones, the exact relationship between the ultramafic and mafic rocks is unclear.

3.1.1.2.4. Serpentinized Peridotite and Dunite

Peridotite forms most of the ultramafic component of the BTLIC. Peridotitic rocks, as observed in drill core, are 90% or more serpentinized. Relict textures are well preserved and reflect a medium to coarse grained, equigranular, cumulus olivine texture. At irregular intervals along the drill core, a grey-blue serpentine pseudomorphs primary olivine. Late, serpentinizing fluids have formed 1-2 mm wide veinlets of apple green, amorphous serpentine that cut the cumulate rocks.

Olivine shows progressive serpentinization from grains with a serpentine core surrounded by randomly oriented serpentine fibres, to grains in which fibres have grown parallel to one another and perpendicular to grain edges. Iron from olivine has formed very fine grained magnetite that outlines original grains and also occurs along irregular fractures. Re-entrants in olivine form amoeboid grains (Martin and Maclean 1973) in which reaction rims of serpentine replace, rather than coat, the original grain. Borthwick and Naldrett (1986) interpret this texture to result from a peritectic reaction between olivine and a large volume of interstitial liquid.

Pyroxene, which is pseudmorphed by serpentine (lizardite), occurs as an intercumulus mineral, as overgrowth rims on olivine, and as reaction rims replacing olivine. Intercumulate pyroxene is the most common form, and in some cases forms oikocrysts enclosing olivine (Borthwick and Naldrett 1986). The original clino- and orthopyroxene are indistinguishable in their serpentinized form (Wicks and Whittaker 1977).

Serpentinized plagioclase occurs as relatively clear, magnetite-free, intercumulate patches, and oikocrysts containing olivine. Contacts between olivine and plagioclase grains are smooth, and suggest equilibrium between olivine and intercumulate plagioclase liquid (Borthwick and Naldrett 1986). Serpentine fibres after plagioclase form an extremely fine grained, interlocking mesh texture.

Minor layers of dunite are found in the middle of the peridotite unit, between 190 and 248 m in section A-A' of Borthwick and Naldrett (1986) and in the upper levels of drill holes along section 2000N, south of Leopard Point (Figure 3.2). Dunite, with associated chromitite layers, occurs in both drill holes, about 3.2 km apart, in Section 2000N. further to the south, north of Nemeigasaubins Lake (Figure 3.2), chromitite layers occur in the middle to upper parts of drill holes along section 800 S (Whittaker 1980). In many cases, the chromitite layers underlie coarse grained dunite layers that contain re-entrant olivine grains.

3.1.1.2.5. Gabbro and Anorthosite

Partially to completely serpentinized gabbro cuts serpentinized peridotite in drill core. The gabbro is medium grained, equigranular, and dark black-green. Drill intersections of the gabbro are 10 m thick, and have narrow (1 cm) chilled margins.

Anorthositic gabbro grades compositionally, with increasing amounts of plagioclase, to anorthosite found in small amounts. Anorthosite, in lenses several metres in length, and gabbroic anorthositic both contain subhedral to euhedral plagioclase grains up to 20 cm long. These coarse textures are best

observed at Leopard Point, and more anorthositic rocks are exposed along the southern shore of Bibby Bay at the eastern end of Big Trout Lake (Figure 3.2).

Intercumulus mafic minerals have been altered to fine grained chlorite, which is usually well foliated. Chloritisation of mafic minerals is complete, while plagioclase is variably altered: large plagioclase crystals are weakly saussuritized, with fresh cores.

Anorthositic rocks, particularly those containing gabbroic or other more mafic layers, should be examined for PGE. Chromite-sulphide or sulphide bearing layers in anorthositic rocks are also prospective targets. In addition, the recognition of late, cross cutting, gabbroic to anorthositic pegmatite dikes may also be important for PGE exploration, especially if sulphide-bearing.

3.1.1.2.6. Chromite

Chromite occurs in disseminated form, as layers of disseminated chromite, and as chromitite layers. Disseminated chromite is evenly distributed as an accessory mineral. Layers of disseminated chromite consist of 60% to 90% subhedral to euhedral chromite. These define layered zones up to several metres thick. The layered zones include individual chromite-rich layers, 1 to 4 cm wide, and are separated by variable widths of less chromitiferous dunite. Layer boundaries are sharp.

Chromite layers containing 90% or more subhedral to euhedral chromite are referred to as chromitites. Layer boundaries are sharp with individual, 1 to 4 cm thick chromite layers, separated by 1 to 10 cm of peridotite to dunite (Figure 3.3).

3.1.1.2.7. Sulphides

Pyrrhotite is the major sulphide mineral; minor amounts of chalcopyrite and pentlandite are also present. Chalcopyrite and pyrrhotite occur as sparse, disseminated, anhedral grains in net-textured form within the serpentinized groundmass, as thin films on and between chromite grains, and, rarely, as inclusions in chromite grains. Pentlandite occurs as exsolution 'flames' in pyrrhotite and as discrete grains adjacent to pyrrhotite. Where two or more chromite grains are close enough, a sulphide bleb may be trapped between them. This is most common in disseminated chromite layers, and in chromitite layers. A small amount of pyrrhotite and chalcopyrite occurs in chromite grains as fine inclusions, either individually or as two-phase, anhedral inclusions. Sulphides account for less than 5% of most chromite-bearing layers, but are important as indicators of potential PGE-bearing zones.

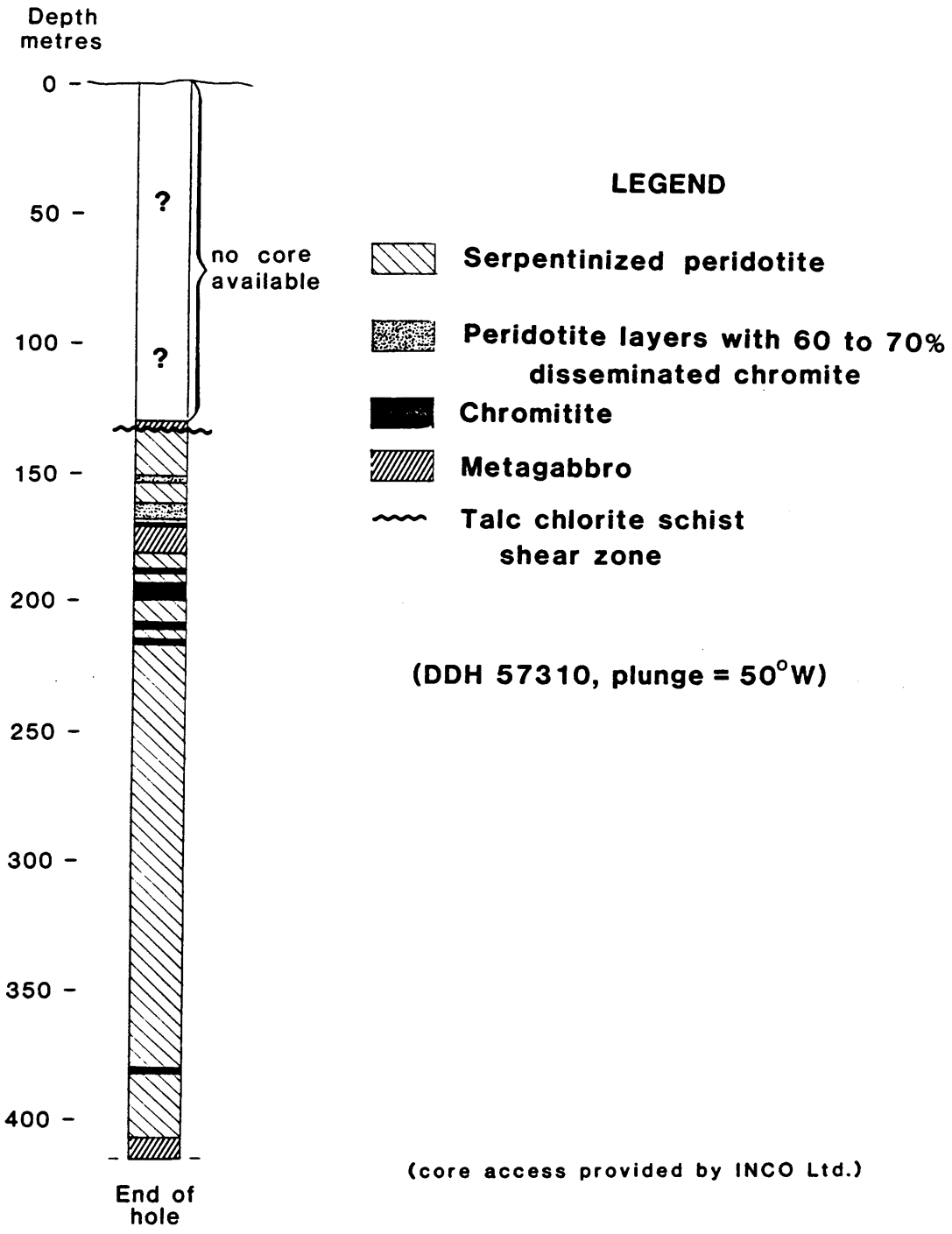


Figure 3.3 : Distribution of layered chromitite in peridotite, Big Trout Lake Complex (core provided by Canadian Nickel Company, 1979).

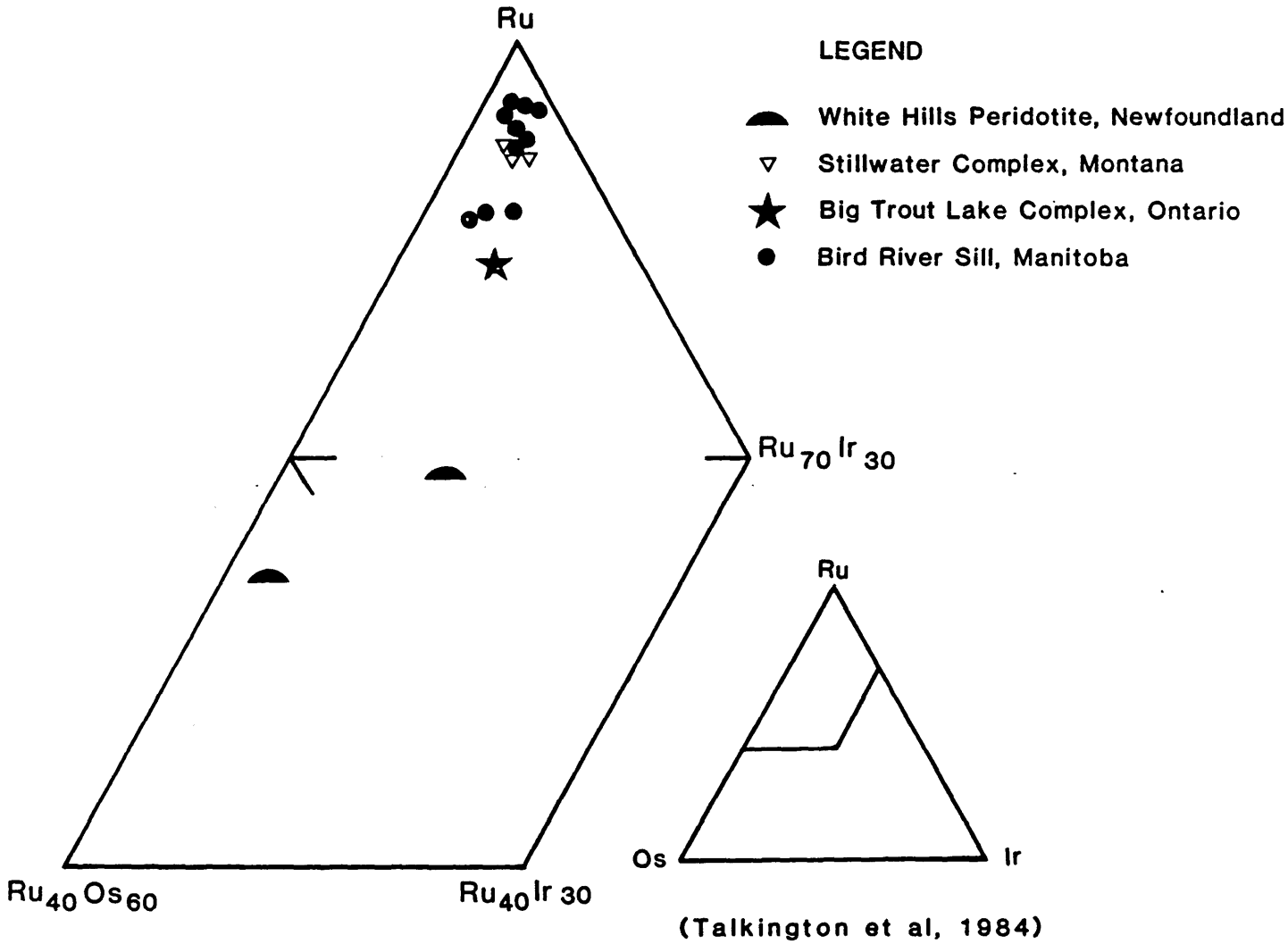


Figure 3.4 : Ru-Ir-Os Compositions of Laurite grains (ideally RuS_2), Big Trout Lake Complex (Talkington et al. 1984).

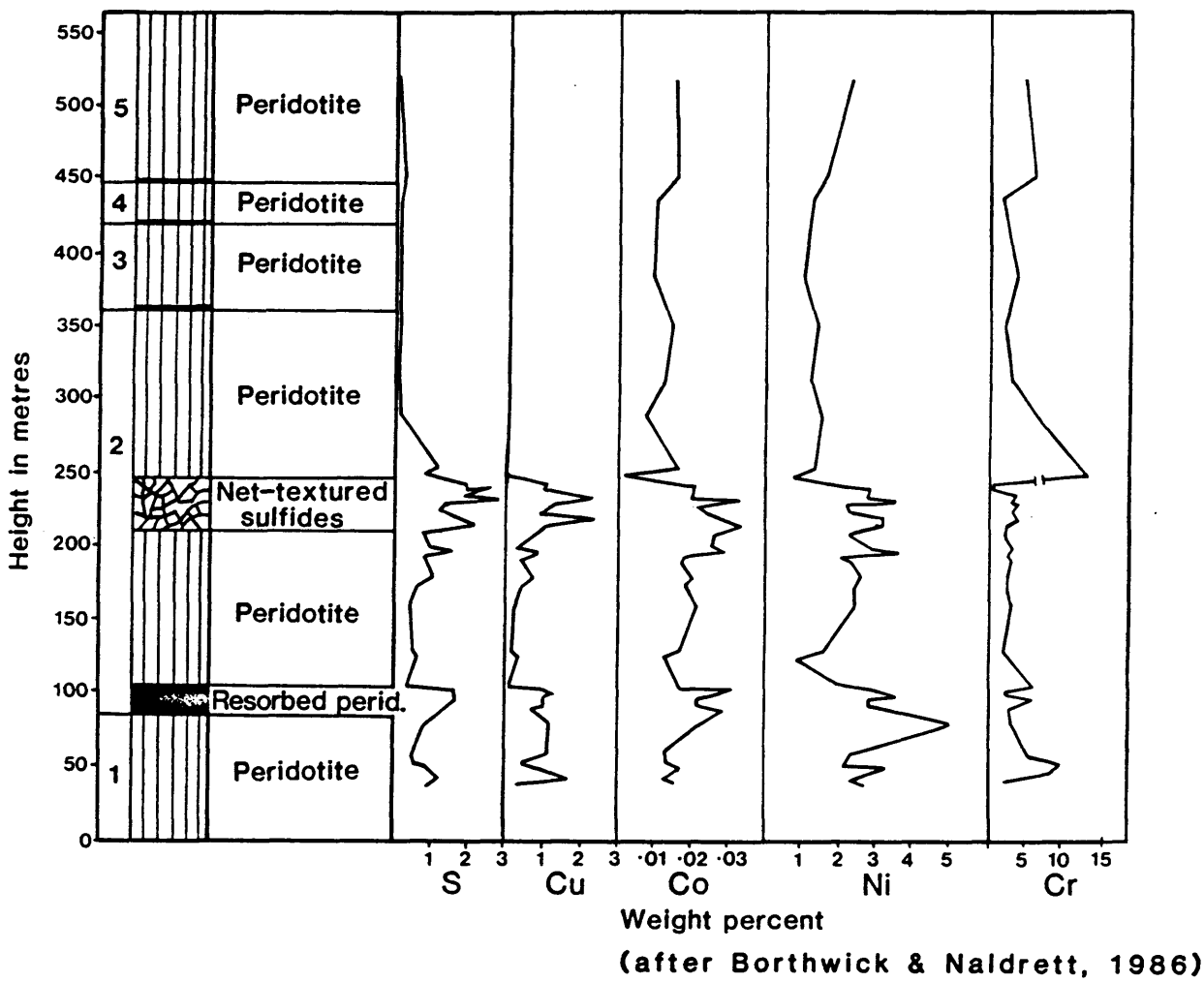


Figure 3.5 : Variation in S, Cu, Co, Ni and Cr with stratigraphy (Borthwick and Naldrett 1986).

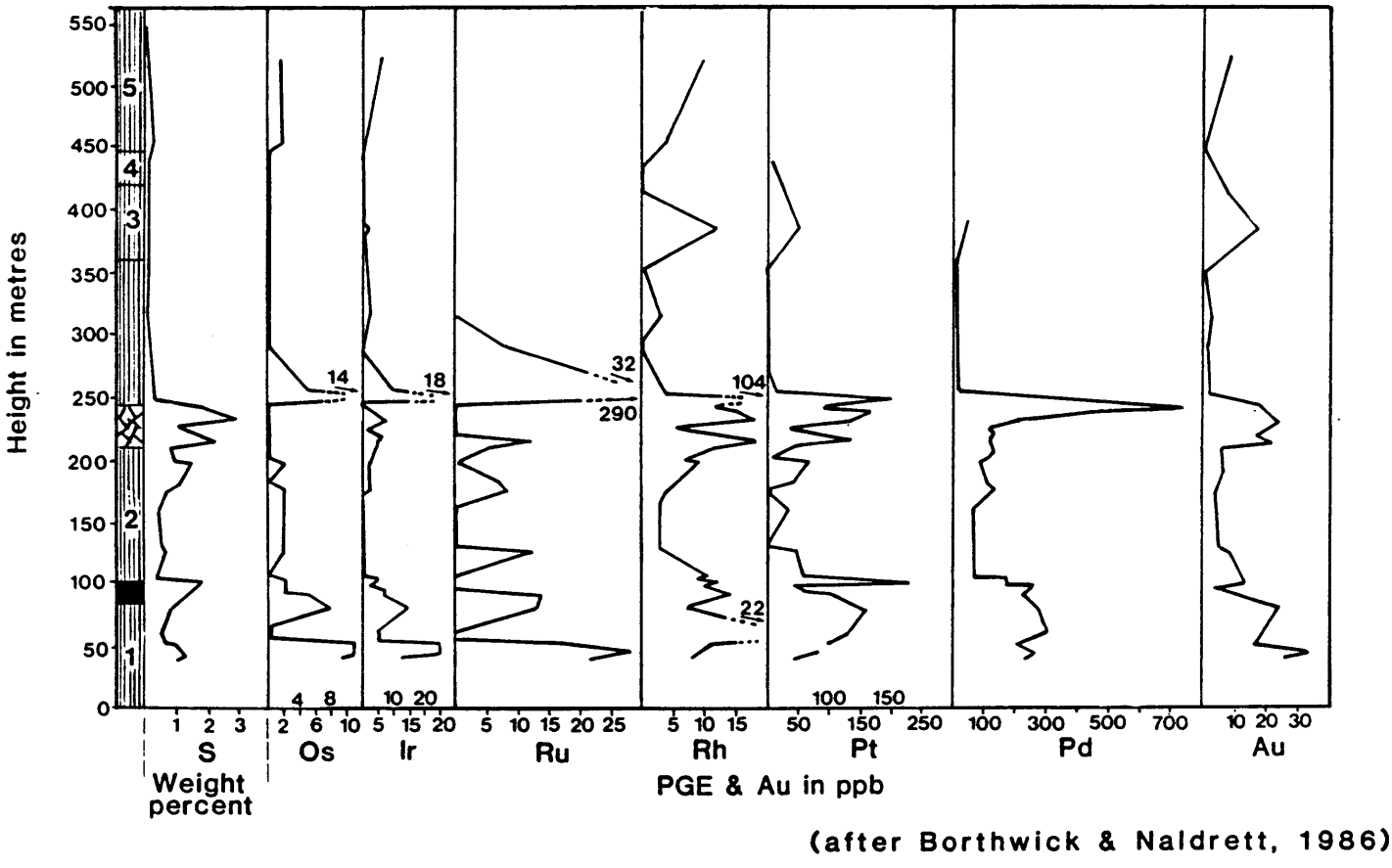


Figure 3.6 : Variation of S, PGE and Au with stratigraphy. Legend as for Figure 3.5. (Borthwick and Naldrett 1986).

3.1.1.2.7. Platinum Group Elements

Platinum-bearing sulphides occur as sparsely distributed, euhedral, discrete inclusions in chromite. These inclusions rarely exceed 20 microns in diameter, have a bright white reflectance, and may occur next to a second sulphide inclusion, commonly of chalcopyrite. Electron microprobe analyses (Figure 3.4, Talkington et al. 1984) of the inclusions reveal Ru-rich compositions of laurite (RuS_2), with small amounts of Os and Ir.

PGE distribution is controlled, in part, by sulphides and chromite. Higher contents of Os, Ir and Ru, which reflect the presence of the laurite inclusions, are associated with chromite, and higher values of Pt and Pd are associated with net-textured sulphides. The latter are unusually low in Os, Ir and Ru (Borthwick 1984, Borthwick and Naldrett 1982, 1983, 1986).

The distribution of S, Cu, Co, Ni, Cr and PGE in the peridotite has been investigated by Borthwick and Naldrett (1986). The results of their work, which focused on a section of peridotite from south of Leopard Point, is discussed below and shown in Figures 3.5 and 3.6. The base of this section was arbitrarily taken at the first chromitite layer.

The first 250 m of the peridotite section are marked by fluctuations in S, Cu, Co, Ni, PGE and Au (Figures 3.5, 3.6). The lowest layer of resorbed peridotite, characterised by re-entrant olivine, has high S, Cu, Co and Ni values (Figure 3.5). Cr reaches a high value below this relatively thick (about 15 m) re-entrant olivine layer, and a net-textured sulphide horizon. Cu, Co and Ni values also increase in the net-textured sulphide horizon, while Cr increases immediately above it. This high Cr value would be expected to correspond to an increase in chromite (Figure 3.5). All of the metals decrease in abundance above the net-textured sulphide horizon, reflecting their overall depletion in the magma that formed the upper levels of the peridotite, and an absence of new injections of magma.

PGE and Au values decrease from the the base of the peridotite section to about the level of the resorbed peridotite layer where they show a marked increase (Figure 3.6). Platinum attains its highest value (about 240 ppb) in this section at the upper contact of the resorbed peridotite layer. Pd and Au, however, show a steady decrease in concentration through this layer. These variations in concentration could represent steady depletion of an early magma below the resorbed peridotite, which may mark a new influx of magma.

Above the resorbed peridotite layer, metal values generally decrease, with minor fluctuations, upwards to the net textured sulphide layer at about 220 m (Figures 3.6). Gold increases sharply at the lower contact of this layer, and Rh, Pt and Pd show rapid, fluctuating increases toward its upper contact. The immediately overlying peridotite contains increased amounts of Cr, Os and Ir and Ru, which should be reflected in more abundant chromite. Talkington et al. (1984) have documented the presence of laurite inclusions in chromite from this horizon.

Above the net-textured sulphide layer, most PGE and Au concentrations decrease steadily upward (Figure 3.6), with minor increases in Rh, Pt, Pd and Au approximately 375 m above the base of the section.

The variation in PGE throughout the peridotite unit of the BTLIC illustrates two environments for PGE concentrations: (a) Net-textured sulphide layers, with associated chromite, in peridotite or dunite should represent one PGE and Au target; (b) resorbed peridotite layers, with associated sulphides, may also contain higher concentrations of PGE and Au, from several metres below to several metres above the resorbed layer.

By analogy with the Bushveld and Stillwater Complexes (Sections 1.3 and 2), the mafic component of the BTLIC also deserves close attention. Evidence should be sought for zones where a primitive magma has intruded the gabbroic and anorthositic portions of the complex.

3.1.1.3. Rottenfish River and Muskrat Dam Lake Greenstone Belts

3.1.1.3.1 Location and Access

The Rottenfish River and Muskrat Dam Lake greenstone belts are approximately 240 km northwest of Pickle Lake, 370 km north of Sioux Lookout, and 300 km north-northeast of Red Lake, in an area bounded by longitudes 91^{o} 00' and 92^{o} 30', and latitudes 53^{o} 10' and 53^{o} 35' (Figures 3.1 and 3.7).

Access to these belts is by float equipped aircraft from Sioux Lookout, Pickle Lake, or Red Lake.

3.1.1.3.2. Previous Work

Parts of the area were traversed in 1886 by Low (1887), who noted the metavolcanic rocks of the Muskrat Dam Lake belt along the Severn River. In 1912, Tyrrell (1913) crossed the eastern end of the Muskrat Dam Lake belt while traversing the Schade River. Satterly (1938) mapped the western end of the Muskrat Dam Lake belt and an area near the Rottenfish River in 1937, and Hudec (1964) briefly examined the northeastern corner of the area while mapping at Big Trout Lake. Satterly (1939), Carruthers (1961) and Donaldson (1961) mapped areas to the south, and Satterly (1937) mapped an area to the north. Ayres (1964a-f, 1969) and assistants mapped the area in 1963 and 1964 by canoe and pace and compass traverses; preliminary maps P.217 (Ayres 1964d) and P.295 (Ayres 1965) were issued from this work. Compilation maps P.213 and P.256 (Ayres 1964a,f) were issued at 1:125 000 scale. The area was also included in Operation Lingman Lake (Bennett and Riley 1969), a regional, helicopter-supported survey conducted by the Ontario Department of Mines. A similar reconnaissance program (Thurston et al. 1979) covered adjacent areas to the east and south of the Rottenfish River and Muskrat Dam Lake belts.

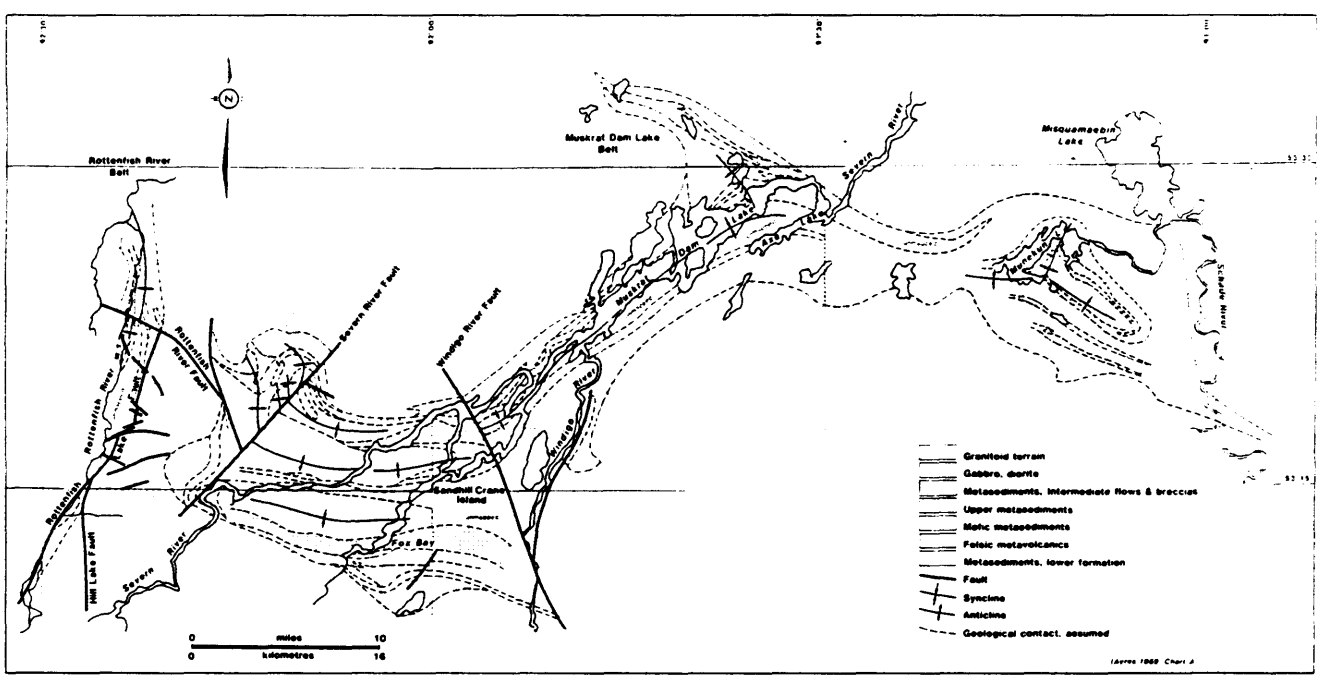


Figure 3.7 : Geology of the Rottenfish River and Muskrat Dam Lake greenstone belts (after Ayres 1969).

3.1.1.3.3. Geology of the Rottenfish River and Muskrat Dam Lake Greenstone Belts Pertinent to Exploration for PGEs

Previous workers have described features of the geology of the Rottenfish River and Muskrat Dam Lake greenstone belts that are significant to exploration for PGEs. These descriptions are the basis of the following discussion.

The Muskrat Dam Lake greenstone belt includes lower and upper mafic successions, and lower and upper sedimentary formations (Ayres 1969). The greatest thickness (6.4 km) of felsic volcanic rocks occurs along the centre of an anticline, flanked by synclines to the north and to the south, at the southwestern end of the Muskrat Dam Lake belt. Gabbroic to dioritic sills, with potential to host PGE mineralization, intrude both greenstone belts (Figures 3.7, Ayres 1969). In the Muskrat Dam Lake belt, these sills occur in both the lower and the upper volcanic successions along the 80 km strike length of the belt. Sills can be traced continuously for up to 24 km. In the Rottenfish River Belt, sills occur along a 13 km strike length of the belt.

The sills, which are locally discordant, are predominantly gabbro, and predate regional metamorphism. They are medium grained, equigranular rocks with green to dark green weathered surfaces and black-green fresh surfaces. In the Rottenfish River belt, the sills are 30 cm to 300 m thick; in the Muskrat Dam Lake belt, they are up to 770 m thick. Chilled margins are relatively narrow; e.g. only 60 cm thick in the Fox Bay Sill. The lower parts of some sills display preserved subophitic to ophitic textures, and are massive to locally weakly foliated. Four major sills in the Munekin Lake area of the Muskrat Dam Lake belt define a crudely concentric structure with two, acutely intersecting, synclinal axes.

The gabbros have been metamorphosed to regional greenschist grade along the cores of the greenstone belts, and to almandine amphibolite grade along the margins of the belts where they are in contact with granitic rocks. Plagioclase is andesine-labradorite, locally altered to albite. Pyroxene has been metamorphosed to amphibole. Mafic minerals comprise about 50% of the rock, and quartz is usually less than 10%. Some leucogabbro, containing 23% to 35% mafic minerals, occurs in the Fox Bay Sill.

The gabbro sills show little evidence of fractionation, with only slight increases in quartz content and decreases in mafic mineral content from bottom to top of sills. In the Munnekin Lake Sill, leucrocratic tonalite dikes locally intrude the upper, earlier crystallized zone, and may represent a final differentiate. Serpentinitized gabbro is reported from the top of the sill on the north limb of the Sandhill Crane Anticline. Rare anorthosite lenses, from 15 cm to 3 m thick, occur, separated from gabbro by 15 cm wide gradational contacts.

3.1.1.3.4. Dioritic Pegmatites

Irregular bodies of dioritic pegmatite occur in central parts of most of the gabbro sills. These are ovoid in shape, average 23 cm in length, and have sharp contacts with the surrounding gabbro. Most are coarse grained, with 2 to 3 cm hornblende phenocrysts forming radiating blades 10 cm in length. The pods usually consist of 45% plagioclase (oligoclase-andesine), 20% uralitized

clinopyroxene, 20% primary green amphibole, 10% Fe-Ti oxides, and 5% biotite, quartz and apatite.

3.1.1.3.5. Mafic Spheroids

Medium to coarse grained, rusty weathering, mafic-rich spheroidal structures occur in the upper parts of the Munekun Lake Sill. These structures, which are 2 to 15 cm in diameter, contain a greater proportion of mafic minerals and Fe-Ti oxides than does the enclosing gabbros. The origin of these spheroids is not clear, although they may indicate the mixing of more than one magma type.

3.1.1.3.6. Mineral Occurrences

Ayres (1969) described occurrences of sulphide mineralization in the metavolcanic and metasedimentary rocks and metagabbros of the belts; however, sulphide concentrations are rare. The area of most abundant sulphide occurrences (> 10% sulphides, mostly pyrite and pyrrhotite) is along the northern shore of the eastern part of Muskrat Dam Lake.

Occurrences of sulphides within the metagabbro sills are of interest in exploration for PGE. Two have been described (Ayres 1969) from a sill east of the Windigo River (Figure 3.7). The northern occurrence comprises 5 to 10% disseminated pyrite, narrow (1 to 2 mm) pyrite veins, and rare chalcopyrite, associated with quartz lenses, up to 60 cm wide, in a sheared part of the sill. This mineralization was traced 55 to 60 m along strike. The southern occurrence, located approximately 3 km from the northern, consists of massive pyrite and chalcopyrite in lenses up to 15 cm long.

3.1.1.3.7. Discussion

Several features of the gabbroic sills, particularly in the Muskrat Dam Lake greenstone belt, are indicative of potential PGE enrichment. These features include:

(1) The occurrence of small volumes of serpentinized peridotite indicates the presence of an ultramafic component. Zones of transition from ultramafic to mafic cumulates are worthy of further work.

(2) Anorthositic gabbro and anorthositic lenses within gabbro sills should be examined for the presence of sulphides and associated PGE. This association, if present, may be similar to PGE-bearing sulphides in the upper An II anorthosite of the Picket Pin Pt-Pd deposit in the Stillwater Complex (Boudreau and McCallum 1985a, 1986).

(3) Dioritic pegmatites, particularly if sulphide-bearing, may have PGE potential, and their distribution in the gabbro sills should be determined. The similarity of these pegmatites to PGE-bearing pegmatites of the Lac des Iles Complex (R. Sutcliffe and A.J. Macdonald, Geologists, Ontario Geological Survey, personal communication 1986) or to gabbroic pegmatites in the Port Coldwell Complex (D.H. Watkinson, Professor, Carleton University, personal communication, 1986) should be examined.

(4) Mafic spheroids with above normal iron-titanium oxide and mafic silicate mineral contents could contain PGE concentrations. Their mineralogy and distribution in the sills should be determined.

(5) Sulphide-bearing quartz veins related to shear zones, e.g. east of the Windigo River, should be examined for PGE. Hydrothermal activity, associated with shearing and vein emplacement, could cause redistribution and concentration of PGE in the sulphide minerals, e.g. Rathbun Lake deposit in Nipissing Diabase (Rowell and Edgar 1985).

(6) Sulphide lenses in gabbroic sills, although small, should be further mapped and sampled for PGE.

3.1.1.4. Small Mafic to Ultramafic Intrusions

3.1.1.4.1. Kasabonika Lake

Medium- to coarse-grained gabbro occurs at Kasabonika Lake (Table 3.1). Pyroxene forms 45 modal percent of the gabbro; plagioclase (An_{54}) and minor oxides comprise the balance of the rock. Pyroxene has been altered to colourless and green hornblende, which in turn is partly altered to chlorite. A relict ophitic texture is defined by plagioclase laths and interstitial hornblende.

3.1.1.4.2. Croal Lake

Metamorphosed gabbro and pyroxenite occur at Croal Lake (Table 3.1). The gabbro displays a cumulate texture, with medium- to coarse-grained, dark green, mafic phenocrysts and 10 mm phenocrysts of plagioclase (An_{54}). Plagioclase is poikilitically included in hornblende oikocrysts, as are minor quartz and opaque oxide minerals. The pyroxenite is fine grained, and contains dark green clinopyroxene phenocrysts. The phenocrysts have been partially uralitized, and are rimmed by hornblende and chlorite. About 5 percent highly altered feldspar is also present.

3.1.1.4.3. Stanley Lake

Five gabbroic dioritic sills are exposed along the southern shore of Stanley Lake (Table 3.1), north of the western end of Eyapamikama Lake. The sills intrude a succession of metasedimentary rocks, range from 30 m to 90 m in thickness, and have a maximum length of 7.6 km (Satterly 1939). They are massive to weakly foliated, fine to medium grained, light grey to dark green, and have been metamorphosed to amphibolite grade (Satterly 1939).

3.1.1.4.4. Weagamow Lake

Dunite forms two small outcrops near the northern end of Weagamow Lake (Table 3.1). Weathered surfaces are rough and are cut by 3 mm wide veinlets of amorphous green serpentine. Relict olivine forms 10 to 15 percent of the dunite, with the remainder composed of serpentine minerals, carbonate, magnetite and minor talc (Thurston et al. 1979, p.71).

3.1.1.4.5. Wunnumin Lake

Both ultramafic and mafic rocks are exposed in the Wunnumin Lake area (Figure 3.1). A single outcrop of peridotite on the Winisk River occurs 5 km west of Nibinamik Lake (Table 3.1). It is a medium to fine grained, has a dull lustre, and is medium to dark green on fresh surfaces. Weathered surfaces are brownish green. The rock consists of serpentinized olivine and about 3 percent magnetite, some of which is interstitial to olivine (Thurston et al. 1979).

Gabbro forms sills and discordant intrusions into metavolcanic and metasedimentary rocks in the Wunnumin Lake area. Where gabbro has intruded metavolcanic rocks it is difficult to distinguish from thicker mafic flows, but against metasediments, well-developed chill margins can be observed. Gabbro is medium to coarse grained, green, dark green and mottled green-brown on fresh surfaces. Weathered surfaces are green to green-brown. Gabbro sills are usually massive bodies with uralitized clinopyroxene and subhedral to anhedral amphibole replacing the pyroxene. Mafic minerals form 60 to 65 percent of the rock. Fresh to moderately altered labradorite (An_{65}) forms the remainder. Quartz and opaque oxides constitute the accessory phases (Thurston et al. 1979).

3.1.2. MAFIC INTRUSIONS OF THE UCHI SUBPROVINCE

3.1.2.1. GENERAL DISCUSSION (H. Wallace)

Figure 3.8 shows the location of major mafic intrusive bodies identified to date within the Uchi Subprovince. It should be emphasised that, with some exceptions, the extent, form, composition, complexity and PGE potential of these intrusions are poorly known. This is particularly true in the eastern part of the subprovince, i.e. that portion east of Miminiska Lake, where few such bodies have been adequately documented because of minimal exposure and lack of detailed geological mapping. Some intrusions, such as those at Abazotikichuan Lake (A), Wabassi Falls (B), and Kagiami Falls (C, Figure 3.8), have been outlined mostly on the basis of aeromagnetic data. They are believed to be dominantly gabbroic, but have been examined only on a reconnaissance scale (Thurston and Carter 1970). Similarly the stock and sills north of Washi Lake (D, Figure 3.8) are metagabbro and anorthositic gabbro (Jackson 1962). A sill or series of sills up to 700 m thick extends from Weese to Shabuskwia Lake.(E, Figure 3.8) and consists predominantly of anorthosite, anorthositic gabbro and minor ultramafic phases (Thurston and Carter 1970, Wallace 1981).

At the western end of the subprovince, the Red Lake and Birch-Uchi Lakes belts are relatively well exposed and have been mapped recently in detail (Wallace et al. 1986; Beakhouse and McNeil 1986, Good 1986). Although mafic and ultramafic sills up to hundreds of metres thick are common in both belts, none have been characterized by survey geologists as layered or differentiated bodies. The largest body in that region occurs north of Bruce Lake (F, Figure 3.8). Its shape and dimensions have been defined mostly on the basis of its geophysical expression; scattered outcrops examined by Shlanka (1970) were identified as gabbroic.

In the central part of the Uchi Subprovince, between Pickle and Cat Lakes, a number of potentially economically significant intrusions are known in addition to the body described separately below (Section 3.1.2.2.) which hosts the Thierry Cu-Ni mine (G, Figure 3.8). Recent mapping by Stott (1986) and Stott and Kay (1986) found several extensive intrusions in the Lake St. Joseph and Meen-Dempster Lakes areas (see Figures 3.9 and 3.10) which were previously unrecognized or mapped as much smaller masses. So far these bodies have only been delineated and examined in reconnaissance fashion.

A large elliptical mass plus a series of consanguinous sills averaging 600 m thick occur at the western end of Lake St. Joseph (H). These are known to be crudely layered and differentiated (Berger 1981, Smith 1977, Stott and Kay 1986), and consist of textural varieties of metagabbro, magnetite-rich leucogabbro and anorthosite, peridotite, pegmatitic gabbro and granophyre. In a few places fine rhythmic layering and cross-layering have been noted within the sills.

In the central part of Lake St. Joseph, Stott and Kay (1986) interpret the presence of a very large (15 x 6 km) metagabbroic mass (I) most of which is covered by lake waters. Where it is exposed this intrusion appears massive. South of that area along Doran and Thelma Lakes (J) there is a major sill-like intrusion up to 10 km long, consisting of metagabbro and minor ultramafic phases.

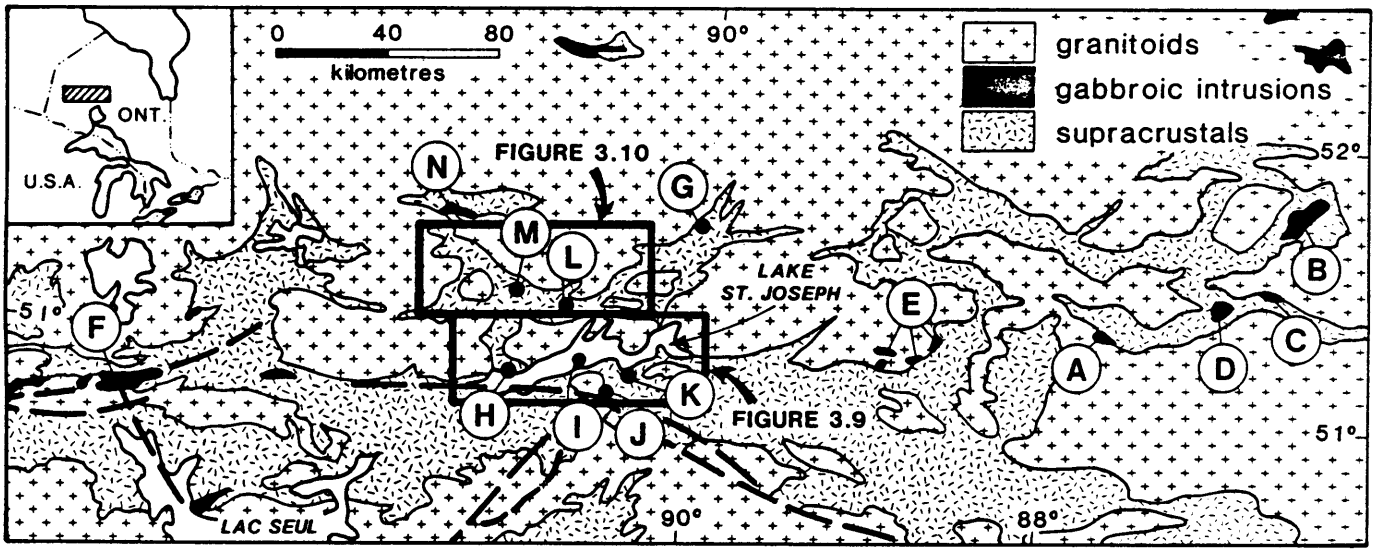


Figure 3.8 : Mafic intrusions, Uchi Subprovince. A-N refer to intrusions described in text.

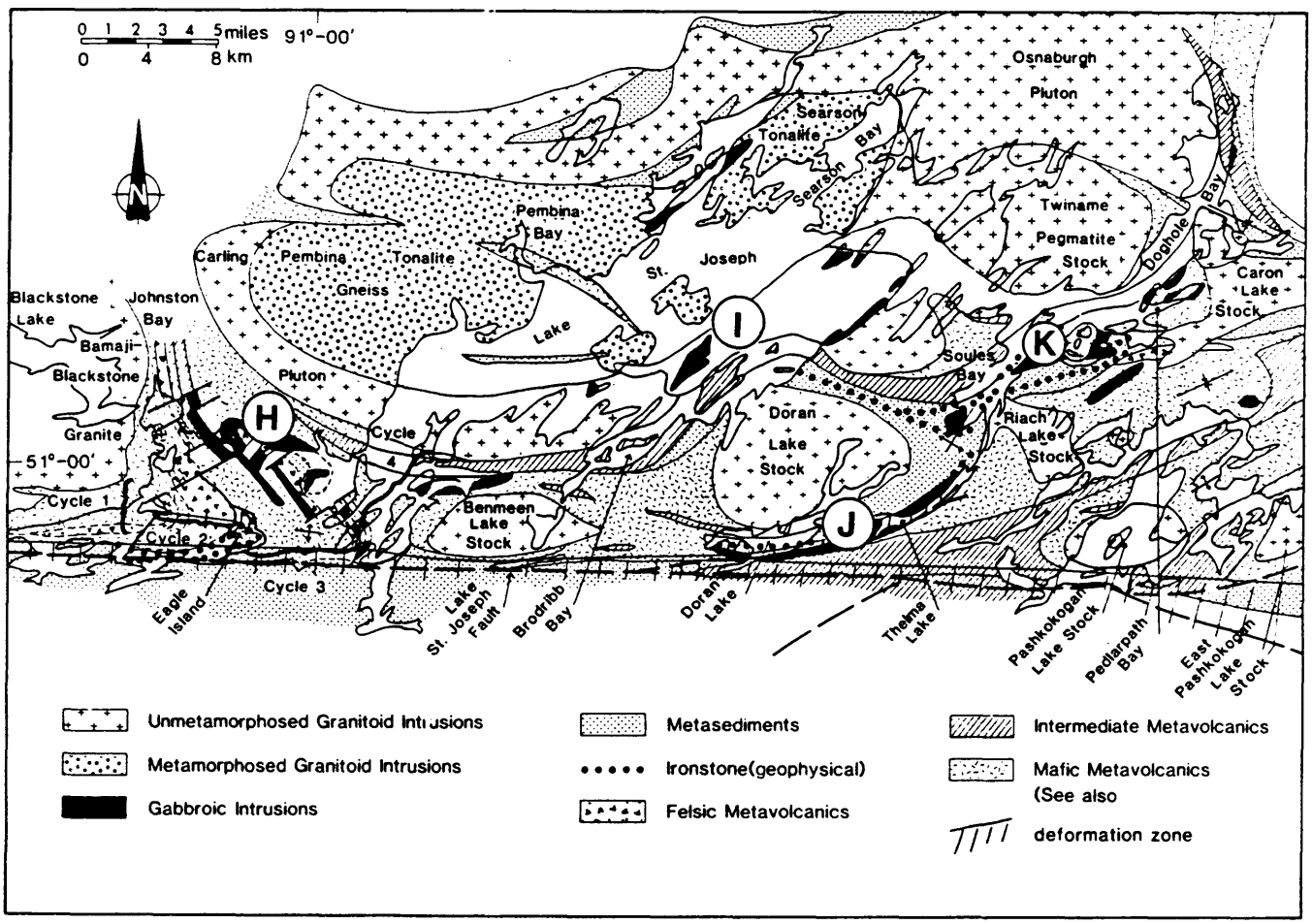


Figure 3.9 : Geology of the Lake St. Joseph Area (Stott 1986).

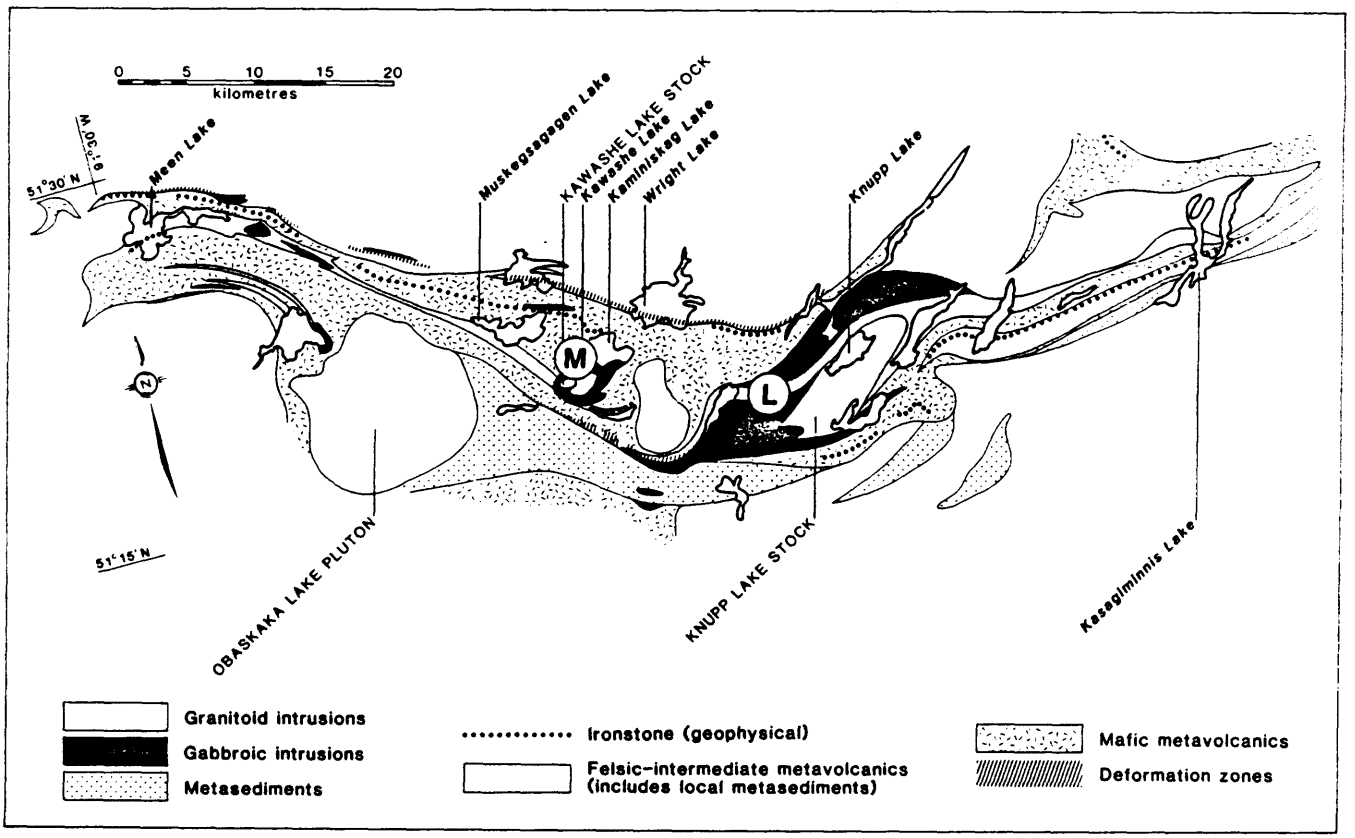


Figure 3.10 : Geology of the Meen-Dempster Lakes area (Stott and Kay 1986).

A number of smaller mafic bodies, some of which exhibit zones of compositional layering, also occur at the eastern end of Lake St. Joseph. Typically these intrusions consist of several phases; metagabbro is again most abundant, and ultramafic rocks occur locally marginal to the bodies. An example is along the northeastern shore of Soules Bay (K) where an intrusion is characterized by magnetite-rich layers and compositional layering.

To the north of Lake St. Joseph in the Meen-Dempster Lakes supracrustal belt the largest mafic intrusive body has been called by Stott (1986) the Dempster Lake Gabbro (L). Although typically gabbroic, the body contains anorthositic gabbro and leucogabbro, and has a quartz-bearing dioritic phase along its southern margin. The Kawashe Lake Stock (M) (Stott 1986), which is roughly 4 km in diameter, is mostly gabbroic and massive, but metapyroxenitic phases have been identified near its southern margins. A number of metagabbroic sills which appear massive also occur to the northwest near Muskegsagagen Lake.

In the Lang - McVicar Lakes belt a stock consisting of anorthosite, anorthositic gabbro and gabbro occurs along the southern side of McVicar Lake (N) (Fenwick 1970).

3.1.2.2. THE THIERRY MINE (G.C. Patterson and D.H. Watkinson)

3.1.2.2.1 Introduction

One of the most extensively studied mafic intrusions in the Uchi Subprovince is located at the past-producing Thierry Mine, owned by Umex Inc., northwest of Pickle Lake, and 450 km northwest of Thunder Bay, (Figure 3.11, and location G, Figure 3.8). Diamond drilling has delineated nearly 14 million tonnes containg 1.6% Cu (Northern Miner Handbook, 1984). The mine is currently under care and maintenance (Janes, 1985).

3.1.2.2.2. Geology of the Thierry Mine

The Thierry Mine occurs in the Pickle Lake portion of the Uchi Lake Subprovince (Figures 3.8, 3.11) of the Superior Province (Sage and Breaks 1982). The greenstone belt consists of an east-trending, Archean metavolcanic rocks, dominated by pillowed mafic flows with minor felsic volcanic and sedimentary rocks and mafic to ultramafic rocks that range in composition from gabbro to amphibolite. The regional metamorphic grade is middle amphibolite facies. Mineral and chemical data suggest that metamorphic temperature and pressure attained approximately 600^{o} C and 5.5 kbar (Patterson 1980). In addition, the rocks have experienced late dynamic metamorphism associated with both a shear zone that strikes ENE, and a set of conjugate faults (Figure 3.12). Shearing of metamorphosed mafic and ultramafic rocks produced a mylonite, consisting of fragments of hornblende in a matrix of chlorite and biotite. In addition, chemical alteration was associated with the dynamic metamorphism. Whole-rock data indicate that calcium, sodium and silica have been removed from the mylonite, and that potassium was added (Patterson and Watkinson 1984a).

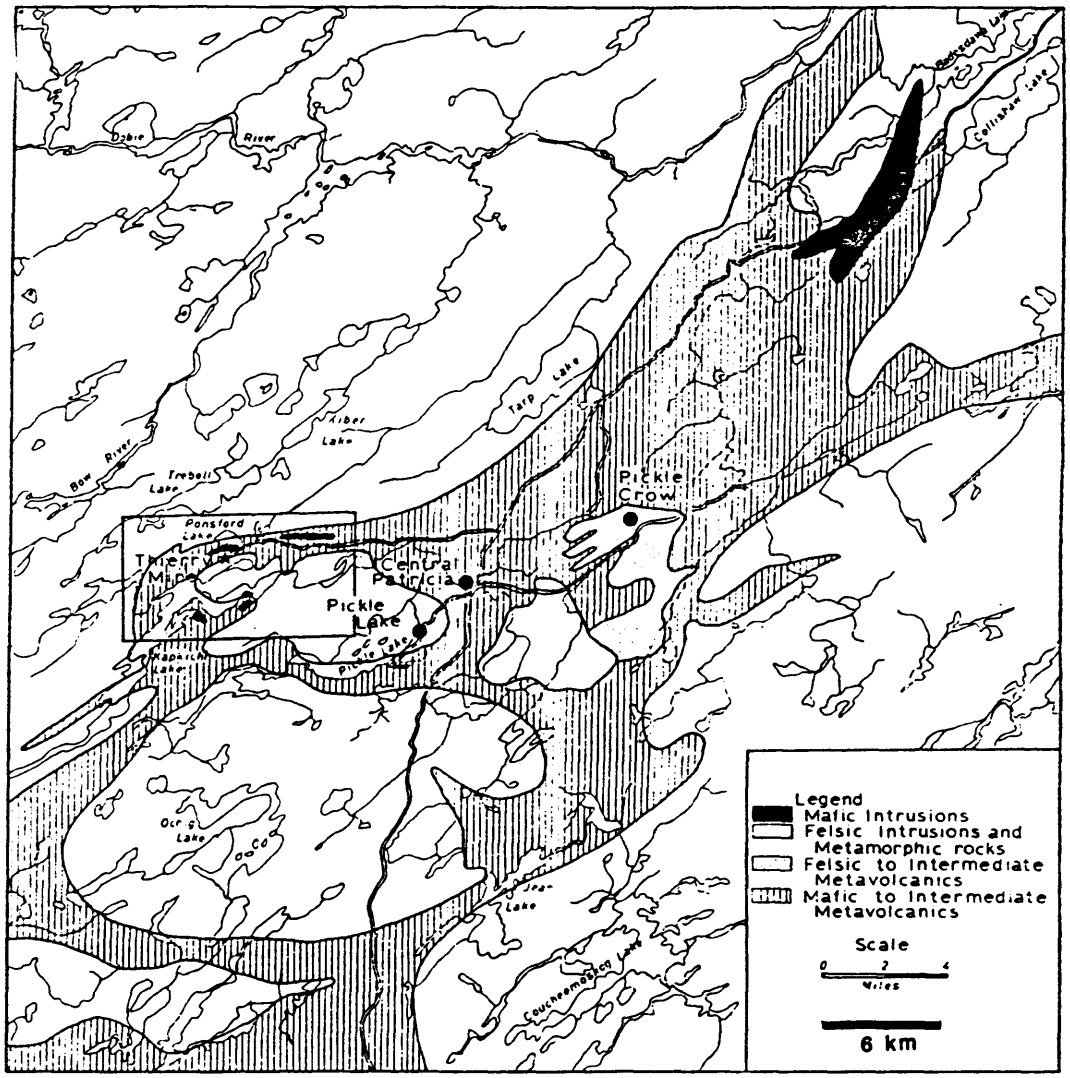


Figure 3.11 : Location of the Thierry Mine, 10.5 km west-northwest of Pickle Lake.

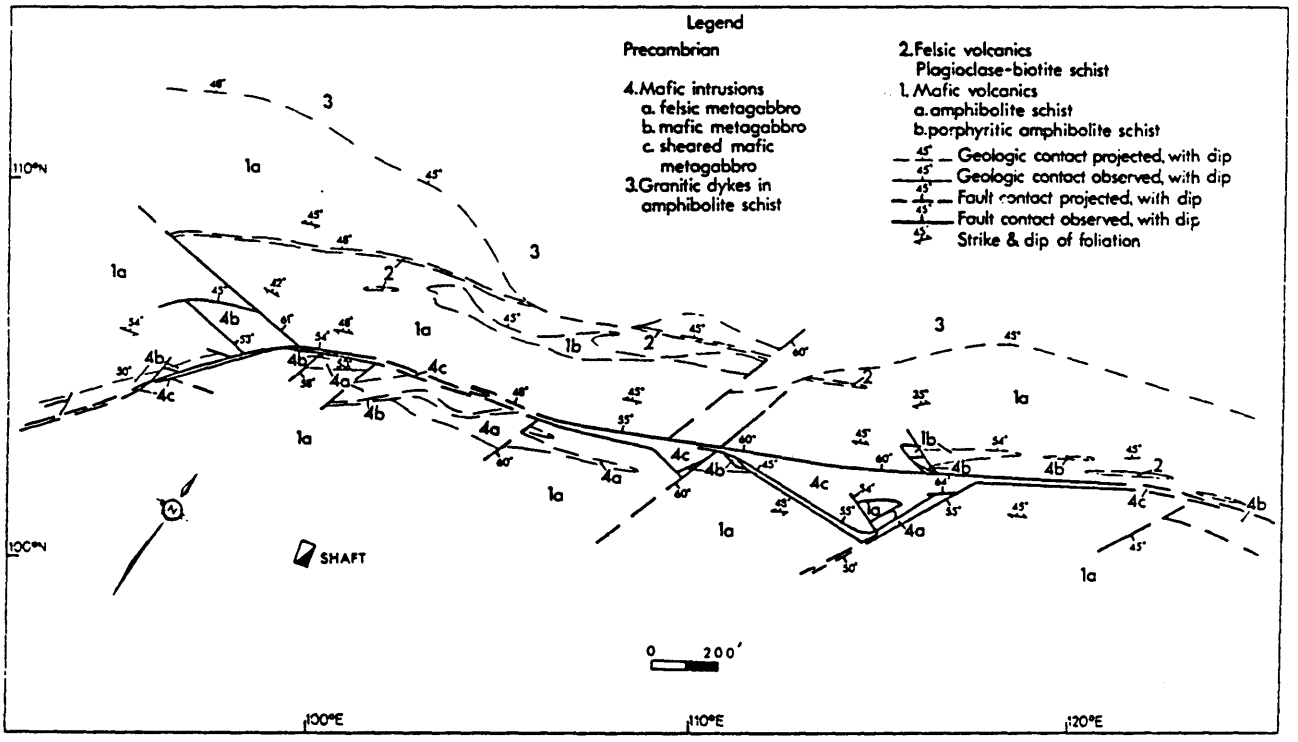


Figure 3.12 : Geological interpretation of the 100 foot (approximately 30 metre) level, Thierry Mine.

3.1.2.2.3 Copper-Nickel Mineralisation

Four principal types of sulphide ore are recognized at the Thierry Mine (Patterson and Watkinson 1984b): breccia ore, mylonite ore, bornite ore and disseminated sulphides, comprising 40%, 58%, 1% and <1% respectively, of the ore body. The disseminated sulphides, interpreted to be metamorphosed primary magmatic sulphides, occur as composite blebs of chalcopyrite, pyrrhotite and pentlandite between relict olivine grains, or serpentine-talc pseudomorphs after olivine. Within the main shear zone, bornite ore contains from 1% to 5% sulphides as stringers and disseminations of chalcopyrite and bornite in carbonate veins associated with blocks of amphibolite schist, interpreted to be altered and deformed mafic volcanic rocks. The stringers commonly cut the metamophic foliation. Mylonite ore contains 5% to 20% sulphides as stringers of chalcopyrite, pyrrhotite, pentlandite and pyrite that are stretched parallel to the foliation. Breccia ore is composed of 20% to 50% sulphides and consists of angular to rounded fragments of the various host rocks, such as mafic metagabbro, mylonite and amphibolite, in a matrix of chalcopyrite, pyrrhotite, pyrite and pentlandite (which is partially altered to violarite by supergene processes). While breccia ore is localized in fault zones and contains fragments of mylonite, it is gradational into mylonite ore.

Mylonite ore and breccia ore have a copper:nickel ratio of 8:1, compared to a 2:1 ratio in disseminated sulphides. In addition, the ratio of chalcopyrite:pyrrhotite is approximately 1:1 in mylonite ore and 1:10 in the disseminated sulphides (Patterson 1980).

3.1.2.2.4 Platinum-Group Elements and Silver Mineralisation

Precious metals minerals have been found in the Thierry Mine in two distinct associations:

1) In breccia ore, the precious metal minerals merenskyite, moncheite, stutzite (a silver telluride) and an unnamed mineral, Ag_3BiTe_3, occur with chalcopyrite, pyrhotite, pentlandite, pyrite and violarite.

2. In bornite ore, the precious metal minerals, native silver, acanthite, stutzite, and merenskyite are associated with chalcopyrite, bornite and copper-bismuth sulfosalts (wittichenite and emplectite).

Electron microprobe analyses of the precious metal minerals are published in Patterson and Watkinson (1984b).

Moncheite occurs as grains up to 0.55 mm in diameter. All observed grains of moncheite contain stutzite (Photo A,B,C,F) as very fine lamellae and blebs along grain boundaries. The grains of moncheite are included in chalcopyrite and pentlandite.

Merenskyite (Photos D & E) also commonly contains stutzite. High silver values in the merenskyite (up to 9.53%) may be due to fine sub-microscopic lamallae of silver tellurides. Merenskyite grains are lensoid in shape and associated with pentlandite and pyrrhotite. One grain of mersenskyite contained a kotulskite lamella.

Table 3.2 Precious Metal Analyses, Thierry Mine

	Cu	Ni	Au	Ag	Pt	Pd
1	0.48	2.97		0.24	0.030	0.070
2	1.70	0.58	0.030	0.36	0.010	0.070
3	0.51	4.04		0.20	0.040	0.030
4	0.45	0.13		0.20	0.030	0.010
5	19.40	0.05	0.020	3.37	0.005	0.005
6	2.70	0.39	0.010	0.20	0.008	0.012
7	6.16	0.65	0.014	1.32	0.064	0.120
8	3.96	0.10	0.017	0.22	0.012	0.018
9	0.02	4.20	0.250	0.10	0.298	0.327
10	2.40	0.48	0.020	0.36	0.15	0.045
11	5.01	0.29	0.008	0.34	0.005	0.009
	12	13	14	15	16	17
Fe%	57.20	30.50	31.67	71.10	56.50	32.78
Cu%	0.56	33.53	33.10	0.20	0.41	32.86
Ni%	1.44	0.08	0.11	0.07	1.28	0.46
S%	34.70	34.50	35.26	0.24	28.59	33.88
Total	93.90	98.61	10.14	71.61	86.78	99.98
Mineralogy Composition Based on Average Composition						
Cpy	1.13	97.15	95.8	0.58	0.77	95.22
Po	81.76	1.13	4.03	-	68.3	0.33
Pn	2.44	0.20	0.23	0.20	2.25	1.29
Mt	1.44	0.49	0.29	99.48	22.70	4.89
Precious Metals Oz/Ton						
Pt	0.013	0.020	0.006	0.005	0.036	0.003
Pd	0.096	0.038	0.112	.tr	0.059	0.006
Au	0.005	.tr	0.008	.tr	0.006	0.019
Ag	0.330	3.860	3.83	.tr	.tr	4.419

1. Breccia ore in ultramafic rocks, 600-102E-15°NW depth 320'
2. Chalcopyrite rich in veins in amphibolite 400 level section 101E
3. Breccia ore, 60-102E-55° depth 376'
4. Breccia ore, 600-102E-55° depth 376'
5. Chalcopyrite rich vein with epidote-feldspar, 1200 level drift 116 x south wall.
6. Sulphides in silicified amphibolite, 1200 level 117E
7. Breccia ore, 600 level 10950N
8. Breccia ore, level 10885N
9. Pyrrhotite rich breccia ore, open pit bench 85
10. Chlorite-biotite schist, open pit bench 85
11. Breccia-ore, open pit bench 85, amphibolite fragments in chalcopyrite pyrrhotite matrix
12. Pyrrhotite fraction of breccia ore, west open pit, 1st bench
13. Chalcopyrite fraction of breccia ore, west open pit, 1st bench
14. Breccia ore (12 + 13) west open pit, 1st bench, cpy rich
15. Magnetite veins in ultramafic, 500 level hanging wall drift
16. Pyrrhotite rich breccia, west pit, bench 85
17. Chalcopyrite in epidote vein in massive amphibolite, east pit, lower bench.

(Precious metals in oz/ton, Cu & Ni in %)

Table 3.3 Metal Analyses of Composite Pulp and Mill Feed, Thierry Mine

	Au	Ag	Pt	Pd	Cu	Ni
October 1976	0.005	0.19	0.007	0.017	1.02	0.125
November 1976	0.0042	0.198	0.005	0.013	1.10	0.134
January 1977	0.0052	0.24	0.005	0.016	1.28	0.155
February 1977	0.0042	0.203	0.005	0.016	1.17	0.150
March 1977	0.0062	0.191	0.004	0.013	1.11	0.136
April 1977	0.0040	0.194	0.006	0.016	1.05	0.152
May 1977	0.0040	0.211	0.005	0.014	1.30	0.188
June 1977	0.0045	0.226	0.005	0.014	1.31	0.171
July 1977	0.0035	0.200	0.005	0.013	1.23	0.185
September 1977	0.0050	0.310	0.006	0.021	1.48	0.139
Average	0.0046	0.216	0.005	0.015	1.21	0.154

Precious metals in oz/ton, Cu & Ni in %

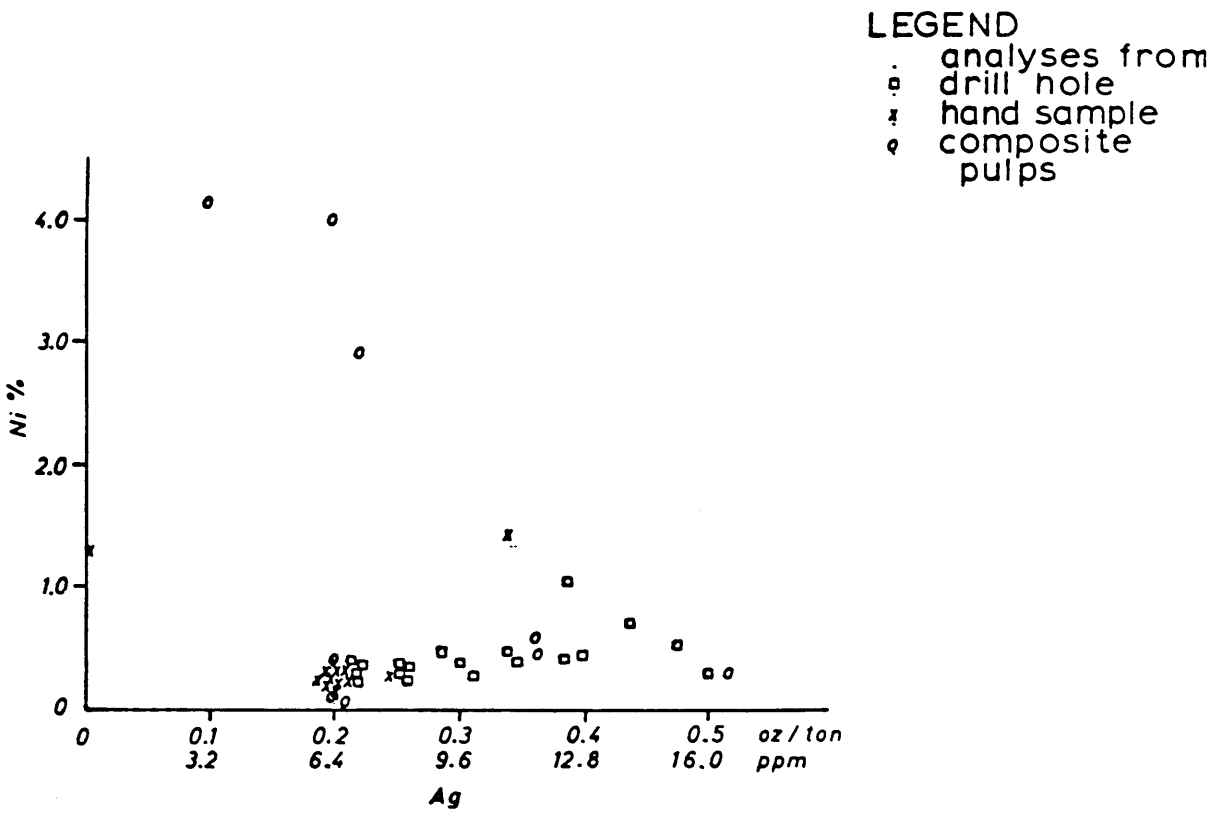


Figure 3.13 : Ni versus Ag, Thierry Mine head grades.

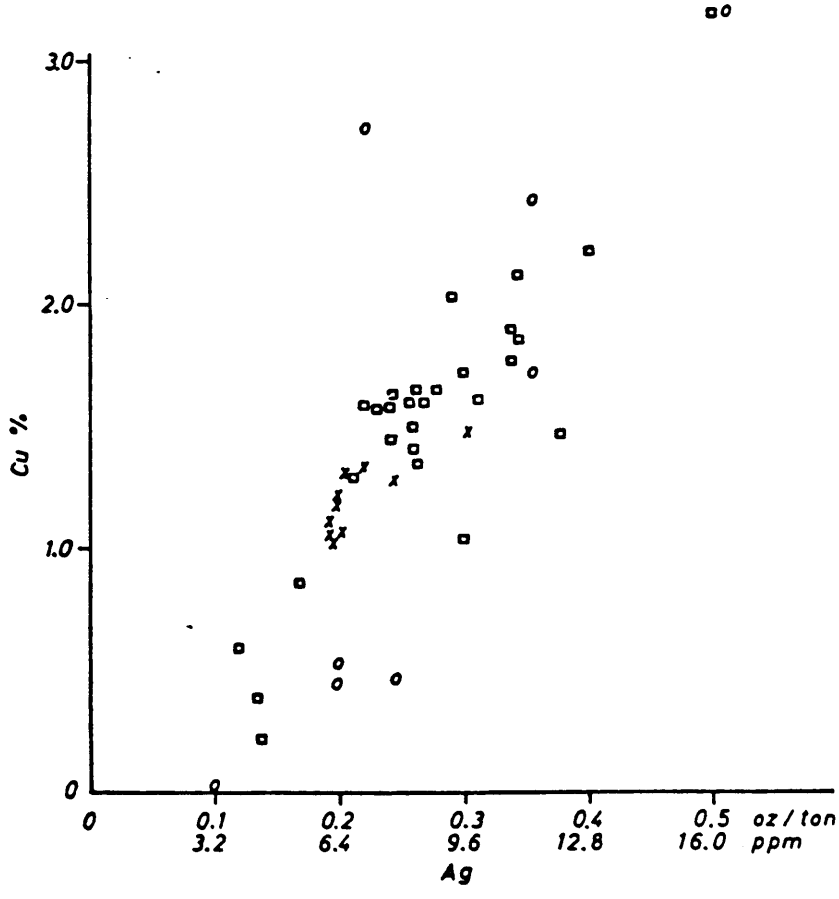


Figure 3.14 : Cu versus Ag, Thierry Mine head grades.

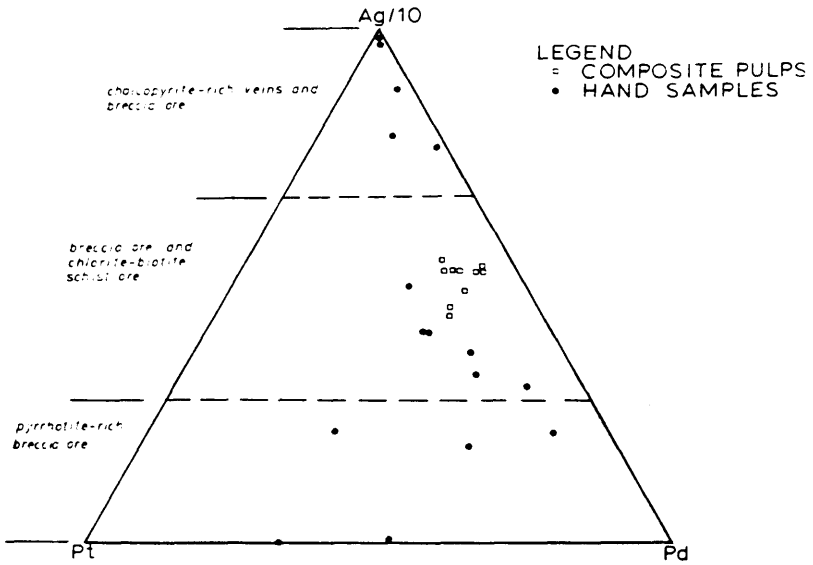
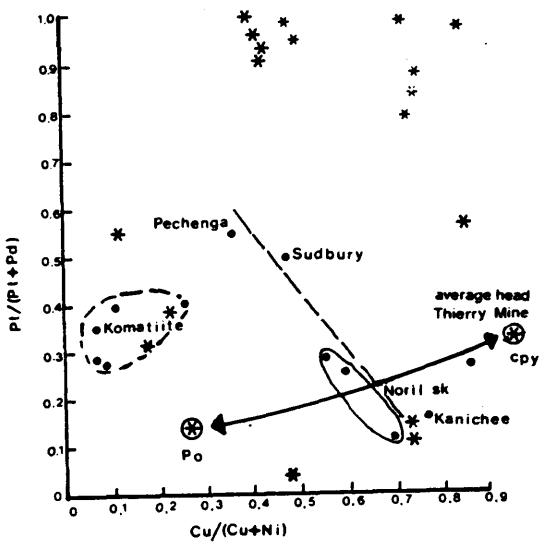


Figure 3.15 : Silver, platinum, palladium inter-relationships, Thierry Mine.



The relationship between Pt/(Pt+Pd) and Cu/(Cu Ni) ratios in sulfide ores. (after Naldrett and Cabri, 1976).

Figure 3.16 : Pt/(Pt+Pd) versus Cu/(Cu+Ni) in sulphide ores (modified after Naldrett and Cabri 1976).

Stutzite occurs as lamellae in both merenskyite and moncheite in breccia ore and as discrete grains with native silver in bornite ore. The unnamed Ag_3BiTe_2 phase occurs as intergrowths with stutzite and merenskyite in breccia ore. Native silver (containing 2.1% gold) occurs associated with acanthite and stutzite.

3.1.2.2.4 Distribution of Precious Metals

Table 3.2 shows analyses on a wide variety of ore types (Sample 1-11) and sulphide concentrates (Samples 12-17). Average head grades obtained by analyzing crushed ore collected at one hour intervals over a one-month period are shown in Table 3.3.

A negative correlation exists between silver and nickel at values of nickel greater than 0.5% (Figure 3.13). Silver and copper display the highest positive correlation coefficient 0.82 (Figure 3.14. *n.b.* extremely high silver values were not included in this calculation).

Silver, platinum and palladium inter-relationships are shown in a ternary diagram (Figure 3.15). The diagram can be subdivided on the basis of ore type: chalcopyrite-rich veins and breccia plot close to the silver apex: breccia ore and chlorite-biotite schist mylonite ore plot in the central area and pyrrhotite-rich breccia ore near the platinum-palladium base of the diagram. Figure 3.16, a plot of Pt/(Pt + Pd) versus Cu/(Cu + Ni) shows average head grades of the Thierry Mine to be enriched in copper and somewhat in platinum when compared to other Ni, Cu + PGE-bearing deposits (Naldrett and Cabri 1976). The Thierry data plot in two groups, both plot well off a trend defined by Naldrett and Cabri (1976) for PGE-bearing, Ni-Cu sulphides. A sample was split into a pyrrhotite-rich and chalcopyrite fraction (the line joins the two fractions on Figure 3.16). The copper-rich sample contains more platinum than the nickel-rich sample.

3.1.2.2.5 Conclusions

The ores at the Thierry Mine have undergone intense modification after their initial deposition as magmatic sulphides. Dynamic metamorphism has mobilized much of the breccia and mylonite ores; for example, mylonite fragments occur within breccia ore, which is localized along faults related to the main shear. The occurrence of bornite ore in amphibolite blocks (altered mafic volcanic rocks) included in the mylonite suggest that the sulphides were mobilized into amphibolite during dynamic metamorphism. It is also important to note the occurrence of merenskyite in carbonate veins within bornite ore. These veins cut the metamorphic fabric, which suggests that PGM were also mobile during and after dynamic metamorphism.

Any model of ore genesis at the Thierry Mine must take into account the unusual Cu/Ni, Pt/Pd and chalcopyrite/pyrrhotite ratios in the rocks. According to Naldrett and Cabri (1976), intrusive complexes similar to those at Thierry Mine, although less altered and deformed, contain sulphides with a copper:nickel ratio of 2:1, a platinum:palladium ratio of 1:2 and a chalcopyrite:pyrrhotite ratio of 1:10. These ratios at the Thierry Mine, however, are approximately: copper:nickel 8:1, platinum:palladium 1:4, and chalcopyrite:pyrrhotite 1:1. The most likely process that gave rise to these anomalous ratios is stress-induced diffusion, which selectively mobilized copper, silver and platinum, relative to nickel, iron and palladium during

deformation (Patterson and Watkinson 1984b). The operation of such an alteration mechanism suggests that uneconomic deposits in undeformed rocks could be upgraded in areas that have undergone dynamic metamorphism. This gives rise to the possibility that economic PGE deposits could be generated by a similar mechanism. The New Rambler deposit, Wyoming (McCallum et al. 1975) may be of this class. Some care should be taken in assuming that PGE are refractory or immobile phases in metamorphosed rocks, as dynamic metamorphism has been demonstrated to modify metal ratios.

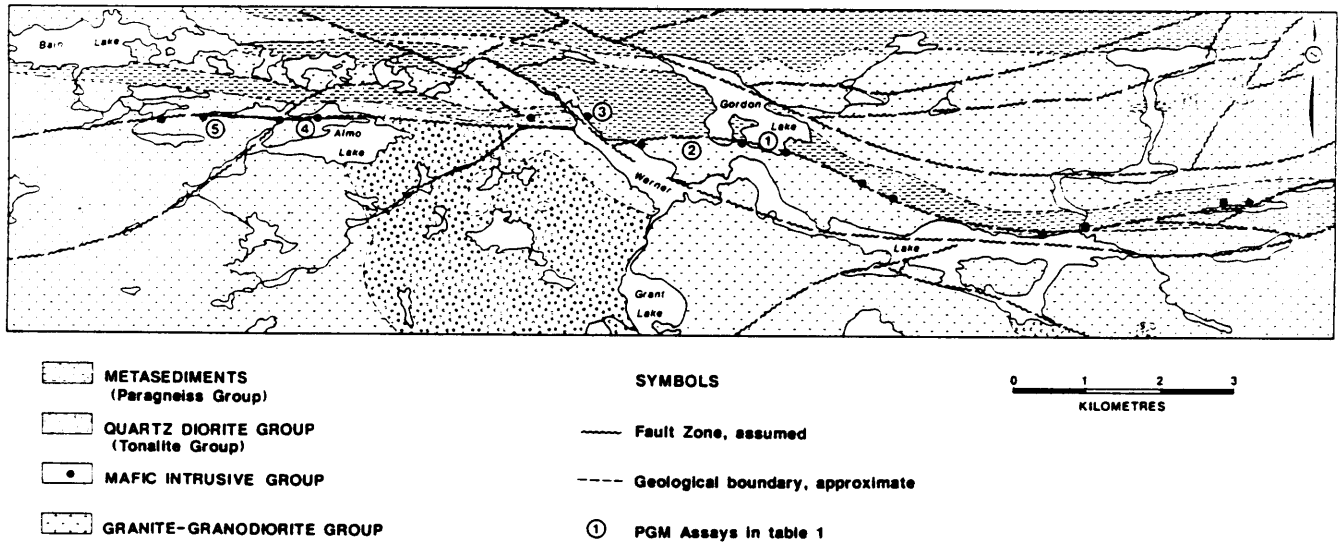


Figure 3.17 : Geological Map, Werner-Rex Lakes Area, modified from Carlson (1958).

3.1.3. ENGLISH RIVER SUBPROVINCE (A.J. Macdonald)

3.1.3.1. General Discussion

The English River Subprovince is located south of the Uchi Subprovince and in contrast to the latter, contains conspicuously few economic mineral deposits; an exception is the Griffith iron mine between Ear Falls and Red Lake. Past Ni-Cu producers are located in the Werner and Gordon Lakes area (Figure 3.17) of the English River Subprovince (Figure 1.6), close to the Manitoba Border, and are of interest in exploration for the PGE.

The Sydney Lake Fault Zone (Stone 1981) defines the boundary betwen the Uchi Subprovince to the north and the English River Subprovince to the south (Stockwell 1964). The Werner Lake-Rex Lake Fault system (Carlson 1958), is located approximately 20 km southwest of Sydney Lake. The dominant lithologies in this portion of the English River Subprovince include gneissic metasediments, tonalitic and granulitic intrusions and volumetrically minor, but economically important, mafic and ultramafic intrusive rocks.

The Werner-Rex Lakes area is accessed by float plane from communities in Ontario, such as Kenora, or by minor road via Lac du Bonnet, Manitoba.

3.1.3.2. Werner-Rex Lakes

The Werner Lake - Rex Lake fault zone is subparallel to the regionally extensive Sydney Lake fault zone to the north, and the two may be related. Small discontinuous plugs and lenses of peridotite and associated mafic rocks have intruded the fault zone (Carlson 1958). Copper-nickel sulphides, with local cobalt and PGE enrichments are associated with the mafic/ultramafic intrusions. At least 15 discrete intrusions are shown along the Werner Lake-Rex Lake fault zone on OGS maps 1957-2, 1957-3 accompanying Carlson (1958). Surface exposure is, however, limited, as much of the fault zone is coincident with lakes, drift-filled linear valley and swamps. Lawson and Zuberec (1987) mapped a number of occurrences in the Gordon and Werner Lakes area.

Carlson (1958, p.21) noted that most of the showings were discovered by prospectors working with "an idea and a grub hoe". As many of the ultramafic rocks have been subjected to serpentinization, forming accessory magnetite, the rocks are amenable to detection by geophysical means (magnetic susceptibility survey).

The three most intensely explored properties are known as (a) the Eastern Mining and Smelting Corporation Limited (EMSCL) property, at Gordon Lake, and (b) the Norpax Oils and Mines Limited Property, 3 km west of Werner Lake, and c) the Werner Lake-Cobalt Mine of Kenora Prospectors and Miners Limited at the west end of Werner Lake (Carlson 1958).

Ni-Cu Sulphide mineralization was discovered at the Gordon Lake Property of EMSCL in 1942. Subsequent diamond drilling and underground development revealed at least a dozen small plugs of peridotite asssociated with a gently curving, easterly-striking fault zone. Each peridotite plug is sheathed in a hornblende-biotite schist of variable thickness. Sulphide mineralization occurs within and between the mafic/ultramafic plugs, as lenses, streaks and seams of massive sulphide up to just over 1 m in thickness. The sulphides consist of variable proportions and quantities of pyrrhotite, pentlandite, chalcopyrite and pyrite. Two zones were investigated in detail by EMSL; the G

zone contained an estimated 542,000 tons to a depth of 750 feet (230 m), with an average grade of 0.42% Ni, 0.68% Cu, 0.07 oz/t PGE (2.4 g/t PGE). The B zone is estimated by EMSCL to contain 786,000 tons with an average grade of 1.15% Ni, 0.30% Cu and 0.12 oz/t PGE (4.11 g/t PGE).

The Norpax property was first staked in 1953 and was explored by diamond drilling from surface and by underground exploration and development. As at the Gordon Lake property, sulphide mineralization is spatially associated with perdotitic bodies, and associated mafic rocks, that are intrusive into an easterly-striking fault zone. The sulphides occur as disseminated to massive bodies of pyrrhotite, pentlandite, violarite, chalcopyrite and pyrite. No reserve estimates are available.

Cobalt mineralisation in the area was first discovered at the Werner Lake Cobalt property in 1920. In 1932 some 70 tons of cobalt ore were mined and contained 20,000 pounds (9072 kg) of Cobalt. Total production to 1944 exceeded 140,000 pounds of Cobalt (63,504 kg). The mine property is traversed by two faults of the Werner Lake - Rex Lake fault zone. One is an extension of the structure that hosts mineralization on the Norpax and Gordon Lake properties to the west and east, respectively. Mineralization in the Werner Lake Cobalt mine is associated, on the other hand, with a splay off a second fault that strikes N60^{O}W. In this case, there is no observed ultramafic intrusion associated with mineralization. Instead, sulphides are hosted by amphibolite which appears similar to mafic rocks spatially associated with peridotite intrusions on the other properties described above (Carlson 1958).

Metallic minerals in the Werner Lake Cobalt Mine mineralization include cobaltite, chalcopyrite, pyrrhotite, pyrite and magnetite, present in pods, lenses and disseminations. Exploration assays were reported up to 7.8% Cu, 2.4% Cu and 0.5% Ni. The average grade is approximately 2% Co, 0.75% % Cu and <0.1% Ni. No tonnage, nor PGE values are reported (Carlson 1958).

Mineralization of the style seen at Werner-Rex Lakes lends itself to modern geophysical prospecting techniques to localize the mafic/ultramafic intrusions spatially associated with locally PGE-bearing sulphides. Magnetic susceptibility surveys can indicate the presence of altered ultramafic bodies (serpentinised olivine is relatively magnetite-rich). Coincident IP or EM anomalies may suggest sulphides are associated with the mafic/ultramafic bodies. In areas of overburden, the geophysical anomalies will require testing by diamond drilling.

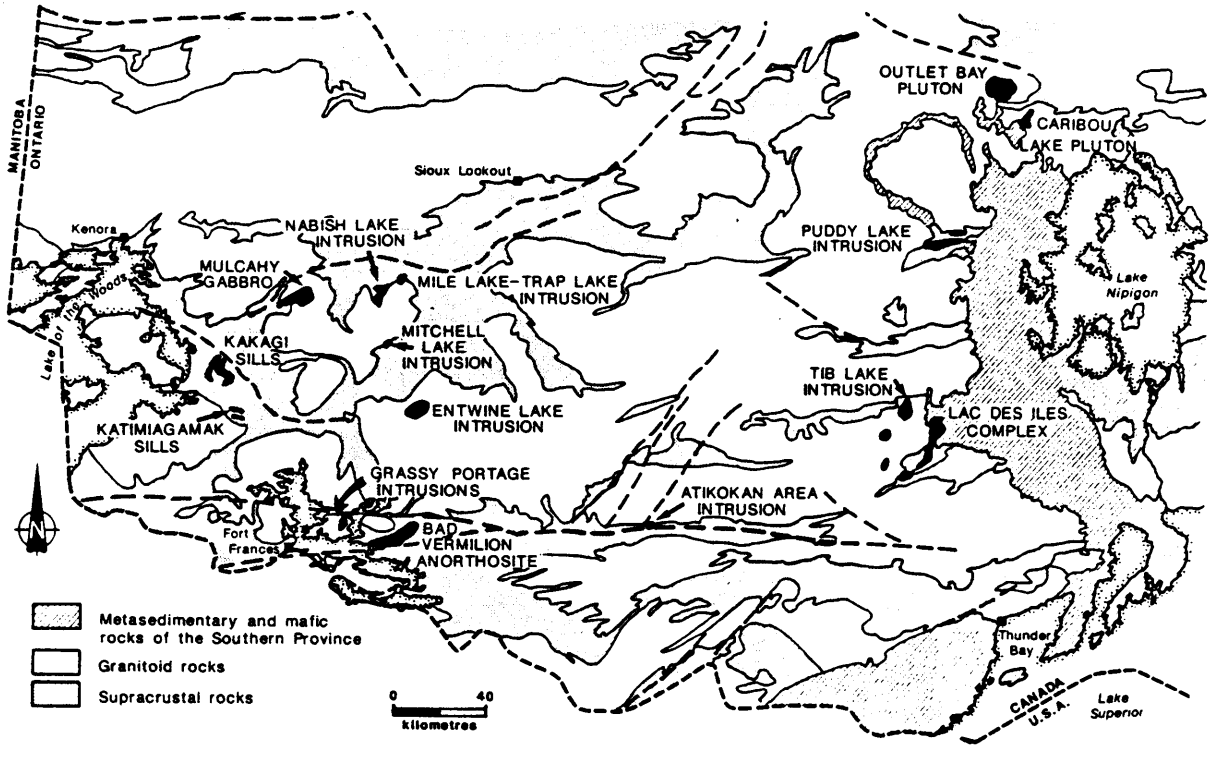


Figure 3.18 : Geological Map of the Western Wabigoon Subprovince

3.1.4. GEOLOGY AND PGE-POTENTIAL OF MAFIC INTRUSIONS IN THE WESTERN WABIGOON SUBPROVINCE

3.1.4.1. General Discussion (R.H. Sutcliffe)

3.1.4.1.1. Introduction

Mafic to ultramafic intrusions occur in a variety of spatial and temporal associations within the western Wabigoon Subprovince (Figure 3.18). Typical associations include:

a) Mafic to ultramafic sills within supracrustal belts which are interpreted to be contemporaneous with mafic metavolcanic rocks into which they are intruded (e.g. Katimagamak Lake sills (Davis and Edwards 1985) and Bad Vermilion Anorthosite (Phinney 1981).

b) Syntectonic mafic to ultramafic intrusions situated at the margins of major batholiths and associated with coeval felsic plutonism and/or dacitic volcanism e.g. Mulcahy Gabbro (Davis 1985a; Sutcliffe 1985) and other intrusions in the vicinity of the Atikwa-Lawrence Batholith.

c) Syntectonic to post-tectonic mafic to ultramafic intrusions situated within major granitoid and gneiss terrains which are also coeval with late felsic plutonism (e.g. Lac des Iles (Sutcliffe and Sweeney 1986) and the Entwine Lake Intrusion (Davies 1965). Some of these intrusions have tectonic similarities to Alaskan-type mafic/ultramafic complexes.

d) Ultramafic intrusions such as the Chrome-Puddy Lakes intrusion which are interpreted to have similarities with Alpine-type peridotites (Whittaker 1980). The Chrome-Puddy Lakes mineralisation is described in Section 3.1.4.4.

Associations (b) and (c) appear to be the most abundant types of large mafic to ultramafic intrusions in the western Wabigoon region.

U-Pb zircon geochronology by Davis and Edwards 1982, 1985a) indicate that at least two ages of mafic intrusion occurred within the western Wabigon area. Further studies will undoubtedly reveal more ages. The Katimagamak sills and the Mulcahy Gabbro have been dated at 2731.7 (+4.0/-2.9) and 2733.2 (+1.0/-0.9) Ma, respectively. The former age represents the oldest lithology in the Kakagi Lake area and is interpreted as being the same age as mafic volcanism (Davis and Edwards 1985). Although the Mulcahy Gabbro is of similar age, this intrusion is contemporaneous with extensive tonalitic plutonism and intrudes the adjacent mafic to intermediate metavolcanic sequence. A younger age of mafic intrusion, represented by the Kakagi Lake sills, has been dated at 2728.2 (+2.5/-2.3) Ma and probably represents the recurrence of another phase of tholeiitic magmatism in the Kakagi Lake area (Davis and Edwards 1985a).

3.1.4.1.2. Composition

Mafic to ultramafic layered intrusions in the Wabigoon Subprovince which have been studied to date are largely of tholeiitic chemistry. Parental magma compositions have been difficult to identify owing to the absence of chilled

contact phases and the apparent contamination of marginal phases and dike rocks by granitoid crust. Characterization of the magmas is therefore largely based on the examination of mineral chemistry within the intrusions. Both magnesian tholoeiite suites (e.g. Lac des Iles Complex) and iron tholeiite suites (e.g. Mulcahy Gabbro) are represented. Some Fe-tholeiite intrusions such as the Mulcahy gabbro are associated with minor ultramafic intrusions with more primitive cumulate phases. Anorthositic intrusions such as the Bad Vermilion anorthosite are interpreted to represent plagioclase cumulates derived from high-iron tholeiitic parental magmas (Phinney 1981).

Many of the layered tholeiitic mafic intrusions are remarkably fresh and have well-preserved primary mineralogy. Crystallization sequences defined by the order of appearance of cumulus phases are variable. Most intrusions have a sequence olivine, pyroxene, plagioclase; however, the nature of the first pyroxene to crystallise is variable and may depend on silica activity in the melt with orthopyroxene preceeding clinopyroxene at high silica activity. The resulting sequences are: olivine, orthopyroxene, clinopyroxene, plagioclase which is typified by the Kakagi Lake Sills and Mulcahy area intrusions, and olivine, clinopyroxene, orthopyroxene, plagioclase which occurs at the Lac des Iles complex. Anorthositic intrusions such as the Bad Vermilion anorthosite may be characterized by crystallization sequences olivine, plagioclase, pyroxene (Phinney 1981). Based on analyses of olivine in the Mulcahy area and Lac des Iles several of the intrusions are characterized by the most primitive olivine having compositions of Fo_{80-82}.

3.1.4.1.3. Relationship to PGE Mineralization

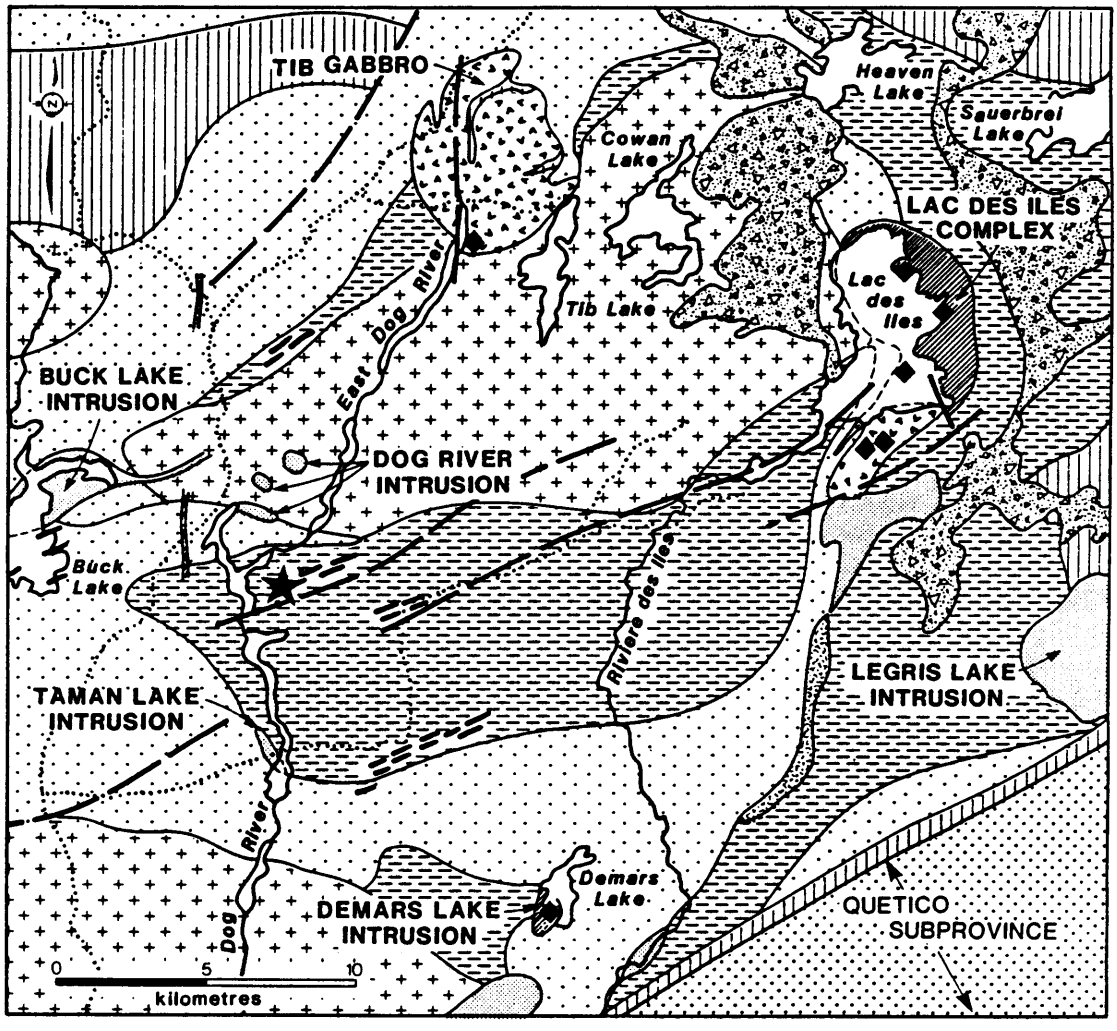
At present the data on PGE distribution in many of the mafic to ultramafic intrusions is too limited to draw definitive conclusions relating PGE mineralization to specific tectonic or temporal associations. Known Archean PGE mineralization within the Wabigoon Subprovince is restricted to syntectonic to post-tectonic, mafic to ultramafic intrusions situated within major granitoid and gneissic terrains in the vicinity of Lac des Iles and smaller intrusions in the Atikokan area along the Wabigoon-Quetico interface.

The present data, however, suggests that mafic rocks in the Thunder Bay area, from Marathon in the east to Atikokan in the west, contain many of the significant PGE occurences in north central and northwestern Ontario. This spatial association includes both Archean and Proterozoic lithologies and suggests that the PGE concentrations may be controlled by an underlying subcontinental mantle which is the source of the mafic magmas, rather than by tectonic or temporal settings. Known PGE occurrences in this region includes the Boston Bay Mines Ltd. property and other occurrences in the Lac des Iles Complex, Fleck Resources Ltd. property in the Keweenawan Coldwell Complex, the Great Lakes Nickel Limited property in the Keweenawan Crystal Lake Gabbro, and occurrences within Archean intrusions in the Atikokan area.

Based on the limited data from the Wabigoon Subprovince, it appears that complexes with magnesium-rich cumulate sequences have higher potential for PGE-rich sulphide mineralization than fractionated iron-rich intrusions. Homogeneous iron rich hornblende gabbro intrusions such as Caribou Lake (Sutcliffe 1981) and Legris Lake near Lac des Iles have limited associated sulphide occurrences and appear also to have limited potential for PGE.

PGE occurrences in the western Wabigoon as exemplified by the Lac des Iles area appear to be characterized by low Pt/(Pt+Pd) ratios and are

associated with disseminated Fe-Cu-Ni sulphides. Very little data have been reported on abundances of Ir, Os, Ru within these rocks. Data of Naldrett (1981b) indicate low abundances of these elements at Lac des Iles.



PROTEROZOIC

diabase

ARCHEAN

Late Granitoids

biotite granodiorite to tonalite

biotite-hornblende tonalite

Late Mafic to Ultramafic Rocks

mafic dikes

ultramafic

gabbro to gabbronorite

hornblende gabbro, hornblendite

hornblende diorite

Early Granitoid Rocks

foliated to gneissic biotite tonalite

Supracrustal Rocks

mafic metavolcanics

metasediments

fault

PGE occurrence

contact

breccia zone

road

Figure 3.19 : Geological Map of the Lac des Iles area.

3.1.4.2. Lac des Iles Area (R.H. Sutcliffe)

3.1.4.2.1 Introduction

The Lac des Iles area northwest of Thunder Bay contains several mafic to ultramafic intrusions (Figure 3.19). These intrusions form a circular structure approximately 30 km in diameter and have broad lithological, tectonic and metallogenetic similarities. The Lac des Iles mafic to ultramafic complex is the largest intrusion in the area and this complex is host to the Boston Bay Mines Limited deposit, currently optioned to Madeleine Mines Ltd. To date, 20.4 million tonnes of palladium and platinum mineralization with an average grade of 5.75 grams per tonne platinum group metals and a platinum:palladium ratio on the order of 1:7 have been outlined (Canadian Mines Handbook, 1976-1977) in a zone named the Roby Zone, after M. Phillip Roby, of Boston Bay Mines Ltd., who determined the NNW strike of the zone.

Regional mapping has shown that the mafic to ultramafic intrusions in the Lac des Iles area are emplaced into older gneissic granitoid host rocks. The centre of the circular structure defined by the mafic to ultramafic intrusions is occupied by a suite of younger granitoid plutons ranging in composition from hornblende tonalite to biotite granite. Hornblende tonalite plutons show evidence of mixing well with mafic magma and these granitoids are interpreted to be of similar age to the mafic intrusions. Biotite granodiorite to granite largely postdates the emplacement of the mafic intrusions and tonalite.

The mafic to ultramafic intrusions have moderately- to well-preserved primary igneous mineralogy. The lithologies range in composition from ultramafic peridotite (wehrlite) and pyroxenite (clinopyroxenite and websterite) to magnesian gabbronorite and iron-rich gabbro. Marginal zones rich in hornblendite occur around the perimeter of some intrusions and are interpreted to be due to contamination of mafic magma by a granitoid component.

On both a regional and local scale, the intrusions in the Lac des Iles area exhibit several features characteristic of the Mesozoic Alaskan Zoned Ultramafic complexes (Irvine 1967; Taylor 1967). These similarities include: an association with marginal zones of hornblende-rich ultramafic rocks; variation in rock types within the complexes, due to processes of multiple magma injection and some *in situ* fractional crystallization; and, the association of ultramafic rocks with gabbroic rocks which are not clearly cogenetic at the exposed crustal level. The Lac des Iles area is part of a linear belt of generally small, amphibole-rich, mafic to ultramafic intrusions occurring near the Wabigoon-Quetico boundary between Atikokan and Lake Nipigon. This may reflect a similar tectonic setting to the Alaskan ultramafic intrusions which are intruded into metamorphic rocks after regional tectonism but prior to major batholith emplacement (Taylor 1967). An important difference between the Lac des Iles area and the Alaskan ultramafics, however, is that the latter are silica undersaturated and do not form cumulus orthopyroxene. The Lac des Iles mafic intrusions appear to be derived from a more typical tholeiitic magma.

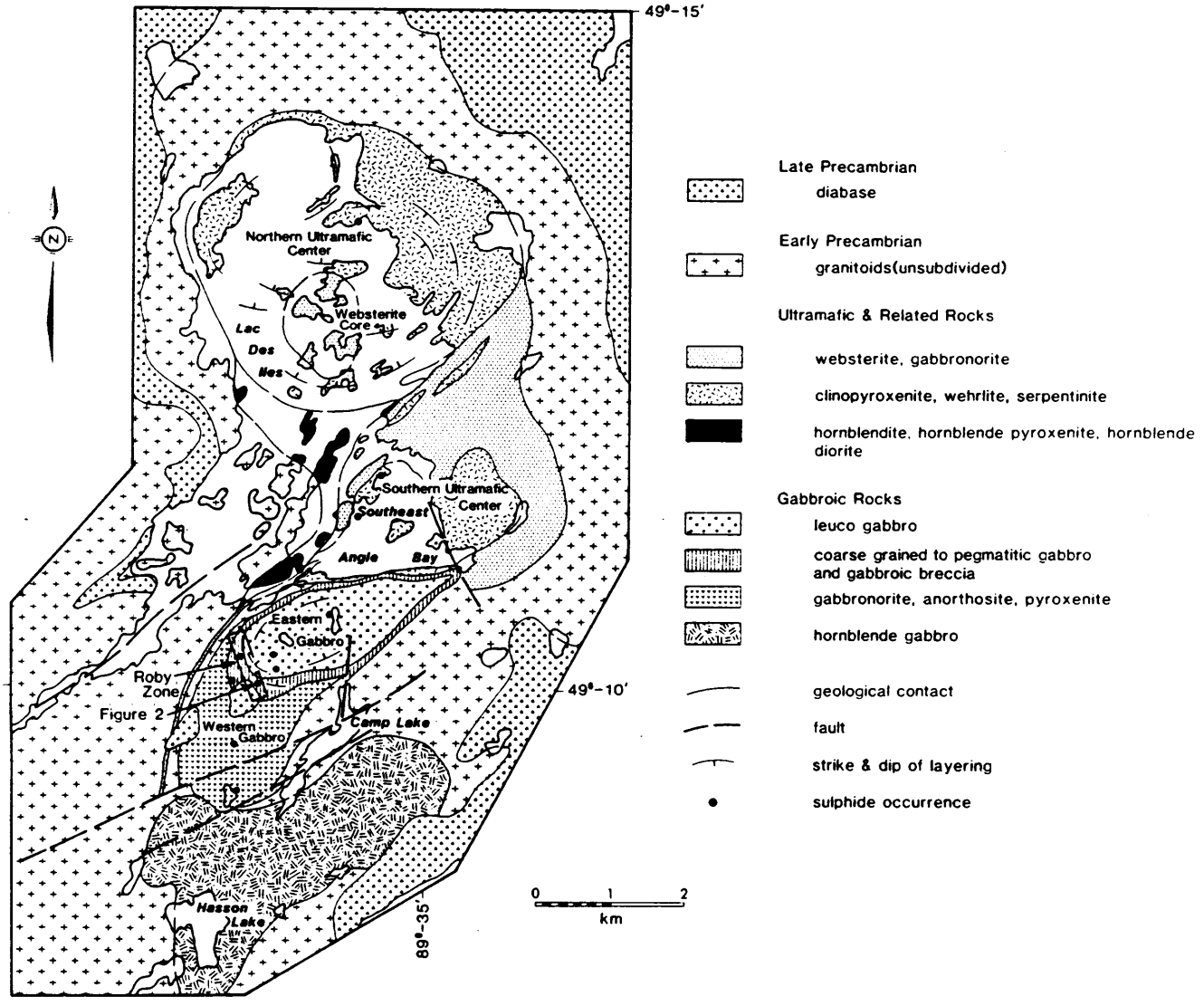


Figure 3.20 : Geological Map of the Lac des Iles Igneous Complex.

3.1.4.2.2. The Lac des Iles Complex
3.1.4.2.2.1. General Geology

The initial mapping of the Lac des Iles Complex was by Pye (1968) who determined the extent of the complex. Guanera (1967), Dunning (1979), and Watkinson and Dunning (1979) studied aspects of the petrology of the complex with emphasis on the relationship of gabbroic rocks to mineralization. The platinum group minerals have been studied by Cabri and Laflamme (1979) and Talkington and Watkinson (1984) reported on the distribution of platinum group elements in the Roby Zone. Sutcliffe and Sweeny (1986) completed detailed mapping of the complex and Macdonald (1985) reported on results of further investigations on the Roby Zone. Information reported here is taken from Sutcliffe and Sweeny (1986).

The Lac des Iles Complex (Figure 3.20) consists of an ultramafic intrusion centred on Lac des Iles and a gabbroic intrusion south of the lake (Pye 1968; Dunning 1969).

The ultramafic intrusion is composed of two coalescing centres, each of which consist of several intrusive phases. The centres are defined by the distribution of lithologies and attitudes of layering. The lithologic sequence of early peridotitic rocks, followed by clinopyroxenite, and finally by late websterite and gabbronorite, suggests that the ultramafic rocks follow a crystallization sequence of olivine, olivine-clinopyroxene, clinopyroxene, clinopyroxene-orthopyroxene, and finally clinopyroxene-orthopyroxene-plagioclase.

The northern ultramafic centre is nearly circular in plan, with a diameter of approximately 4 km, and consists of serpentinite and wehrlite (olivine-cumulates), olivine-clinopyroxenite, and clinopyroxenite (olivine-clinopyroxene and clinopyroxene cumulates), and websterite (orthopyroxene-clinopyroxene cumulates).

These lithologies occur in several cycles which probably represent fractional crystallization of separate pulses of magma in the chamber. Olivine cumulates occur primarily around the perimeter of the structure and the rocks become progressively more pyroxene-rich toward the core. Attitudes of layering suggest that the northern centre has an upright funnel-shaped form. This structure however, is complicated by the discordant websterite core.

The southern ultramafic centre is elliptical in plan, with an irregular wehrlite core centred on the South East Angle of Lac des Iles. The wehrlite core is surrounded by websterite which at several locations contains inclusions of wehrlite. In contrast to the northern ultramafic centre, the southern centre is predominantly composed of massive rocks, and lacks well-defined igneous layering.

The ultramafic rocks generally have fresh to moderately altered pyroxenes. Olivine is usually moderately to completely altered to serpentinite and magnetite, however some fresh olivine is locally visible in hand specimen. Plagioclase is normally absent from the ultramafic rocks, except in websterite where it is fresh. Locally, with increased plagioclase content, the websterite grades to gabbronorite. Minor chromite is reported to

occur in the peridotite and pyroxenite (Watkinson and Dunning 1979) and a thin 3 mm chromitite seam is present in the northern part of Lac des Iles.

In the northern centre, some of the ultramafic rocks exhibit igneous layering and lamination, however, most of the rocks are massive. Where present, layering is defined by modal mineral variations, and less commonly, by grain size variation. Modal layering, due to variations in proportions of feldspar and pyroxene, olivine and clinopyroxene, and clinopyroxene and orthopyroxene, was observed. Generally the layers are several centimetres thick, and are observed to be continuous for metres to tens of metres.

On the southwestern contact of the intrusion, a marginal zone of medium- to coarse-grained hornblendite, pyroxene hornblendite, and hornblende diorite is present. The diorite commonly forms the matrix of agmatitic breccia with hornblendite fragments. The contact between this unit and the granitoid rocks displays contradictory age relationships and, therefore, the two are considered to be contemporaneous. To the east, hornblende appears to grade into pyroxene.

Gabbroic rocks within the complex are primarily confined to an elliptical intrusion south of Lac des Iles. This intrusion can be subdivided into three zones. The southwestern part of the intrusion consists of predominantly medium-grained gabbronorite and has been referred to as the western gabbro by Dunning (1979). The western gabbro contains several zones of pegmatitic gabbro with grain sizes up to 2 cm which are mineralized. Toward the top of the western gabbro, in the northeastern part of this zone, minor pyroxenite and anorthosite phases are present. The northeastern part of the intrusion consists of medium-grained leucogabbro to gabbro, and is referred to as the eastern gabbro (Dunning 1979). The eastern gabbro is weakly layered due to the development of magnetite-rich layers, pyroxene-rich layers, and locally has an igneous lamination.

The eastern gabbro and western gabbro are chemically distinct. The latter is characterized by higher MgO, MgO/(MgO + FeO), and lower Al2O3 and CaO than the former. In addition, clinopyroxene of the eastern gabbro is strongly uralitized and contrasts with the preservation of fresh clinopyroxene and orthopyroxene in the western gabbro. This suggests that the eastern gabbro magma may have contained a higher proportion of volatiles than the western gabbro. Dunning (1979) also determined that the eastern gabbro is sulphide-poor, and probably not comagmatic with the western gabbro.

At the top of the western gabbro is a 60 to 300 m thick unit of heterogeneous gabbro, which contains coarse-grained to pegmatitic gabbro with sulphide mineralization. The heterogeneous unit contains numerous gabbroic phases of varying composition and texture and may be a result of mixing of the eastern and western gabbros. Minor pegmatitic gabbro also occurs outside of the heterogeneous zone within the eastern and western gabbros.

The attitudes of layering within the gabbroic rocks and the concentric distribution of lithologies indicates that the intrusion has elongated funnel or canoe-shaped geometry. In general, the gabbroic rocks are moderately to strongly uralitized and saussuritized. The freshest rocks occur in the southern portion of the western gabbro. The gabbro is cut by several faults and numerous fractures, most of which have a sinistral offset.

South of the western gabbro and centred on Hasson Lake, hornblende gabbro to hornblende leucogabbro with minor quartz is the predominant rock

type. This phase is interpreted to form a separate intrusion since it is lithologically distinct and is partially separated from the western gabbro by a tonalite septum. The hornblende gabbro is medium grained, massive to weakly foliated, and is locally intruded and brecciated by quartz diorite.

West of the gabbro and outcropping on the southern shore of Lac des Iles is an approximately 50 m wide dike, which may be a feeder dike for the ultramafic rocks. The dike is composite, and is composed of medium-grained olivine gabbronorite, olivine websterite, and locally hornblende diorite.

Fine-grained to medium-grained dike rocks ranging in composition from mafic amphibolite to diorite intrude all of the Archean lithologies of the area, including rocks of the Lac des Iles Complex. Several dikes intrude gabbro in the vicinity of the Roby Zone. One of these dikes has brecciated the gabbro, resulting in an intrusion breccia of subangular fragments of tonalite and various gabbroic rock types in a matrix of amphibolite.

3.1.4.2.2.2. Sulphide Mineralization

Exploration by Texasgulf Canada Limited and Boston Bay Mines Limited in 1975 and 1976 outlined a zone of PGE mineralization, the Roby Zone, along the contact of the eastern and western gabbro intrusions (Figure 3.21). A detailed study of the zone by Dunning (1979) and Watkinson and Dunning (1979), showed that vysotskite (Pd,Ni)S is the most abundant platinum group mineral and is associated with pentlandite and chalcopyrite. Most of the sulphide mineralization is contained within the western gabbro, where it occurs as intercumulus blebs, and less commonly, as net-textured sulphide. The sulphide mineralization is interpreted to be a magmatic phase forming from PGE, Cu, Ni and S contained in the western gabbro liquid (Watkinson and Dunning 1979; Dunning 1979). Sulphide assemblages consisting of chalcopyrite, pyrite, pentlandite and pyrrhotite are interpreteted as being slightly metamorphosed equivalents of primary exsolution products from monosulphide solid solution. Millerite and violarite are present in metamorphosed assemblages (Watkinson and Dunning 1979). Ratios of Pt/(Pd + Pd) and Cu/(Cu + Ni) were determined to be aproximately 0.07 and 0.5 respectively (Watkinson and Dunning 1979). Results of analyses by Naldrett (1981b) are shown in Figure 3.22. Further work by Talkington and Watkinson (19874) demonstrated that later processes involving a fluid phase have altered the primary silicates, redistributed the Cu-Ni sulphides and produced the platinum group minerals. Sutcliffe and Sweeny (1986) suggested that the redistribution of sulphide mineralization may be related to the emplacement of late pegmatitic gabbro phases and associated intrusion breccia zones.

The mineralization is largely confined to the heterogeneous gabbroic unit at the top of the western gabbro. Textures in the heterogeneous unit are complex but mixing of eastern and western gabbro magmas is suggested by the complex intercalation of gabbronorite and leucogabbro phases and by the rounded cuspate inclusions of leucogabbro in gabbronorite.

Also present in the heterogeneous gabbro are inclusions of amphibolite, coarse-grained gabbro and pyroxenite. The igneous layering is cut and disrupted by mineralized zones of intrusion breccia defined by an abundance of rounded inclusions in a matrix of altered gabbro to melagabbro. The intrusion breccias are locally cored by pegmatitic gabbro dikes, or have pegmatitic dikes emanating from them. It is suggested that these zones represent conduits in which mineralized, volatile-rich fluids were channeled.

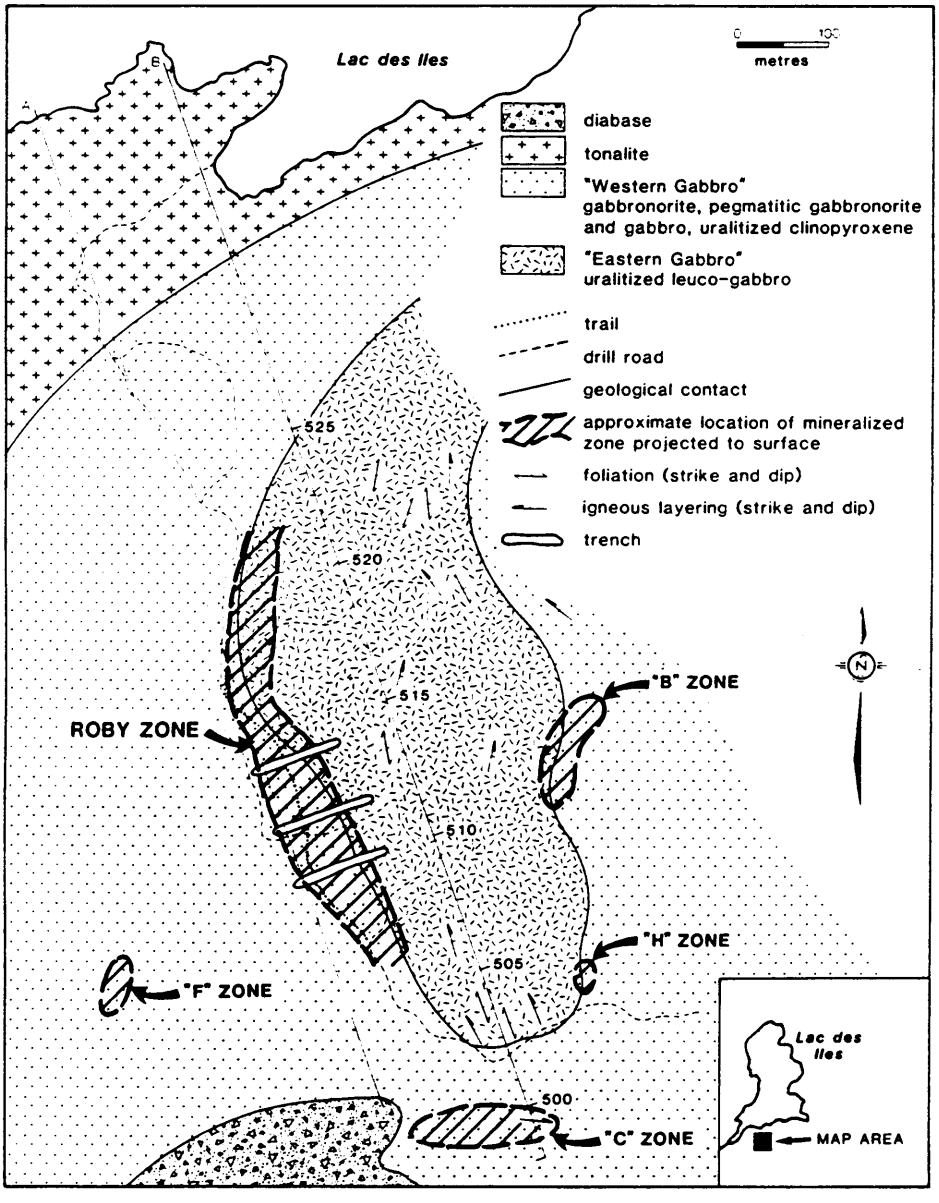


Figure 3.21 : Geological Map in the vicinity of the Roby Zone, Lac des Iles.

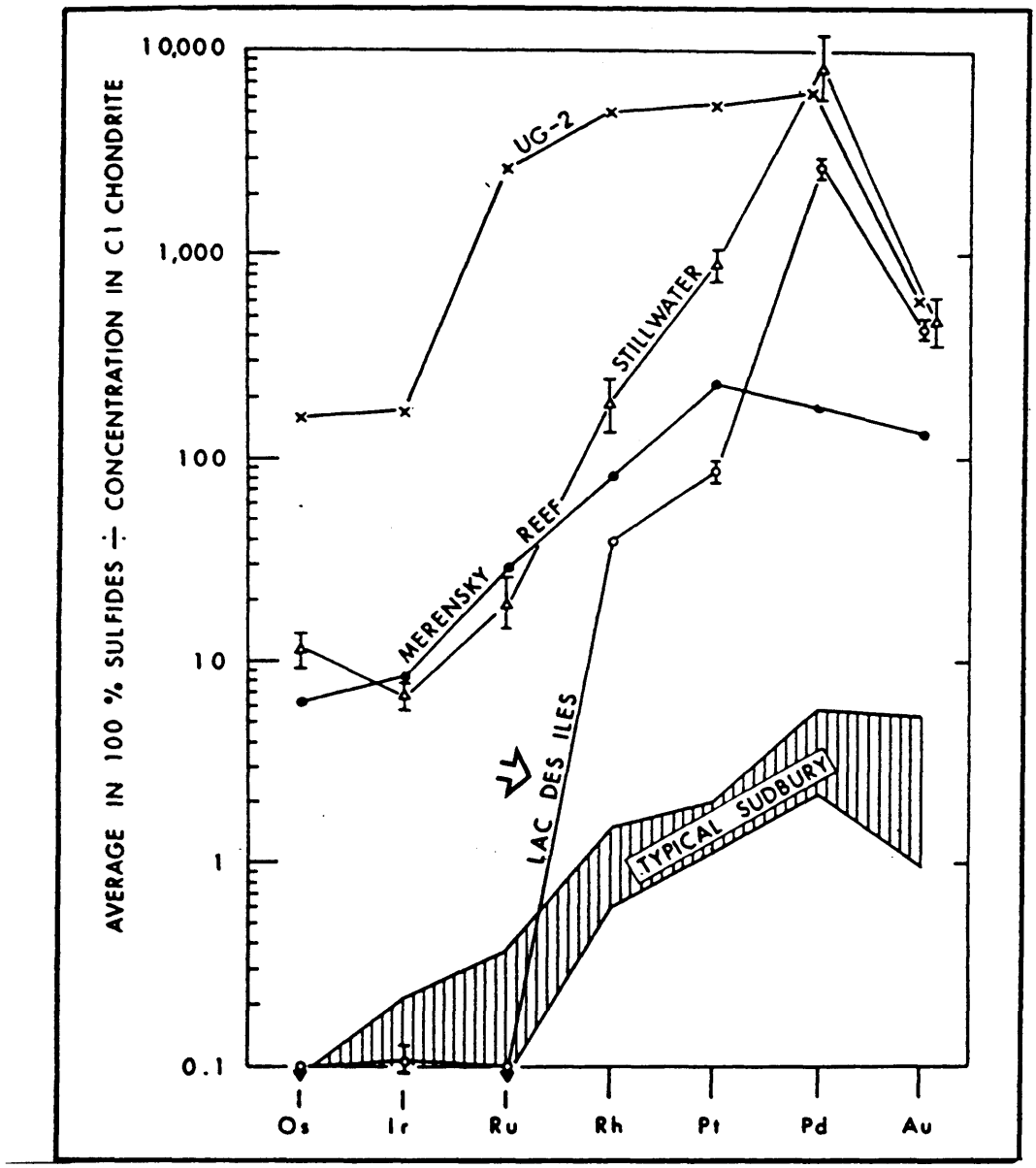


Figure 3.22 : Chondrite normalised PGE in 100% Sulphide from Lac des Iles (arrow), compared with data from other PGE deposits (from Naldrett 1981b).

A tentative sequence of events leading to the development of the mineralized zone, as suggested by the surface geology, is: 1) intrusion of western gabbro; 2) emplacement of eastern gabbro into the chamber above the western gabbro resulting in magma mixing and segregation of magmatic sulphide phase; development of a pegmatitic gabbro phase at the top of the western gabbro, an increase in fluid pressure, possibly associated with the volatile-rich eastern gabbro, results in the intrusion of discordant pegmatitic gabbro dikes and leads to development of discordant intrusion breccia zones which redistribute sulphide mineralization formed earlier.

Sutcliffe and Sweeny (1986) reported up to 2% disseminated to net textured chalcopyrite and pyrrhotite mineralization in the ultramafic rocks. This type of mineralization is associated with websterite and gabbronorite.

3.1.4.2.3. Other Intrusions in the Lac des Iles Area

3.1.4.2.3.1. Tib Gabbro

The Tib Gabbro was mapped by Kaye (1966) who delineated the extent of the intrusion and established the overall gabbronorite composition. The intrusion is situated 10 km northwest of the Lac des Iles complex, is elliptical in plan and has a cross sectional area of approximately 30 km^2. The gabbro contains occurrences of Cu-Ni sulphide mineralization and assays of up to 3.57 ppm {Pt+Pd} have been reported in the southern part of the intrusion (Assessment Files Research Office, Toronto).

Current mapping by Smith and Sutcliffe (1987) has shown that the Tib Gabbro has moderately well-developed modal layering defined by pyroxene-rich layers (orthopyroxene-clinopyroxene cumulates), anorthositic layers (plagioclase cumulates) and locally magnetite-rich layers. The mineralogy is well preserved and in many cases orthopyroxene and clinopyroxene can be distinguished in hand specimen. Uralitic alteration is commonly limited to zones along fractures and is rarely pervasive throughout exposures. The layering suggests that the intrusion faces to the northeast and layering dips at 40^{o} northwest to vertical. Several cyclic units on the order of a kilometre in thickness are defined by pyroxene-rich cumulates at the base and grade upward to magnetite-rich cumulates at the top. Pegmatitic gabbro patches and layers are concentrated in the southeast part of the intrusion, but occur sporadically throughout the intrusion.

The northwest part of the Tib Gabbro is a hybrid zone consisting of hornblende gabbro and hornblende-clinopyroxene diorite which is intrusive into foliated to gneissic tonalite. The diorite contains fine-grained gabbroic inclusions which locally have chilled margins. The textures suggest that this is a zone of mixing and hybridization of gabbroic and felsic magmas similar to the upper zone of the Mulcahy gabbro (Section 3.1.4.3.2). On the southern margin, the Tib Gabbro is intruded by biotite granodiorite-granite and hornblende-biotite tonalite. Close to the southern margin minor quartz is present in the gabbro and pyroxenes reacted to form hornblende.

Sulphide mineralization in the Tib Gabbro is concentrated in pegmatitic gabbro patches and conformable pegmatoidal gabbro layers. The gabbro pegmatites are most abundant along the southern contact of the intrusion where up to 5% pyrite-chalcopyrite-pyrrhotite mineralization occurs. In this zone the pegmatites contain minor quartz and biotite in addition to pyroxene and plagioclase. Contamination with a granitoid component may have been an

important process of generating the pegmatoid development and sulphide mineralization.

3.1.4.2.3.2. Demars Lake

Kaye (1969) outlined a small mafic intrusive southeast of Demars Lake which was reported as metapyroxenite. A limited investigation by the author indicated that the intrusion contains fresh websterite to mela-gabbronorite similar to that occurring in the ultramafic part of the Lac des Iles Complex. Minor disseminated Cu-Ni sulphides are reported from the intrusion (Kaye 1969) which is considered to have favourable potential for PGE mineralization.

3.1.4.2.3.3. Dog River Intrusion and Taman Lake Intrusion

Both the Dog River Intrusion and Taman Lake Intrusion, in the southwest part of the Lac des Iles area are indicated by pronounced aeromagnetic anomalies. Limited investigation indicates that the intrusions consist of hornblende pyroxenite to hornblende melagabbronorite with marginal hornblende-clinopyroxenite diorite phases. The hornblende melagabbronorite in the Dog River Intrusion consists of 2 mm cumulus grains of clinopyroxene and orthopyroxene with intercumulus plagioclase and large poikilitic hornblende to 2 cm. The extensive hornblende development and marginal diorite phases are considered to be a result of contamination and hybridization. Sulphides have not been reported from these intrusions which have similarities to parts of the Lac des Iles Complex and are therefore considered to have potential for PGE mineralization.

3.1.4.2.3.4. Legris Lake Intrusion

Pye (1968) determined that the Legris Lake intrusion, located approximately 10 km southeast of the Lac des Iles Complex, consists of quartz gabbro grading to quartz diorite which is intrusive into metasediments. The intrusion is medium grained and consists of plagioclase (calcic andesine) hornblende, pyroxene, biotite and oxides. Based on the available mineralogical information, the intrusion may be too fractionated to be a favourable target for platinum group metals.

3.1.4.3. Atikwa-Lawrence Area

3.1.4.3.1. Introduction

The Atikwa-Lawrence plutonic-volcanic terrain south of Dryden forms a circular complex approximately 60 km in diameter. Davis and Edwards (1985b) determined that the arrangement of lithologies is roughly concentric, with an outer sequence of folded mafic to felsic volcanic rocks intruded by gabbroic and tonalitic plutons which form a discontinuous rim around the central batholith. Massive to foliated trondhjemitic (leucrocratic tonalite) to granodiorite phases form the central batholithic core of the complex.

Gabbroic plutons around the margin of the Atikwa-Lawrence batholith include the Mulcahy Gabbro, Nabish Lake Gabbro, Mile Lake-Trap Lake Intrusion, intrusions in the Denmark Lake - Populus Lake area, and the Mitchell Lake Intrusion.

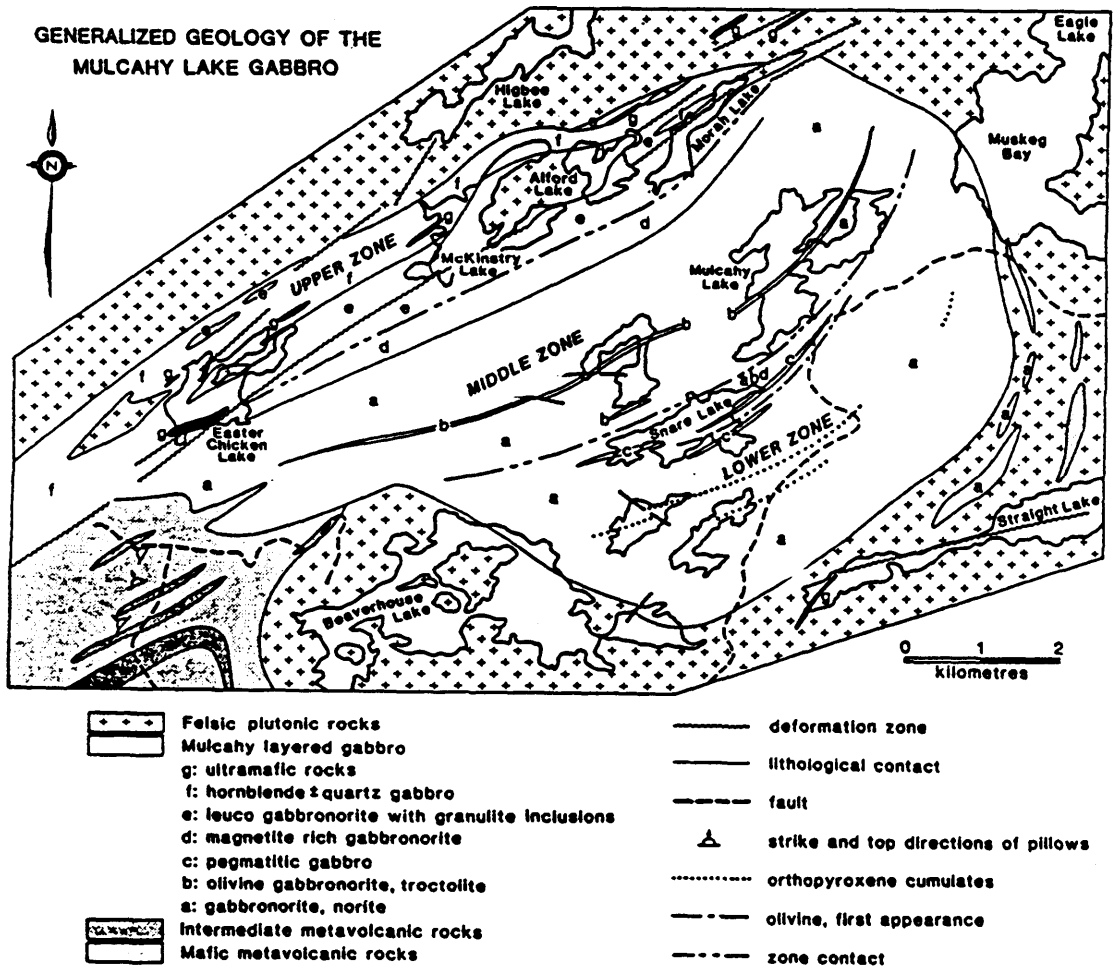


Figure 3.23 : Geological Map of the Mulcahy Gabbro

The Mulcahy Gabbro (Figure 23) is the largest of these intrusions and has recently been mapped in detail (Sutcliffe and Smith 1985) and studied geochemically (Morrison et al. 1986). The Gabbro is a differentiated iron-rich tholeiitic intrusion which has well developed igneous layering and exceptionally well-preserved primary igneous mineralogy. Other intrusions in the area such as the Nabish Lake Gabbro and the Mile Lake Gabbro appear to be similar in character to the Mulcahy Gabbro but are less well preserved. Ultramafic rocks are present within the intrusions but do not appear to form part of the layered sequence. The ultramafic rocks in the vicinity of the Mulcahy Gabbro and in the Trap Lake Intrusion are dominantly harzburgite and appear to form later intrusive dikes, sills and plugs.

The Mulcahy Gabbro has been dated at 2733 (+1.0/-0.9) Ma by U-Pb zircon geochronology (Morrison et al. 1985). This is the same age as the border tonalites of the Atikwa batholith which have been dated at 2731.8 (+1.6/-1.3) Ma (Davis et al. 1982). Davis and Edwards (1985b) have documented contact relations between the Mulcahy Gabbro and adjacent tonalites and suggest that both phases were liquid at the same time.

Occurrences of platinum group elements have not been reported in the mafic intrusions of the Atikwa-Lawrence batholith. Minor occurrences of Cu-Ni sulphide mineralization occurs in the Mulcahy Gabbro, Nabish Lake Intrusion and Mile Lake-Trap Lake Intrusions. A major occurrence of Cu-Ni sulphide mineralization related to mafic intrusive rocks in the Populus Lake area was investigated by Falconbridge Copper Limited in the 1950's. Underground development was undertaken but no production occurred.

3.1.4.3.2. Mulcahy Gabbro

3.1.4.3.2.1. General Geology

The Mulcahy Gabbro (Figures 3.18, 3.23) is a layered intrusion located approximately 45 km southwest of Dryden. The intrusion has an iron rich tholeiitic composition and displays well developed rhythmic and cryptic layering. The primary igneous mineralogy is very well preserved.

The initial reconnaissance mapping of the Mulcahy Gabbro by Moorehouse (1941) and Davies and Watowich (1958) delineated the extent of the intrusion. Subsequent work by Blackburn (1978) indicated that the intrusion was emplaced as a sheet which has subsequently been tilted vertically and faces northwest. The Mulcahy Gabbro is approximately 7 km thick and has a cross-sectional area of 60 km^2. Morrison et al. (1986) studied the mineralogical and chemical variation along a cross-section of the intrusion through Mulcahy Lake. Detailed mapping of the intrusion at a scale of 1:15,840 was completed by Sutcliffe and Smith (1985). Information on the general geology presented here is largely taken from the results of this mapping.

Morrison et al. (1986) and Sutcliffe and Smith (1985) divided the Mulcahy Gabbro into lower, middle, and upper zones based on mineral and rock chemistry. The lower and middle zones represent distinct magma pulses which crystallized from the bottom of the zone upwards. The top of the lower and middle zones represent peaks in an iron enrichment trend. The upper zone is considered by Morrison et al. (1984) to be a roof cooling regime which fractionated toward the floor. Sutcliffe and Smith (1985) consider that the upper zone, however, is a roof zone consisting of hornfels of mafic to intermediate composition which has been intruded by sills ranging from

peridotite to granite. These rocks are not clearly related to the fractionation sequence in the lower and middle zones.

The 2.5 km thick lower zone consists of a sequence of massive norite grading into layered norite with orthopyroxenite (orthopyroxene cumulate) and anorthosite (plagioclase cumulate) layers. High in the lower zone, clinopyroxene, inverted pigeonite, apatite, magnetite, and finally iron-rich olivine appear as cumulate phases. At the top of the lower zone, the rocks are characteristically well layered, olivine-bearing, magnetite-rich gabbronorites. In the vicinity of Snare Lake, the lower zone gabbros are extensively uralitized and there are numerous layers of pegmatite gabbro up to several metres thick. These rocks may have developed due to metasomatic replacement of the gabbronorite by intercumulus fluids which concentrated toward the top of the lower zone.

The 2.5 km thick middle zone is characterized by gabbronorite with well defined, intermittent modal layering. A 20 to 30 m thick unit of troctolite (olivine - plagioclase cumulate) which is a prominent marker horizon within the intrusion, is located 600 m above the base of the middle zone. Toward the top of the middle zone, magnetite and apatite become more abundant and iron-rich olivine locally reappears. Gabbro pegmatite dikes are present in the upper part of the middle zone. At the top of the zone the dominant rock is magnetite-rich gabbronorite with pegmatitic clots of clinopyroxene, amphibole, magnetite, and locally quartz.

The upper zone is considered here to begin with the appearance of numerous fine-grained, locally plagioclase-phyric, mafic to intermediate inclusions in a host of leucocratic gabbronorite to diorite. Morrison et al. (1984) interpreted the inclusions to be cognate xenoliths intruded by fractionated gabbro. Sutcliffe and Smith (1985) however, suggest that these rocks represent a roof zone of a mafic to intermediate volcanic or subvolcanic protolith which has been metamorphosed to a pyroxene hornfels and partially melted to produce a mesocratic orthopyroxene - clinopyroxene diorite. Sills of peridotite, hornblende - quartz gabbro, gabbronorite, quartz diorite, quartz - feldspar porphyry, and granite intrude the hornfels roof zone.

Although the Mulcahy Gabbro does not have a chill zone, a distinct marginal facies is associated with the lower and middle zones. The marginal facies is 150 to 300 m wide and is best characterized in thin section by higher concentrations of apatite and magnetite (Morrison et al. 1984). Other characteristics of the marginal facies include: clinopyroxene-magnetite clots, similar to those near the top of the middle zone, which may represent residue from assimilated mafic enclaves; locally well-developed fluxion texture; and layering parallel to the contact of the intrusion. Recognition of a distinct marginal zone suggests that the lower part of the Mulcahy Gabbro has not been stoped away by the adjacent granitoids.

The Mulcahy Gabbro exhibits several types of layering including: planar lamination of feldspar and pyroxenes, rhythmic modal layering of minerals, and cryptic layering defined by systematic compositional variation. Intermittent rhythmic modal layering, defined by a concentration of one or more cumulate phases within a relatively uniform gabbroic host, is a prominent feature of the Lower and Middle zones. Orthopyroxenite (orthopyroxene cumulate), anorthosite (plagioclase cumulate), troctolite (olivine-plagioclase cumulate), and magnetite cumulate are present as modal layers. The modal layering is typically on a scale of centimetres in width and individual layers are observed to be continuous over a strike length of tens to 100s of metres.

Trough bedding, cross bedding and angular unconformities are evidence that flow mechanisms (Irvine 1980b) have been locally important in the development of layering within the Mulcahy Gabbro. These structures are best developed in orthopyroxene and orthopyroxene-magnetite cumulates which are probably deposited from dense crystal-rich magma flows originating in the walls of the magma chamber.

Mineralogically graded layers, defined by grading of pyroxene and/or olivine versus plagioclase, are common in the middle zone and to a lesser extent the lower zone. This rhythmic type of layering closely resembles intermittent modal layering in the Skaergaard intrusion (McBirney and Noyes 1979, plate 5A) and probably forms *in situ* on the floor of the magma chamber by mechanisms such as double diffusive convection (McBirney and Noyes 1979).

On the northern and eastern contacts of the intrusion, granitoid rocks consisting of predominantly biotite-hornblende quartz diorite intrude the Mulcahy Gabbro. On the southern margin of the intrusion, in the vicinity of Straight Lake, contact relationships are less certain and the Mulcahy Gabbro is in contact with a variety of dioritic rock types ranging from hornblende clinopyroxene diorite to biotite-hornblende quartz diorite and locally granodiorite. The dioritic rocks locally contain abundant inclusions of amphibolite, mafic diorite, and gabbroic rocks similar to the Mulcahy Gabbro. Fine-grained mafic hornfels and intercalated intermediate fragmental rocks are also observed in this zone adjacent to the Mulcahy Gabbro. These rocks are interpreted as a relict mafic metavolcanic sequence which has been partially melted to produce dioritic rocks during the emplacement of the Mulcahy Gabbro. Peridotite on Straight Lake, previously considered to be stoped from the base of the Mulcahy Gabbro (Davies and Watowich 1958), is found to be part of an ultramafic dike intruding the dioritic rocks.

On the western margin of the intrusion, the gabbro intrudes a metavolcanic sequence. The metavolcanic rocks consist of northwest facing, massive to pillowed mafic flows, intercalated with intermediate (andesitic) plagioclase - phyric fragmental rocks, and minor tuff and metasedimentary rocks. These rocks commonly contain metamorphic hornblende indicating a medium grade of metamorphism. The substantial intermediate component in the metavolcanic sequence and the presence of abundant enclaves of intermediate rock of possible volcanic origin in the upper part of the Mulcahy gabbro, suggest that the gabbro was intruded into calc-alkalic metavolcanic rocks and therefore is emplaced into a high level of the Wabigoon metavolcanic sequence.

3.1.4.3.2.2. PGE Potential

The Mulcahy gabbro consists of a substantial thickness of mafic cumulate rocks which record a history of repeated fractionation and replenishment within the magma chamber. This sequence suggests that there is considerable potential for the segregation of magmatic sulphides with associated PGE in the intrusion (cf. Campbell et al. 1983). A negative aspect of the intrusion from the exploration standpoint, however, is that there is no primitive ultramafic cumulate sequence associated with the intrusion and therefore the magma of the Mulcahy Gabbro was relatively fractionated before entering the chamber. Such a fractionated magma may have been depleted in PGE before entering the chamber. Grab samples of sulphide-bearing gabbroic rocks collected during the

mapping by Sutcliffe and Smith (1985) did not reveal significant values for PGE.

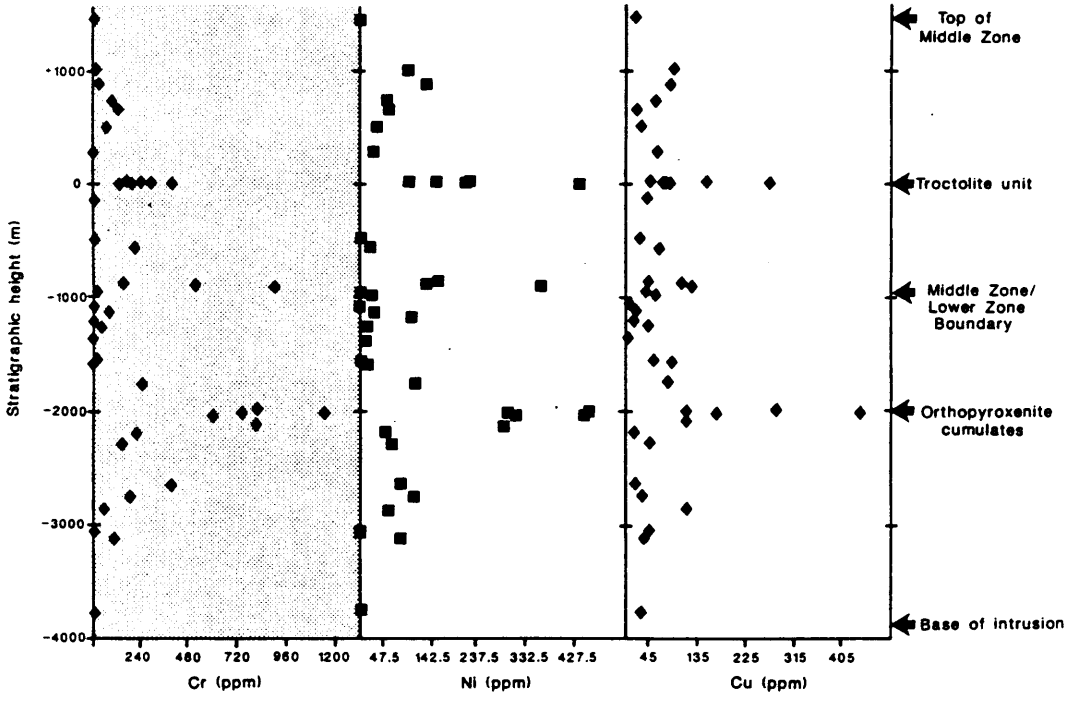


Figure 3.24 : Chemical variation in the troctolite unit, Mulcahy Gabbro.

Evaluation of major and trace element chemistry within the Mulcahy gabbro indicates that there are three horizons in which elements such as Cu, Ni and Cr are substantially elevated. These enrichments occur in: a) orthopyroxenite cumulates one kilometre above the base of the Lower Zone; b) at the lower zone-middle zone boundary and; c) at the troctolite unit (Figure 3.24). The three horizons are relatively well-defined stratigraphically and probably represent the most significant targets for further evaluation. Minor disseminated chalcopyrite and pyrrhotite mineralization was observed in the zone boundary and the trocolite unit. Pegmatitic phases of the gabbro are particularly abundant near the top of the lower zone and to a lesser extent the middle zone. These units were locally observed to contain traces of sulphide and may also warrant further investigation.

3.1.4.4. CHROME LAKE (P.J. Whittaker)

3.1.4.4.1. Introduction

A lens-shaped, serpentinized ultramafic intrusion occurs at Chrome and Puddy Lakes (Figure 3.25), and is 5.5 km long by a maximum of 1.3 km wide. It is bounded to the north by quartzofeldspathic gneiss, and to the south by conglomeratic to argillaceous metasedimentary rocks. A porphyritic quartz monzonite is in contact with the serpentinite at the southwestern end of Puddy Lake. Chrome and Puddy Lakes are 175 km northwest of Thunder Bay and 47 km southwest of Armstrong (Figure 3.25). The area is 50 km west of Lake Nipigon, and is accessible by float-equipped aircraft from either Thunder Bay or Armstrong.

3.1.4.4.2 Previous Work

Graham (1930), Hurst (1931) and Kidd (1933) did early geological work in the area. More detailed mapping was done by Kustra (1966). Simpson and Chamberlain (1967) described a nickeliferous zone in the serpentinite, and detailed work on disseminated chromite and chromitite layers has been completed more recently by Whittaker (1979, 1980) and by Watkinson and Mainwaring (1979, 1980, 1982).

3.1.4.4.3 : Geology of the Chrome Lake Ultramafic Body

The Chrome Lake ultramafic body consists of peridotite and irregularly distributed lenses of pyroxenite and dunite. Chromite layers and disseminated chromite occur adjacent to pyroxenite and dunite lenses at the eastern end of the body, and at the northern end of Chrome Lake (Figure 3.25). A generally chromitiferous zone extends between these points, following the northeastern contact of the ultramafic body. Outcrop in the area is limited, but is sufficient to indicate that the body is strongly sheared along its northern and southern boundaries. Abundant talc is developed in the shear zones. Deformation and lack of outcrop make determination of stratigraphic relationships within the body difficult. However, where primary magmatic textures have been preserved, serpentine pseudomorphs of the original mineralogy indicate that peridotite (harzburgite) was the most abundant rock type and it contained minor lenses of pyroxenite and dunite.

Chromitite layers, exposed at the northern end of Chrome Lake, are 1 mm to 3 m thick and can be followed for 20 m along a north-northeast strike. Chromitite layers reflect both ductile and brittle deformation: early ductile deformation has produced pinch and swell structures, boudins, and isoclinal folding of some layers, and later brittle deformation has resulted in angular pull-apart fragments. Minor concentrations of sulphide (2 to 3%) are associated with chromite.

Petrographic examination of chromite from massive chromitite layers indicates that sulphide minerals are present within chromitite grains and in the silicate groundmass. Chromite hosts yellowish, usually subhedral to anhedral, grains of pyrrhotite and chalcopyrite. Laurite (RuS_2) has been tentatively identified by reflected light microscopy (Whittaker 1980); this identification should be confirmed by electron microprobe analysis. Laurite grains, which are similar to those found at Big Trout Lake (Section 3.1.1.2.), are 2 to 10 microns in size, euhedral, and highly reflective with a silvery white colour.

Sulphide minerals in the groundmass should be examined for additional PGE, which might occur in solid solution or as discrete inclusions in chalcopyrite and pyrrhotite. These sulphides might be expected to contain Pt and Pd. The same sulphides occur as inclusions in chromite grains. The distribution of chromite in the chromitiferous zone that extends from the northern end of Chrome Lake to the eastern end of the serpentinite should be carefully examined for PGE-bearing sulphides.

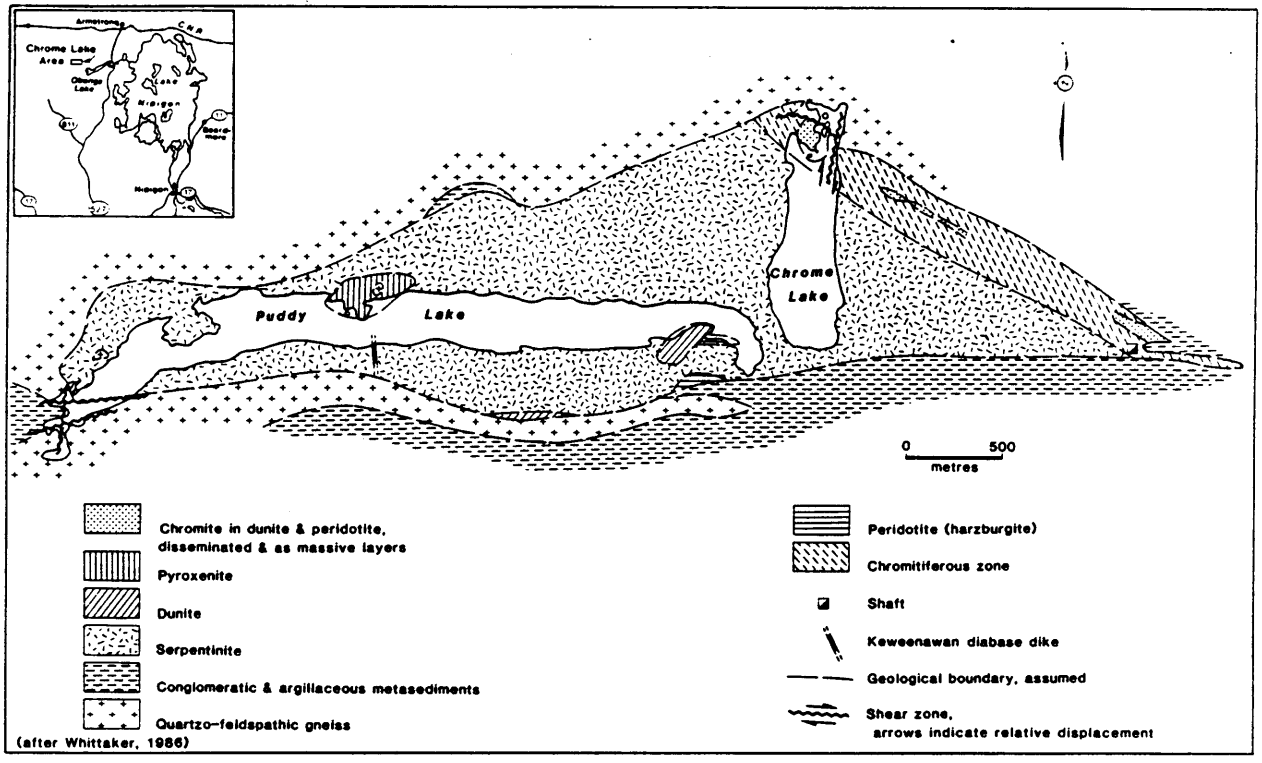


Figure 3.25 : Geological map of the Chrome and Puddy Lakes area (Whittaker, 1986)

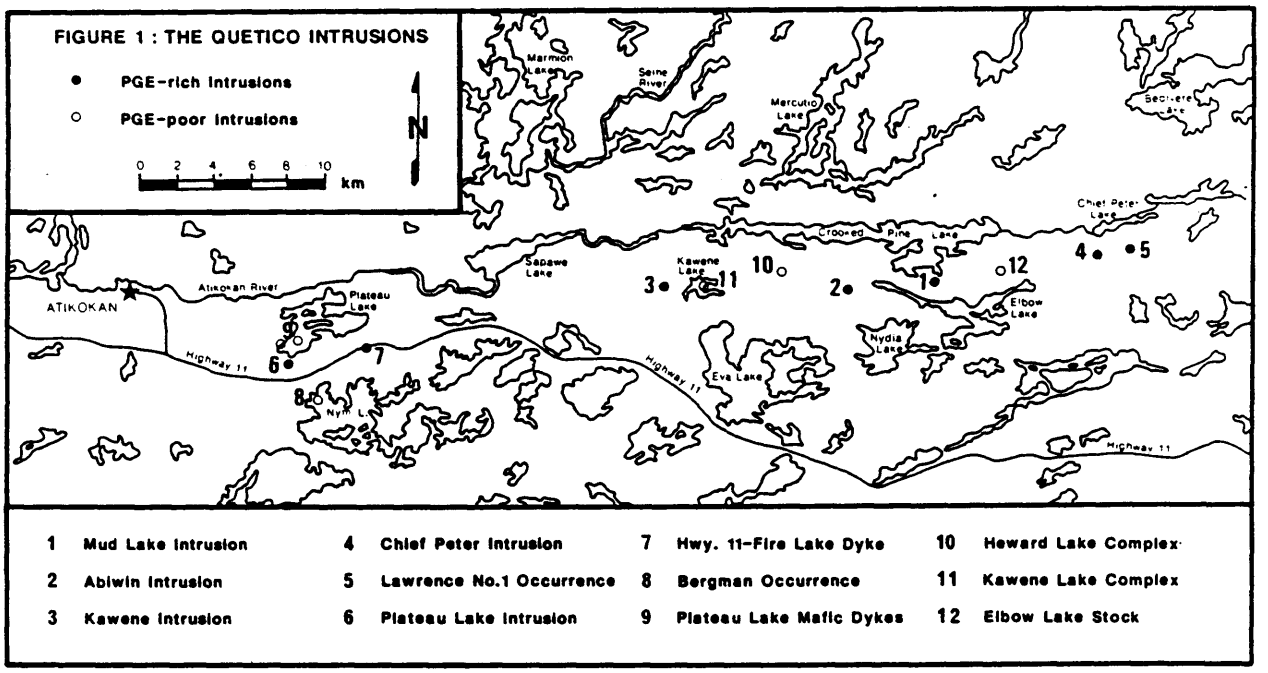


Figure 3.26 : Location of mafic/ultramafic intrusions in the vicinity of the Quetico Fault Zone.

3.1.5. QUETICO SUBPROVINCE (A.D. MacTavish and R. Dutka)

3.1.5.1. General Discussion

The known Quetico Intrusions are a series of 16 syntectonic mafic to ultramafic dykes, sills, plugs and stocks that intrude a thin belt of metaturbidites which form the Northern Quetico Subprovince. Fifteen occur near Atikokan within a 95 km long zone between McOuat Lake in the west and Lac des Milles Lac in the east. The intrusions are generally small ranging from about 100 m in length and 20 m in width to greater than 850 m in diameter. Thirteen of these intrusions have been examined and sampled by the authors since 1984 (Figure 3.26). Ten intrusions, six of which are described in detail, are known to contain highly variable amounts of PGE mineralization in close association with copper-nickel sulphides. Three bodies, the Mud Lake, Abiwin, and Kawene Intrusions, have been mapped and sampled in detail (MacTavish and Dutka, in Patterson et al. 1986).

The Atikokan area lies within the southern Superior Province of the Canadian Precambrian Shield. The northern part of the area is underlain by rocks of the Wabigoon subprovince, which according to Fenwick (1976) and Pirie (1978), consists primarily of large, felsic intrusive batholiths ranging from biotite and hornblende granites, trondhjemites, quartz monzonites to quartz porphyries, that are deformed to varying degrees. These rocks intrude a number of curvilinear greenstone belts composed of mafic to intermediate metavolcanic rocks, intercalated with felsic to intermediate metavolcanic rocks, and assorted clastic and chemical metasediments. Metamorphic grade ranges from lower greenschist to amphibolite facies. The southern portion of the area is underlain by rocks of the Quetico Subprovince, which consists of:

> *"...marginal metasedimentary rocks with a metamorphic transition from chlorite-muscovite grade at the outside to migmatites adjacent to the core, which is dominantly granite and migmatite."*
> Percival and Stern (1984)

The core of the Quetico Subprovince is dominated by the Quetico Park Batholith Complex, consisting of granite, syenite, tonalite and diorite. The contact between the subprovinces is defined by the Quetico Transcurrent Fault Zone. Kennedy (1984) describes this zone as:

> *"... a steeply dipping zone of dynamically metamorphosed rock ... exhibiting evidence of both brittle and ductile deformation."*

This fault zone is generally narrow, ranging from 10 to 300 m in width. It exhibits a sense of dextral movement and has a complex system of associated splay faults that curve into both subprovinces. The Quetico Intrusions are confined wholly to the Quetico Subprovince and are generally restricted to within 6 km of the fault zone.

The Quetico Intrusions exhibit a characteristic range of hornblende-bearing lithologies. The dyke-like smaller bodies are usually composed of hornblende leucogabbro to hornblende melagabbro and hornblendite with no observable zonation of lithologies. The larger bodies tend to encompass a wider suite of rock types that range from hornblende leucogabbro through hornblendite, hornblende-rich clinopyroxenite and hornblende peridotites (wehrlite). Some of the intrusions exhibit a crude, multiphased zonation of lithologies similar to that commonly observed in larger Alaskan-type,

ultramafic complexes (e.g. Taylor 1967). In the Quetico examples, hornblende peridotite, or hornblende clinopyroxenite are situated in the core areas with hornblendite and gabbro forming discontinuous envelopes.

Textures of the Quetico Intrusions are highly variable ranging from fine- to very coarse-grained to locally pegmatitic. Ultramafic rock types contain large poikolitic grains, or oikocrysts, that can be as large as 3 cm in diameter. The oikocrysts are an interstitial, post-cumulus, crystallization phenomenon that enclose the earlier cumulate crystals. Cumulate layering is neither significant nor readily observable in most of these intrusions; weak and diffuse modal layering is present locally, and is occasionally well-developed, for example in the Mud Lake Intrusion.

PGE mineralization occurs in association with very finely disseminated to sometimes locally net-textured, copper-nickel sulphides. Sulphides and PGE content varies greatly between intrusions, within intrusions, and within single sulphide zones. Such zones are irregular in size and shape and can contain from less than 1% to greater than 30% chalcopyrite, pyrrhotite, pyrite and pentlandite. In many cases significant PGE mineralization occurs in rocks that contain less than 8% sulphides, and usually less than 5% sulphides.

3.1.5.2. The Mud Lake Intrusion

The Mud Lake intrusion is a comma-shaped, sill-like mafic to ultramafic body over 800 m long and between 10 m and 100 m thick. It is located on the western shore of Mud Lake about 40 km east of Atikokan and 500 m south of Crooked Pine Lake. The thickest and most highly mineralized portions of the sill have been mapped and sampled in detail by the authors (Patterson et al. 1986).

Emplacement of the Mud Lake body has involved two separate intrusive episodes. Initial intrusion resulted in a modally layered ultramafic cumulate (possibly an adcumulate) composed of discontinuous and disrupted, coarse to very coarse grained, oikocrystic, locally feldspathic, hornblendite and porphyritic hornblende melagabbro layers. Isolated anorthositic layers and patches occur in some areas. After partial cooling of the mafic to ultramafic layers, a fine-to coarse-grained, relatively massive, locally pegmatitic, possibly hybridised, hornblende leucogabbro to hornblende gabbro was subconcordantly intruded above the earlier rocks. Where the contact between the two intrusive bodies is exposed, a thin chilled zone within the later massive gabbro supports the postulate that the layered rocks were partially cooled prior to the second intrusive event.

Gabbro pegmatite dikes and pods are present throughout all rock types. They are usually found along shears, fractures and joints; however, they also occur as isolated segregations, unrelated to subsequent deformation.

Sill emplacement was responsible for a thin, contact metamorphic aureole extending 1 m to 5 m into the surrounding metasedimentary rocks. Regional, amphibolite grade, dynamothermal metamorphism, plus the heat of the intrusion, was responsible for a quartz monzonitic to granodioritic mobilisate above, and locally below, the sill.

It is possible that the sill was folded during or after metamorphism although this has not been confirmed. Faulting on both a large and a small scale is readily evident. Two major east-west striking faults, one observed

in outcrop and the other implied by mapping and confirmed by past diamond drilling, have been responsible for (a) dextral offset of the northern limbs of the intrusion about 125 m to 150 m eastwards; (b) formation of an intense shear zone 30 m to 50 m wide in the metasedimentary rocks 50 m south of the intrusion. The action of these faults has produced a series of small-scale, right- and left-lateral faults striking between 135^{o} and 160^{o}, within the intrusion, resulting in offsets of 0.10 m to 15 m.

Much of the sulphide mineralisation occurs in small pods and patches that are composed of <1% to 5% very finely disseminated pyrrhotite, pyrite and chalcopyrite. The ubiquitous gabbro pegmatites locally concentrate the sulphides up to 15%.

PGE concentrations have been detected in a small trench on Discovery Island, which is located about 100 m east of the western shore of Mud Lake. Platinum was also detected in diamond drill core from holes drilled on the mainland and on the lake ice by Ardel Exploration in 1971. The drill results suggest that the continuous mineralization present in the core for over a 350 m strike length is from the same zone that outcrops on Discovery Island (Resident Geologist's Assessment Files, Ministry of Northern Development and Mines, Thunder Bay). The sulphide content of this zone ranges from 12% to 30% disseminated, net textured, stringer and locally semi-massive pyrrhotite, chalcopyrite, pyrite and pentlandite. Chalcopyrite content increases in stringer sulphides and locally sheared zones. Although exploration by Ardel was specifically Cu-Ni oriented, sporadic Pt assays returned values ranging from trace to 0.1 oz/ton (approximately 3 g/t). Some of Ardel Exploration's assay results and later assay results taken by the authors are listed in Table 3.4.

Table 3.4 : Mud Lake Intrusion Assay Results

Sample Number	Cu (%)	Ni (%)	Pt (ppb)	Pd (ppb)	Co (ppm)	W (ppm)
Ardel 2322	0.25	0.42	3430	-	-	-
Ardel 2321	0.23	0.71	3430	-	-	-
?C	0.87	0.16	tr.	-	200	-
AM-2-85	0.37	0.09	33	60	-	-
AM-8-85	0.21	0.05	3	8	-	2715
AM-9-85	3.45	0.07	95	115	-	-
AWM-1-86	1.72	0.20	65	50	-	-
AWM-2-86	5.12	0.25	9	525	-	-
AM-21-85	35 ppm	35 ppm	<1	<1	57	1855

Table 3.4 also lists two samples that contain significant quantities of tungsten. Close examination of the tungsten-rich samples reveals that the mineral scheelite ($CaWO_3$) occurs in thin quartz-carbonate stringers within hairline fractures in most rocks in the intrusion. The source of mineralization is likely late hydrothermal fluids and is probably not related to the Mud Lake intrusive events.

3.1.5.3. Abiwin

The Abiwin Intrusion is a small, highly deformed dike-like body approximately 200 m in length and up to 40 m in width. It is situated on the north shore of a small, unnamed lake 37m east of Atikokan and 2.8 km northwest of Nydia Lake. The intrusion is hosted by metasedimentary migmatites and is composed of locally sheared, slightly to highly altered, medium- to coarse-grained, locally porhyritic hornblendite and feldspathic hornblendites.

The dynamic and thermal processes that formed the migmatites have produced pull-apart structures within the dike, locally causing it to appear truncated, faulted, rotated, or elongated. The entire intrusion appears to be a remnant slice of a former, more extensive body, and now has little vertical or along-strike continuity.

Mineralisation consists of small, irregular pods up to 10 m in width, and one larger zone approximately 40 m long and 10 m wide. These zones occur in both ultramafic and mafic rocks and contain 2% to 35% very finely disseminated pyrrhotite, pyrite, chalcopyrite and pentlandite. Most of the zones contain anomalous PGE and Cu-Ni values, with the largest zone returning one very high PGE assay (39,500 ppb Pt, 3,750 ppb Pd, Table 3.5). The mineralised zones occur near contacts with other ultramafic and mafic rocks or the country rocks.

Analysis of polished thin sections have shown the existence of very small, discrete grains of as yet unidentified, platinum-group minerals.

Table 3.5 : Abiwin Intrusion Assay Results

Sample No.	Cu (%)	Ni (%)	Pt (ppb)	Pd (ppb)	Co (ppm)	Ag (ppm)
AAb-5-84*	2.20	0.084	39500	3750	62	-
AAb-5-84	-	-	12000	740	-	-
AAb-6-84	0.604	0.078	260	430	54	5.8
AAb-7-84	0.270	0.058	720	310	48	7.9
AAb-8-84	0.266	0.060	55	8	56	<3
AAb-2-85	0.620	0.145	85	45	96	3
AAb-5-85	0.295	0.118	25	35	103	-
AAb-7-85	0.335	0.079	135	650	44	3
AAb-9-85	0.570	0.064	420	425	50	-
AAb-10-85	2.040	0.070	180	530	46	16
AAb-12-85	0.485	0.244	82	65	205	-
AAb-19-85	0.039	0.012	285	210	20	-
AAb-24-85	0.408	0.115	300	290	92	2

* : re-assay

3.1.5.4. Kawene

The Kawene Intrusion is a stubby, almost plug-like body approximately 500 m long and up to 200 m wide. It is located about 500 m west of Kawene Lake, 500 m north of the CNR (Canada National Railroad) tracks, and 27 km east of Atikokan. Larsen (1974) and the author's mapping (in Patterson et al. 1986) indicate that the most dominant lithologies within the intrusion are moderately to highly altered, fine- to coarse-grained, grey to dark green, oikocrystic hornblende peridotite. Hornblendite and feldspathic hornblendite are common locally, usually near the margins of the intrusion. Local plagioclase-rich patches are common throughout the intrusion. Gabbro pegmatite patches and dikes occur near the contact with the country rock. Some thin, isolated pegmatite dikes are also associated with the sulphide zones.

The contact between the intrusion and metsedimentary rocks is sharp and undulatory. No apparent major contact metamorphic aureole is present, with only a 2 or 3 m zone with little or no schistosity or primary sedimentary structures. Minor assimilation of country rock by magma is indicated by a thin, 30 cm to 100 cm thick, plagioclase-rich zone within the intrusion at its contact with metasediments. The absence of a significant contact metamorphic aureole, or a noticeable chill margin suggests that the ultramafic mass was probably intruded into an already hot, dry country rock. The excess heat from the intrusion may have caused some partial melting of the sediments, producing a series of granitic dikes that occur for a short distance stratigraphically above and north of the intrusion. This same phenomenon has also been observed at the Mud Lake Intrusion.

Very finely disseminated patches and zones of sulphides containing < 1% to 3% pyrrhotite, pyrite and some chalcopyrite are common throughout the intrusion. In addition, an irregular, elongated zone of 1 to 25% finely disseminated to net-textured Cu-Ni-Pt-Pd rich (see Table 3.6) pyrrhotite, chalcopyrite, pentlandite and pyrite is present near the contact of the eastern lobe of the intrusion. It is approximately 40 m in length and up to 25 m in width, and has been exposed by 17 deeply weathered pits and trenches. The mineralisation straddles an undulatory and possibly disrupted, contact between a fine to medium grained, altered, grey-green pyroxenite and a medium to very coarse-grained, green to dark green, highly altered and deeply weathered, oikocrystic hornblende pyroxenite.

The sulphide grains present in the main mineralized zone characteristically exhibit pyrrhotite cores with chalcopyrite rims. In addition, rocks with low sulphide percentages show visible alteration halos around the rimmed sulphides that extend a few millimetres into the surrounding silicate grains. Where higher sulphide percentages occur these alteration halos coalesce, resulting in pervasive alteration throughout the rock.

Table 3.6 : Kawene Intrusion Assay Results

Sample No.	Cu (ppm)	Ni (ppm)	Co (ppm)	Pt (ppb)	Pd (ppb)	Rh (ppb)	Ir (ppb)	Au (ppb)
AK-1-84	780	180	98	27	4	-	-	-
AK-2-84	102	226	58	3	2	-	-	-
AK-3-84*	2060	2480	234	240	550	-	-	-
AK-3-84	-	-	-	190	570	55	23	14
AK-4-84*	12600	1320	134	750	1100	-	-	-
AK-4-84	-	-	-	630	1200	17	7.7	34
AK-5-84*	1650	490	68	460	280	-	-	-
AK-5-84	-	-	-	460	410	15	6.5	-
AK-6-84*	1370	840	96	230	260	-	-	-
AK-6-84	-	-	-	270	280	5	2.4	18
AK-7-84	88	50	5	2	3	-	-	-
AK-8-84*	4500	2160	192	1100	1000	-	-	-
AK-8-84	-	-	-	1000	920	110	39.0	25
AK-9-84*	2070	660	72	440	320	-	-	-
AK-9-84	-	-	-	380	430	10	4.7	460
AK-1-86	870	550	83	185	410	-	-	5
AK-2-86	2780	515	67	340	600	-	-	17
AK-3-86	4300	1330	126	805	530	-	-	28
AK-4-86	2700	1000	98	265	350	-	-	13
AK-5-86	3020	315	43	465	360	-	-	190
AK-6-86	1680	640	78	170	135	-	-	10
AK-7-86	9300	1870	375	69	360	-	-	21
AK-8-86	10700	1960	410	63	260	-	-	18
AK-9-86	2660	980	88	315	340	-	-	7
AK-10-86	3720	850	85	520	525	-	-	18
AK-11-86	4720	605	85	600	525	-	-	33
AK-12-86	355	245	46	165	78	-	-	38
AK-13-86	810	485	58	135	130	-	-	30
AK-14-86	170	285	59	5	5	-	-	<2

* : Re-assay

3.1.5.5. Chief Peter Lake Intrusion:

The Chief Peter Lake Intrusion is a plug-like ultramafic body approximately 760 m long and 460 m wide. It is situated 1.6 km south of Chief Peter Lake, 4.5 km north of Quetico Station on the CNR, and 51.5 km east of Atikokan. According to Irvine (1963) it is composed of a narrow NE/SW trending medium to coarse grained, serpentinized hornblende peridotite core surrounded by a main mass of medium to coarse grained, dark green, biotite-bearing, locally feldspathic, hornblendites. Irvine (1963) also states that the contact between the hornblende peridotite and the hornblendite is gradational, marked by the decrease and eventual disappearance of pyroxene and olivine.

Table 3.7 : Assays from Chief Peter Intrusion

Sample No.	Cu (ppm)	Ni (ppm)	Co (ppm)	Pt (ppb)	Pd (ppb)	Au (ppb)
ACP-1-86	6300	1580	100	1550	1020	530
ACP-2-86	290	370	88	7	8	8
ACP-3-86	3920	1120	92	1020	1050	330
ACP-4-86	215	180	53	5	3	8
ACP-5-86	745	445	82	130	90	40
ACP-6-86	162	465	81	60	46	31
ACP-7-86	166	104	85	<1	2	<2
ACP-8-86	148	104	72	<1	1	<1
ACP-9-86	34	225	60	10	4	<2

Sulphides are present in one locality near the southwestern contact of the peridotite. Diamond drilling, in the 1950's, also indicated appreciable sulphides within the peridotite at depth to the northeast (Resident Geologist's Assessment Files, Ministry of Northern Developmnent and Mines, Thunder Bay). The 25 m by 10 m surface showing has been exposed by 3 trenches, and contains from 1% to 8% finely disseminated to locally net-textured pyrrhotite, chalcopyrite, pyrite and possibly pentlandite. Two of the mineralized peridotite samples analysed during this study contained appreciable Cu, Ni, Pt, Pd and Au values (see Table 3.7).

3.1.5.6. Lawrence No. 1 Occurrence:

The Lawrence No. 1 Occurence is contained within a narrow northeast striking, northwest dipping, ultramafic dike, which is 400 m in length by 60 m in width, and is composed chiefly of medium- to coarse-grained hornblendite and feldspathic hornblendite (Irvine 1963). The intrusion exhibits a sharp, and apparently chilled contact with the Quetico metasediments. Some contamination of the dike by assimilated country rock has occurred. Information in the Resident Geologist's Assessment Files, Ministry of Northern Development and Mines, Thunder Bay, indicates the presence of finely disseminated Cu-Ni sulphides throughout the dike, with some concentration near the southwestern contact. This zone was trenched in the 1920's and was later drilled, along with the rest of the intrusion, in the late 1950's and early 1960's. The sulphide zones contain 0.17% to 0.34% Ni, 0.41% to 2.95% Cu, trace to 0.07 oz/ton Pd (approximately 2.4 g/t Pd) and trace to 0.3 oz/ton Pt (approximately 10 g/t Pt) (Resident Geologist's Assessment FIles, Ministry of Northern Development and Mines, Thunder Bay).

3.1.5.7. Plateau Lake Intrusion:

The Plateau Lake Intrusion is a deformed, dike-like body that is composed of medium to very coarse grained, altered hornblendite with a small core of fine to medium grained, oikocrystic, altered hornblendite pyroxenite. This intrusion is approximately 650 m in length and up to 100 m in width. A larger dike-like, dioritic to gabbroic body occurs just a short distance east of the ultramafic intrusion. Both intrusions were emplaced sub-concordantly

within the surrounding metasedimentary rocks, and appear to have been deformed along with the sediments.

Sulphides were observed in the ultramafic intrusion only, and have been concentrated within the altered hornblende pyroxenite. A series of trenches, pits, and shallow shafts (which date from *circa* 1900) have exposed the main zone. The sulphide content ranges from less than 10% to greater than 40% finely disseminated, to net-textured chalcopyrite, pyrrhotite and pyrite. The average sulphide content is between 5% and 15%, with chalcopyrite present in greater quantities than the other sulphides. Platinum and palladium contents are up to 700 ppb and 440 ppb respectively, with the majority of the higher values obtained from the copper-rich zones (see Table 3.8).

Table 3.8 : Plateau Lake Intrusion Assay Results

Sample No.	Cu (ppm)	Ni (ppm)	Co (ppm)	Pt (ppb)	Pd (ppb)	Au (ppb)	Ag (ppm)
API-1-84*	10900	2060	-	270	165	140	0.22
API-1-84	-	-	-	250	140	86	-
API-2-84*	15600	250	-	270	420	165	0.34
API-2-84	-	-	-	300	540	92	-
API-3-84	94	220	-	4	4	-	-
API-4-84	114	260	-	<1	<1	-	-
AWS-1-85	6200	3160	-	230	100	90	4
AWS-2-85	100	186	-	70	30	14	2
AWS-3-85	3100	220	-	290	70	50	12
AWS-4-85	44000	730	-	185	125	250	16
AWS-5-85	5120	2500	-	440	85	185	4
79-LKK-1	2700	600	100	103	343	343	tr
79-LKK-2	3500	300	80	103	69	343	tr
79-LKK-3	21200	3900	400	343	171	343	tr
79-LKK-4	5000	4600	500	206	137	343	tr
79-LKK-5	3800	7300	600	240	274	686	20.5
79-LKK-6	4200	2200	200	69	137	tr	tr
79-LKK-7	23200	1600	200	206	274	343	10.6
79-LKK-8	3500	800	100	34	69	tr	tr
79-LKK-9	3400	1400	100	34	103	tr	tr
79-LKK-10	11400	4200	700	171	240	343	tr
CK-4-1	9300	2400	-	686	tr	-	-
CK-9-1	4100	tr	-	1028	686	-	-

* : Re-assay
tr : Trace

3.1.5.8 Exploration Guidelines and Summary

The Quetico intrusions are relatively small mafic to ultramafic bodies with, locally, high concentrations of copper, nickel, cobalt, platinum, palladium and, in at least one intrusion, tungsten mineralization. Base metal, and in particular PGE potential, is high in these and other similar bodies.

The Quetico Intrusions have a number of common distinguishing features that might help in locating other similar bodies and the mineralization contained within them:

a) They occur as small isolated bodies within the relatively thin belt of turbiditic metasedimentary rocks that comprise the northern part of the Quetico Subprovince.

b) They are slightly more erosion resistant than the surrounding metasedimentary rocks and occur as topographic highs:

c) They exhibit distinctive, relatively isolated and intense airborne magnetic anomalies. In some cases this magnetic signature should be discernible even when the intrusion is mantled by a thin cover of metasedimentary rock;

d) Copper-nickel sulphide mineralization that is enriched in the PGE usually occurs near an internal contact between rock types, or near the contact with the surrounding metasedimentary rocks;

e) The sulphide zones that are PGE-rich tend to occur in ultramafic, rather than mafic host rocks.

3.1.6 WAWA SUBPROVINCE

3.1.6.1. General Discussion (A.J. Macdonald)

Although recent investigations suggest that the Wawa and Abitibi greenstone belts reflect one contiguous subprovince within the Superior Province, dissected by the Kapuskasing Structural Zone (e.g. Percival and Card 1985), the two subprovinces have historically been treated as separate entities; this distinction is retained here.

Most interest for PGE exploration within the Wawa Subprovince has centred on the Proterozoic Coldwell complex around Marathon, described below in section 3.2.5. INCO's Shebandowan Mine has produced Ni, Cu, Co and PGE from a complex deposit in Archean rocks west of Thunder Bay. Although currently not in production, this deposit type is being re-assessed for its PGE potential and remains a viable exploration target in the Wawa greenstone belt.

3.1.6.2 Shebandowan Mine (G.C. Patterson)

3.1.6.2.1. Introduction

This section provides a summary of available information on INCO's Shebandowan Mine. The main sources of data are Morton (1982), Watkinson et al. (1978), Morin (1973), Whittaker (1986) and the Resident Geologist's Files, Ontario Ministry of Northern Development and Mines, Thunder Bay. The Shebandowan Mine is located 77 kilometres west of Thunder Bay (Figure 3.27). Although the surface exposure was well known, it was not until 1913 that the presence of nickel sulphides was noted by W.W. Benner (Cross 1920).

The Cross brothers carried out a program of trenching and diamond drilling from 1923 to 1926. In that year the International Nickel Company of Canada (INCO) purchased the property. INCO carried out exploration on the property from 1936 to 1968. A commercial deposit was recognized and production commenced in 1972. The mine is currently under care and maintenance.

The deposit reserves (Mineral Resources File: NR-N1 301,000) are unofficially stated at 6 to 7 million tons of ore with nickel over 3% and copper rarely over 2%. Platinum group metals and cobalt are also contained in the ore, although no figures are available in the public domain.

3.1.6.2.2. General Geology

The rocks in the mine area are situated in the Wawa Greenstone Belt (also known informally as the Shebandowan Greenstone Belt) and consist of Archean, mafic to ultramafic volcanic rocks which have been intruded by gabbro to peridotite bodies (Morin 1973). These rocks in turn have been intruded by the Shebandowan Lake Stock, a quartz diorite. A group of "Timiskaming-Type" volcanic and metasedimentary rocks occur as an east-west belt 500 m south of the Shebandowan Mine and extend at least 20 km to the east (M.W. Carter, Ontario Geological Survey, Toronto, personal communication, 1986). A major regional fault, the Crayfish Creek Fault, is approximately parallel to the southern contact of the Shebandowan Lake Stock and subdivides the mine geology into two halves.

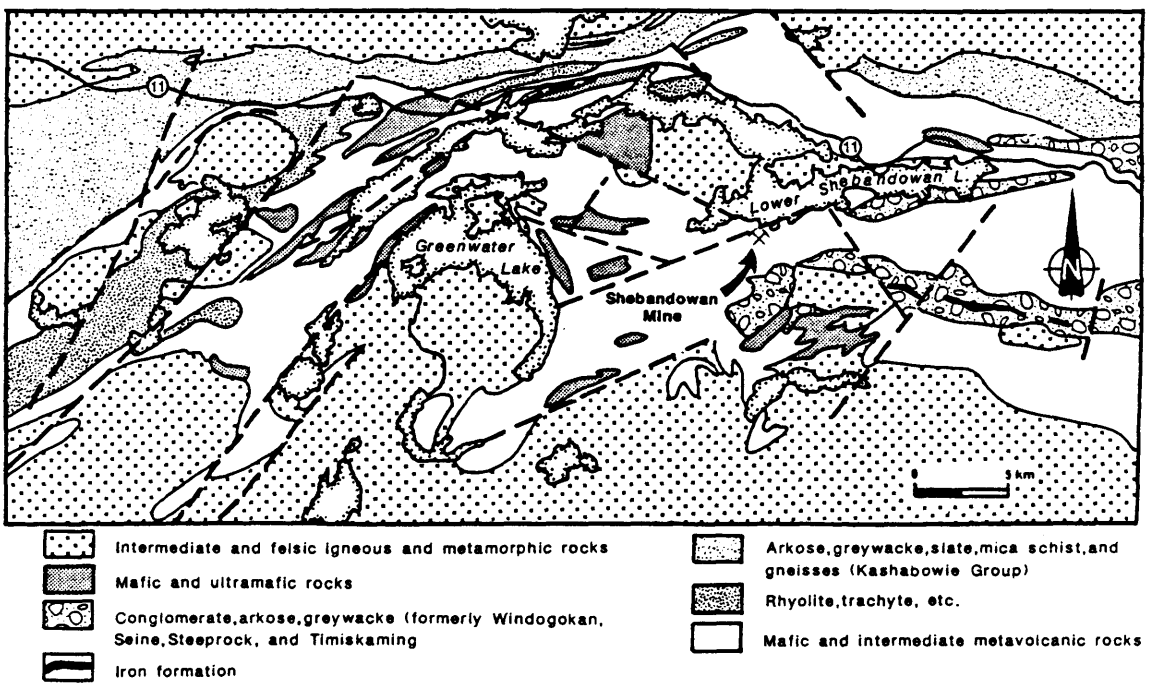


Figure 3.27 : Regional geology of the Shebandowan Mine area (from Pye and Fenwick 1964).

3.1.6.2.3. Mine Geology

Within the mine there are two units, the southern andesitic volcanic rocks and the northern peridotitic intrusions, hosted by mafic volcanic rocks. The units are separated by the Crayfish Creek Fault.

The southern unit consists of agglomerate to lahar-type debris flows that are andesitic in composition. These fragmental rocks are the upper portion of a possible younger volcanic cycle (komatiitic to andesitic) defined by Morton (1982).

The northern unit consists of a complex series of lens-like peridotite and granodiorite masses intruding mafic volcanic rocks. Two main peridotite bodies (A and B) have been identified (Morton 1982).

The southern peridotite (Body B) contains a discontinuous chromite horizon. The chromite is TiO_2- and Fe_2O_3-poor and Fe_3O_4-rich (Morton 1982). Chromite composition changes with stratigraphic position indicating that tops in the sill are to the north (Morton 1982). The northern peridotite (Body A) located approximately 150 m north of Body B, hosts the nickel-copper ore. The peridotite bodies are compositionally similar with each having 32% MgO and 44% SiO_2. Due to deformation in the mine area it is not clear if the host rock is intrusive or extrusive.

3.1.6.2.4. Ore Zones

Morin (1973), Watkinson et al. (1978), and Morton (1982) describe the ore as a series of massive to brecciated lenses within the northern peridotite (Body A); disseminated and stringer ores are rare. The breccia ore comprises rounded to angular fragments of peridotite, pyroxenite, and granodiorite in a sulphide matrix. The sulphides consist of pyrrhotite, pyrite, chalcopyrite and pentlandite with minor millerite, sphalerite and violarite. The main platinum group mineral is merenskyite which is concentrated in copper-rich portions of the ore (Watkinson et al. 1978). Merenskyite in the Shebandowan Mine contains 19.7 to 24.4% palladium and 0 to 0.4% platinum. Pentlandite often occurs as streaky discontinuous layers in a matrix of pyrrhotite, a texture attributable to mechanical deformation below monosulphide solid solution stability (400^{o}C; Groves et al. 1974). Nodular pyrite, partially surrounded by chalcopyrite, occurs in a foliated matrix of pentlandite and pyrrhotite, also suggesting that the deposit is deformed.

Fragments of granodiorite dikes, which cut the host peridotite, occur within the breccia ore, implying that breccia ore was tectonically emplaced after the peridotite and granodiorite dikes. INCO Mine geologists report mineral zoning in the ore:

> *"Ni grade increases eastward, as does the amount of pyrite. Cu is richest in stringer and breccia-sulphide ore, and PGE values vary in direct relation to the amount of chalcopyrite"*
> (Morton 1982).

Morton (1982) noted that the bulk composition of the ore is unusual when compared to other nickel-copper deposits. The Cu/(Cu + Ni) ratio is 0.36 and the Pt/(Pt + Pd) ratio is 0.22 as reported by Eckstrand et al. (1981).

The Cu/(Cu + Ni) and Pt (Pt + Pd) ratios are distinct from the trend defined by Naldrett and Cabri (1976). The ore appears to be enriched in copper relative to nickel. Based on a Cu/(Cu + Ni) vs MgO (27% MgO from olivine remnants, Naldrett and Cabri 1976), the Shebandowan ore appears to be relatively enriched in copper.

The modal ratio of silicate to sulphide is 2500 in the Kambalda ore (Western Australia) and 1000 at Sudbury. At Shebandowan, however, the ratio is significantly lower at 42, (Morton 1982), indicative of the greater sulphide content.

3.1.6.2.5. Discussion and Summary

The Shebandowan deposit occurs as a series of breccia zones in peridotite bodies. The ore contains textures which suggest mechanical deformation after emplacement. The bulk composition of the ore is copper-rich and the ratio of host to sulphide is small when compared to other copper-nickel deposits. There are a number of possible explanations for these features:

a) The original host of the ore crystallised not as an ultramafic rock, but from a magma with a lower MgO content, such as a gabbro. The ore was tectonically emplaced at some later stage into its present position (Morton 1982). This mechanism is consistent with the copper-rich nature of ore (Naldrett and Cabri 1976), the low sulphide to silicate ratio and the observed deformation fabrics.

b) The copper content of the ore was modified by the separation of a monosulphide solution (MSS) from a copper-rich liquid (Craig and Kullerud 1969) possibly by filter pressing. In the system copper, iron, nickel, sulphur at approximately 1000^{0}C, the sulphides would consist of nickel- and iron-rich MSS. If the rock were deformed at this point it may be possible to separate a copper-rich sulphide liquid.

c) Stress induced diffusion in a fault system, may selectively mobilize copper relative to nickel and iron (Patterson and Watkinson 1984a,b). If a sulphide deposit is deformed within a fault zone, it may be possible to mobilize copper relative to nickel due to differences in their chemical characteristics. At the Thierry Mine, near Pickle Lake, such a mechanism is postulated to have enriched the ore zones in copper (Section 3.1.2.2, and Patterson and Watkinson 1984a,b).

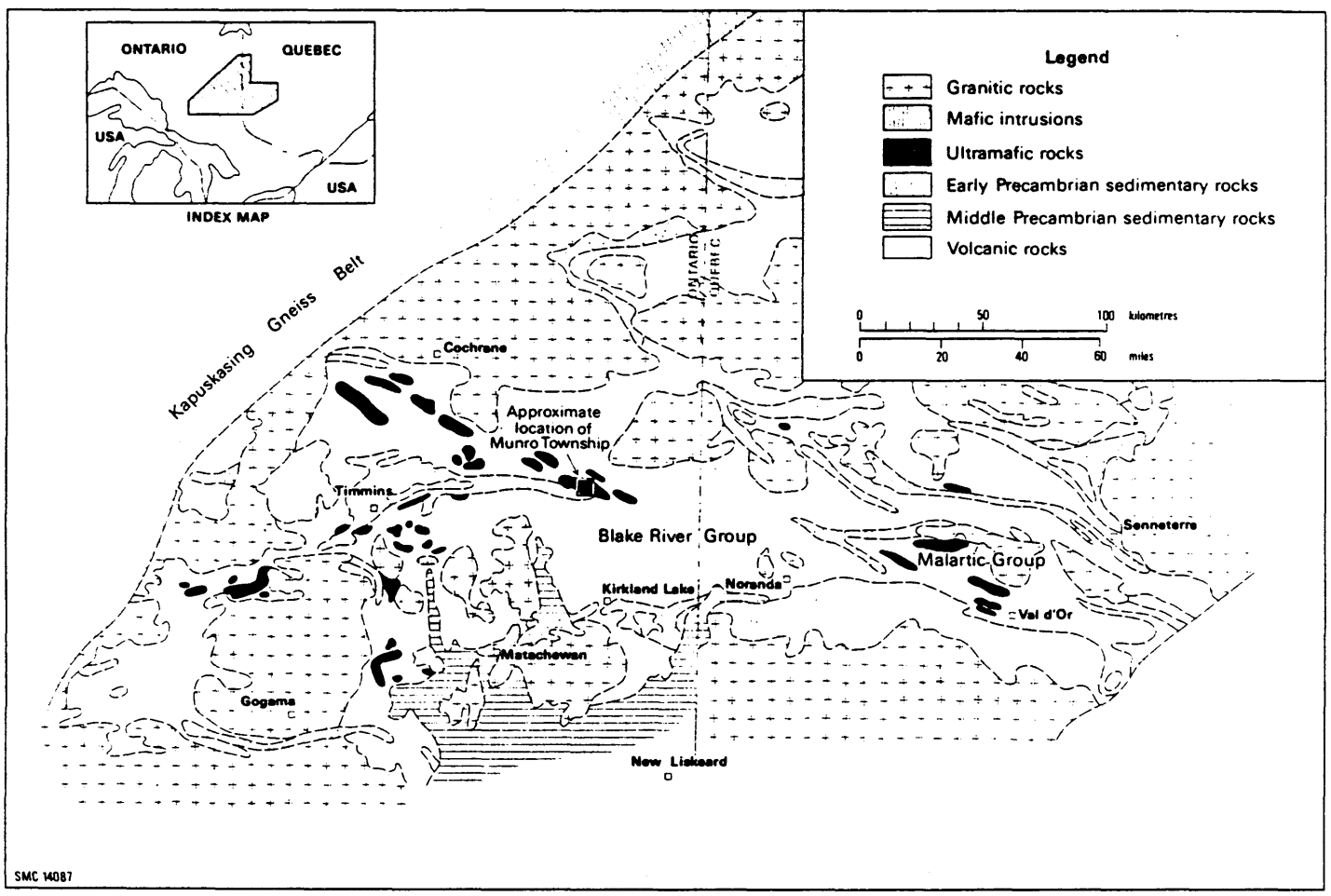


Figure 3.28 : Map of part of the Abitibi Greenstone Belt (after Coad 1979)

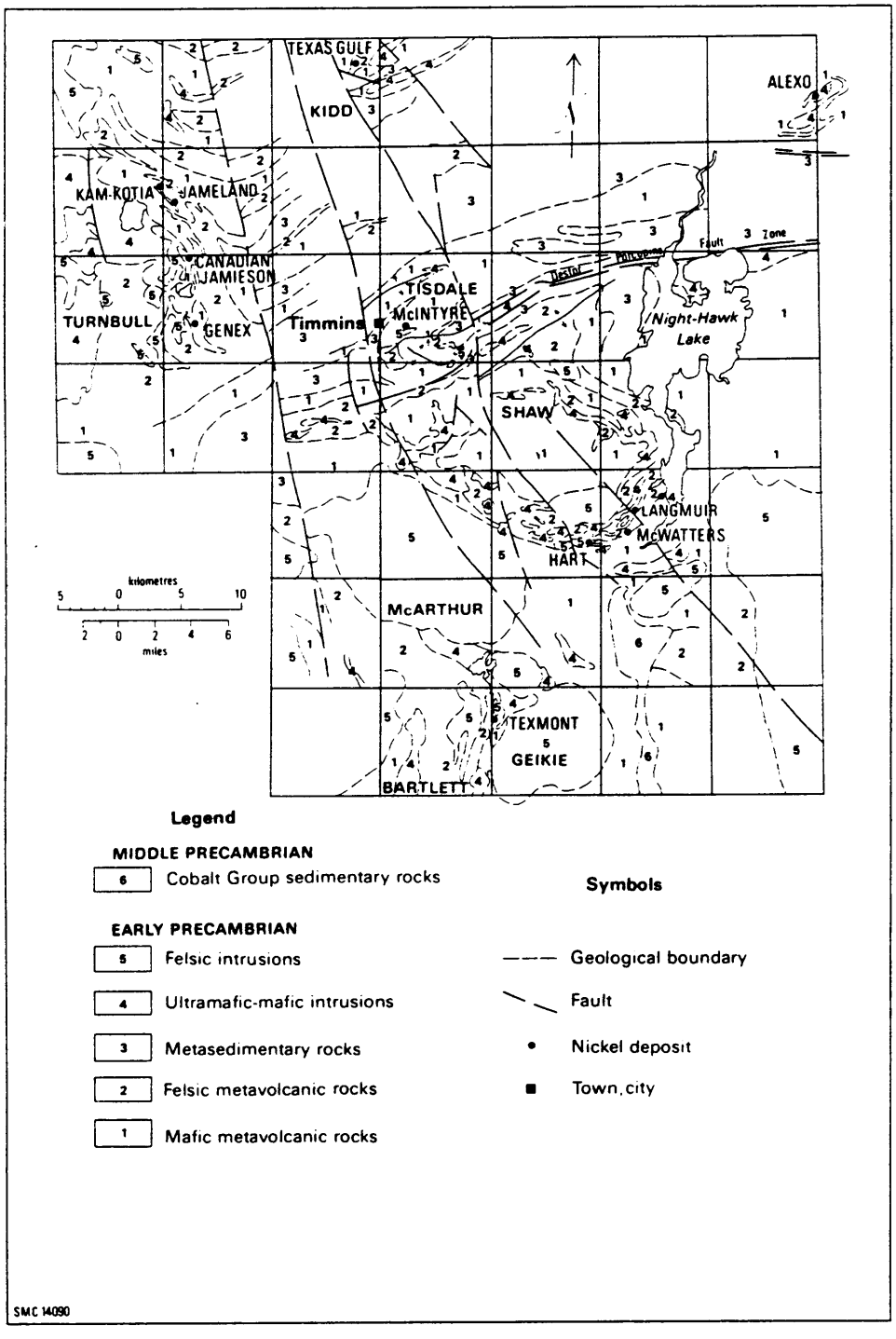


Figure 3.29 : Simplified geology of the Timmins area (after Coad 1979)

3.1.7. ABITIBI SUBPROVINCE (P.J. Whittaker)

3.1.7.1. General Discussion

PGE are associated with sulphide mineral deposits in rocks of komatiitic affinity in the Abitibi greenstone belt. These rocks include fine-grained flows with spinifex textures, and their intrusive equivalents. The rocks range from dunite to peridotite, and are olivine- and pyroxene-rich. Some thicker sills show limited differentiation to gabbro. In many cases, it is difficult to distinguish between thick flows and thin, synvolcanic, hypabyssal sills.

Komatiitic rocks occur in the lower part of the volcanic stratigraphy of the Abitibi greenstone belt near Timmins and to the east, towards Quebec (Figure 3.28). Near Timmins, sulphide mineral deposits occur in komatiites at the top of the Deloro Group near the base of the overlying Tisdale Group (Coad 1979). In the Munro Township area to the east, komatiitic rocks occur in the Stoughton-Roquemere Group (Pyke et al. 1973a), that is overlain by the tholeiitic Kinojevis Group (Jensen 1984).

Komatiite-hosted sulphide mineral deposits in the Timmins area are distributed around the Shaw Dome, a northwest-trending, 19 km by 29 km structure, in Shaw Township approximately 20 km SE of Timmins (Figure 3.29) and is outlined by ultramafic rocks at the top of the Deloro Group and the base of the Tisdale Group. Massive and disseminated sulphide deposits, originally examined for their Ni and Cu contents, occur within ultramafic rocks at the stratigraphic boundary between these two groups. The Langmuir, McWatters, Hart and Texmont deposits, described by Coad (1979), appear to be contained within parts of komatiitic flows and represent volcanic environments worthy of consideration for PGE. The Alexo and Sothman deposits are similar, but are associated with zoned, possible sill-like bodies of peridotite and dunite rather than distinct flows. The relationship of the Alexo Deposit to others in the district is further complicated by the Destor-Porcupine Fault Zone, which separates it from the deposits in the Timmins area. Barnes and Naldrett (1987) have described PGE + Au fractionation at Dundonald, Alexo, Texmont, and Hart, and present a genetic hypothesis for the formation of this deposit type. Good (in progress, 1987) is further investigating the geology and economic potential of PGE-bearing rocks in the Abitibi belt.

3.1.7.2 Langmuir Deposit

The Langmuir deposit, in Langmuir Township 32 km southeast of Timmins (Figure 3.29) and consists of two zones in a succession of komatiitic flows about 30 m thick (Figure 3.30). This succession overlies felsic to intermediate crystal tuffs and, locally, cherty sulphide iron formation of the Deloro Group. This stratigraphy has been isoclinally folded about the Shaw Dome on both local and regional scales. Komatiites are interfingered with Deloro Group intermediate to felsic volcanic rocks and are overlain initially by alternating tholeiitic and komatiitic flows and subsequently by a succession of komatiites.

Sulphide deposits occur at the basal contact of the lowest ultramafic flow where mineralisation is within 30 m of the footwall contact. Sulphides occur in massive, disseminated to net-textured, as breccia ore and filling interstices between spinifex blades (Green and Naldrett 1981).

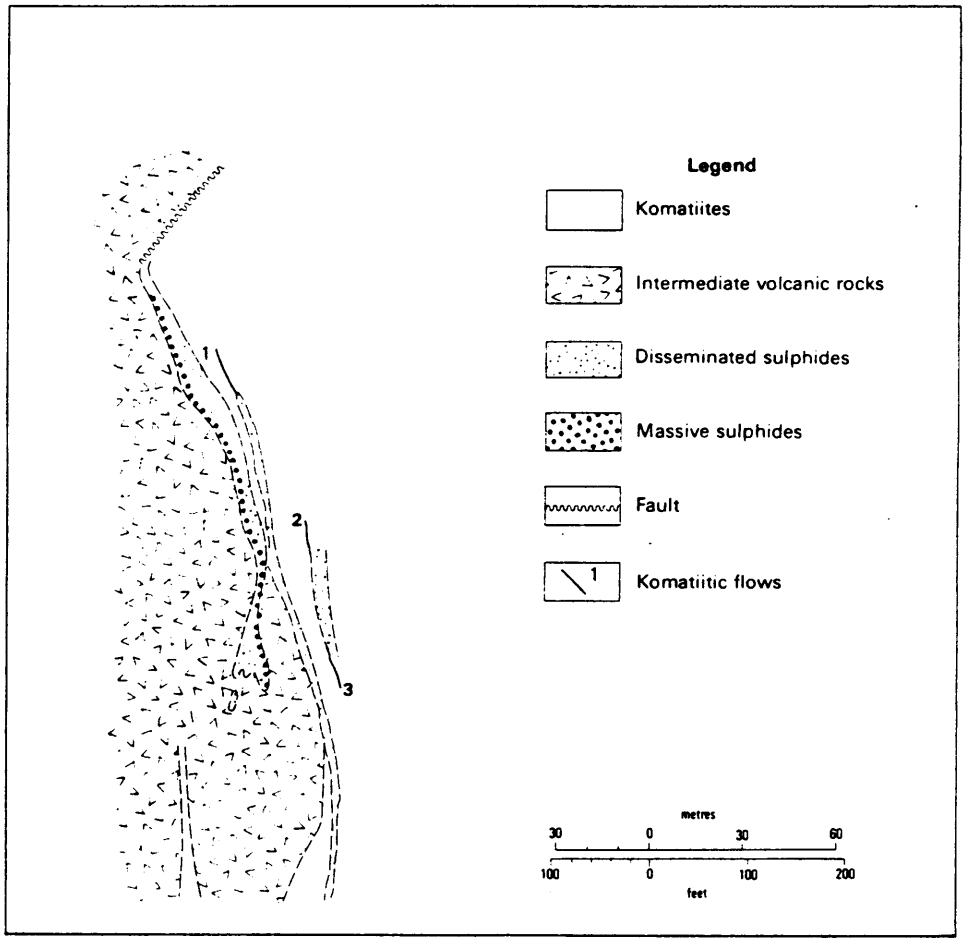


Figure 3.30 : Vertical east-west section of the Langmuir Nickel Mine, looking north, line 7600N (from Coad 1979).

Massive sulphides form concordant lenses 0.3 to 2.5 m thick and are locally banded parallel to the footwall contact. Pentlandite crystals form 2 mm to 10 mm wide layers alternating with fine-grained chalcopyrite. Pyrrhotite and pentlandite form a recrystallized granular mosaic texture with minor interstitial chalcopyrite, pentlandite and pyrite. Chromite defines 10 cm thick layers at the top and bottom of the massive sulphide lenses. Locally, lenses of massive sulphides occur within footwall volcanic rocks up to 15 m below the main sulphide horizon.

Disseminated sulphides form irregularly shaped lenses and occur above the footwall contact and main sulphide horizon. They have been interpreted as either the lower parts of two overlying ultramafic flows or deformed segments of footwall mineralization (Coad 1979).

Breccia sulphides are located in the footwall where ultramafic flows overlie intermediate to felsic volcanic rocks. The breccia consists of irregularly shaped and sized peridotite fragments in a recrystallised sulphide matrix. Fragment boundaries are often ill-defined. Groundmass sulphide mineralogy is similar to that of the massive sulphide lenses.

Mineralised spinifex forms part of the basal section of the ultramafic flow at the Langmuir # 2 deposit. Pyrrhotite, pentlandite and minor pyrite fill interstitial areas between olivine blades. Some sulphides show local alteration to fine grained magnetite.

Naldrett (1981b) gives PGE analyses of two samples from the Langmuir Mine: a sample of relatively unaltered ore from the Langmuir # 2 deposit, contained approximately 60% sulphide, 9% Ni, 0.4% Cu, 27 ppm As, 4 ppm Se, 534 ppb Pt, 960 ppb Pd, 138 ppb Rh, 450 ppm Ru, 144 ppb Ir, 248 ppb Os, and 109 ppb Au. An altered specimen from the Langmuir # 1 body, on the other hand, contained 34% sulphide, 10% Ni, 0.3% Cu, 34 ppm Se, 904 ppb Pt, 2159 ppb Pd, 156 ppb Ru, 143 ppb Ir, 347 ppb Os and 156 ppb Au.

3.1.7.3. Texmont Deposit

The Texmont deposit is located 35 km south of Timmins on the border between Geikie and Bartlett Townships (Figure 3.29). The property was originally staked for asbestos in 1950 by Dominion Gulf Company; nickel was discovered in 1951. Reserves are reported at 3,800,000 tons of 1 percent nickel (Coad 1979).

The deposit is hosted by steeply dipping, south striking, komatiitic ultramafic flows forming a 300 m thick succession (Figure 3.31). These overlie footwall rocks consisting of felsic tuff, volcanic breccia, siltstone and both sulphide and oxide facies iron formation of the Deloro Group. The lower 105 m of the komatiites consists of flows 15 to 30 m thick. Spinifex-texture is best developed in the upper part of the succession and aids in interpreting contacts between successive flows. Siliceous metasediments also occur in association with volcanic rocks exhibiting spinifex texture. Stratigraphy at the deposit has been modified by late cross-faulting, with carbonatization locally developed along some faults. Footwall rocks consist of felsic to intermediate, volcanogenic metasediments and tuffs. Pyrrhotite, pyrite and minor chalcopyrite are commonly distributed throughout the metasediments. Fine-grained tuff commonly marks the contact between footwall

rocks and overlying ultramafic flows; in places the contact has been intruded by a gabbro sill.

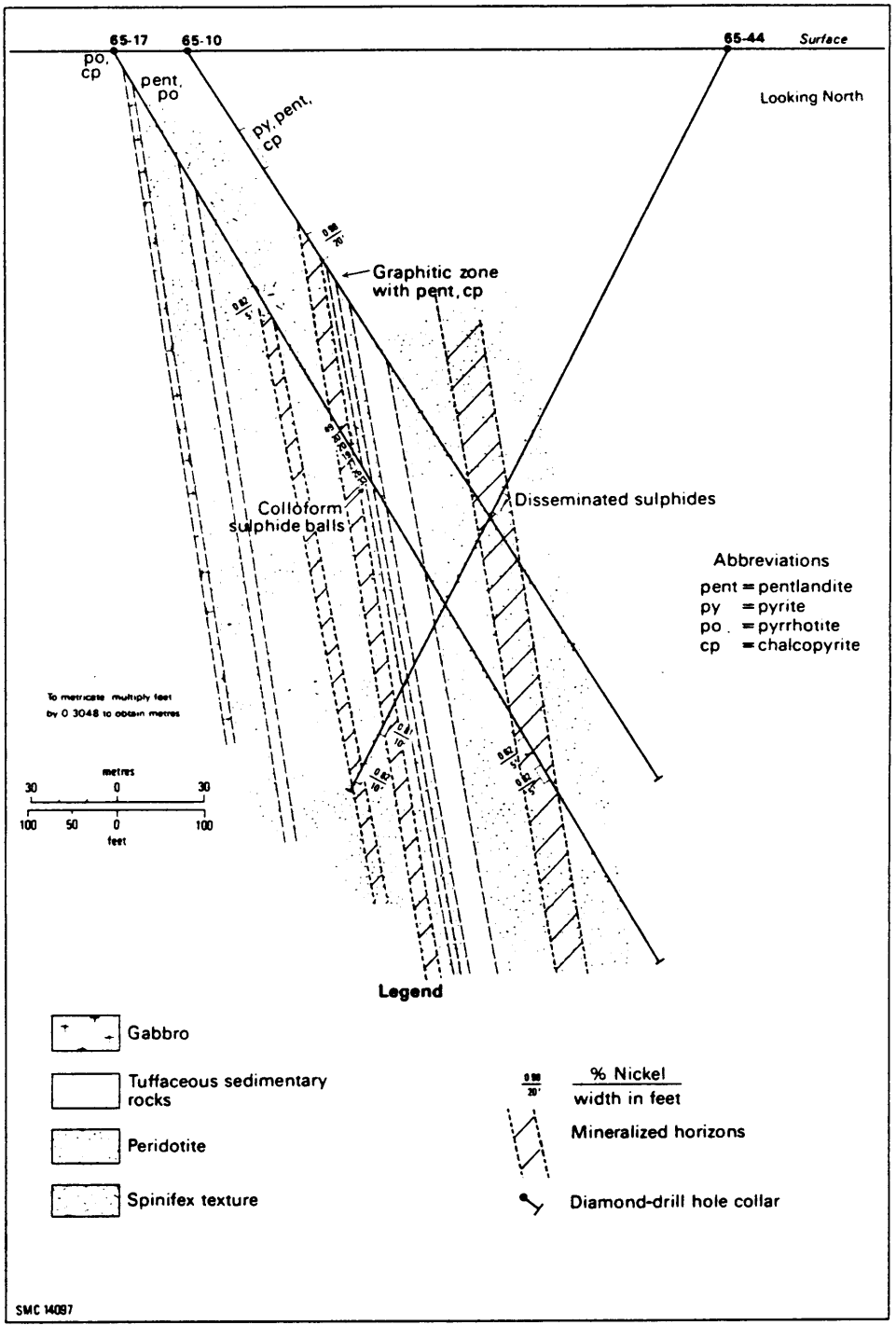


Figure 3.31 : Geology of The Texmont Mine, Vertical Section 42+50N; assays from Texmont Mines Limited (Coad 1979).

Sulphides at the Texmont deposit are hosted by fine grained, peridotitic komatiites, exhibiting brownish-white weathering and black-green fresh surfaces. Cumulate texture may be locally preserved with 1 to 2 mm diameter olivine grains. Bladed olivine spinifex is preserved in scattered patches of irregular size and shape, but generally about 10 cm in diameter. Olivine is the main principal cumulus mineral (80% to 85%) with intercumulus pyroxene, chlorite, serpentine and chromite forming the remainder of the rock.

Sulphide mineralisation occurs in the basal and central part of the ultramafic succession and consists of pentlandite, pyrrhotite, minor millerite, heazelwoodite, pyrite, and chalcopyrite. Sulphides are disseminated as intercumulate blebs in cumulate textured, peridotitic komatiite. Mineralized zones are usually carbonatized. In the lower komatiites, sulphides define concordant lenses at flow bases and as disseminated sulphides in spinifex textured, upper portions of flows.

Barnes and Naldrett (1987) report assays from several samples of disseminated sulphides from Texmont, with maximum Ni grades of 13.4%, Cu to 0.8%, Co to 0.2%, and the following maximum PGE and Au contents : Pt 227 ppb; Pd 760 ppb; Rh 188 ppb; Ru 1,130 ppb; Ir 235 ppb; Os 351 ppb; Au : 594 ppb.

3.1.7.4. Hart Deposit

The Hart deposit is located in southeastern Eldorado Township, about 23 km south east of Timmins (Figure 3.29). Initial work included trenching in 1964 with subsequent diamond drilling.

The deposit is at the base of a succession of ultramafic flows that form the lower part of the Tisdale Group (Figure 3.32), and overlie felsic volcanic rocks near the southern edge of the Shaw Dome. The lower flows are peridotitic komatiites which are overlain by pyroxenitic flows, high-Mg basalts and intermediate volcanic rocks. This succession forms part of the steeply southeast-dipping north limb of an easterly plunging syncline.

Sulphides are hosted by serpentinized peridotitic komatiite which is massive and locally altered to chlorite, carbonate and talc. Sulphides occur at the base of the succession and are overlain by more pyroxene-rich ultramafic flows, exhibiting both pyroxene and olivine spinifex. The lower contact of the basal komatiite is also pyroxene-rich. The mineralized zone is 200 m long, 9 m wide and follows the footwall contact where ultramafic flows overlie pyroclastic rocks and sulphide-facies iron formation. Irregularly shaped and discontinuous pods of massive pyrite are concordant with the footwall peridotite and follow the 50^{o} SE plunge of open cross folds, on the northern limb of the main syncline. Disseminated sulphides overlie pods of massive sulphides and both consist of pyrite, pyrrhotite, pentlandite and minor chalcopyrite. Barnes and Naldrett (1987) report several assays from the Hart deposit, with the following maximum grades: Ni 3%; Cu 0.06%; Co 0.06%; Pt : 165 ppb; Pd : 475 ppb; Rh : 78 ppb; Ru : 162 ppb; Ir : 37 ppb; Os : 40 ppb; Au : 32 ppb.

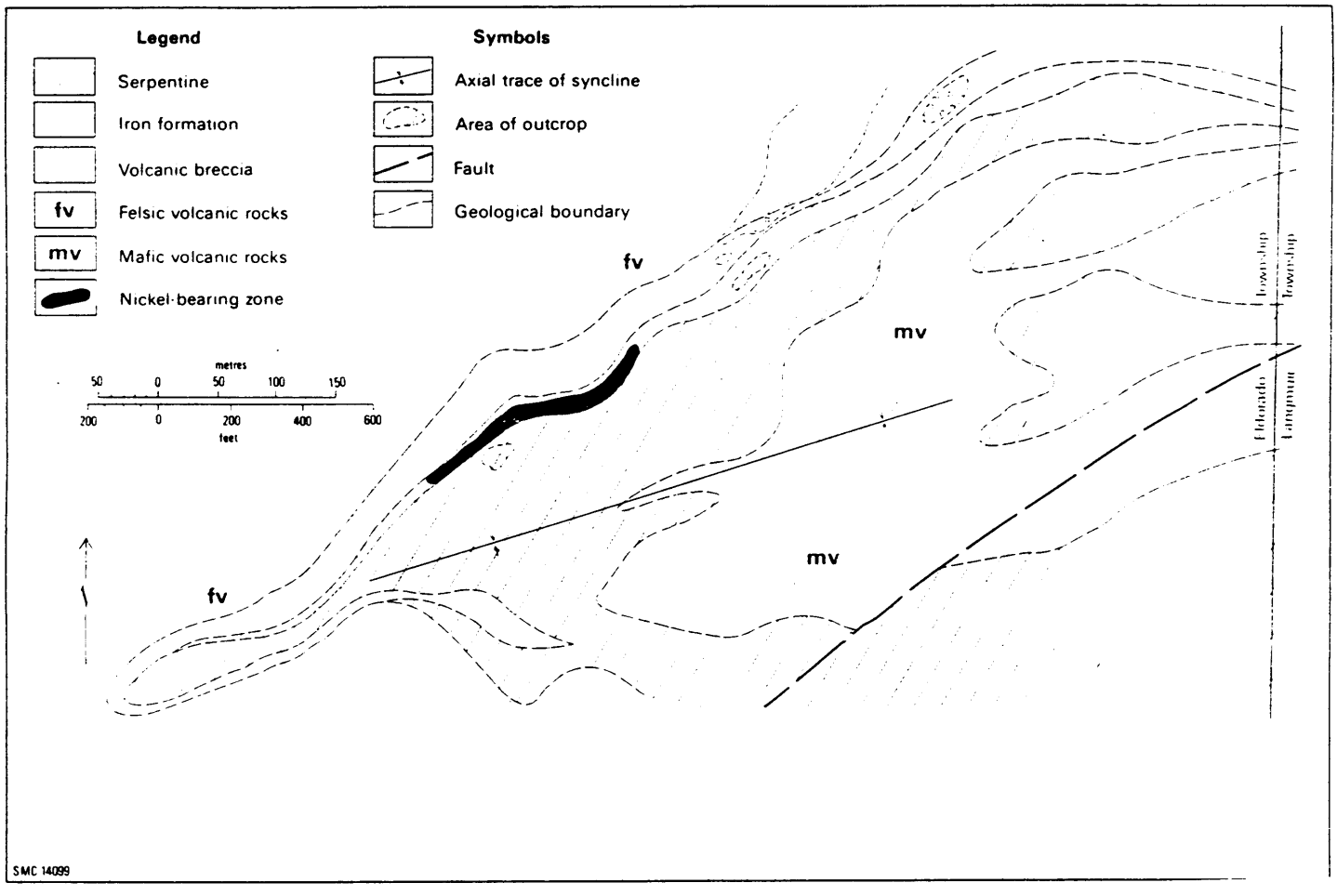


Figure 3.32 : Geological plan of Hart Nickel Deposit (Coad 1979).

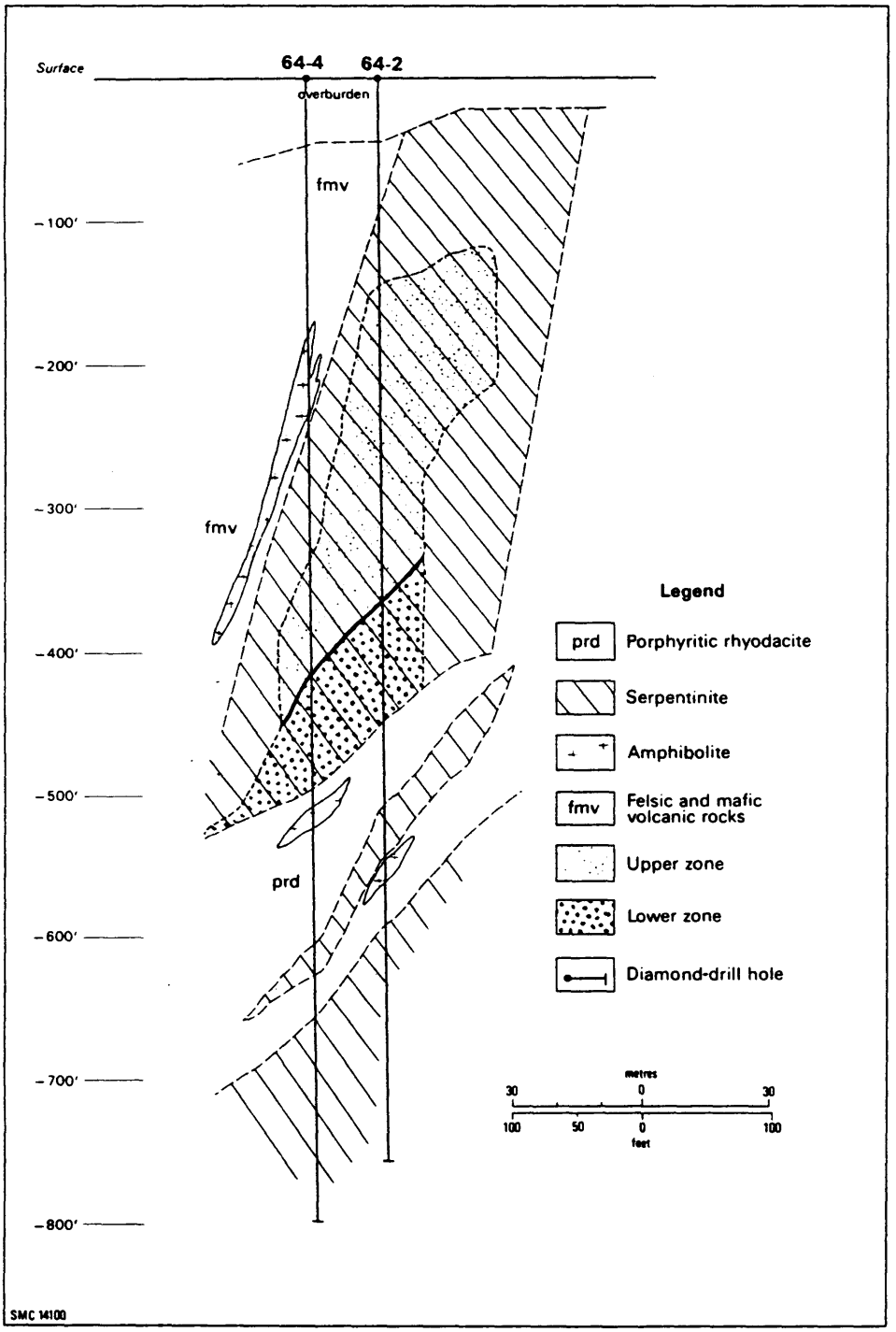


Figure 3.33 : Geology of The McWatters deposit, Vertical Section 1+00N (Coad 1979).

3.1.7.5. McWatters Deposit

The McWatters deposit is located in Langmuir Township, about 24 km southwest of Timmins (Figure 3.29). Work was first performed on the property in 1947 when Dominion Gulf Company conducted an airborne magnetometer survey (Coad 1979). Diamond drilling by McWatters Gold Mines Limited in 1961, intersected 60.6 m of nickel sulphide mineralization containing 0.428 percent nickel (Coad 1979).

The deposit is hosted by a locally discordant ultramafic sill that intrudes intermediate to felsic pyroclastic rocks of the Deloro Group (Figure 3.33). The ultramafic sill is 487 m thick, strikes northeast and dips steeply southeast. The ultramafic rocks are serpentinized and are locally altered to talc, chlorite and carbonate. Massive and cumulate textures are best preserved near the centre of the sill where pyroxene occurs as an intercumulus phase.

Country rocks beneath the sulphide-bearing portion of the sill are mainly felsic volcanic breccias and tuffs. Elsewhere, massive to fragmental, intermediate to felsic metavolcanic rocks occur.

Nickel sulphide mineralization defines upper and lower zones near the centre of the sill, above a porphyritic rhyodacite unit (Figure 3.33). The combined upper and lower zones constitute a deposit 90 m long and 15 m wide containing approximately 475,000 tons grading 0.73 percent nickel in the upper zone and 165,000 tons grading 1.92 percent nickel in the lower zone (Coad 1979). The sulphides include pyrite, millerite, pentlandite and chalcopyrite. Pyrrhotite and violarite are present, in minor amounts, with magnetite and chrome spinel; the latter forms euhedral grains, often rimmed by magnetite. Sulphides occur in disseminated form with minor stringer and bleb-like sulphides in the lower zone. Locally, peridotite breccia fragments occur in the matrix of massive to disseminated sulphides in the lower zone. Fragment-bearing sulphide horizons up to 1.5 m thick may occur. Zones of massive sulphides, up to 2 m thick, occur locally along the footwall of the lower mineralized zone and adjacent to porphyritic rhyodacite. Here, sulphides exhibit a granular texture caused by recrystallization. Naldrett (1981) gives assays from a McWatters deposit sample: 13% Ni, 0.3% Cu, 0.2% Co, 680 ppb Pt, 1435 ppb Pd, 436 ppb Rh, 880 ppb Ru, 337 ppb Ir, 319 ppb Os, 94 ppb Au.

3.1.7.6. Alexo Deposit

The Alexo deposit is situated in Dundonald Township, about 50 km northeast of Timmins (Figure 3.29). The deposit was discovered in 1907 and the Alexo Mining Company removed 52,000 tons of ore between 1912 and 1919. Average grades were 4.5% nickel and 0.5 % copper.

The deposit occurs as a concordant lens with peridotite margins and a dunite core. This sill-like intrusion overlies a series of high-Mg basalts with intercalated hyaloclastite and is 70 m thick and about 500 m long. The zoned ultramafic body strikes northeast and dips 80^{o} west. The Alexo sill is north of and overlies the Dundonald sill (Naldrett and Mason 1968), which consists of peridotite, pyroxenite and gabbro (Figure 3.34). Pillowed basalts containing scattered varioles, separate the Alexo and Dundonald Sills. Thin hyaloclastite beds are intercalated with flows adjacent to the peridotite-volcanic contact.

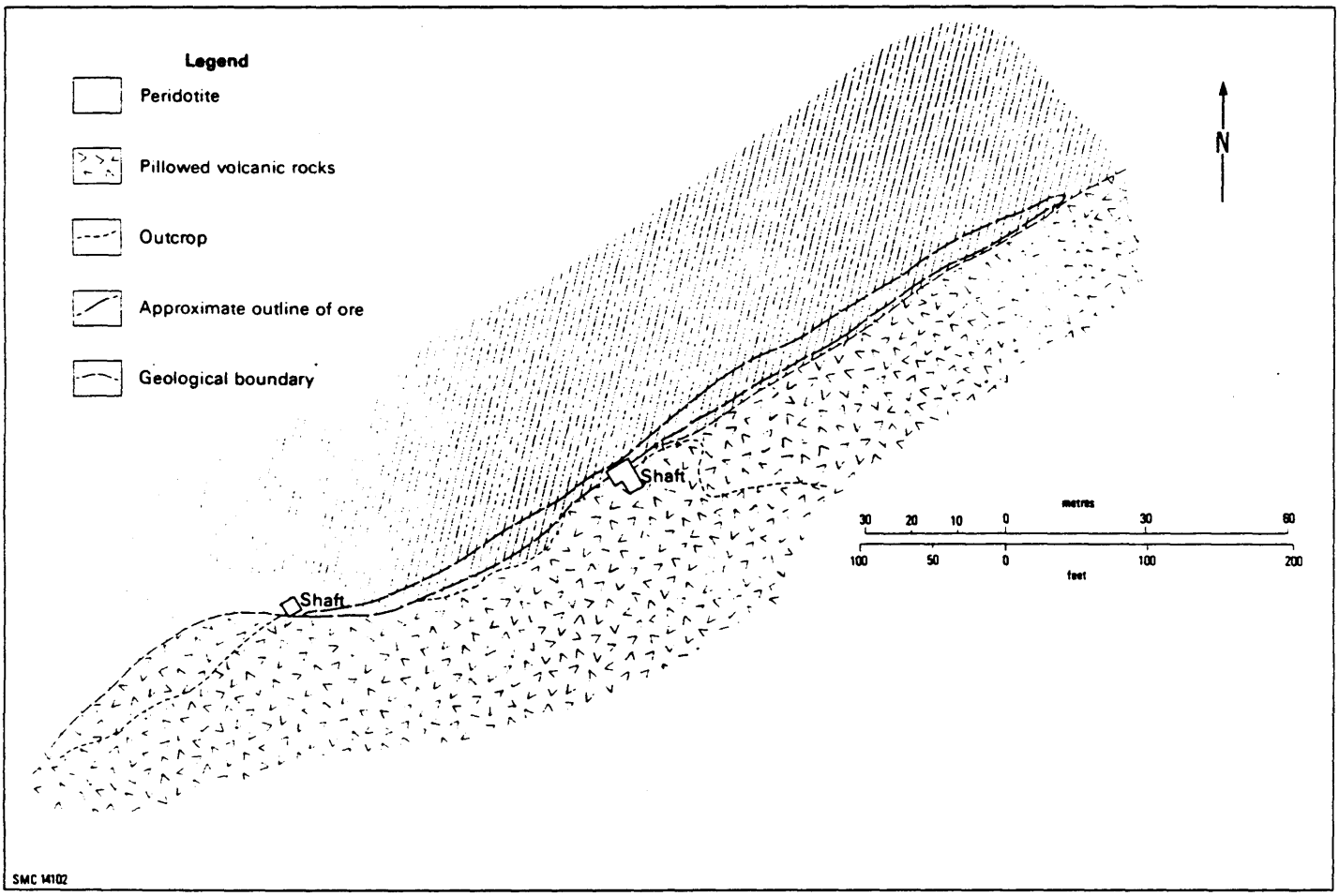


Figure 3.34 : Geological map of the area around the Alexo Deposit (Coad 1979).

Massive to disseminated sulphides occur in shallow embayments along the footwall contact; in decreasing order of abundance the sulphides consist of pyrrhotite, pentlandite, heazlewoodite, chalcopyrite and violarite. The massive sulphide zone is 5 cm to 3 m thick and overlies the basal peridotite, or lies directly on footwall volcanic rocks (Coad 1979). Locally, massive sulphides penetrate up to 5 m into footwall volcanic rocks (Naldrett and Gasparrini 1971).

Disseminated sulphides overlie the massive sulphide layer, with a sharp contact between the two. Disseminated sulphides are net-textured and form a layer 4 m thick above the massive sulphides. Net-textured sulphides also occur locally along the pyroxene-rich peridotite underlying the massive sulphide zone. In the peridotite, sulphides define 2 to 5 cm wide layers separated by barren peridotite.

Massive sulphides are fine grained, with pyrrhotite defining a granular mosaic. Pentlandite anhedra and "eyes" occur between grains of pyrrhotite and rarely as exsolution lamellae in the latter. Chalcopyrite is uncommon, but where present is associated with pentlandite embayments into pyrrhotite. Chalcopyrite also forms 2 mm, or thinner, layers at the base of the massive sulphides.

Barnes and Naldrett (1987) present 34 analyses of samples from the Alexo deposit; maximum values attained were: 9.6% Ni, 0.8% Cu, 0.3% Co, 1316 ppb Pt, 4905 ppb Pd, 397 ppb Rh, 764 ppb Ru, 104 ppb Ir, 69 ppb Os, 455 ppb Au.

3.1.7.7. Sothman Deposit

The Sothman deposit is in southeastern Sothman township, 72 km south of Timmins (Figure 3.35). The deposit was discovered in 1950 by prospectors working for Dominion Gulf Company who located nickeliferous float on the property. Subsequent geophysical surveys and geological maping led to the drilling of 37 holes, which outlined a mineralized zone 48 m long, 2 m wide and 84 m deep with a 1.4 percent nickle and minor copper (Coad 1979).

The deposit is situated on the south limb of an anticlinal dome structure, the "Halliday Dome". Sulphides are hosted by an ultramafic sill that forms a belt outlining the edge of the dome, and which plunges steeply to the west. The core of the dome is underlain by dacitic to rhyolitic metavolcanic rocks of the Deloro Group. The peripheral ultramafic rocks may be correlative with those of the Timmins area (Coad 1979). Locally, spinifex textures have been described in peridotite at the edge of the dome (Coad 1979).

The ultramafic sill, has peridotitic margins and a dunitic core. The sill is 4 km long and 200 m wide, strikes east and dips steeply south. Cumulate textures are locally preserved in drill core from the centre of the intrusion with olivine forming equant, 1 mm diameter grains. The sill is cut by gabbro dikes. Footwall rocks consist of felsic metavolcanic rocks, breccia and tuff (Figure 3.35). Amygdaloidal basalt occurs locally and is usually mineralised with disseminated pyrite, pyrrhotite and colloform marcasite.

Nickel-sulphide mineralisation occurs in net-textured form along footwall embayments. Three separate sulphide lenses have been described along the footwall contact (Watkins 1972). The sulphide lenses are 10 to 11 m in width, up to 360 m long and reach depths of 180 m. Mineralised zones also

occur 3 to 5 m above the basal contact of the sill. The deposit is estimated to contain 210,000 tons of 1.29 percent nickel (Coad 1979).

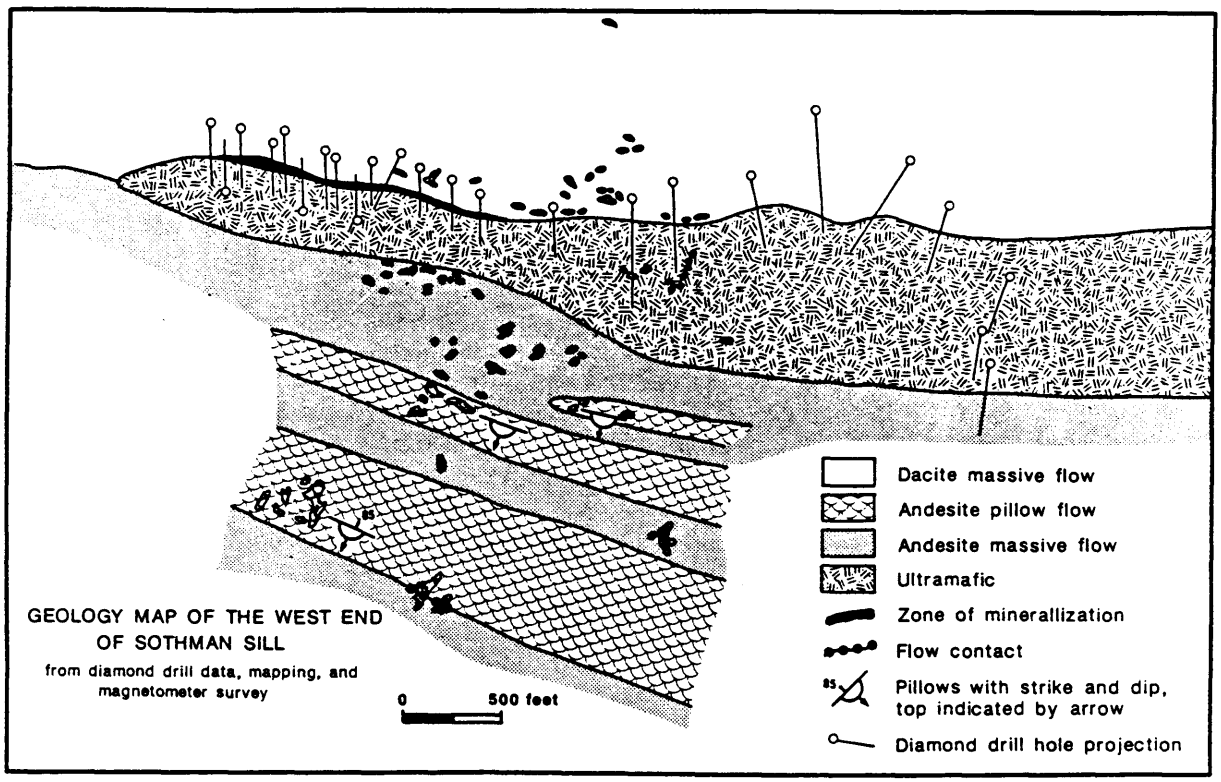


Figure 3.35 : Geological map of the Sothman deposit (Watkins 1972).

The sulphides include pyrrhotite, pentlandite, violarite and chalcopyrite. Pentlandite often forms exsolution lamellae in pyrrhotite or small anhedra interstitial to olivine. No PGE values have been reported from this deposit.

3.1.7.8. Kanichee Deposit

3.1.7.8.1 Geology and mineralisation

The Kanichee deposit (also known as the Cuniptau Mine) is located within the Temagami greenstone belt, a southern extension of the Abitibi Subprovince, about 7 km northwest of the town of Temagami (Figures 3.36, 3.37). The deposit was first described by Knight (1920) as a 90 m by 25 m gossan zone at the northern end of the intrusion. Intermittent work was done at the deposit starting in 1910 (Bennett 1978), and most recently by Ajax Minerals Ltd. from 1972 to 1975 when an open pit was developed (James and Hawke 1984). Sandefur (1943) described the geology and ore paragenesis, Cabri and Laflamme (1974) examined mineral chemistry of vein sulphides and Naldrett et al. (1979) and Naldrett (1981) described Au and PGE in samples with a range of textures. More recently, detailed work on surrounding greenstone belt stratigraphy, petrology and geochemistry has been performed by Johnston et al. (1986), Borne et al. (1986) and James (1986).

The layered intrusion has a length of approximately 1050 m and a width of about 730 m with a roughly northwest trend. The dominant magmatic layering strikes approximately northeast. The intrusion consists of five cycles of dunite to gabbro; a quartz gabbro body, south of the main intrusion, is included within cycle five (Figure 3.37; James and Hawke 1984). Cycle one, of enigmatic relationship to the stratigraphically overlying cycles, consists of peridotite and includes the sulphide zone at the north end of the intrusion (Figure 3.38). Cycle two is clinopyroxenite and cycle three is initially an olivine-rich peridotite which evolves upwards to peridotite. Dunite marks the beginning of cycle four and is also capped by peridotite. Cycle five is the most complete, commencing with dunite and fractionates to peridotite, clinopyroxenite and finally olivine gabbro (Figure 3.37). Quartz gabbro to the south, is in fault contact with the main intrusion and its exact relationships are uncertain. Mafic dikes intrude parts of cycles one and two, that comprise the "keel" at the northern end of the southeastward-plunging intrusion (Figure 3.38).

Mineralized peridotite (Figure 3.38) consists of disseminated to net-textured sulphides consisting of pyrrhotite, chalcopyrite, pyrite and pentlandite, together with magnetite within olivine cumulates. Cycles above this contain small amounts of disseminated sulphides and chromite, which occur predominantly in dunites that mark the beginning of each cycle. Cumulus chromite in dunite, is enclosed by olivine and rapidly decreases in abundance from dunite into overlying peridotite. Cumulate rocks at the base of the intrusion exhibit pervasive alteration, contrasting with overlying cycles. All ultramafic rocks are serpentinized to some extent, but those of cycle one contain considerable talc, carbonate minerals and chlorite, developed at the expense of serpentine (James and Hawke 1984). Alteration minerals commonly pseudomorph primary silicate phases and are also found as veins in rocks of cycles one and two.

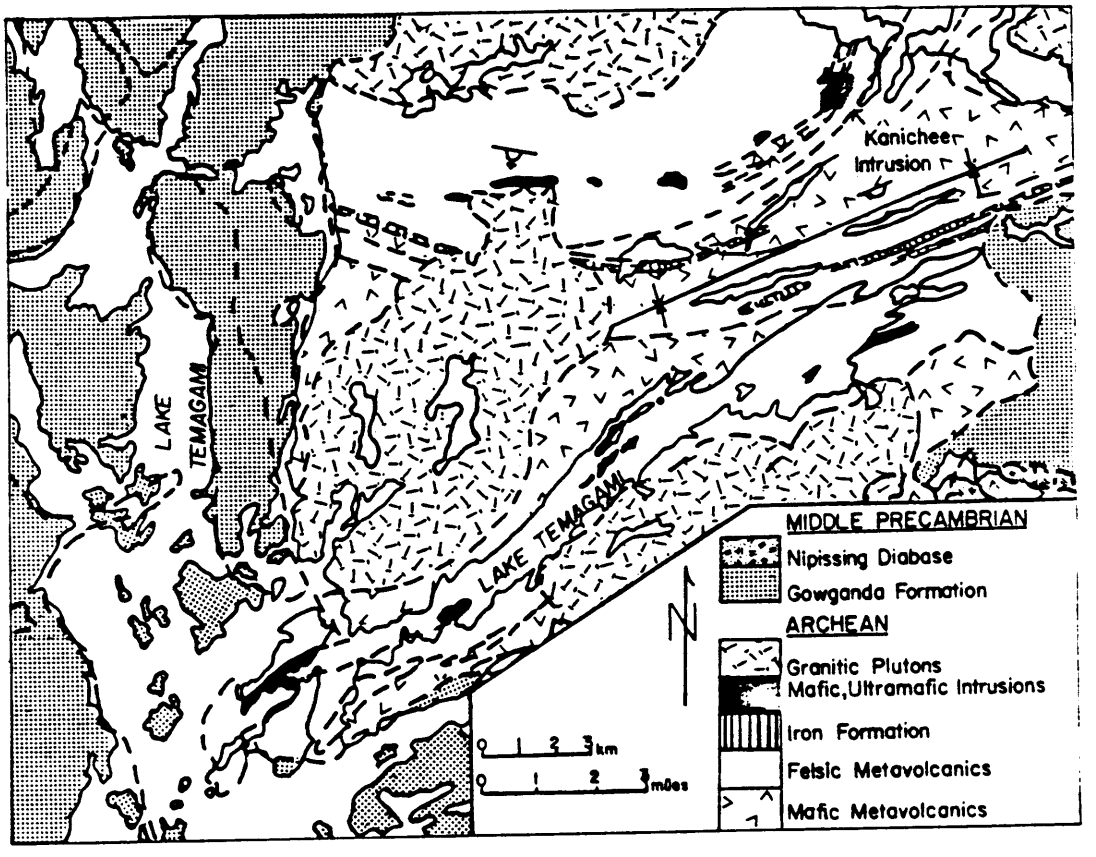


Figure 3.36 : Regional Geological map of the Temagami area showing the location of the Kanichee Layered Intrusion (after James and Hawke 1984, based on Bennett 1978).

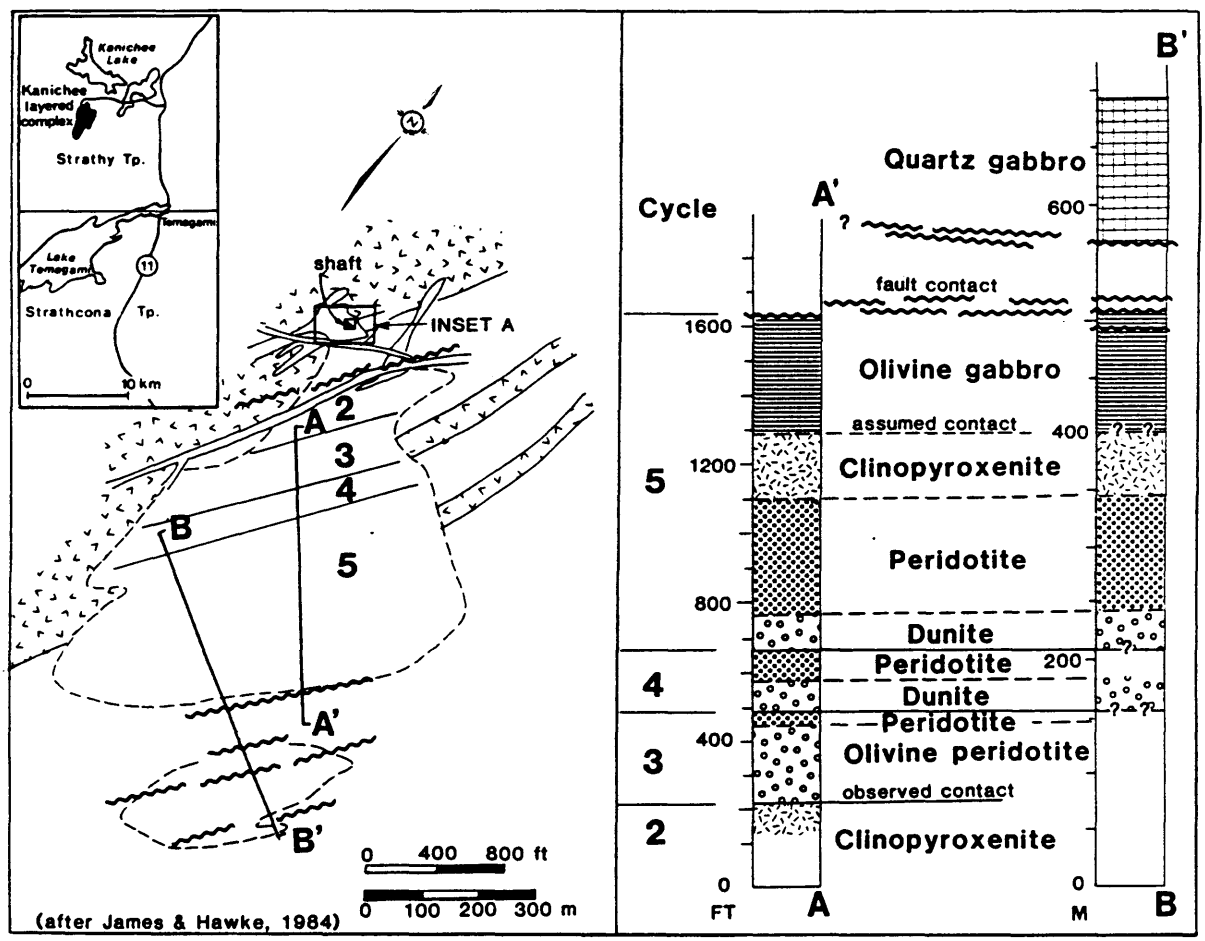


Figure 3.37 : Geological map and idealised section, showing five cycles in the Kanichee layered complex. (after James and Hawke, 1984).

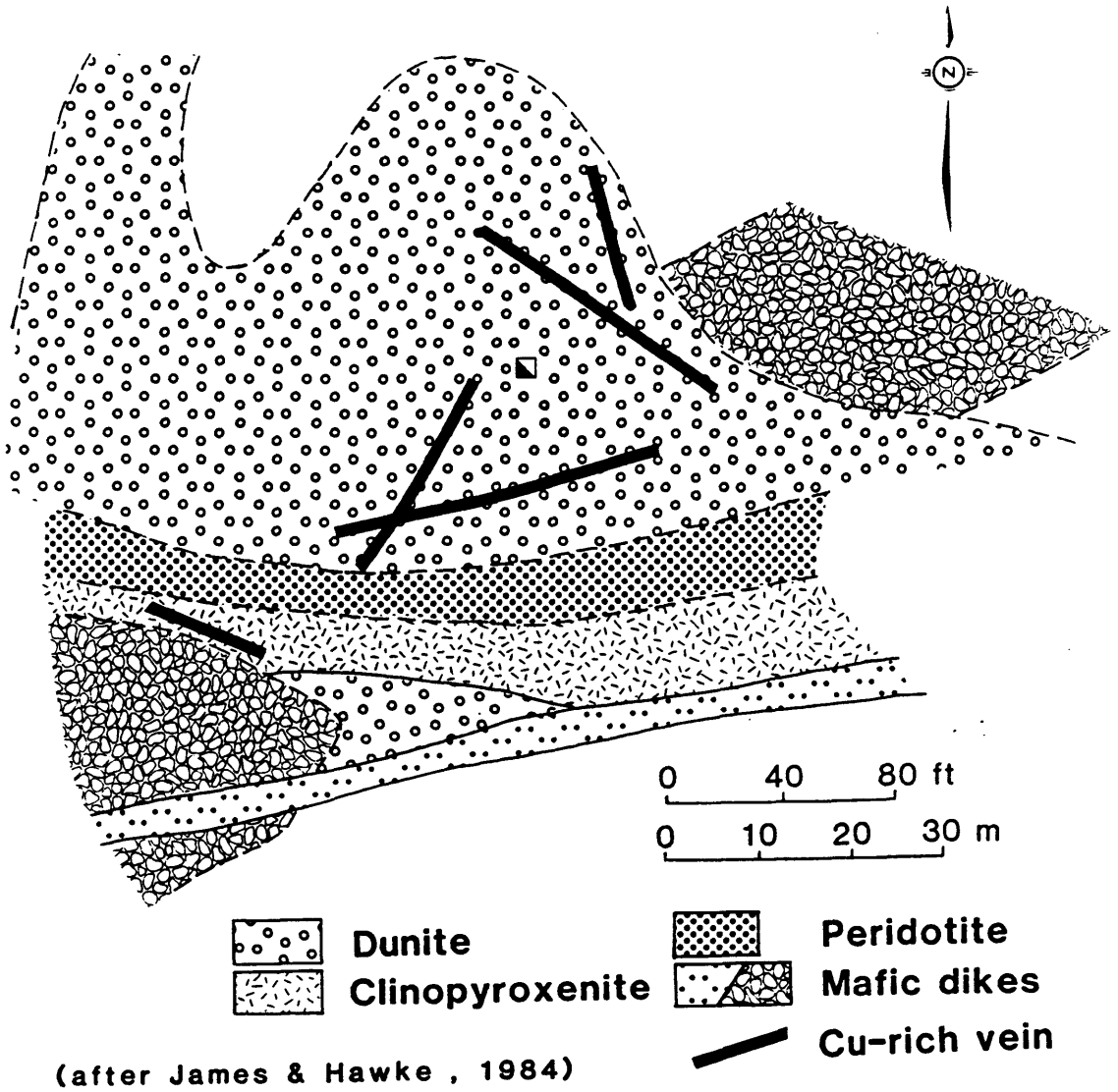


Figure 3.38 : Simplified geological map of cycle 1, Kanichee layered intrusion (after James and Hawke 1984).

Disseminated sulphides contain nickel, copper and iron throughout olivine-rich cumulates of all five cycles. In the upper 4 cycles, background contents of {Cu + Ni} are 0.2 to 0.5 wt. %, whereas the sulphide deposit in cycle one typically contains about 0.5 to 1.09 wt. %. Least altered parts of mineralized peridotite contain irregularly shaped and sized patches of net-textured sulphides, generally from 2 to 4 cm in diameter. Net-textured patches define a poikilitic texture consisting of pyrrhotite, chalcopyrite, pentlandite and magnetite enclosing an open framework of serpentinized olivine grains. In mineralized peridotite, with intermediate degrees of alteration, there is extensive talc development and minor carbonate at the expense of pre-existing serpentine. Net-textured sulphides remain recognizable in these rocks. In the most altered peridotite, with highest {Ni + Cu} grades, talc and carbonate are pervasive and the rock is cut by hairline fractures, which has produced an anastomosing network of chlorite, dolomitic carbonate and occasional talc veinlets. Sulphide veins and stringers are often associated with the anastomosing veinlets (James and Hawke 1984).

The sulphide-carbonate-quartz veins, the principal target during mining in the 1970's, are confined to mineralized peridotite at the north end of the intrusion (Figure 3.38). Veins are up to one metre wide with lenses of massive chalcopyrite, pyrite and pentlandite. Some sulphide lenses show crude layering with 2 to 5 cm thick layers approximately parallel to vein walls. Veins are usually bordered by an alteration assemblage of tremolite, chlorite or talc. In contrast to the zone of disseminated sulphides where pyrrhotite is most abundant, chalcopyrite is the predominant sulphide in the vein sulphide assemblages. R.S. James (Professor, Department of Geology, Laurentian University, Sudbury, Ontario, personal communication, 1986) has suggested that the vein assemblage represents reconstituted sulphides from the disseminated sulphide zone in the adjacent peridotite.

Platinum group elements are associated with both disseminated and vein-hosted sulphides in mineralized peridotite (James, Profesor, Department of Geology, Laurentian University, Sudbury, Ontario, personal communciation, 1986). Copper sulphide-rich veins have significantly higher PGE contents than adjacent disseminated sulphides. Platinum and palladium contents are highest, with lesser contents of the other PGE. In addition to the vein asociation, Pt and Pd show increases from least altered mineralized peridotite (Pt + Pd : 500 ppb total), through altered peridotite (Pt + Pd : 2,600 ppb) to vein hosted sulphides (Pt + Pd: 76,500 ppb, all values approximate). In addition to increases in PGE values, copper also becomes increasingly enriched from less than 0.5 wt. % in unaltered peridotite to about 1 wt. % in altered peridotite and about 20 wt. % in vein sulphides (James, Professor, Department of Geology, Laurentian University, Sudbury, Ontario, oral communication, 1986).

It is proposed that the Kanichee layered complex is an Archean synvolcanic intrusion with well-developed magma cyclicity (James and Hawke 1984) and represents an environment in which significant PGE concentration occurred. Layering in intrusions of this sort is an indication that cumulate processes have played a role during crystallization; in the lower parts of intrusions such as this, intercumulus sulphides may form.

At the Kanichee deposit PGE values in disseminated sulphides of cycle one are relatively low (500 ppb). A further concentrating process is required to upgrade PGE values to ecnomically interesting levels. Alteration of peridotite to a talc-carbonate assemblage reflects a hydrothermal process perhaps capable of concentrating PGE, as indicated by the higher PGE values in

altered peridotite. Hydrothermal alteration is carried to a further extreme in the cross-cutting veins, where, talc- and chlorite-rich, haloes to carbonate-quartz-sulphide veins contain the highest PGE values. PGE-enriched sulphides in veins are restricted to veins cutting the mineralized peridotite of cycle one, possibly suggesting that the PGE source was from the adjacent peridotite containing disseminated sulphides. In addition to PGE enrichment, copper also increases in concert with intensity of alteration and could be used as an indicator of PGE potential. In the Kanichee example, areas of alteration and veining, with associated sulphides, are of principal economic interest with respect to higher grade PGE potential. Larger tonnage, low grade deposits may occur, associated with primary, disseminated magmatic sulphides, whereas higher grade deposits can be associated with rocks that have experienced secondary, hydrothermal concentrating processes.

3.1.7.9. Exploration Guidelines

Although these deposits in the Abitibi Greenstone Belt were initially of interest for nickel, their association with ultramafic host rocks and in some cases with chromite, suggests that there exists a potential for economically interesting PGE contents. Two deposit types are represented by sulphides in komatiitic rocks. The first of these is sulphide associated with basal portions of komatitic flows (e.g. Langmuir, Texmont and Hart deposits). These deposits represent accumulations of immiscible sulphides within paleotopographic depressions over which the flows passed (e.g. Green and Naldrett 1981). The second type of deposit involves a similar sulphide concentration into depressions in the basal contact, but this time in sill-like bodies, some of which are zoned from peridotite margins to dunitic cores (e.g. McWatters, Alexo and Sothman deposits). These may also have been thick or ponded komatiite flows that underwent mechanical flow differentiation to form peridotite margins and dunitic cores.

A third PGE-bearing deposit type in the Abitibi Subprovince, is exemplified by the past-producing Kanichee Mine, at Temagami. High PGE potential in this environment may occur with both massive and disseminated sulphides. Areas where any evidence for hydrothermal alteration modifying primary magmatic sulphides (e.g. Kanichee) would also be of interest. Sulphide-bearing (e.g. Langmuir) komatiitic rocks are found typically in the lower stratigraphic levels of the greenstone belts; exploration for deposits of this type should therefore incorporate a sound understanding of volcanic stratigraphy.

3.2. PROTEROZOIC MAFIC/ULTRAMAFIC SUITES

3.2.1. NIPIGON PLATE (A.J. Macdonald)

Middle Proterozoic (1109 ± 2 Ma, Davis and Sutcliffe 1985) picritic intrusions and tholeiitic diabase dikes, sheets and sills of the Nipigon Plate (Stockwell et al. 1972) have been described recently by Sutcliffe (in press). The rocks intrude the late Precambrian epicontinental clastic sediments of the Sibley Group (Franklin et al. 1980), which overlie Archean and Middle Proterozoic basement. Sutcliffe (1984) has suggested that the Nipigon Plate reflects a failed arm, or aulacogen, during Keewatin rifting.

The rocks of the Nipigon Plate have not to date provided fertile 'hunting ground' for the PGE. One of the only showings described to date is found in Dorothea Township, on the eastern shore of Lake Nipigon, in a structure termed the Beardmore Cone Sheet by Sutcliffe (in press). Mackasey (1975, p.38) described finely disseminated pyrite and chalcopyrite in an outcrop of medium-grained diabase along the Little Lake River. The diabases of the Nipigon Plate have been informally referrred to as the Logan Sills (Stockwell et al. 1972). Mackasey (19765) reported the results of an assay of the diabase-hosted sulphides: the rock contained traces of copper, nickel and palladium, but undetectable Pt. Interestingly, the Little Lake River occurrence is located in the vicinity of a prominent 110° linear feature, which Mackasey (1975) attributed to an expression of the Paint Lake Fault (PLF). The PLF is a major structure in the Beardmore area, separating the Archean Tashota greenstone terrane in the north from the Archean Beardmore-Geraldton greenstone terrane in the south (Williams 1986). The PLF is also an important control on mineralization in a number of gold deposits, most notably the Brookbank deposit, currently being explored by Metalore Ltd. (Lavigne, Geologist, Ontario Geological Survey, personal communication, 1983). The PLF is considered to be an Archean feature (e.g. Williams 1986) which may therefore, have been re-activated during or after the mid-Proterozoic, such that the Logan Sills at Little Lake River were influenced by faulting. It is possible that fluids, focussed in the fault zone, deposited sulphides with trace attendant Ni, Cu and Pd within the mafic host.

3.2.2 NIPISSING DIABASE

3.2.2.1 General Discussion (G.C. Wilson)

Tholeiitic diabase sheets and related intrusions of late Archean to late Proterozoic age occur in a broad band across the Southern Province of Ontario. The widespread occurrence of basic hypabyssal intrusions emplaced in this epoch extends from Temagami in the east, past the prominent exposures in the Nipigon area, as far west as Lake of the Woods. The Nipissing diabase intrusions *sensu strictu* intrude the Southern Province and its environs between the Cobalt Embayment in the northeast, southwards to Sudbury and westwards to Sault Saint Marie. A recent, precise age date for diabase in the Cobalt-Gowganda area is *circa* 2220 Ma (Corfu and Andrews 1986). Sills may be several hundred metres thick, with quartz diabase contact zones, central hypersthene diabase zones (with both quartz- and olivine- bearing facies) and felsic differentiates. The mafic rocks may be sheared and altered, contain felsic segregations, and be cut by aplitic dykes. Quartz veining may contain carbonates, sulphide and gold (Thomson and Card 1963). In the Elk Lake area

values of Au, Co and Cu are associated with thin aplitic intrusions within the diabase (Johns 1986, p.49). Bornite, chalcopyrite and specular hematite occur in carbonate veins within western Tudhope township, usually associated with aplite (Johns 1986, p.55). Carbonate-rich veins with Cu sulphide containing Cu, Co, Ni, Pb, Ag and Au values in showings near Temagami (Simony 1964, pp.21-23) exemplify interesting occurrences for which no PGE data are reported.

In the Cobalt district, sheets of the Nipissing Diabase reach a maximum thickness of 335 metres. Plagioclase compositions in chilled zones generally cluster quite narrowly around An_{55}, although some chills are albitized. Primary minerals in the gabbro include plagioclase, two pyroxenes, quartz, minor biotite associated with Fe-Ti oxides, and other accessory phases (Dressler 1979, pp.21-24). Since the mineralogy of the Nipissing diabase is well-documented (Hriskevitch 1968, Jambor 1971a, Finn 1981) it is not necessary to discuss here all details of the primary mineralogy. Amphibole is ubiquitous throughout the diabase, except for albitized marginal zones where chloritization is complete. Uralitization of pyroxene tends to be more advanced in the lower quartz diabase than in overlying hypersthene diabase. Secondary 'uralitic' amphibole and primary amphibole both increase upward from the central zones into the most felsic differentiates. One locality in Henwood township (Thomson 1966, pp.23-25) has been described in which 'normal' fine-grained marginal quartz diabase, along the lower contact of a sill against Huronian Lorrain Formation sediments, is overlain by a layer in which apparent deuteric ('autometamorphic') alteration has led to albitization of gabbro and production of prehnite, pumpellyite and calcite. A diabase from the Cobalt area is illustrated in Figure 2.5A.

Conrod and Naldrett (1985) have described Nipissing diabase intrusions at Portage Bay and Cross Lake (Cobalt area) and at Bonanza Lake (south of Lake Wanapitei). These also contain granodioritic to granitic differentiates. Numerous analyses and observations on the diabase and associated mineralization in the area to the west of Cobalt are given by Card et al (1973). They noted evidence for differentiation; settling of orthopyroxene primocrysts, and local igneous layering. A differentiation trend from early pyroxene-rich mafic rocks to late granophyric rocks describes the common arc across an AFM plot (see e.g. Cox et al 1979). 29 whole-rock analyses (Card et al. 1973, pp.42-43) indicate that Ni and Cr are concentrated in the pyroxene-rich (earlier) lithologies.

It is thought that Nipissing intrusions both remobilized metals within sedimentary host units and also assimilated material into the upper portions of sill-like intrusions (Innes and Colvine 1984). This latter process has been invoked by Mainwaring and Naldrett (1977) for the Water Hen intrusion of the Duluth Complex, in Minnesota, U.S.A. A characteristic alteration in both metavolcanic and metasedimentary country rocks within 100 metres or so of the diabase manifests as the development of chloritic spots. Significant fluid flow must have surrounded the cooling intrusions in order to support this large volume of (pre-ore) contact alteration (Jambor 1971b). Most chilled marginal material is also extensively altered (Jambor 1971c). Wallrock alteration and silver-carbonate veining occurred after much or all of the cooling of the host diabase (see e.g. Andrews et al 1986a).

Within the Cobalt area diabase displays variable grainsize throughout exposures possessing the same mineralogy (Hriskevich 1968), similar to features noted by Macdonald (1985) in Archean rocks at Lac des Iles. These 'varied textured' zones may display development of granophyre, and occur below

the quartz diabase of the upper contact. Quartz and micropegmatite may comprise up to 6% of the rock; apatite needles occur, and the plagioclase is 'invariably at least partially altered to white mica, epidote, and zoisite' (Hriskevich 1968). The varied-texture diabase is intruded by diabase pegmatite. This mafic pegmatite is not abundant, is largely confined to the varied-texture zone, and shows generally sharp but not chilled margins against the diabase host (Jambor 1971a, p.47). Granophyre is also commonly present in the varied-texture masses, containing abundant fine-scale intergrowth of quartz and K-feldspar. Ilmenite and magnetite may be common accessories in the varied-texture zone, quartz diabase occurs within and the granophyre is locally radioactive relative to the remainder of the sill (Owsiacki and Lovell 1984, pp.39-41).

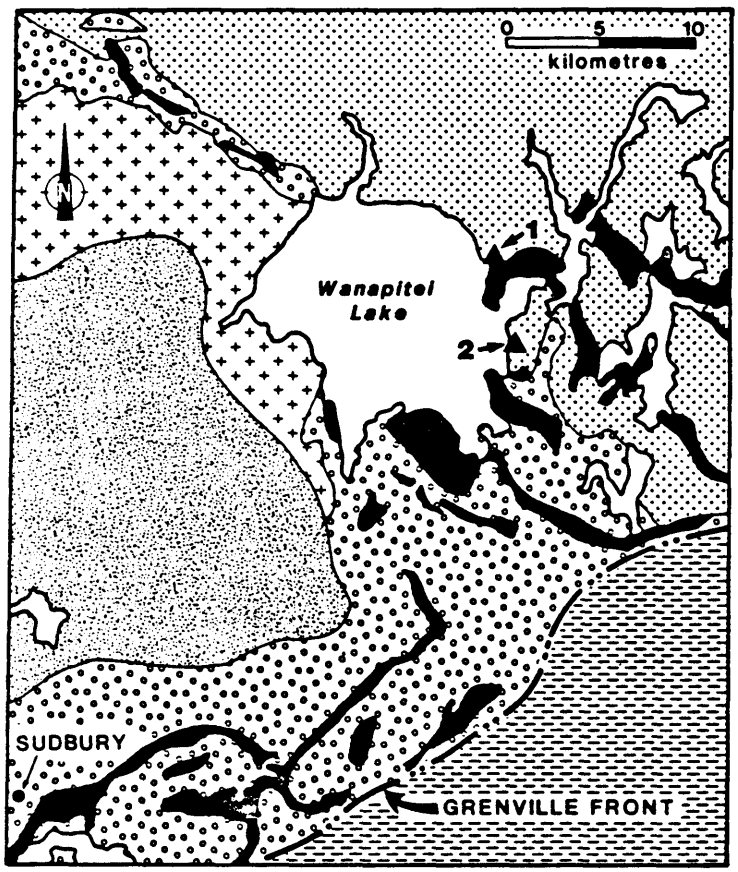
All phases of the diabase contain minor quantities of opaque phases (Jambor 1971a), locally rising to several percent of the mode in some pegmatitic and granophyric diabases. Ilmenite is the dominant phase in the central hypersthene diabase, but titanomagnetite with exsolution lamellae of ilmenite are more abundant toward the margins. Oxide does not generally exceed 1 percent of the mode, and sulphides are usually present only in trace amounts. Brown biotite is a minor component throughout the diabase, implying relatively hydrous conditions in late crystallization. P_2O_5 must also have been enriched in the late-stage volatiles, inasmuch as the peak abundance of apatite is in pegmatitic and granophyric diabases. Fractional crystallization generally produced normal differentiation trends, with the Wanipitei Intrusion a notable exception (Finn 1981).

The major platiniferous outcropping of the Nipissing suite discovered to date is the Wanapitei intrusion northeast of Sudbury (Finn et al 1982, Dressler 1982, pp.29-63), a gabbronorite mass with felsic differentiates in its upper levels. This is described in detail by Dressler et al. (Section 3.2.2.2), and only a brief resume is given here. A small sulphide lens at Rathbun Lake (the Burton Prospect of Shklanka 1969, pp.260-261), carries very high (ounce/ton level) Pt and Pd values in Ni-Cu ore; Pd is concentrated into tellurides (bismuthian merenskyite and lesser amounts of kotulskite, michenerite and temagamite), whereas Pt primarily in the arsenide sperrylite (Rowell and Edgar 1984, 1986). Rowell and Edgar (1983) found that PGE enrichment in the Wanapitei intrusion was confined to the sulphide-bearing gabbronorite samples, implying that the small sulphide-rich targets had to be sought, and that whole-rock analyses from elsewhere in the intrusion would be no clue to the nearby mineralization.

Finn et al (1982) concentrated upon the Wanapitei intrusion and the possible economic aspects of its gabbronoritic geology. In order to explain the reverse differentiation trend of the intrusion they postulated mixing of magma injections from one or more subsidiary magma chambers.

In the Sudbury-Espanola area to the west, auriferous quartz veins occur in metasediments, and at or near the contact with Nipissing diabase and/or amphibolite intrusions. The mineralized showings may exhibit carbonatization, silicification, sulphides and chloritic alteration, a common Au signature seen in many areas, including parts of the Grenville province (Section 3.2.6). One prospect with PGE values is located in central Curtin township (study by F.H. Toews, in Meyer et al. 1986, p.260). A steeply dipping, sill-like body of Nipissing diabase intrudes Gowganda Formation sediments, and PGE and Au values are reported to be associated with sulphides in an area of brecciated and sheared rocks. Disseminate pyrrhotite, chalcopyrite and pyrite are associated with brecciated rocks, and the copper sulphide fills fractures within the

gabbro. Elsewhere Thomson (1966, p.38) noted chalcopyrite-rich carbonate veining in fractured diabase. Results of exploration for Cu-Ni sulphide deposits in an area east of Sudbury are described by Dressler (1979); discernible carbonatization occurs in some showings, but as usual the older data never include PGE assays.



PGE OCCURRENCES

1. Rathbun Lake Occurrence
2. Flag Resources Southern Boundary Showing (approx. location)

Figure 3.39 : Geological Map of the area around the Sudbury Igneous Complex

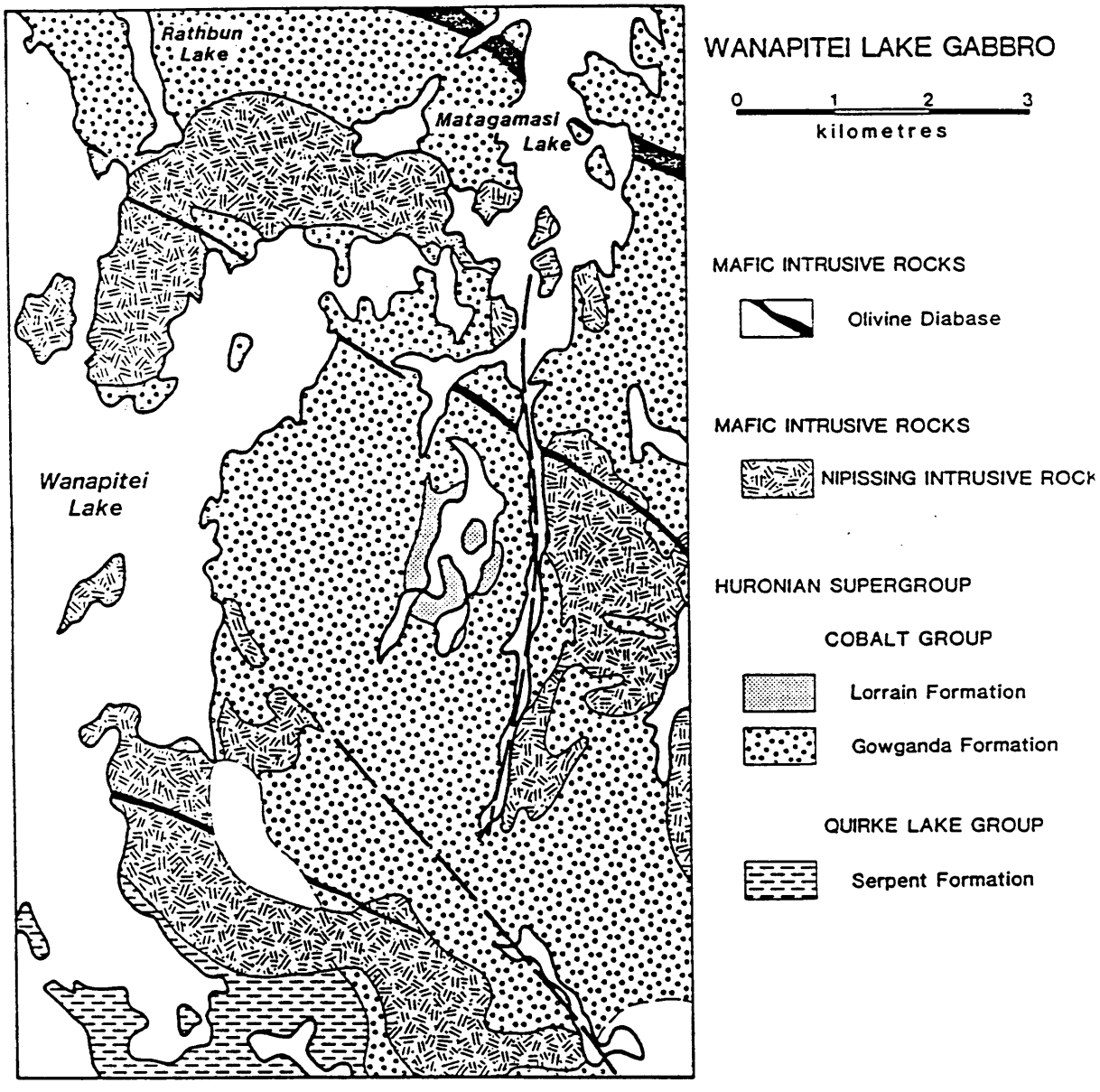


Figure 3.40 : General Geology of the Wanapitei Lake Nipissing Gabbro Intrusion

3.2.2.2 The Rathbun Lake PGE Occurrence (B.O. Dressler, W.F. Rowell and A.D. Edgar)

Exploration for platinum group element (PGE) mineralization associated with Nipissing Diabase to date has been very limited. The potential for economic discoveries, however, exists, as indicated by two PGE occurrences in Nipissing Diabase east of Sudbury and Wanapitei Lake (Figure 3.39). One occurrence is associated with a shear zone and is presently being explored by trenching and diamond drilling (M. McLeod, Flag Resources, June 1986, personal communication). Surface mineralization, within the shear zone, yielded up to 200 ppb platinum and 1950 ppb palladium.

A second occurrence east of Wanapitei Lake in the district of Sudbury is known as the Rathbun Lake occurrence. It has been tested by geological and geophysical methods and by diamond drilling. Its geology has been the subject of several detailed investigations (Finn, 1981; Dressler, 1982; Rowell, 1984; Edgar, 1986; Finn and Edgar, 1986; Rowell and Edgar, 1986).

3.2.2.2.2. General Geology

The Lake Wanapitei Nipissing Gabbro Intrusion (Dressler, 1982) is open ring-shaped and located east of Wanapitei Lake in Rathbun and Scadding Townships. The Rathbun Lake occurrence is at the northwestern boundary of the intrusion, (Figure 3.40) which is a two-pyroxene gabbronorite of tholeiitic composition. Its mineralogy and chemistry do not differ from other Nipissing gabbros and Dressler (1982) published 32 modal analyses obtained from the intrusion, which are summarized in Table 3.9.

Table 3.9: Modal Composition of Nipissing Gabbronorite Hosting PGE Mineralization at Rathbun Lake.

	Mean (n=32)	Range	S.D.
Quartz	6.7	trace - 23.8	5.49
Plagioclase[1]	47.5	39.8-55.3	4.56
Orthopyroxene[2]	2.1	0.0-12.0	4.32
Clinopyroxene[2]	5.8	0.0-35.5	8.74
Amphibole[3]	25.2	0.0-49.9	16.34
Granophyre	trace[4]		
Biotite	1.8	0.0-16.9	3.38
Chlorite	8.4	0.0-48.5	13.75
Epidote	16.8	0.0-42.7	15.3
Apatite	trace		
Titanite	trace		
Opaque Minerals[5]	1.5	0.0-3.75	1.0

1) Little altered plagioclase only.
2) Commonly altered, many samples therefore without pyroxene
3) Mainly actinolite after pyroxene
4) In places only
5) The one ore sample analysed contained 42.4% opaque minerals

Dressler (1982, Figure 8, p.44) has shown that, in general, the gabbronorite intrusion is least altered at its base, around the periphery of the intrusion, and that sericitization and epidotization are pervasive towards the top of the body. This pervasive alteration is believed to be of deuteric and not of metamorphic origin. The hydrothermal, deuteric solutions that altered the upper portion of the gabbro body may also be related to the quartz veins, that, in places are auriferous, for example at the Crystal Gold Mine (Figure 3.40).

Dressler (1982) studied the geochemistry of the Lake Wanapitei Nipissing Gabbro Intrusion and, based on almost 100 whole rock and trace element analyses, established differentiation trends across the northwestern part of the gabbro body. From the base, MgO, Cu, Ni, and Co increase upwards. This behaviour seems to be in contrast to normal differentiation trends in a gabbro intrusion. However, an initial increase in the content of these elements near the base (i.e. the outer parts of the open ring-shaped body at Wanapitei Lake) of a sill is quite normal and has been observed in other mafic/ultramafic bodies, for example in the Stillwater Complex (Jackson 1961) and the Bushveld Complex (Cameron 1980). The origin of the reverse differentiation is attributed by Finn (1981) "*to the presence of a slightly differentiated auxillary magma chamber or chambers which are periodically tapped*". In the upper portion of the gabbroic intrusion at Wanapitei Lake the rocks behave 'normally' and the content of the above mentioned elements decreases. Dressler (1982) shows several clear differentiation trends within the gabbro body. Ni, Cu, Co, and MgO contents decrease, and Fe_2O_3, K_2O, and Na_2O contents increase eastward, i.e. upward. Figure 3.41 shows the variation of Ni and Cu within the intrusion. (For other variations see Dressler, 1982). PGE concentrations within the gabbro body outside the Rathbun Lake occurrence were too low for the laboratory techniques available in 1978-1980 and no attempt was made to map the distribution of the PGE within the intrusion.

Nickel and copper are somewhat enriched in the lower section of the intrusion (Figure 3.41), where the Rathbun Lake copper-nickel-PGE mineralization is located (Figure 3.40). Rowell (1984) studied the distribution of Pt, Pd and Au in the western margin of the intrusion and compared his results with average values for mafic igneous rocks (Parthe and Crocket, 1972). The Lake Wanapitei Nipissing Gabbro Intrusion appears to be somewhat enriched in Pt, Pd and Au (Table 3.10).

Table 3.10 : Pt, Pd and Au Values (in ppb) from the Western Margin of the Lake Wanapitei Nipissing Gabbro Intrusion (from Rowell 1984).

	Pt	Pd	Au
Average(n=62)	13	18	4
Range	<10-37	<2-110	<2-20
# of Analyses below d.l.	23 (d.l.<10 ppb)	5 (d.l.<2 ppb)	10 (d.l<2 ppb)
Average, Mafic Igneous Rocks	9	16	1.7

d.l. : Detection Limit

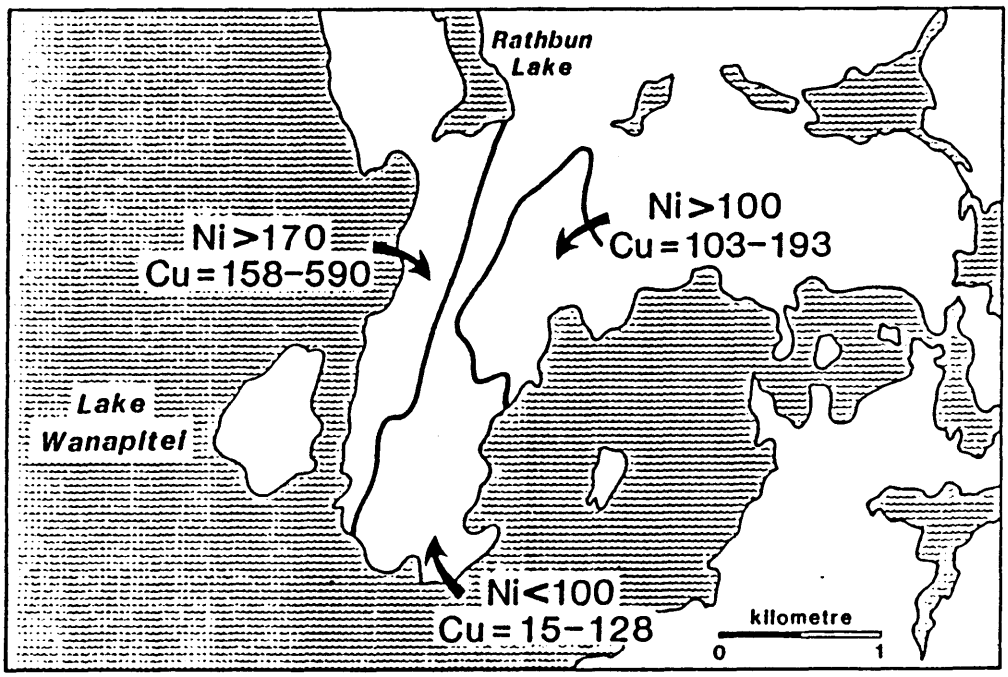


Figure 3.41 : Variation of Nickel and Copper (in ppm) within the Wanapitei Lake Nipissing Gabbro Intrusion.

3.2.2.2.3 Mineralization

The Rathbun Lake mineral deposit occurs at the lower contact of the Lake Wanapitei gabbronorite with wackes of the Gowganda Formation (Figure 3.40). An examination of the mineralization in place is no longer possible as most of the small deposit has been excavated and access to it, via a small abandoned, water and debris-filled shaft, is not possible. Samples from the shaft dump were studied by ore microscopy (Dressler 1982; Rowell, 1984), by electron microprobe and by geochemical methods (Koulomzine, 1955; Dressler, 1982; Rowell, 1984; Edgar, 1986). Koulomzine (1955) estimated the ore zone to be at least 12 m long; and in a report to Dolmac Mines Limited, Consulting Geologist M. Ogden (1957) described the orientation of the mineralized zone as perpendicular to the sediment-intrusion contact. The mineralization is hosted entirely within the intrusion and does not pass across the sediment contact. According to Ogden (1957) a fault zone possibly "*displaces the mineralization for perhaps some hundreds of feet*". About 60 m northeast of the shaft a chalcopyrite occurrence has been described by Ogden (1957) which possibly represents a displaced portion of the main occurrence.

Both massive and disseminated mineralization has been observed; in both types chalcopyrite makes up approximately 50-60% and pyrite 35-45% of the sulphides. Rowell (1984, published by Edgar 1986) reported several other ore minerals, namely millerite, violarite, arsenopyrite, magnetite, pyrrhotite and platinum group minerals. Covellite, molybdenite and gold were observed in trace amounts.

Pyrite occurs mainly in the massive sulphides and commonly contains small inclusions of chalcopyrite and magnetite, less commonly platinum group minerals and rarely gold. In massive sulphides chalcopyrite fills interstices between pyrite, in disseminations, and in tiny fractures. Millerite occurs as fine, anhedral grains, commonly associated with chalcopyrite. About 25% of the original millerite has been altered to violarite and in many places millerite is rimmed by violarite.

Platinum group minerals in the Rathbun Lake occurrence are merenskyite, kotulskite, michenerite and temagamite (Rowell and Edgar, 1986). Approximately 70% of 1252 grains of platinum-group minerals observed are merenskyite, 20% kotulskite and 5% each are michenerite and temagamite. Only one grain of sperrylite was identified optically and by electron microprobe analysis.

According to Rowell and Edgar (1986) 64% percent of the palladium minerals occur in the gangue, commonly in clusters of up to 40 grains. The remainder are found associated with sulphides, 18% at chalcopyrite-silicate interfaces, 7% as inclusions in chalcopyrite, and 11% as inclusions within pyrite.

Merenskyite (< 1 to 100 lm in diameter) contains minor Sb. Many of the larger grains are part of clusters in the gangue. Kotulskite (< 1 to 40 lm in diameter) has a large Sb content. About 50% of this mineral is associated with merenskyite and temagamite either in exsolution textures or composite grains. Michenerite ranges in size from 65 to 80 lm and occurs in small groups in the gangue. Temagamite grains are less than 20 lm in diameter (Rowell and Edgar, 1986).

In Table 3.11 the results of chemical analyses of ore samples reported by Koulomzine (1955), Dressler (1982), Rowell (1984), and Edgar (1986) are listed. Table 3.12 presents PGE and Au contents of chalcopyrite and magnetite concentrates and in Table 3.13 electron microprobe analyses of platinum group minerals from the Rathbun Lake occurrence are listed (Rowell 1984; Rowell and Edgar, 1986). In Table 3.14 (Rowell 1984) concentrations of PGE, Au, Cu and Ni in 100% Sulphide are presented.

Table 3.11: Ni, Cu, S, PGE, Ag and Au contents of Rathbun Lake Mineralization.

Sample	Ni	Cu	S	Pt	Pd	Rh	Ru	Ir	Os	Ag	Au
1	0.21	7.03	-	37028	25370					18857	12343
2	-	17.26	-	3017	32570					67815	69
3	0.50	5.51	-	13028	25370					10285	6857
4	0.11	19.92	-	720	5828					-	-
5	0.35	7.25	-	3086	18514					-	-
6*	0.29	1.31	-	2400	5486					-	-
7	0.22	19.9	23.4	1800	23000	17	<5	0.1	<3	-	250
8	0.22	9.1	19.4	74	35000	14	20	0.3	6	-	890
9	0.26	8.3	18.4	18000	37000	8	<5	0.3	11	-	1300
10	0.16	4.7	9.4	33000	19000	3	40	0.2	23	-	950
11	0.36	2.3	2.4	190	12000	23	15	28.0	3	-	2800
12	0.14	10.2	-	1920	118626	-	-	-	-	76113	686
Mean	0.25	10.13	14.6	10169	32025	13	25	6.3	10.7	43267	2905
S.D.	0.12	6.1	8.5	13573	30237	8	13	12	9	33492	4110

Data for Ni, Cu, S in Weight Percent, remainder in parts per billion
Samples 1-6:Dolmac Mines Limited (Koulomzine, 1955; original figures in ounces/short ton).
* Sample No.6 from mineralization SW of shaft; values not considered in calculating average.
Samples 7-11: Rowell (1984)
Sample 12: Dressler (1982; original values in troy ounces/short ton)

S.D. : Standard Deviation

Table 3.12 : PGE and Au Contents (in ppb) of 5g Chalcopyrite and Magnetite Separates (Rowell 1984; Edgar, 1986)

	Pt	Pd	Th	Ru	Re	Ir	Os	Au
Chalcopyrite	290	4800	7	<50	<5	<0.5	<10	300
Chalcopyrite	6300	12000	10	50	<5	1.2	23	370
Magnetite	<5000	1200	7	<50	5	180	<23	24000

Table 3.13 : Electron Microprobe Analyses of PGM from the Rathbun Lake Occurrence (Rowell, 1984; Rowell and Edgar, 1986). Values in Weight Percent.

	Pt	Pd	Bi	Te	As	Sb	Hg	Total
Sperrylite n=1	56.71	nd	nd	nd	42.73	nd		99.4
Kotulskite	0.3	36.5	17.7	33.9	nd	7.9		96.3
Range	nd - 0.6	32.6- 41.0	12.1- 19.5	27.4- 41.0		5.1- 18.6		
Temagamite	nd	34.0	0.3	40.4		1.5	20.3	96.6
Range		32.9- 34.4	0.2- 0.4	39.3- 40.9		1.0- 2.5	19.8- 20.8	
Merenskyite	nd	25.7	16.5	53.5		0.7		96.4
Range		23.3- 31.0	12.5- 20.4	49.3- 59.6		0.2- 2.2		
Michenerite	1.5	23.4	40.8	35.1		0.7		98.7
Range	1.5- 1.5	22.8- 24.0	40.6- 41.0	33.0- 37.2		0.6- 0.7		

Table 3.14 : Concentrations of the PGE, Au, Cu and Ni in Samples (100% Sulphide) from the Rathbun Lake Deposit

Ni	Cu	Pt	Pd	Rh	Ru	Ir	Os	Au
0.35	31	2826	36110	27	8	0.16	5	1444
0.48	20	163	76930	31	44	0.66	13	1957
0.61	19	41940	86210	19	12	0.47	26	3029
0.71	21	146850	84550	13	178	0.70	102	4227
5.0	32	2646	167160	320	209	390.0	42	39004

Ni, Cu in Weight Percent, remainder in parts per billion

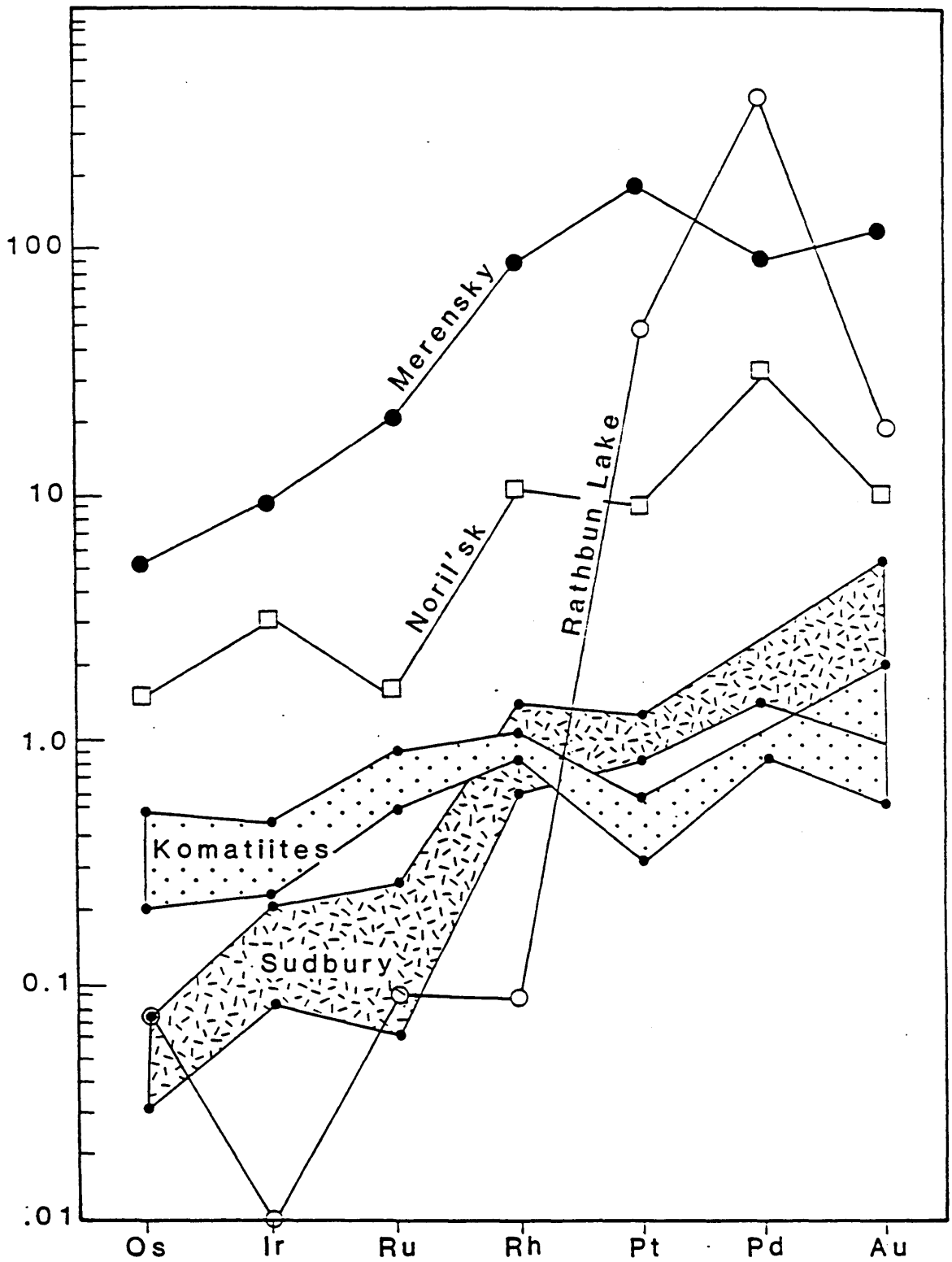


Figure 3.42 : Chondrite normalised values of platinum group elements and gold based upon values recalculated to 100% sulphide for the Rathbun Lake Occurrence relative to other PGE deposits (after Naldrett et al., 1980)

In Figure 3.42 (Rowell, 1984) chondrite normalized 100% sulphide PGE and Au values for the Rathbun Lake mineralization and other deposits are presented.

Dressler (1982) studied one thin section of gabbro host rock of the Rathbun Lake occurrence and three polished thin sections of the mineralization. The host rock exhibits a common gabbronorite mineralogy with an alteration index of 23 (Dressler 1982, p.44). An alteration index of 0 characterizes an unaltered sample, an index of 100 a completely altered rock. Dressler (1982) did not observe any pyroxene or amphibole in the gangue minerals of the mineralization and noted that plagioclase of the gangue appears to be little more altered (sericitized) than the plagioclase of the host rock. This observation is in disagreement with the observations by Rowell (1984) who describes very fine grains of somewhat altered, difficult to identify relicts of pyroxene making up less than one percent of the gangue. Rowell (1984) also describes a strong saussuritization of plagioclase. Other gangue minerals observed by Dressler (1982) are quartz, chlorite and traces of biotite. Chlorite appears to be the major alteration mineral.

3.2.2.2.4 Origin of the Rathbun Lake Mineralization

Dressler (1982) stated that the PGE-Cu-Ni occurrence at Rathbun Lake probably formed schlieren within the Nipissing gabbronorite. Dressler's microscopic observations and the lack of any obvious alteration of the wackes in contact with the mineralized gabbronorite, and the location of the deposit at the lower contact of the intrusion possibly indicates a magmatic origin for the sulphide deposit.

Rowell (1984), however, favours a hydrothermal origin and bases his interpretation on "*the spatial coincidence of altered gabbronorite and the altered ore body, the replacement of magmatic silicates by ore minerals, the abundance of pyrite and the extremely large {Pt + Pd}/{Os + Ir + Ru} ratio*".

Rowell and Edgar (1986) also favour a hydrothermal origin for the occurrence and state that the mineralization "*is located in an area of the Wanapitei intrusion where circulated fluids have altered the mineralogy of the host gabbronorite to chlorite, sericite, saussuritized plagioclase, epidote and biotite. Pt occurs primarily in sperrylite and Pd in bismuthotelluride minerals which are considered to be characteristic of low temperature hydrothermal deposition in other deposits*".

3.2.2.3 Summary and recommendations for exploration in Nipissing Diabase (G.C. Wilson)

Clearly the PGE-bearing outcrops of the Nipissing diabase intrusions are a relatively minor subset of the whole, unless the lure of the famed silver lodes has blinded eyes to subtler forms of mineralization since Fred LaRose's 1903 silver strike at Cobalt. Indeed, the calcite-dominated gangue and variable Ag-Co-Ni-Fe-As mineralogy of the silver veins (Petruk 1971) forms a distinctive target for the prospector. These veins are commonly less than 10 cm in width and carry distinctive petrographic clues in the sulphide mineralogy of their wallrocks (Goodz et al. 1986). Barren carbonate veins also occur; nevertheless, Ag deposits are a clear target, and have been the greatest single economic factor in the mining of an area which also has Cu and

U deposits in the vicinity of the diabase intrusions. In the case of platinum, given the Wanapitei intrusion as the one well-documented case, one might conclude that the ideal target is the largest, thickest intrusions, in localities cut by shear zones, and affected by quartz veining, carbonatization and other signs of alteration. An ongoing petrochemical study of the Nipissing Diabase (Lightfoot et al 1986, Conrod and Naldrett 1985) has not as yet found firm evidence for generation of large volumes of magmatic sulphides; any PGE may have been retained in the cooling melt to a comparatively late stage. Fractured (faulted, sheared, brecciated) diabase, particularly if copper-mineralized, should be assayed for Pt, Pd and Au, as should sulphidic pegmatites/pegmatoids (in the Bushveld sense; veins and patches), particularly if these also contain abundant biotite. Given the limited PGE results to date from an area so well prospected for silver, the chances of finding a small, hydrothermally-affected PGE concentration seem far better than those for a classical magmatic sulphide deposit.

3.2.3. PGE Mineralization Associated with the Sudbury Igneous Complex (B.O. Dressler)

3.2.3.1. Introduction and General Geology of the Sudbury Structure

The Sudbury Structure (Figure 3.39) hosts the largest known nickel-copper deposits on earth. Platinum group elements and gold are valuable by-products of the nickel-copper production and the mines in the Sudbury mining camp are the only present (1987) producers of platinum group elements in Ontario.

A geological sketch map of the Sudbury Structure is shown in Figure 3.43. Footwall Breccia, in places underlying the Sudbury Igneous Complex, and the breccias of the Onaping Formation are products of the "Sudbury event", an endogenic explosion or impact of a meteorite. The Onaping Formation is the lowermost unit of the Whitewater Group and is overlain by the mudstones of the Onwatin Formation and the wackes of the Chelmsford Formation. The Main Mass of the Sudbury Igneous Complex intruded along the lower contact of the Onaping Formation. Its age is 1850 Ma (Krogh et al., 1984). The Sublayer, the youngest phase of the Igneous Complex, lies at the lower contact of the Main Mass of the Complex and also forms more or less concentric or radial dikes, the so-called "offsets".

The ore bodies associated with the Sudbury Structure occur in the Sublayer, the Footwall Breccia and in footwall rocks close to the Igneous Complex. Both the general geology and the mineralization of the Sudbury Structure have been described in detail in a recent publication on the Geology and Ore Deposits of the Sudbury Structure (Pye et al. 1984). Most of the following summary account on the platinum group element mineralization in Sudbury is based on this publication.

3.2.3.2. Platinum Group Elements in the Sudbury Ores

The sulphide deposits of the Sudbury Complex, their geological setting, mineralogy and composition have been the subject of many investigations and publications by, amongst others, Hawley (1962), Hawley and Stanton (1962), Keays and Crocket (1970), Hoffman et al. (1979), Naldrett et al. (1979) and Naldrett et al. (1982). Naldrett (1984a) summarized much of the results of these investigations.

In 1985 Falconbridge Limited and INCO Limited produced platinum group elements at the Sudbury operations worth approximately $148,440,000. In Table 3.15 the 1984 and 1985 production and the total Ontario production since 1902 are listed. The estimated PGE reserve in the Sudbury Complex is 280 tonnes of the metals (Buchanan 1979).

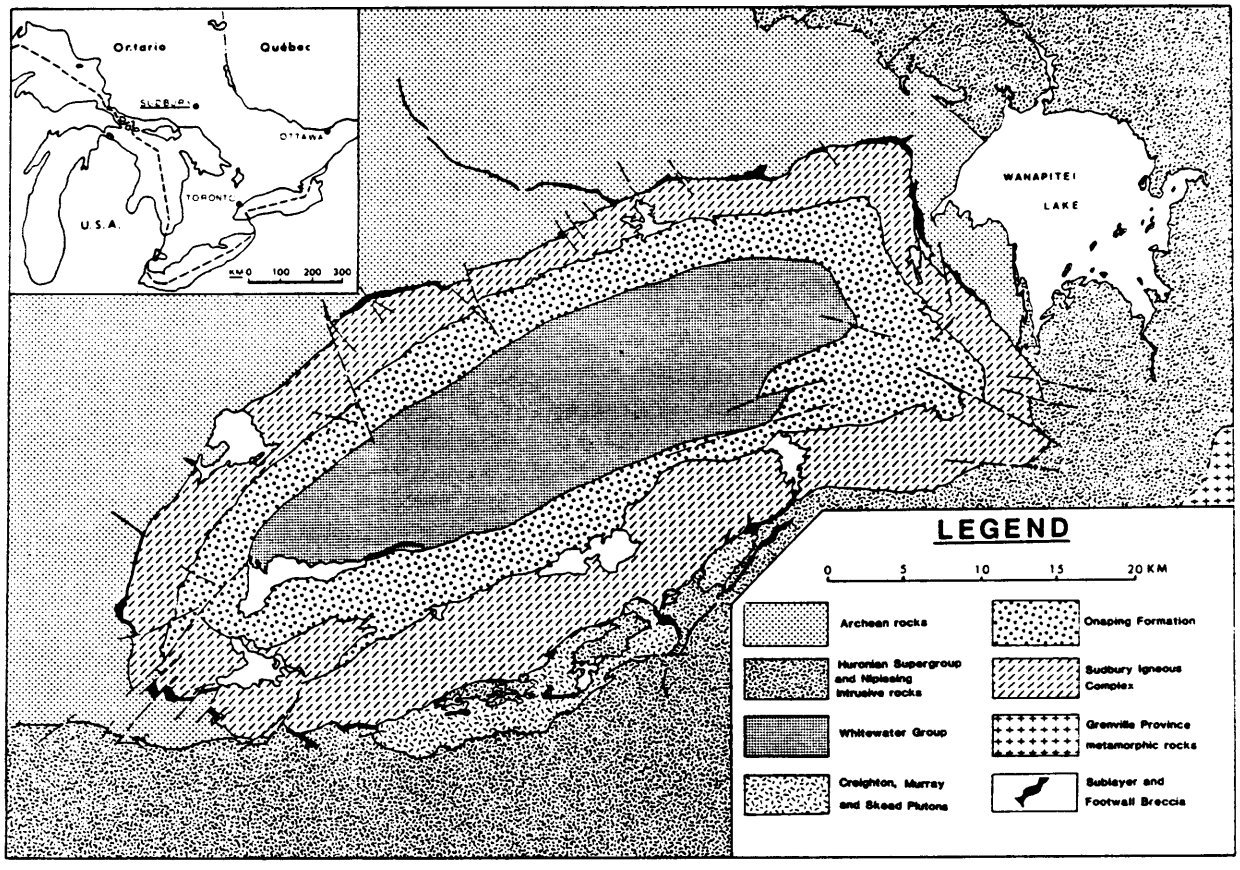


Figure 3.43 : Geological Sketch map of the Sudbury Structure.

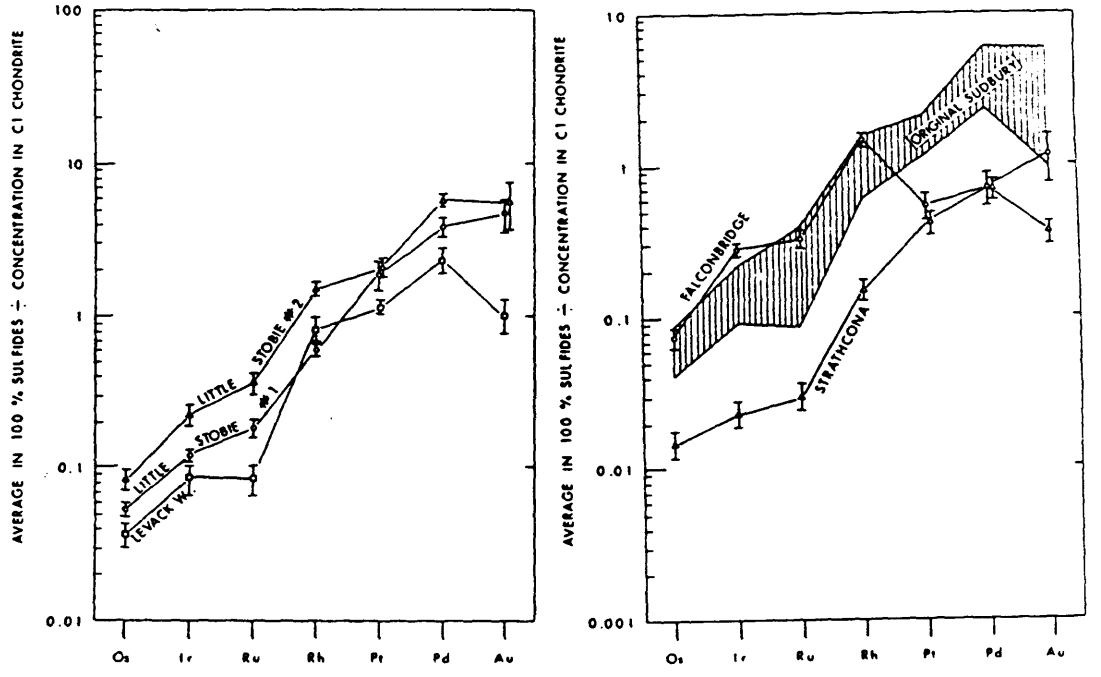


Figure 3.44 : Chondrite normalised values of platinum group elements and gold based upon values recalculated to 100% sulphide for the Sudbury Igneous Complex (i).

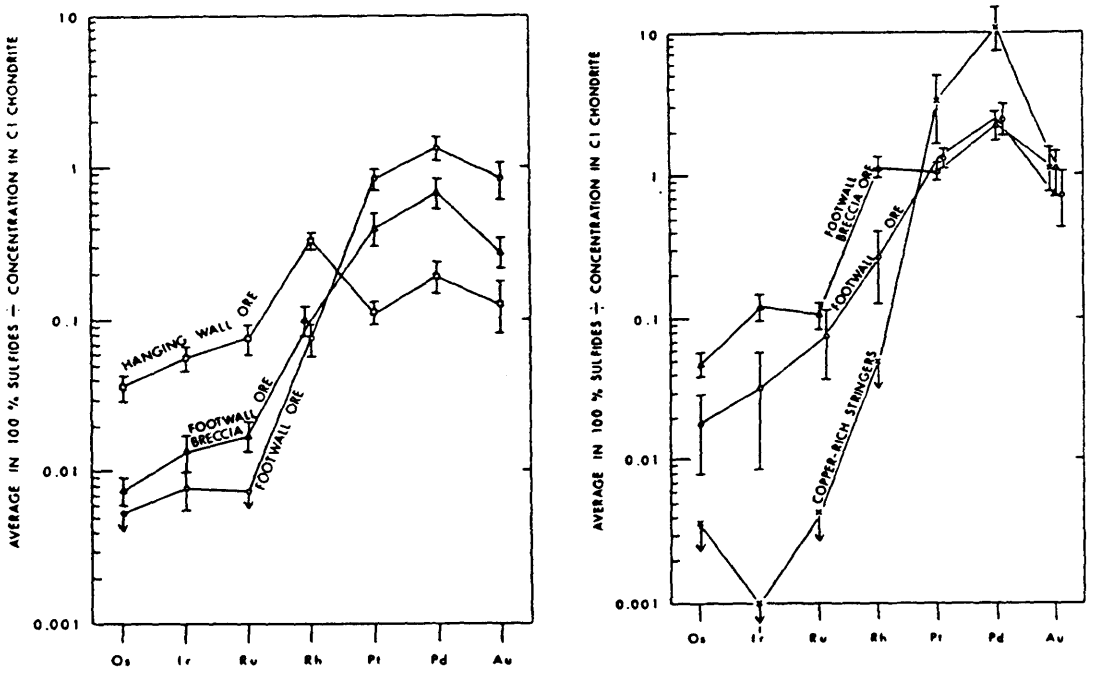


Figure 3.45 : Chondrite normalised values of platinum group elements and gold based upon values recalculated to 100% sulphide for the Sudbury Igneous Complex (ii).

The main sulphide minerals of the Sudbury ores are pyrrhotite, pentlandite, chalcopyrite and pyrite. Naldrett (1984a) lists 35 additional ore minerals including native gold, silver and bismuth. Amongst these are platinum group minerals given by Naldrett (1984a). Four of these minerals, namely froodite, moncheite, niggliite and sperrylite are also found in the ores of the copper zone of the North Range of the Sudbury Complex. A fifth platinum group mineral in the copper zone ores is stannopalladinite (Pd_3Sn_2) (Coats and Snajdr 1984). The copper zone mineralization occurs in veins in which chalcopyrite and cubanite form the bulk of the mineral assemblages (Coats and Snajdr, 1984). Figures 3.44 and 3.45 (from Naldrett, 1984) show the chondrite normalized concentrations of platinum group elements and gold in the sulphide fraction of some Sudbury ore types. In Table 3.16 the metal content of Sudbury ores are recalculated to 100 percent sulphide (from Naldrett, 1984). A number of features of the Sudbury ores and host rocks led Naldrett and Macdonald (1980) to propose that contaminant of the mafic magma by relatively silica-rich wallrock was the cause of sulphide liquation. This is discussed further in Section 5. These features include (a) the high percentage of normative quartz, co-existing with pyroxenes and plagioclase whose composition is relatively primitive, reflecting little differentation; (b) numerous, partially digested inclusions in the hostrocks (Stevenson and Colgrove 1968); (c) the relatively high Sr^{87}/Sr^{86} ratio of 0.706 for the noritic hostrock (Gibbins and McNutt 1975); d) the relative lack of cyclical units and modal layering, when compared with mafic intrusions of similar size, suggesting a viscous magma which is consistent with elevated silica content.

Table 3.15 : Volume and Value of Production of Platinum Group Elements in Ontario*

Year	Troy Ounces	Kilograms	1985 Dollars	1985 Dollars/Kilogram
1984	329,384	10,245	138,112,320	13,480.95
1985	353,658	11,000	148,440,000	13,494.55
Total from 1902	18,425,379	573,061	5,905,109,205	

* Almost all of this production from the Sudbury mines (Falconbridge Limited and INCO Limited)

Data from: Ministry of Northern Development and Mines
Ontario Mineral Score 1985

Table 3.16 : Metal content of Sudbury Ores Recalculated to 100% Sulphide (from Naldrett, 1984).

Mine	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Au	Zn	Pb	As	S/Se	$\delta^{34}S$	Cu/(Cu+Ni)	(Pt+Pd)/(Ru+Ir+Os)
LEVACK WEST (NR)																	
Footwall Breccia Ore	5.6	3.3	0.17	1098	1223	228	73	62	26	166	153	28	-	4900	2.6	0.37	14.4
Footwall Ore	5.8	5.3	0.11	1334	1350	53	22	17	10	97	529	39	-	4050	2.9	0.48	54.8
Cu-rich Stringers	2.6	27.8	0.027	3370	5948	10	<3	0.3	<2	167	3716	258	-	1860	3.13	0.91	1760
Average[2]	5.7	3.7	-	1150	1250	186	60	47	22	150	227	31	<3.5	4550	2.71	0.39	18.6
STRATHCONA(NR)																	
Hanging Wall Ore	3.1	0.37	0.21	111	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](SR)																	
Average	3.8	4.4	0.19	1930	2120	119	123	62	29	862	100	15	160	3800	1.08	0.54	18.9
LITTLE STOBIE NUMBER[2](SR)																	
Average	4.0	3.6	0.17	2130	3170	303	247	113	46	868	96	14	93	3600	0.46	0.47	13
FALCONBRIDGE(SR)																	
Average	5.35	1.52	0.22	546	381	287	225	144	40	174	120	14	-	-	-	0.22	2.3

Ni, Cu, Co in wt.%; Zn, Pb, As in ppm; precious metals in ppb.

1 Zn, 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.
NR North Range of Sudbury Igneous Complex
SR South Range

3.2.4. CRYSTAL LAKE GABBRO (P.J. Whittaker)

3.2.4.1. Introduction

A description of the Crystal Lake Gabbro has been provided by Whittaker (1980), from which the following is condensed. At the time of writing (1987) A. Smith (Precambrian Section, Ontario Geological Survey) is commencing a study of the Crystal Lake Gabbro, and its regional setting. The Crystal Lake gabbro is a layered gabbro to anorthosite body of Proterozoic age intruding Rove Formation Shales. The gabbro is located in Pardee Township, 47 km southwest of Thunder Bay and may be an extension of the Duluth Complex in northern Minnesota, which contains similar sulphide mineral assemblages. Sulphides were of interest originally for nickel and copper (Great Lakes Nickel deposit), but chromite is also present and potential exists for PGE with both sulphides and chromite.

3.2.4.2. Geology of the Crystal Lake Gabbro

The Crystal Lake Gabbro (Figure 3.46) intrudes shales of the Proterozoic Rove Formation (Figure 3.47), fragments of which have been incorporated as xenoliths in the gabbro. The metamorphic age of the Rove Formation is coincident with the Penokean Orogeny at 1.7 Ga (Peterman 1966). Rove Formation shales were intruded first by olivine and quartz-bearing gabbros of the Logan Sills at 1.4 Ga (DuBois 1962). Olivine diabase dikes were then emplaced, followed by intrusion of the Crystal Lake Gabbro, thought to be related to the Duluth Complex at 1.1 Ga (Goldich et al. 1961). The presence of a well developed anorthositic gabbro phase distinguishes the Crystal Lake Gabbro from Logan Sills.

The Crystal Lake gabbro is a cone shaped intrusion open at its western end (Figure 3.47). On surface the intrusion crops out as a "Y" shaped body with northern and southern limbs having outcrop widths of 1 km and 0.8 km respectively. Lower parts of the exposed succession consist of a gabbro with numerous, partially resorbed, xenoliths of Rove Formation shale. Upper parts of the intrusion are leucogabbro, to anorthositic gabbro and a few thin (10 to 30 cm) layers of anorthosite. Chromite layers, 1 to 3 cm wide, consisting of very fine-grained chromite are developed at the base of some of the anorthosite layers. Disseminated chromite is scattered throughout the lower part of the north limb of the intrusion. Irregularly shaped and sized patches of gabbroic and anorthositic pegmatites are distributed thorughout the lower and upper parts of the intrusion, towards its central parts.

Phase layering is a well-developed feature of the intrusion and provides some stratigraphic control. Planar layering is best exposed in the north limb, in the area of the Great Lakes Nickel adit (Figure 3.47). Layers of gabbro and anorthositic gabbro dip easterly at 20^{0} to 30^{0} while disrupted layers show some southerly dips.

The Crystal Lake gabbro can be divided into three large scale units; an upper unit of medium grained, massive gabbro to olivine gabbro, about 60 m thick at its western end and widening 0.5 km to the east to about 400 m; a middle zone which extends to within 1 to 6 m of the basal contact and consists of layered anorthositic gabbro with gabbro and pegmatitic olivine gabbro patches; and a basal zone, varying from 1 to 6 m thick, of very fine grained to aphanitic gabbro in contact with Rove Formation shales.

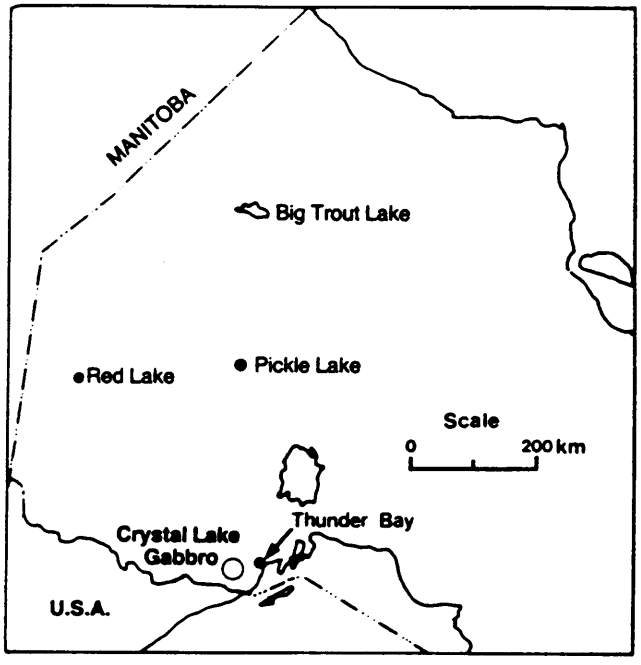


Figure 3.46 : Location of the Crystal Lake Gabbro.

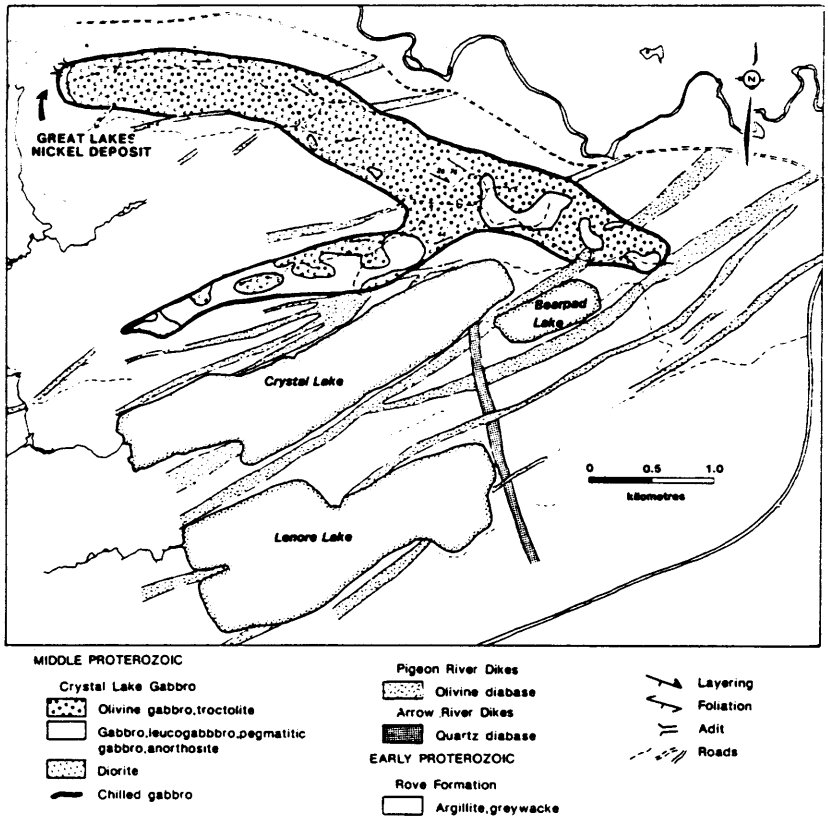


Figure 3.47 : Geology of the Crystal Lake Gabbro (after Smith and Sutcliffe, in prep.).

Phase layering within the lower one-third of the middle zone is planar and is developed on a half metre scale. Contacts between anorthositic gabbro and gabbro layers are sharply defined with variations in modal composition defining layers. Within the upper two thirds of the intrusion, layering again involves anorthositic gabbro, and gabbro, but layers become progressively thinner with increasing stratigraphic height. Uppermost layers are in the order of 3 to 5 cm thick with contacts remaining sharp.

Pegmatitic patches occur in the upper one-third of the middle zone. These patches are elongate and oriented at 087^{o}, dipping 42^{o} to the south. Pegmatites range from 10 cm to 2 m long and up to 20 m thick. They are generally planar and conformable to layering, but may exhibit internal rippling of layers. Most patches are anorthositic in composition, consisting of 5% to 77% euhedral amphibole (2 to 3 cm long) and 93% to 95% subhedral to euhedral plagioclase, also 2 to 3 cm in length. Sulphide minerals may also occur in anorthositic pegmatite patches and warrant further work for PGE potential.

3.2.4.3. Mineralisation

The middle zone is of greatest economic significance, with nickel-copper sulphides occurring at the top of the disseminated chromite zone, but below the layered chromite and anorthosite. Sulphides are disseminated and include chalcopyrite, pyrrhotite and pentlandite. Disseminated sulphides are found throughout anorthositic to gabbroic layers of the middle zone and occur in pegmatitic gabbro and olivine gabbro patches.

Chromite occurs in disseminated and layered form in the Crystal Lake Gabbro and may be of importance for PGE. Disseminated chromite occurs in the lower part of the middle zone and is found in the chaotic, basal contact zone where numerous xenoliths of Rove Formation shale occur. Chromite is intercumulate and forms inclusions in all silicate phases of the olivine gabbro and gabbro. Chromite inclusions in a single plagioclase or olivine grain may have significantly different compositions, particularly with respect to Ti and V. This is thought to represent contamination of the magma from the shale xenoliths which may have triggered chromite precipitation (P. Mainwaring, Research Associate, Carleton University, Ottawa, Ontario, personal communication, 1979). Disseminated chromite typically forms 3 to 4 modal percent of the rock.

Chromite layers occur with anorthosite gabbro and anorthositic layers and are exposed in the upper middle zone of the north limb. These layers are best observed above the Great Lakes Nickel adit. Chromite layers consist of 40 to 50% very fine grained chromite over a thickness of 1 to 3 cm. Individual layers have sharp contacts with underlying and overlying anorthositic gabbro and anorthosite and have a dark grey appearance. Examination of chromite from these layers should concentrate upon any sulphide associations, as either inclusions in chromite or as intercumulate sulphides, for possible PGE potential.

3.2.5. ALKALIC SUITES - THE COLDWELL COMPLEX (G.C. Wilson)

On a worldwide scale there is at least one major carbonatite, the Palabora complex in the Transvaal (Crosson 1984), that contains elevated PGE levels associated with an unusual Cu deposit. Copper, apatite and vermiculite are recovered from a vertical carbonatite pipe intruding Archean granitic basement, along with Fe, U, Co, Zr, Hf, and traces of Ni, Au, Ag and PGE (Guilbert and Park 1986, 354-361). Complex in detail (the 'pipe' is an array of three pipes, each lithologically distinct), the deposit contains unusual apatite- and magnetite-rich rock types.

Alkalic and carbonatitic complexes in northern Ontario have been extensively studied by Sage and co-workers. At least 48 such complexes are known, spanning most of the province (R.P. Sage, Ontario Geological Survey, personal communication, in Whittaker 1979). A major catalogue of alkaline complexes in Canada (Currie 1976) should be consulted for an overview of the distribution of these complexes. Details of individual sites are recorded by Sage in a series of Ontario Geological Survey Open File Reports (numbers 5396-5419) released in 1983.

The possible setting of PGE within these rocks has been summarised up by Sage and Watkinson (1986), based in part on geochronological studies such as the early compilation of Gittins et al (1967). The complexes are spatially related to three major fracture zones - the Trans Superior Tectonic Zone, the Kapuskasing Structural Zone and the Ottawa-Bonnechere Graben system. Emplacement ages fall into four groups; 2700-2400, 1850-1700 and 1250-900 Ma, and, in the Lake Nipissing area, early Paleozoic (565 Ma). Complexes of widely separated age occur close together, suggesting zones of repeated alkalic-carbonatitic magma generation. Mafic lithologies in such intrusions as the Killala and Coldwell complexes may carry base metals and PGE. Economic potential of the intrusions does not appear to correlate with age.

All these periods of alkalic magmatism appear to be related to intraplate rifting events. Norman and Sawkins (1985) note that besides alkalic centres such as The Coldwell, Prairie Lake and Firesand River complexes, Cu-Mo breccia pipes such as those of the Tribag deposit near Batchawana Bay may be associated with transform faulting related to Keeweenawan rifting; this is reinforced by a K-Ar age date of 1055 $\pm$35 Ma for the breccia pipes.

Although some of the alkalic diatreme structures in the region seem to have very limited economic potential (Sage 1982) there are occasional sulphide showings, such as pyrrhotite, pyrite and minor chalcopyrite in amphibolitic supracrustal rocks on the east side of the Chipman Lake stock (Sage 1985, p.31). The Chipman Lake, Clay-Howells, Killala Lake and Prairie Lake complexes were described by Sage (1975). Some localities (e.g. Cargill) have ready access, whereas others such as the Drowning River Complex are remote and poorly- to unexposed at surface (Sage 1983a,b). The latter are unlikely to become viable PGE targets unless a definite alkalic PGE association is identified in northern Ontario. Other than Palabora, it seems that there is no widely-documented association between PGE and dioritic or syenitic lithologies, carbonatites and alkalic alteration (fenitization). Prospective targets in Ontario seem to require a gabbroic component in addition to the alkaline (syenites and nepheline syenites); Killala Lake and Coldwell both contain this 'extra ingredient', and have been explored with some success for sulphides. Gabbroic components aside, the carbonatite-alkaline complexes

appear to be more prospective for U and Nb, Fe and P (apatite), and vermiculite than for PGE.

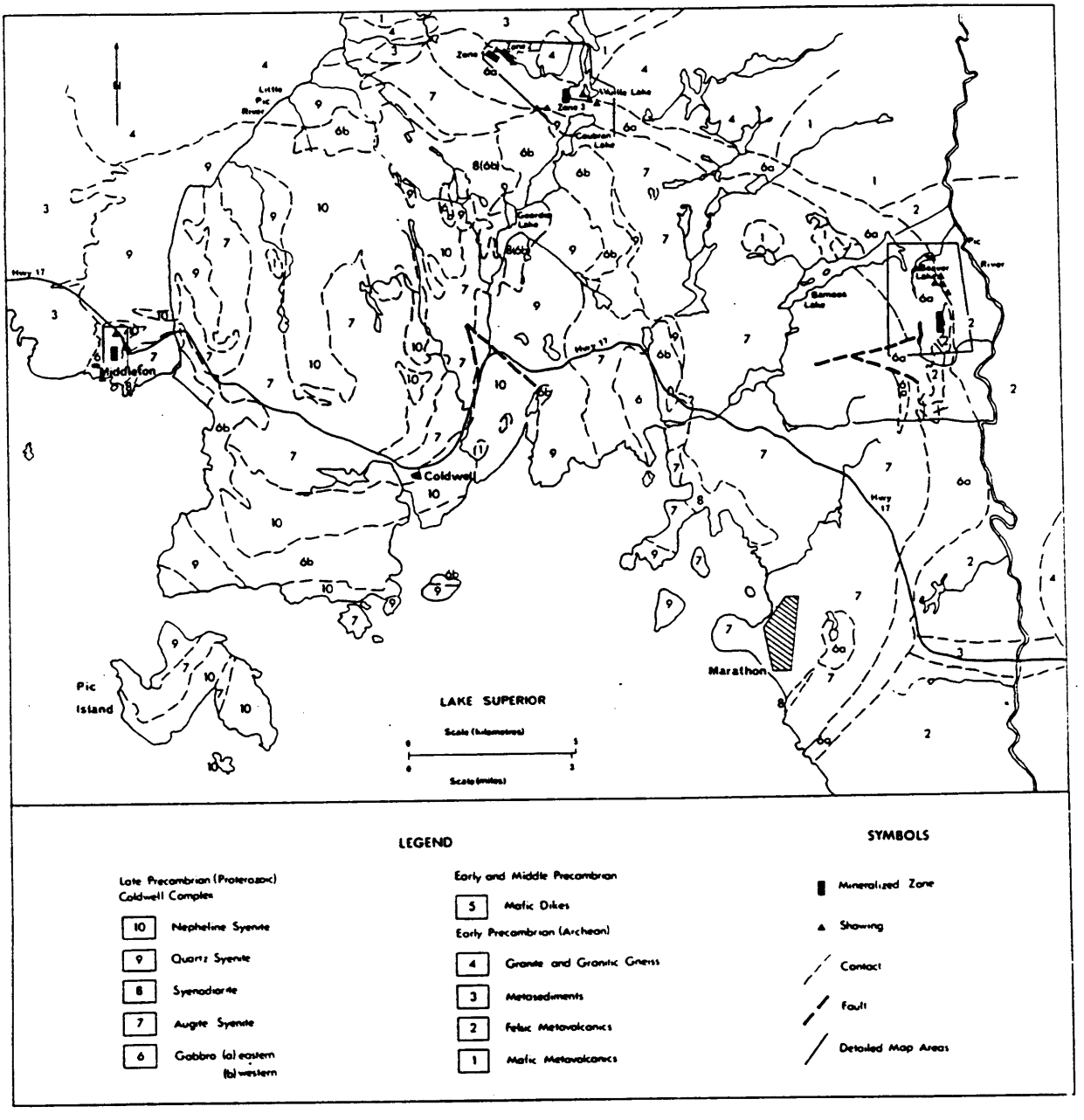


Figure 3.48 : Simplified geology of the Coldwell Complex, from Wilkinson and Colvine (1978). The Marathon PGE deposit is located at the Eastern Margin of the Complex southeast of Bamoos Lake (see mineralised zone symbol.

In the Killala Lake complex (Sage 1975,1983c) there is a concentric zoning from the margin to the core of alkaline gabbro through nepheline syenite to syenite. Disseminated sulphide occurrences have been found in the marginal gabbro, the same spatial relationship as the Coldwell complex mineralization. Pyrrhotite and lesser chalcopyrite dominate the sulphide mineralogy, which is concentrated into felsic layers in foliated marginal gabbro (Coates 1970). 'Magnetite-apatite and sulphides are locally abundant, and may form 15 percent of the rock' (Currie 1976, pp.159-161).

3.2.5.2. Geology of the Coldwell Complex

Emplaced during the last of three Precambrian periods of alkalic-carbonatite magmatism in northern Ontario (Sage and Watkinson 1986), between 1200 and 1000 Ma, the Coldwell Complex contains an extensive low-grade PGE occurrence in its eastern marginal phase (Figure 3.48), known variously as the Anaconda or Fleck deposit (depending upon the exploration company investigating the property) or the Marathon deposit. Estimated area for the whole complex (the southern portion of which lies beneath Lake Superior) is about 500 km^2 (Table 1.6), and it is the largest intrusion of its kind in North America, with a diameter of about 25 km. The Coldwell Complex intruded the deformed metavolcanic - metasedimentary stratigraphy of the Schreiber - White River greenstone belt around the town of Marathon. The age of the complex falls within the time span of the Neohelikian Keeweenawan magmatism associated with the development of the Lake Superior Basin (1170-950 Ma; Platt et al. 1983). Some dykes in the area cut the complex, but others, such as ultrabasic lamprophyres near McKellar Harbour, are linked to an older event by an age of 1650 $\pm$120 Ma (Platt et al 1983). An initial Sr isotopic ratio of 0.70354 $\pm$0.00016 (2 standard deviations) indicates an upper mantle origin for the parental magma of the complex (Platt and Mitchell 1982).

The geology of the eastern Coldwell complex is described in detail by Whittaker (1979). Alkali gabbro formed the first of three intrusive stages, followed by syenite (augite syenite and red syenite) and nepheline syenite. The gabbro is divisible into three units; a massive unit at the base, a unit with irregular flow-layered unit and a well layered, gravity-stratified unit, well exposed near Highway 17. A complex variety of plutonic (Whittaker 1979) and hypabyssal (Whittaker 1979, Laderoute et al 1985) alkaline intrusions succeed the gabbro, but although some related sulphide showings are known these have not as yet shown great economic potential. Wilkinson and Colvine (1978) noted that there were three areas in the complex with concentrations of chalcopyrite and pyrrhotite in heterogeneous gabbro, that the sulphide in the eastern gabbro was the most significant, and that contamination of gabbroic magma by wallrock assimilation might be an important precipitation mechanism. Milne (1967) mapped the Bamoos Lake area. Wilkinson (1983) mapped the eastern occurrence at Bamoos Lake, and also the (north-central) Coubran Lake zone and the western Middleton zone.

In the eastern marginal zone of the complex a fine-grained (grain size to about 2 mm), chilled gabbroic facies of the intrusion contains hornfelsed xenoliths of country rock, and is cut by fractures and joints filled by augite syenite. The syenite is very coarse grained, and contacts between syenite and gabbro are often diffuse over several centimetres (Watkinson et al 1984). The gabbro, which contains 2-3% sulphides, is locally weathered into a gossan. Within it, irregular pods enriched in mafic phases contain up to 8% sulphide, occurring interstitial to silicates up to 1 cm in

grain size. Mafic pegmatites and concentrations of magnetite are abundant in the eastern gabbro. The main sulphides (Wilkinson 1983) are pyrrhotite, chalcopyrite, cubanite and pentlandite. The chemistry is Cu-rich, and associated Cr and V values are presumed to be related to the abundant oxide phase. Four photomicrographs illustrating textural features of Coldwell complex silicates and oxides are presented in Figures 3.49A-D.

The intermediate-mafic lithologies in the ore zone are coarse grained to pegmatitic, and two sulphide-rich zones are separated by a facies with up to 10% ilmenomagnetite. PGE-rich sulphides occur near either granophyric intergrowths or biotite-rich rocks. The PGM are associated with chalcopyrite, pyrrhotite, cubanite and pentlandite (Watkinson et al 1983, 1986). Merenskyite and the Rh-bearing phase hollingworthite have been identified. Biotite in contact with sulphides is rich in Ti, Na and halogens. The restriction of PGM to the basal phase of the intrusion, emplaced prior to the layered series exposed immediately to the west, has suggested that the available PGE in the magma were all scavenged by sulphur available at an early stage in the development of the complex, perhaps by assimilation from the wallrocks (Watkinson et al 1984, 1986; Musial 1987). The major mineralized zone delineated in the complex is controlled by Fleck Resources Ltd of Vancouver. Reported reserves (Dahl et al. 1986) are 47 MT at 0.69 g/t Pt, 1.85 g/t Pd, 0.42% Cu, with 'trace amounts of Ni, Co, Rh, Au and Ag'.

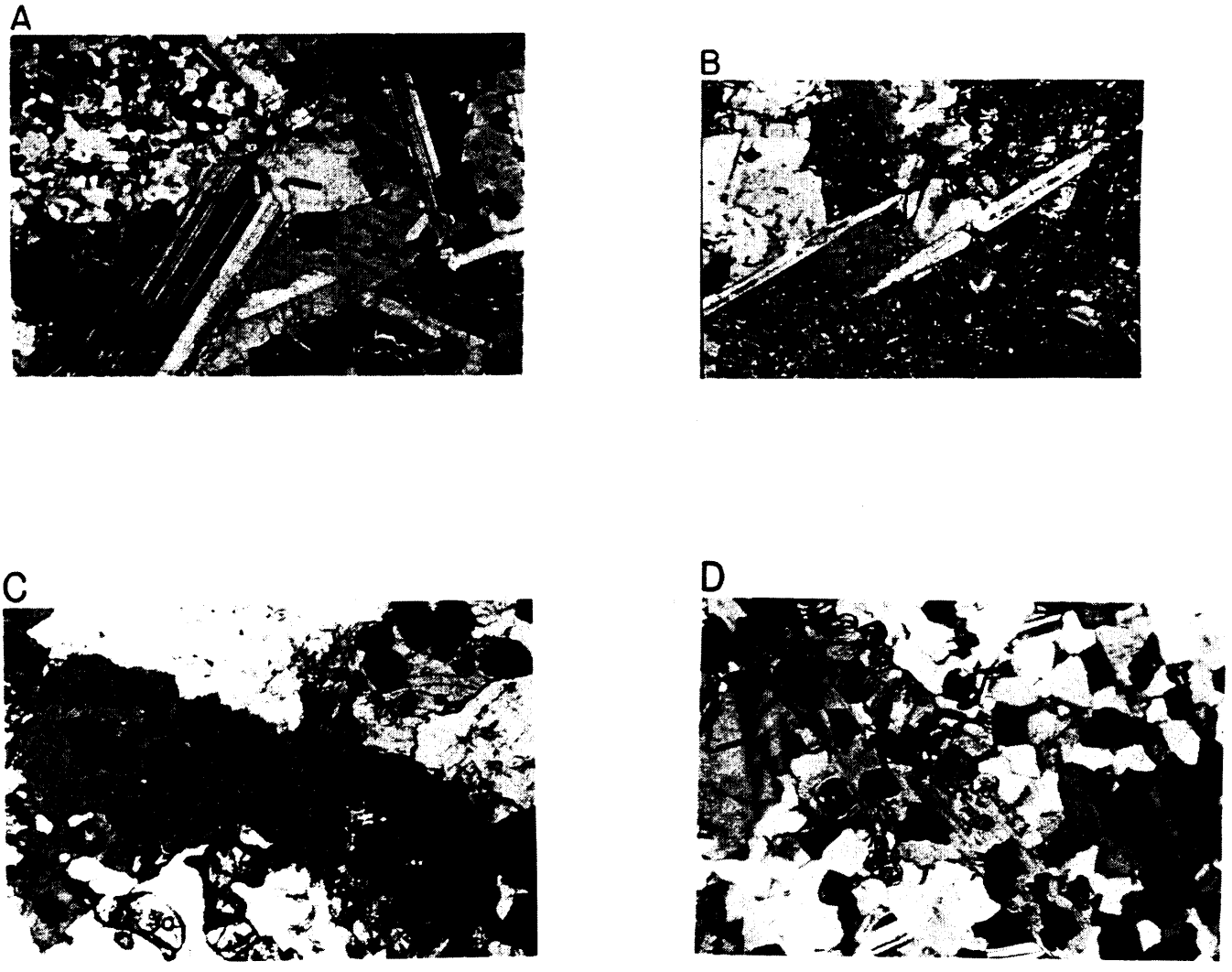


Figure 3.49 : Gabbros of the Coldwell Complex, Ontario -

A. Magnetite in clinopyroxene, subophitically intergrown with plagioclase. From locally pegmatoidal olivine gabbro, on roadcut through east margin of complex south of the Fleck ore zone. Long axis of photo; 4.7 mm, crossed polars.

B. Variable plagioclase habit in same sample; acicular crystals mixed with more typical equant grains of plagioclase and clinopyroxene. Long axis of photo; 2.6 mm, crossed polars.

C. Magnetite-rich gabbro is common in the eastern Coldwell gabbros. Equant magnetite is shown enclosed by a continuous 'ribbon' of biotite. Granular olivine is altered on one side of the biotite, but not the other. Long axis of photo; 2.6 mm, plane polarized light.

D. Another example of 'ribbon' biotite with magnetite. The mica is unstrained, and, in this sample at least, probably trapped the bulk of the hydrous volatile phases still active in the later stages of crystallization of the gabbro. Long axis of photo; 2.6 mm, crossed polars.

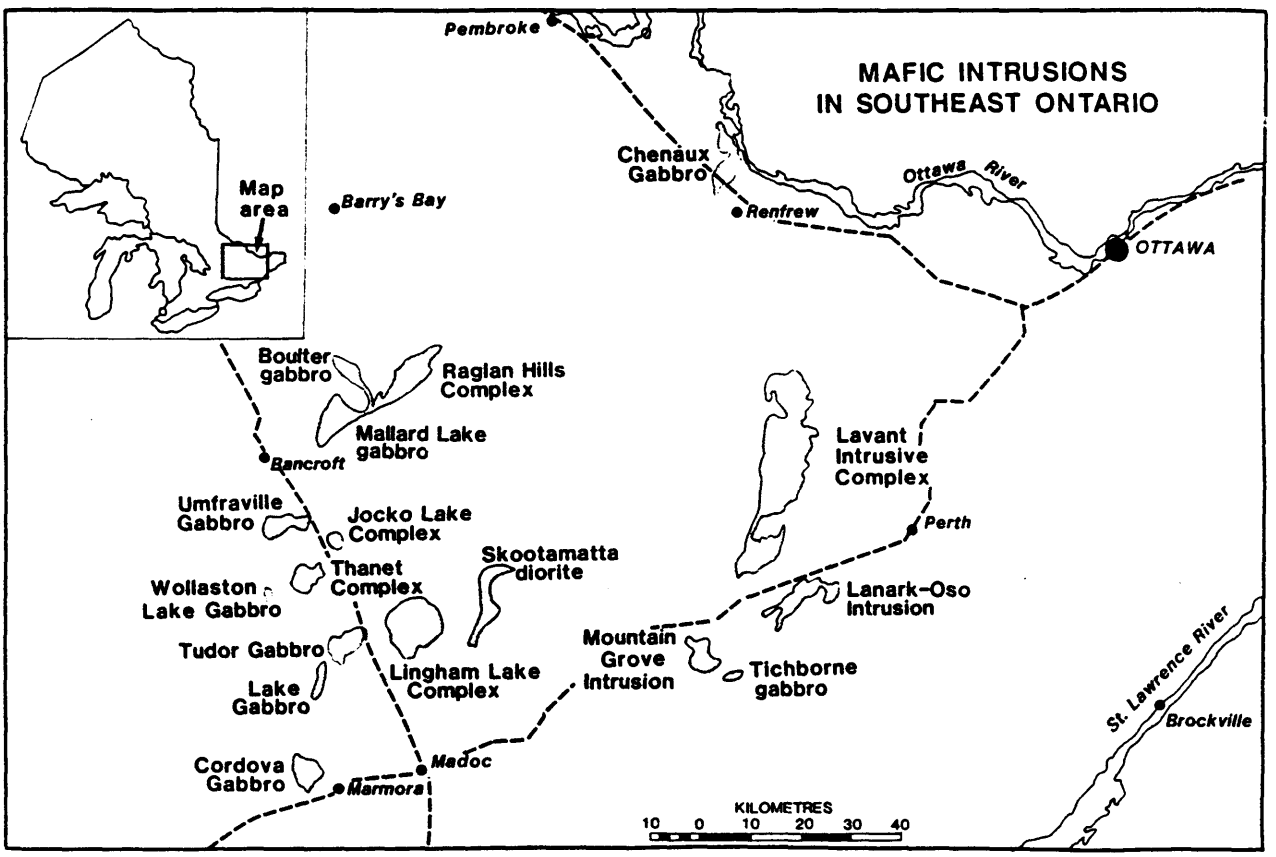


Figure 3.50 : Location map for mafic intrusions in the Central Metasedimentary Belt of the Grenville province in southeastern Ontario. Note that of 17 areas of mafic-ultramafic rock depicted, the Chenaux Gabbro alone is related to later events associated with the development of the Ottawa-Bonnechere graben. See text for details and references. Synonyms; Olden gabbro (Mountain Grove Intrusion), Attewell Lake gabbro (part of Lanark-Oso Intrusion) and Dalhousie gabbro (a central portion of the Lavant Intrusive Complex). Excludes a number of mafic intrusions in the map area, but includes most of the larger and better-known examples.

3.2.6. THE GRENVILLE PROVINCE (G.C. Wilson)

3.2.6.1. Introduction

While the Grenville Province is noted mostly for base metals, gold, molybdenum and industrial minerals, there is some some potential for small PGE deposits. Very few PGE values are available for Grenville rocks, due no doubt to the northward trend in mineral exploration since the 1860s (Smith 1986), coupled with the inherent difficulty of PGE assay (see Section 4), which has not encouraged widespread analysis of sulphide occurrences beyond the more commonplace Ni, Cu, (Au, Ag). As Harding observed (1942, p.51) southeastern Ontario "*which at one time was regarded as the most promising mineral field in the province, drifted into a position of comparative obscurity*". A second statement by Meen (1942, p.32) concerning this region - "*the idea that this section of Ontario has been thoroughly prospected in the search for gold and other economic minerals should be completely set aside*" - may be echoed today, given the accessibility of the area and modern expertise applicable to relatively small and/or low grade deposits. A review of the mineral potential of the Grenville by Carter and Colvine (1985) mentions the occurrence of primary magmatic ore deposits of Ni-Cu and Fe-Ti, but focusses largely on other deposit types in supracrustal rocks. Sangster (1970) advanced the generalised finding that Ni-Cu sulphide mineralisation occurs mostly in older gabbroic rocks, while the larger Fe-Ti oxide deposits are in younger, basic intrusions. A commodity map for part of southeastern Ontario has been compiled by Springer (1978).

A reconnaissance of four intrusions in the summer of 1986 is described below; field, petrographic and geochemical data were gathered for the Cordova, Lingham Lake, Mountain Grove and Raglan intrusives, with emphasis on sulphide occurrences. In the absence of extensive data on PGE in Grenville rocks, the literature review describes the petrology of potential host rocks in some detail. Host rocks that have potential for PGE mineralisation are described, largely avoiding the complex matter of stratigraphy (see e.g. Wynne-Edwards 1972; Emslie, in Stockwell et al. 1976, pp.121-131; Moore et al. 1986). The detailed chapter which follows concentrates on one area of the Grenville in southeastern Ontario (Figure 3.50), and provides a background for assessing PGE potential over the wider contiguous area.

About a dozen Cu-Ni prospects have been recorded in recent compilations of Grenville showings (Carter 1984, Malczak et al. 1985). Sulphide ore occurs in metagabbro and metapyroxenite host rock, the primary mafic silicates of which may be altered to talc and amphibole. The setting is commonly marginal portions of small- to intermediate-sized intrusive complexes, such as Raglan, Thanet, Mountain Grove and Lingham Lake (Figure 3.50). Estimated areas of selected Grenville Province intrusions are presented in Table 3.17. The general distribution of mafic-ultramafic rocks within the Grenville of southeastern Ontario is shown on the Geological Highway Map for Southern Ontario (OGS Map 2441, revised 1979; see also McCrank et al. 1981), and selected intrusions are displayed in Figure 3.50. The latter shows the S.W. end of the Central Metasedimentary Belt; it has been estimated that gabbros in this area have a thickness of 2.6 km, based on gravity data (Real and Thomas 1987). Note that the units marked on the Highway Map as gabbro and related rock types vary widely in lithological type, even in an area (such as part of Oso township; Harding 1947, p.24) which is dominantly gabbroic. Several phases of intrusion are more the rule rather than the exception, as was noted by Carter (1981, pp.65-66) in the case of the gabbro and granodiorite of the Lavant intrusive complex. Pyroxenites are the most

commonly described ultramafic rocks in the Grenville; peridotites are also present, but a modern survey of mafic intrusions in the area would reveal much larger volumes of gabbroic and dioritic rock, plus a substantial proportion of more differentiated material (Wilson, in prep.). An iron property (magnetite plus ilmenite) occurs in pyroxenic amphibolite in the Umfraville gabbro (Hewitt 1962). Some ultramafic bodies have been thoroughly altered; for example, a lens 4.3 km in length located east of Tweed, now largely altered to anthophyllite, tremolite, talc, antigorite, carbonate and magnetite (Bright 1986, pp.89-91). Pyroxenites associated with post-tectonic (Cambrian) alkalic complexes in the Grenville locally carry concentrations of magnetite and sulphide-rich zones, e.g. Iron Island (Lumbers 1971).

Table 3.17 : Surface Area of Selected Grenville Intrusions

Intrusive Complex	Area (km^2)	Major/minor axes (km)	Map(s)/Ref(s)
Lavant intrusive complex	249	40.0 x 10.0	2441 / 2054 / 2053
Lingham Lake complex	61.7	10.5 x 9.5	2168 / 2053 / 51d
Raglan metagabbro complex	50.3	18.5 x 5.6	2461 / 1953-2
Umfraville gabbro	36.1	9.6 x 7.0	2167 / 2020 / 1957b
Chenaux gabbro	29.1	10.4 x 3.0	2460
Tudor gabbro	28.5	9.3 x 4.1	2168 / 2106 / 1957b / Palmer+Carmichael (1973)
Mountain Grove intrusion	25.0	7.0 x 3.8	2449 / 2053 / 1947-5
Thanet complex	25.0	6.7 x 4.9	2167 / 2020 / 1957b
Cordova gabbro	23.1	5.6 x 5.2	Easton et al (1986, p.17)
Jocko Lake complex	7.6	3.4 x 3.1	2167
Tichborne gabbro	3.3	4.8 x 1.3	2053 / 1947-5

Approximate dimensions of various intrusions, composed in part or whole of mafic rocks, in the Grenville province in southeastern Ontario. Note that in each case the major contiguous area of 'mafic' rocks revealed by or inferred from surface mapping is considered; satellite intrusions are excluded. Areas estimated by the 'trace, cut, and weigh' method. Compare with other intrusions in Ontario (Table 1.5).

Map references (mostly 4-digit numbers) mostly refer to maps published by the Ontario Department of Mines / Ontario Geological Survey, on five scales from 1:253,440 to 1:31,680 (1 inch:4 miles to 1 inch:0.5 miles).

Lavant intrusive; less accurate, as dimensions derived from 1:800,000 regional map.

N.B.; specific geographic notes -

1. The Lingham Lake complex should not be confused with the Tudor gabbro, a separate, elongate, body lying to the west. Early workers, as noted by Meen (1942, p.22) referred to the western part of the Lingham Lake mass as the 'Tudor intrusion'. Lumbers (1969) quotes an equivalent area of 85 km^2; this must include the more felsic portions, excluded here, in the eastern half.
2. For current purposes the Raglan metagabbro complex is truncated in the S.W. at the Mayo town line, excluding the Boulter gabbro and Mallard Lake metagabbro, each of comparable size to Raglan.
3. For the Umfraville gabbro the estimated size is an upper limit (Hewitt 1962), and for the Tichborne gabbro, a lower limit. Tudor gabbro shown larger on old maps; 39.9 km^2 (15.1x3.4 km). See Laakso (1968).
4. The Chenaux gabbro is an 'odd one out' here, since it is postorogenic, related to rifting in the Ottawa-Bonnechere graben (Lumbers 1982, pp.37-39).
5. Ideally, names such as 'complex' should be retained for polyphase intrusions. There is often a shortage of field data, but wide lithochemical variation (as in the intrusives near Lingham Lake) seems to imply multiple intrusion, and possibly assimilation, rather than fractionation of a single magma.

Due to poor surface exposure there is a dearth of information on the geometry of the basic intrusions, although several have been interpreted as sills, such as those in Chandos township (Shaw 1962); their intrusive origin is confirmed by skarn contacts in adjoining metasediments. For example, the metabasites show a pyroxene hornfels facies mineralogy generated by the intrusion of the Loon Lake pluton. No economic showings associated with the skarn were known in 1958. Unambiguous xenoliths of metasedimentary wall rocks may be recognized in some gabbros, confirming the intrusive nature of the latter (e.g. Harding 1947).

The Umfraville gabbro (Figure 3.50) is one of the freshest of the Grenville gabbros (Lumbers 1969), locally displaying rhythmic layering with olivine gabbro, pyroxenite and rare peridotite layers. Lumbers' study (ibid., pp.39-47) is one of the most interesting to date, and contains significant evidence suggesting that the following features are likely to be quite common in adequately-exposed mafic centres in the region;

- Pyroxenitic facies as a minor component to gabbroic stocks,
- Hybridization in areas where mafic rocks are intruded by penecontemporaneous felsic magma,
- crude zoning, with relatively mafic-ultramafic margins and more differentiated cores, - and sulphide mineralization preferentially located in the vicinity of the most mafic lithologies.

Apparently complex field relations and poor outcrop hinder recognition of *in situ* fractionation within the Grenville gabbros. Smith (1956) suggested that the Dalhousie diorite (central area of the Lavant intrusive complex) might show a differentiation trend from a gabbroic (presumed) basal zone, but the common problem of inadequate exposure precluded a definitive conclusion at the time. Wolff (1985, Map 2471) studied the southern portion of the Lavant mass and concluded that it is a high-level intrusion penetrating metasedimentary carbonate cover and including marble screens, and not completely differentiated, although aplitic felsic phases are present. On the other hand, the Lanark-Oso intrusion (Attewell Lake gabbro of Hewitt 1964) to the southeast is anorthosite-rich and exhibits well-developed differentiation from pyroxenite-peridotite to anorthosite. It contains diopside and enstatite, corundum and spinel. Wolff (1985, p. 29-40) suggested that Lanark-Oso is a late (post-metamorphic) body; possibly it is residual anatectic melt analogous to the Lac St. Jean and Marcy (Adirondacks) anorthosites. One attraction of this hypothesis is that it obviates the need for a major volume of gabbroic parental magma required by conventional fractionation processes. The Tichborne gabbro (Figure 3.50), centred near the Mountain Grove intrusion, some 8 km ESE of Long Lake, exhibits a broadly east-west plagioclase variation from oligoclase to labradorite (Harrison 1943, Harding 1947). The basic plagioclase is particularly concentrated in the SW end of the intrusion, which is cut by numerous dykes varying in composition from gabbroic to granitic. Harrison (1943) made one of the few detailed studies of mafic rocks in southeastern Ontario, and concluded that the small Wilkinson anorthosite, located 15 km ENE of Tamworth and 20 km S of Mountain Grove (Figure 3.50), was most akin to the Adirondacks anorthosites, whereas other gabbroic bodies such as the Tichborne gabbro (Figure 3.50) are higher level, more differentiated, and probably more contaminated by the metasedimentary country rocks.

It is interesting to note that three of these intrusions (Lavant, Lanark-Oso, Tichborne) span the range in Table 3.17 from the largest to the smallest of mafic bodies in southeastern Ontario. Much of the early mapping in the Grenville has seen little follow-up since the early years of this

century, and subsequent workers have noted that some of the earliest maps augmented the basic intrusions by erroneously mapping metavolcanic rocks as gabbroic-dioritic, e.g. the Lingham Lake complex (Meen 1942) and the Umfraville gabbro (Hewitt 1962, p.40). In the case of the western Tudor gabbro in Lake township, re-mapping significantly reduced the surface bounds of the intrusive within its carbonate metasedimentary country rocks (Laakso 1968).

The Macassa nickel prospect is perhaps the largest of the Fe-Ni-Cu occurrences; reserves to a depth of 335 metres are approximately 3.9 million tons grading 0.825% Ni, 0.25% Cu and 0.05% Co (Carter and Colvine 1985, p.101), located within peridotite (or pyroxenite) of the Thanet complex (Figure 3.50) in Limerick township. According to Shklanka (1969, p.138) the deposit occurs in an ultramafic host near its contact with gabbro, and the sulphides are pyrrhotite, pentlandite, pyrite and chalcopyrite, with minor cubanite and sphalerite. The gangue to the sulphide is mostly talc, with minor actinolite. The highest Ni assay from diamond drilling was 1.77% Ni over 66 feet (20.1 metres); chalcopyrite veinlets form the latest fraction of the sulphide paragenesis (Lumbers 1969, p. 72-75).

The Lingham Lake sulphide showing is similar, but smaller than the Macassa prospect. Jost (1975) lists eight Grenville showings on his annotated map; the present study has concentrated on locations eastward from Bancroft, but Jost's compilation locates three more prospects in the Parry Sound district (Lumbers 1971), one of them associated with the Caribou Lake intrusion near Port Loring (Friedman 1957). Other mafic suites occur in the intervening areas, such as the Haliburton intrusions represented by the Glamorgan gabbro-anorthosite complex WSW of Bancroft. Sangster and Bourne (1982) note that Bancroft-area Ni-Cu sulphides, including the Bonter occurrence (a mineralized pyroxenite dyke in Marmora township) are all associated with basic-ultrabasic intrusions cutting greenschist to lower amphibolite grade rocks in the Hastings Basin. The Raglan deposit on the north margin of the basin has been metamorphosed to a higher grade, as indicated by subgrain development in pyrrhotite and the growth of poikiloblastic pyrite (Sangster and Bourne 1982, p. 108).

The most valuable summary of the geology and mineral showings on a regional scale (9300 km^2) is the report and four accompanying maps by Lumbers (1982). He distinguishes a biotite diorite intrusive suite whose mafic lithologies are volumetrically subordinate to diorite and tonalite. Strain and recryttallization are very variable within these early intrusions, with gneissose high-strain zones displaying destruction of primary igneous textures preserved elsewhere. Small masses of recrystallized pyroxenite and peridotite in the Raglan Hills body exemplify the most mafic rock types. Cu-Ni showings are associated with mafic gabbro and ultramafic rocks in this suite. The Chenaux gabbroic stock (Figure 3.50) was emplaced within the Ottawa-Bonnechere graben, apparently a failed arm of the St. Lawrence rift system (Mereu et al. 1986). The Chenaux gabbro, in Horton and Ross townships, displays widespread pegmatitic patches which are especially abundant near the margins of the intrusion (Lumbers 1982, p.39). Igneous layering is locally defined by modal variation from anorthositic rocks through gabbro to pyroxene-rich material. Dykes and masses of "*uralitized pyroxenite cut the gabbro locally and contain minor concentrations of pyrite, pyrrhotite, pentlandite and chalcopyrite*" (Lumbers 1982).

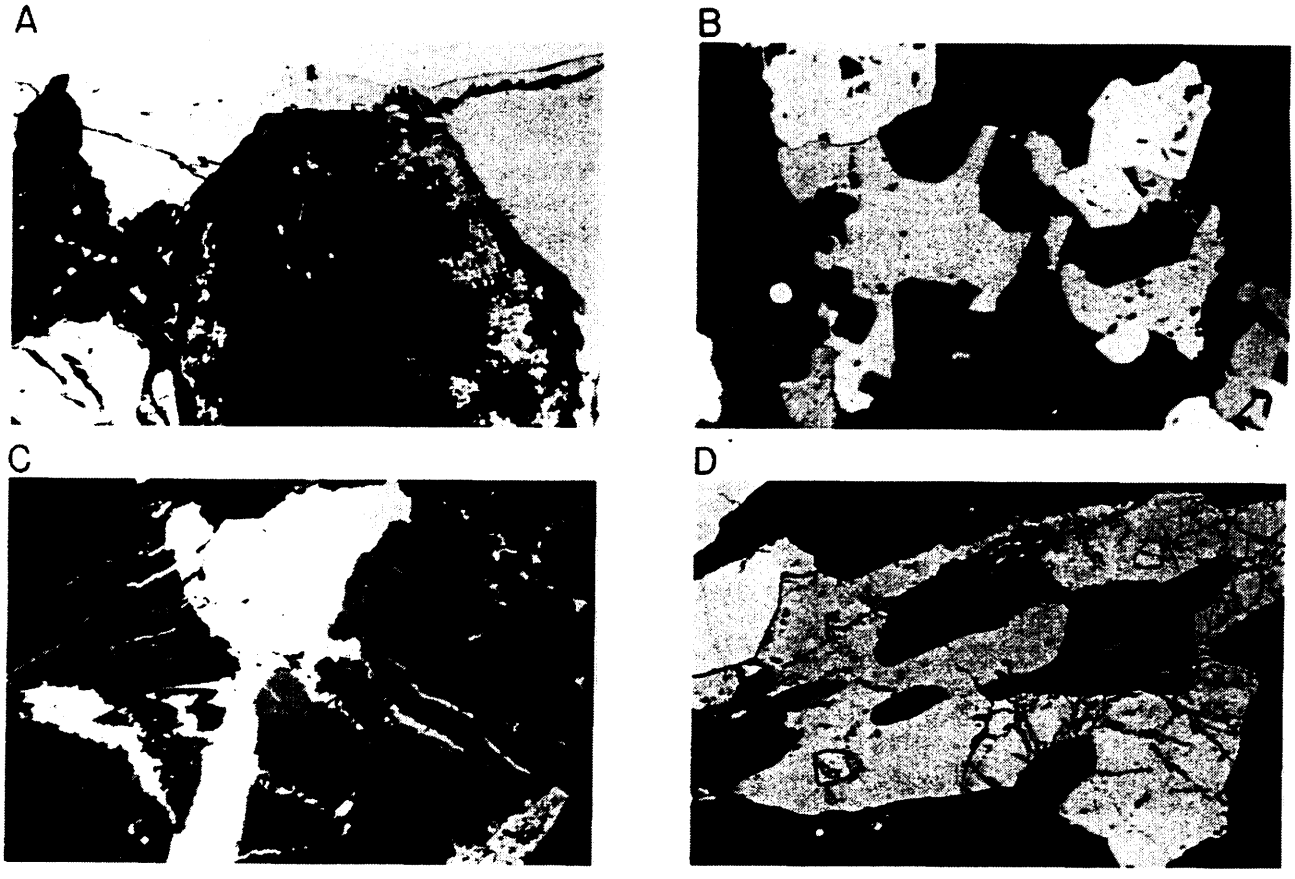


Figure 3.51 : Sulphides in Raglan (Grenville) Metagabbros -
A. Sulphides (chalcopyrite and pyrite in photo, and abundant pyrrhotite beyond) separated from plagioclase (pitted, at centre) by a thin complex rim of mafic minerals (see also Fig. 1.4B). Sample 861A, assayed. Long axis of photo; 3.0 mm, reflected light.
B. Pyrite and epidote (dark) overgrown by chalcopyrite. Cu-rich sulphide mobile at time of late silicate alteration. Long axis of photo; 1.9 mm, reflected light.
C. Chalcopyrite remobilized from polymineralic sulphide assemblage into amphibole cleavage planes. Sample 861A, assayed. Long axis of photo; 1.4 mm, reflected light.
D. Chalcopyrite (with subordinate pyrite and actinolite) prominent in sulphidic shear zone in metagabbro (pyrrhotite is most common sulphide in bulk rock). Sample 863, assayed. Long axis of photo; 3.0 mm, reflected light.

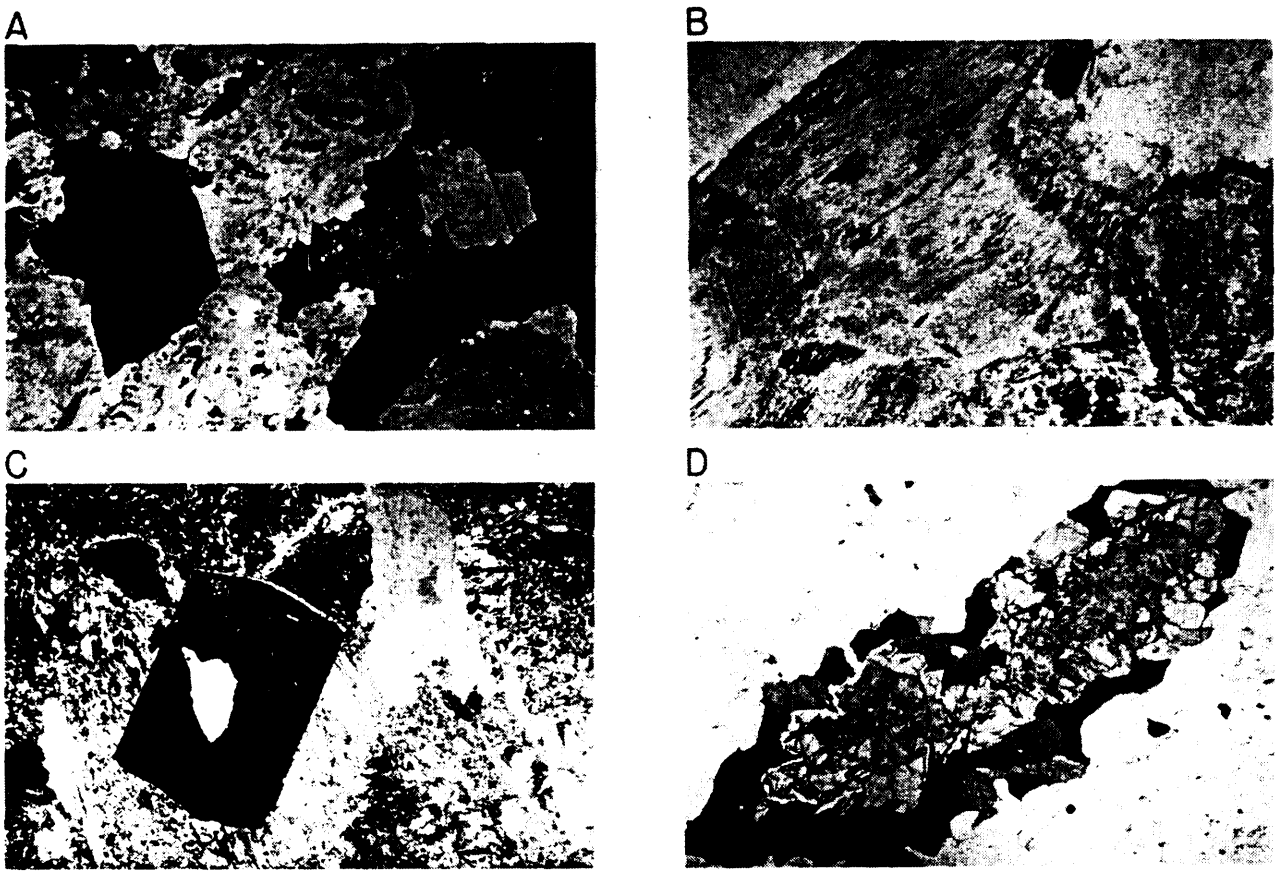


Figure 3.52 : Grenville Metagabbros and Adirondacks Anorthosite -
A. Abundant sulphides between amphibole (secondary, formed from pyroxene in 'uralitization') in Raglan metagabbro. Sample 861A, assayed. Long axis of photo; 5.7 mm, crossed polars.
B. Chlorite on dark-rimmed (zoned?) amphibole in metagabbro of the Mountain Grove intrusion. Textural evidence and/or relict grains of primary pyroxene are commonly preserved. Long axis of photo; 5.7 mm, crossed polars.
C. Coarse pyrite and carbonate in altered gabbro rich in chlorite, quartz and actinolite. Cordova gabbro. Long axis of photo; 5.7 mm, crossed polars.
D. Mafic clot (initially pyroxene and olivine?) rimmed by granoblastic hornblende in anorthosite from Porter Mountain, Adirondacks, New York. Long axis of photo; 6.4 mm, plane polarized light.

3.2.6.2. Raglan

The Raglan deposit (Carter et al. 1980, pp.50-57) contains approximately 1% combined Cu and Ni, is relatively pyrrhotite-rich; sulphides are apparently of magmatic origin, predating the regional amphibolite-facies metamorphism. The Raglan deposit itself is only the largest of four known showings associated with the Raglan Hills Metagabbro Complex (Figure 3.50). The sulphides occur within a metamorphosed ultramafic (pyroxenite) facies of the lithologically diverse, sill-like gabbroic body. Lumbers (1982, p.41) noted that deposits such as Raglan, which occur in mafic phases of the "biotite diorite suite", contain disseminated chalcopyrite, pyrrhotite and pentlandite with variable proportions of pyrite. He also found that "chalcopyrite is generally much less abundant than pentlandite and the iron sulphide minerals", and identified "trace amounts" of cubanite and sphalerite. He had earlier suggested that trace element analysis of magnetic opaque separates from dioritic and gabbroic samples might indicate the prospectivity of associated mafic gabbro and pyroxenite phases for Cu and Ni. Forrester (1957, pp.49,70) noted that magnetite contents in the Lake Renzy ultramafite, in southwest Quebec, were relatively high in proximity to sulphide mineralization.

While descriptions of the Raglan sulphides favour a sulphide-silicate liquid immiscibility origin (cf. Section 2.1), it is necessary to determine whether the initial magma was highly PGE-enriched, and whether the sulphide liquid would have had access to sufficient silicate melt to scavenge economic quantities of precious metals. These questions must be asked in all suspected magmatic-concentration environments, but are most acute with the smaller bodies, such as those in the Grenville Province. Petrographic examination of a chalcopyrite-rich portion of the sulphide at Raglan demonstrates that the mineralisation has clearly been remobilized by local deformation and shearing, e.g. Figures 3.51A-D, 3.52A.

3.2.6.3. Lingam Lake

The Lingam Lake Complex (Figure 3.50) is a large, poorly exposed intrusive mass which appears to be lithologically diverse; Meen (1942) notes quartz diorite and syenite as the dominant rock types, with granite, granodiorite, diorite and also "quartz gabbro and gabbro (which) appear to be of relatively rare occurrence". Meen's field data led him to speculate on the geometry of the complex. His suggestion of a quartz dioritic marginal zone around a more syenitic-granitic core remains untested. Just to the east is the arcuate mass of the Skootamatta diorite (Figure 3.50). Lumbers (1969, pp.76-77) notes metaperidotite as the major lithology near the Lingham Lake sulphide showing (also known as the Triana Explorations Ltd. showing) with lesser metapyroxenite and minor gabbroic material.

3.2.6.4 Mountain Grove

The Mountain Grove Intrusion, equidistant between Madoc and Perth (Figure 3.50), is best known for the Long Lake zinc deposit, hosted in screens of carbonate metasediments preserved within the southeastern portion of the mafic body. It is a late tectonic intrusion lying within a broad synformal structure, with metavolcanic rocks and related gneiss and anatectite to north and south (Wolff 1982; see Map 2449). Granitoid rocks of the McLean Pluton abut the intrusion to east, south and west. Harding (1947) referred to the Mountain Grove intrusion as the Olden gabbro, and to part of the McLean Pluton

as the Leggat Lake granite. The most common rock type is a medium- to coarse-grained gabbro (Figure 3.52B), but anorthosite, quartz gabbro, monzonite and syenite are also present, and a clear differentiation trend is evident from gabbro to syenite (Wolff 1982, pp.30-36). Gabbro is the principal lithology, unlike the dominantly dioritic Lingham Lake mass. The contact between the mafic mass and adjoining granitoids is apparently not exposed (Wolff 1982; Map 2449). However, minor outcrops of granitic pegmatite occur throughout the gabbro, such as a tourmaline-bearing pegmatite, exposed in a roadcut east of Mountain Grove village. Observations by Harding (1947) suggest that felsic intrusions in the area are younger than the gabbro. Sulphide occurrences in the northern section of the gabbro contain pyrite with variable amounts of pyrrhotite and chalcopyrite (Wolff 1982, pp.64-66).

3.2.6.5 Cordova

The Cordova Gabbro is important economically since it hosts the Cordova mine, which produced 22,774 ounces (708 kg) of gold with a Au:Ag ratio of 33:1, from shear zones near the northwestern margin of the gabbro (Gordon et al. 1979, p.38). No native gold has been seen; the metal is probably associated with pyrite in the ore. Gabbro near the mine site displays {carbonate-chlorite-pyrite} alteration superposed on uralitized (pyroxene altered to amphibole) Grenville gabbro (Figure 3.52C). Foliation in the outer facies of the gabbro is thought to be a primary, magmatic layering, which dips inward toward the central portion of the mass, composed of massive and pegmatitic facies which, apart from minor anorthosite pods, comprise the remainder of the intrusion (Easton et al. 1986, pp.16-19). Quartz veins of variable geometry and composition occupy the shear zones, which are variable in width but persistent along strike (Easton et al. 1986, Satterley 1943, pp.36-40). Lopez-Martinez (1982, pp.105-107) described two gabbro samples comprised of a roughly equal mixture of a plagioclase of intermediate composition (approximately An_{50}), and variable-textured secondary amphibole after pyroxene, with significant epidotization of the feldspar, particularly along grain boundaries and twin planes.

3.2.6.6 Selected Geochemical Data for Grenville Gabbros

Five samples of Grenville mafic intrusions were analysed for major elements and precious metals. The results are presented in Table 3.18. Whole-rock data (with or without the estimated content of the sulphide fraction) are plotted onto AFM and cation plots (Figure 3.53, 3.54). The precious metal data are depicted, chondrite-normalised, in Figure 3.55A,B. Normalization to 100 percent sulphide (Figure 3.55C) was carried out as described in Section 4.2. A limited quantity of major/minor element geochemical data is available for comparison, e.g. for the Raglan complex (Carter et al. 1980) and for Mountain Grove (Wolff 1982) and nearby gabbros (Harding 1947, p.26). No previously published PGE data are available in the Grenville literature, except for recently available {Pt-Pd-Au} data from Jonasson et al. (1987), who found 115 ppb Au in a concentrate from the Macassa showing, but quote no values for PGE.

The composition of the matrix of the Raglan samples is still iron-rich after the sulphides are removed, as can be seen by comparison with Mountain Grove data (Wolff 1982, p.32). Four analyses for Raglan gabbro were provided by Carter et al. (1980, p.56). The database is limited and the analytical technique loses accuracy for S-rich samples (giving high totals); the

following observations are therefore speculative, although consistent with known geology.

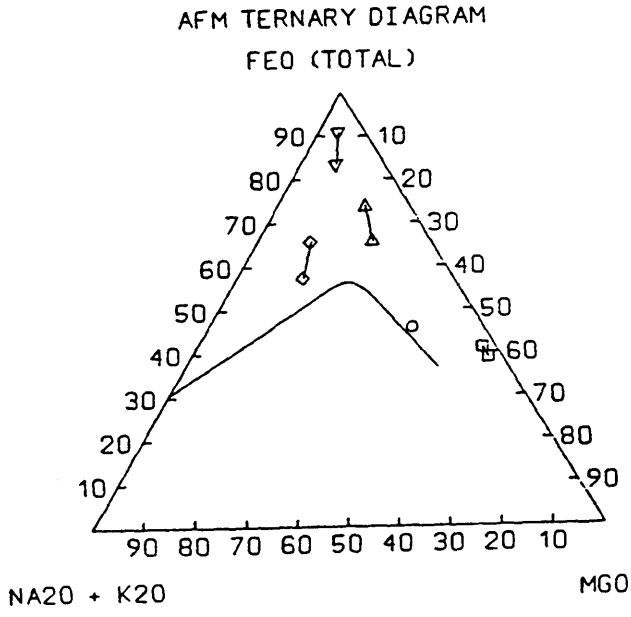


Figure 3.53 : AFM plot of five samples from the Grenville of southeastern Ontario. Four of the samples carry appreciable amounts of sulphides, and the two points correspond to the bulk rock (points nearer Fe apex) and to the calculated (silicate plus minor oxide) residue after subtraction of the silicate fraction.

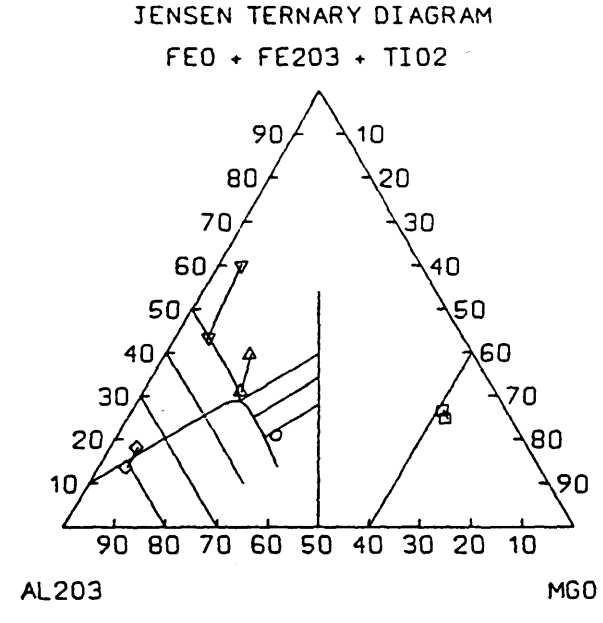


Figure 3.54 : Cation plot for the same samples, drawn after the method of Jensen (1976), as designed for the classification of volcanic rocks. According to this construction, assuming minimal bulk chemical exchange during metamorphism, four of the samples plot grossly in the tholeiitic fields, and one on the komatiitic side.

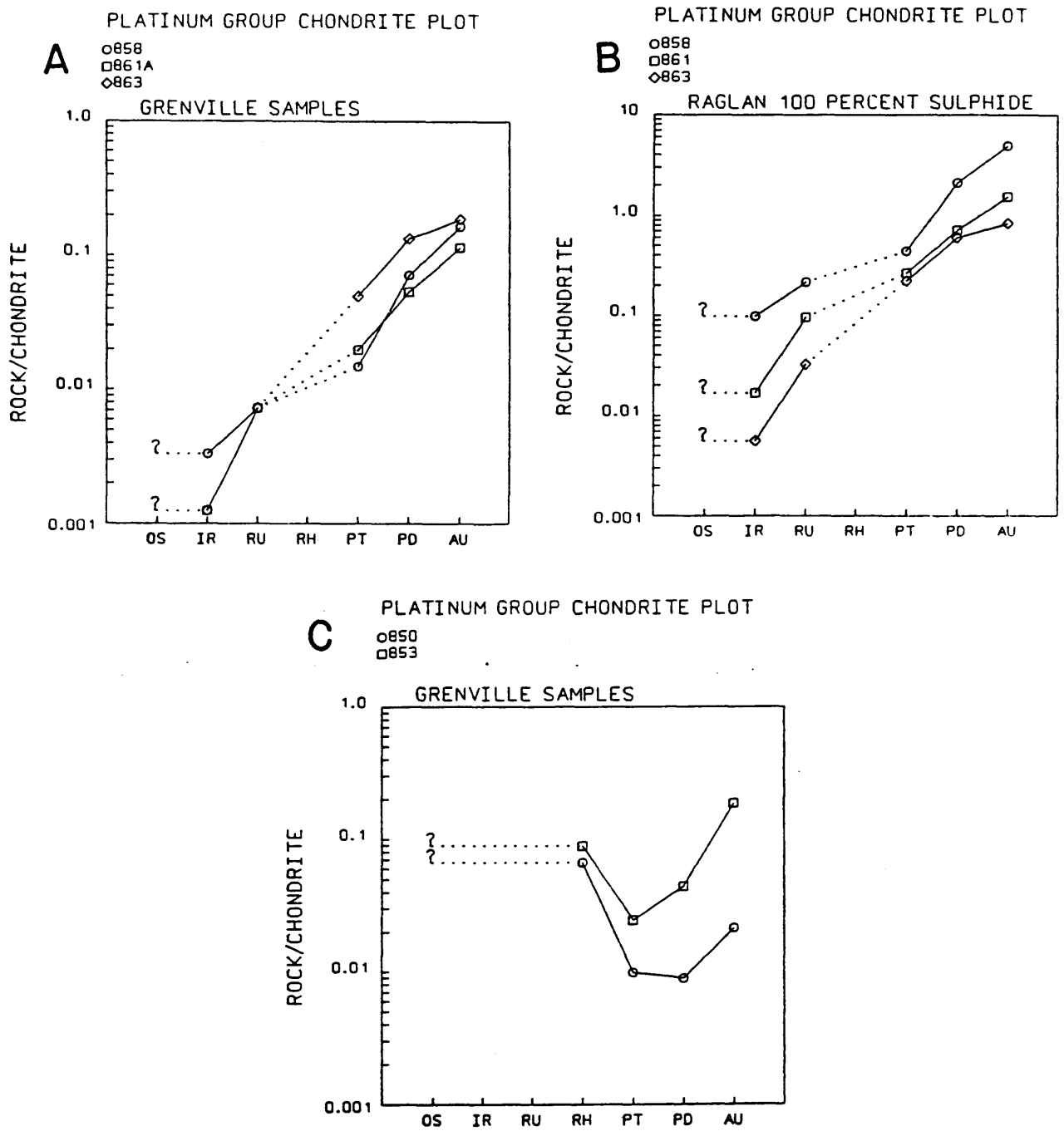


Figure 3.55A : PGE plot for Raglan samples, with whole-rock PGE data normalized to chondritic abundances. Osmium was not detected in any of the Grenville samples.
Figure 3.55B; Raglan data, further normalized to 100 percent sulphide, as calculated in Section 4.2.
Figure 3.55C; PGE plot for Cordova and Lingham Lake samples, with whole-rock PGE data normalized to chondritic abundances.

Table 3.18 : Chemical Analyses of Grenville Mafic Intrusions

Elements	850	853	858	862A	863
Major Elements (wt.%)					
SiO2	46.3	48.3	45.7	46.1	27.1
Al2O3	17.7	4.15	25.6	14.3	13.7
Fe2O3	2.40	1.43	1.29	2.24	9.21
FeO	8.1	10.5	7.2	15.8	24.2
MgO	9.05	16.2	1.35	4.25	1.40
CaO	7.36	11.9	12.4	7.60	6.04
Na2O	2.85	0.41	2.76	1.05	1.65
K2O	0.24	0.32	0.26	1.08	0.22
TiO2	0.66	0.85	0.21	0.28	0.19
P2O5	0.04	0.08	0.03	0.03	0.02
MnO	0.16	0.17	0.03	0.06	0.03
LOI	4.00	3.08	2.39	4.77	10.5
Total	98.86	97.39	99.22	97.56	94.26
Extra data (for PGE analysis) (wt.%)					
Ni	<0.01	0.08	<0.01	<0.01	0.08
Cu	<0.01	0.16	0.12	0.20	1.28
Pb	0.16	0.16	0.16	0.20	0.20
S	<0.01	0.64	1.32	2.96	8.68
Trace elements (ppm)					
Cr	60	1770	60	130	70
Sr	280	20	850	300	280
Ba	160	70	90	390	250
Precious metals (ppb)					
Os	<3	<3	<3	<3	<3
Ir	<0.1	<0.1	1.6	0.6	0.6
Ru	<5	<5	5	5	5
Rh	9	12	<1	<1	<1
Pt	10	25	15	20	50
Pd	5	25	40	30	75
Au	3	26	23	16	26

N.B.; Analyses by X-Ray Assay Laboratories Ltd. Major and minor elements by XRF (detection limits 0.01 % and 10 ppm respectively). FeO by wet chemistry (d.l. 0.1 %). LOI measured after heating for 1000°C for 30 minutes; provides a measure of (S+CO2+H2O) contents. Total for 863 probably deviates from 100% due to problem of high S content. Precious metals by ICP mass spectrometry. Precious metals detection limits marked on null readings (except 5, 5 and 1 ppb for Pt, Pd and Au, respectively). Other elements analysed and not reported; Rb, Y, Zr and Nb all 20 ppm or less, and Re<5 ppb. Samples from Cordova gabbro (850), Lingham Lake intrusive (853) and Raglan Metagabbro Complex.

Even after subtraction of the sulphide-related Fe, the sulphide-rich samples appear Fe-rich (Figure 3.53). The samples are much richer in Fe than the anorthosite suite in the Burwash and North Bay areas sampled by Lumbers (1975, p.83). The unmineralized samples are magnesium-rich compared with the Mountain Grove analyses, consistent with occurrence of sulphides in the relatively mafic portions of Grenville intrusions. The material sampled here represents the iron-rich portion of the classic magmatic differentiation trend illustrated by Wolff (1982). This reconnaissance focussed on sulphide-bearing material; a clearer picture of the chemistry of the host rocks will be complimented by analyses of essentially barren rocks (Wilson in prep.).

Metal ratios have been employed in many Cu-Ni-PGE deposits to discriminate between different styles of PGE mineralisation (cf. Section 1.1). 8 samples of Mountain Grove gabbro (from a total of 12 samples of gabbroic and anorthositic samples) analysed by Wolff (1982) give an average Cu/(Cu+Ni) ratio of 0.45 $\pm$0.17 (0.40 $\pm$0.17 for all 12; maximum S content 0.38 wt.%). The average {Cu/Cu+Ni} ratio for the two relatively S-poor samples of Carter et al. (1980) is 0.41. In randomly selected, sulphide-rich hand specimens, the base metal ratio may be expected to fluctuate wildly, depending on sample size, bulk composition, and the component of remobilized (Cu-rich) sulphide involved. For comparison, the quoted sulphide reserves at the Macassa deposit (Carter and Colvine 1985) have a higher Ni content for a {Cu/Cu+Ni} ratio of 0.23. A {Cu/Cu+Ni} ratio of approximately 0.4 is assumed to be representative of Grenville mafic intrusions.

The PGE results can be compared to a compilation of PGE data for magmatic ores in Ontario (Naldrett et al. 1980). It is worthwhile to calculate the Pt/(Pt+Pd) ratio for the three Raglan samples, although the low concentrations will limit the accuracy of the result; the mean value is 0.36 $\pm$0.07. When this is combined with the published whole-rock data for base metals (average Cu/(Cu+Ni)=0.4, above), the result plots on the chart of Figure 1.1B immediately below the Sudbury suite. Sample 863 is an exception, with Cu/(Cu+Ni)=0.94; this rock is sheared and enriched in remobilized chalcopyrite-rich sulphide.

Total (Pt+Pd) from the four samples associated with the Raglan and Lingam Lake Ni-Cu showings vary from 50 to 125 ppb, with average Pt:Pd ratio of 1:1.7. The PGE patterns are skewed toward the less refractory elements (Figure 3.55), indicating a sulphide-related magmatic association. The very low values for the Cordova sample (sample No. 850, Table 3.18), which contains only minor euhedral pyrite, is consistent with a sulphide association related to gold mineralisation at the nearby mine. The lack of Rh in sulphide-rich samples (Nos. 858, 861A, 863) is striking, and may imply that this element is not concentrated in sulphide to the same extent as Pt and Pd. The calculations suggest mean precious metal contents for the sulphide phase of the Raglan samples of 116-681 ppb Au, 223-444 ppb Pt, and 335-1180 ppb Pd. Given the limited amount of data, conclusions regarding PGE in the Grenville are currrently unwarranted, and analysis of many samples for Pt-Pd-(Au) will be required in order to directly assess the potential of the many gabbros in the area. It suffices to note that the chemistry presented here is consistent with the petrography in indicating magmatic sulphides in the mafic intrusives.

3.2.6.7 Tectonic Setting of Grenville Mafic Intrusions

The major area of the Grenville province in North America is a 1500-km section in eastern Canada, although small inliers are exposed within later

Appalachian terrain from Newfoundland to Vermont (Poole 1976). The rocks of the province record events over a long time interval, e.g. in eastern Labrador, Scharer et al. (1986) outlined a geological history ranging in age from 1710 to 925 Ma. For Ontario dates the GRENTIME database can be sought for original citations (Easton 1986).

A variety of tectonic models have been proposed for the Grenville province. For a consideration of some of the hypotheses regarding this topic, refer to Farquhar and Fletcher (1980). The plate tectonic environment of the Grenville region, particularly in the 1300-1000 Ma time scale, should place constraints on the tectonic setting of potential PGE host rocks. According to Wynne-Edwards (1972, pp.323-326) the thickness of the preserved sedimentary pile is up to 7.6 km (25,000 feet), but volcanic sequences are not common except in the Hastings Basin, one of the areas where the supracrustal sequence is thickest and the metamorphic grades are the lowest. By his estimation, roughly 8 million km^3 of rock were removed by erosion before 800 Ma, and no ophiolitic remnants exist to suggest a former plate boundary, unless they are south-east of current outcrops, buried under the Appalachians. This is the basis for the contention that the Grenville developed upon a single continental plate, which became a zone of uplift and erosion on the margin of the cratonic foreland beyond the Grenville Front (Wynne-Edwards 1972). However, the occurrence of synkinematic metabasite dykes emplaced into ductile shear zones in the Lac St. Jean region of Quebec suggests tensional stress and rifting (Woussen 1985). The dykes in this region cut the older gneiss and the anorthosite-mangerite masses, but are absent from younger granites. Hence the postulated rifting occurred before the peak of the Grenville orogeny, and is ascribed to the "Elsonian event". There is, therefore, a suggestion of rifting in the Grenville, quite distinct from the later postorogenic rifting with which the Chenaux gabbro (Lumbers 1982), alkalic complexes in the Parry Sound - North Bay area (Lumbers 1971), and the tholeiitic dykes of the Ottawa rift (Kretz et al. 1985) are correlated. Patchett et al. (1978) suggested that basaltic volcanism extending from eastern Canada through Greenland to Scandinavia 1260-1190 Ma might represent continental separation preceding the Grenville- Sveconorwegian orogeny, but this speculation remains unproven (York 1984).

3.2.6.8. The Grenville : Exploration Guidelines

There is little published data directly applicable to prospecting for PGE in the relatively small basic intrusions in the Grenville. A negative factor pertaining to PGE exploration in the Grenville is the generally high grade of regional metamorphism. Almandine amphibolite to granulite facies rocks have been subjected to much higher temperatures and pressures than, for example, the greenschist facies host rocks of the bulk of the gold deposits in the Abitibi greenstone belt. Metamorphic grade in southeast Ontario generally increases outward from the Hastings Basin (see e.g. Brown et al. 1975, Sampson 1972). Au, Pd and probably Pt may be mobilized significantly at high metamorphic grade; circumstantial evidence for this is seen at the Cordova gold deposit, situated in the relatively low-grade terrain of the Hastings Basin, where gold showings are commonly in quartz veins hosted by metavolcanic rocks near the margin of intrusions of biotite diorite (Lumbers 1982, p.41).

In prospecting terms, Cu-Ni showings and ultramafic rock outcrops should be inspected carefully. All true gabbroic rocks should also be examined, although the relatively iron-rich anorthositic suites which may be related to the Adirondacks massif anorthosites (McLelland 1986, and Figure

3.52D) are not considered favourable for PGE. Grenville anorthosites are described by e.g. Lumbers (1975). Sulphide contents of these rocks tend to be low, and the intrusions may record a spectrum of metasedimentary assimilation, as suggested by Harrison (1943).

Deformation within the metamorphosed and altered mafic rocks should be closely scrutinized. Competent gabbro and diabase are relatively resistant to deformation, and a rapid decrease in strain state may be noted away from quartzose host rocks in some localities; nevertheless, gabbro may be sheared and mylonitized (Davidson 1986, pp.14-16), and in the case of the Cordova gold mine, shear zones may be loci for Grenville mineralization (Easton et al. 1986). In northwestern Ontario, MacTavish and Dutka (Section 3.1.5.) noted a similar phenomenon; brittle fracturing in a gabbro and ductile shearing in metasedimentary host rocks, with high PGE values in sulphide pods within metamorphosed ultramafite. Chalcopyrite is commonly mobile later than the other sulphides; this has been observed in numerous localities. Lumbers (1971) described sulphide concentrations in the Memesagamesing Lake stock, in Hardy township, north of Port Loring, apparently hosted in shear zones in norite, including, in decreasing order of abundance, pyrrhotite, pyrite, magnetite and chalcopyrite.

Mineralogically, the present observations, based on a limited sampling program and substantial literature search, suggest two distinct alteration styles. One is associated with Au mineralization, and is characterized by carbonate-chlorite-sericite alteration, microscopic veining and alteration of feldspar, and growth of cubic pyrite crystals. The Cordova samples examined conform to this model. Cu-Ni$\pm$PGE mineralization is pyrrhotite- or chalcopyrite-dominant, depending perhaps on the degree of late local mobilization of the sulphides. The sulphide showings within the Raglan mass exemplify this style. Clinopyroxene is strongly uralitized and plagioclase is variably sericitized.

To conclude, possible Grenville targets should include disseminated, net-textured sulphides in gabbroic bodies, sulphides in sheared mafic or ultramafic host rocks, and other features associated with proven PGE resources, as outlined in Section 2 of this report. Ultramafic lithologies such as pyroxenites and peridotites should be examined closely for sulphides and for evidence of magma mixing. In this context, intrusion (perhaps rheomorphic back-injection) of the abundant felsic plutonic rocks into gabbro should be considered in the vicinity of contacts. At the Caribou Lake nickel prospect, west-northwest of Port Loring (Shklanka 1969, pp.213-214) sulphides occur in norite which intruded granite and granite gneiss, and is in turn cut by granite pegmatites. Detailed outcrop-scale fieldwork in any Grenville gabbros with lithological complexity will undoubtedly provide insights into the mechanics and sequence of the intrusive phases. Harding (1947, p.27) concluded that in the suite of gabbros he examined between Perth and Madoc "all the intrusives, ranging from gabbroic anorthosite to granite and alaskite, are genetically related and were derived by differentiation from a primary parent magma". Wallrock assimilation, postulated as cause of sulphide-PGE precipitation in the Duluth intrusion (Mainwaring and Naldrett 1977) and the Coldwell complex (Wilkinson and Colvine, 1978), has certainly occurred in some of the Grenville intrusions. An interesting case is the Attewell Lake (Lanark-Oso) gabbro in Oso township, west of Perth and south of Highway 7, where crystals of corundum and quartz and inclusions of greywacke and limestone occur within the intrusion (Harding 1947, pp.22-24). Corundum and spinel occur in zones of anotthosite in the Lanark-Oso body, S.E. of Silver Lake (Wolff 1985, pp.29-40). Regarding possible hydrothermal activity,

unusual fluidized gabbroic breccia pipes (Williams 1984) indicate at least a limited role for magma mixing and volatile segregation within the province. Tourmaline occurs in granitic pegmatites within the Mountain Grove gabbro; although a good indicator of volatile activity and a common gangue phase in some Archean gold deposits, its occurrence (e.g. Bain 1960, pp.107-109) in Grenville granites and their country rocks (including a talc deposit near Madoc) is probably an index of relatively late granitic evolution and wallrock interaction, and irrelevant to possible (earlier) hydrothermal PGE. Pegmatites containing hydrous phases, and sheared gabbros containing significant copper-rich sulphide mineralization, should always be examined with care. Some very small intrusions in Ontario contain Ni-Cu sulphide bodies which have been mined even in the last decade (e.g. Kanichee, Section 3.1.7.8.). The fact that Kanichee was a producer of precious metals implies that none of the intrusions described here can be rejected as exploration targets by size alone, even if one assumes that current exposures give any indication of original magma volumes. The logistical problem is perhaps not a lack of mafic-ultramafic rocks in the Grenville Province, but a surfeit; sulphide+PGE mineralization tends to occupy restricted areas within larger intrusions; for example, the Bushveld, Stillwater, Coldwell and Lac des Iles intrusions, to name but four.

4.0 : ANALYTICAL METHODS AND DATA TREATMENT

4.1 : Analytical Methods for Platinum (C. Riddle)

4.1.1 : Introduction

This contribution provides a review of the available methods for the determination of platinum in geological materials. The reader is referred to a previous article on gold analysis (Riddle 1983) for a review of analytical terminology and sampling theory. Unlike gold, for which extensive analytical data exist for a wide variety of geological environments, the paucity of analytical data available for platinum means that its modes of occurrence are not as well documented as those for gold.

An excellent text on the analysis of noble metals (Beamish and Van Loon 1977) is available and provides detailed accounts of analytical procedures. This article therefore concentrates on recent advances in the determination of platinum in geological samples. It should be mentioned however that 'new' is not always 'better', especially in the area of precious metals analysis. Thus the traditional fire assay method for gold analysis, having been around for over 2000 years, continues to be the standard for the accurate determination of economic levels of gold.

The natural abundance level for platinum, 0.05 parts per billion (ppb), is eighty-fold lower than that for gold (Ronov and Yaroshevskii (1972). Platinum typically occurs as individual grains in alluvial deposits, in association with gold ores and nickel sulfide, and disseminated in basic and ultrabasic igneous rocks. The sampling problems associated with gold, due to the heterogeneous distribution within its host rocks, are therefore duplicated for platinum and compounded by the lower levels of occurrence.

Geologists of the Ontario Geological Survey have indicated that they require the routine determination of platinum in rock samples for occurrences in the range 1-1000 ppb, with relative precision of 10-20% at the 95% confidence level, and comparable accuracy. These requirements can generally be met by the methods described below. The determination of platinum at levels of occurrence above 1 part per million (ppm) is rarely needed. In such cases a semi-quantitative determination by a modified version of one of the listed methods is usually adequate. Methods of interest to concentrators and refiners are therefore not discussed in detail.

4.1.2. : Sampling

In sampling, a small amount of material is taken to be representative of some larger amount. To be representative a sample must contain the same relative proportions of all constituents as the original feature. Subsequent handling of the sample must preserve its representative nature. In addition, the final analytical subsample must contain a sufficient number of particles of the element of interest (platinum) to be capable of yielding statistically tound analytical data.

A variety of methods has appeared in the literature to calculate the number of particles in a sample. These vary from crude 'rules of thumb' to sophisticated mathematical treatments. Anyone submitting a sample for the determination of platinum would be well advised to perform some form of these

calculations in order to gain an insight into the possible significance of the analytical result.

It has been shown in this laboratory that silicate rocks, prepared for analysis by grinding to -170 mesh, may contain anywhere from 2 million to 15 billion grains per gram. If platinum were to be present in discrete grains at the 10 ppb level then for a sample to contain a single grain of platinum, on average, would require from 7-500 g of material (taking into account the high density of platinum compared to that of most rock matrices). To give statistically sound data at least 20 grains per subsample are needed and hence a subsample size of 140 g to 10 kg.

At the ppb level, platinum is generally well disseminated as a minor component of a major mineral. In this case there will be many more platinum-containing grains compared to the case above in which only grains of pure platinum are assumed to exist. Nonetheless the consequences of proper sampling at the ppb level must not be overlooked if meaningful interpretations are to be placed on the analytical data.

In any detailed study it will be important to determine and report the confidence limits associated with analytical results. These may be determined by replicate subsampling and analysis of a single sample.

Gy (1979) has written a definitive text on sampling and Clifton et al (1969) have provided a useful technique for estimating the size of sample required to provide a representative sample for gold and other heavy metals. The reader is referred to these and the standard analytical texts for further discussion of the subject.

4.1.3. : Analytical Methods in general use

An analytical method may best be described in terms of the techniques that comprise the method. These will typically be techniques of sample attack, separation, measurement, and data reduction.

4.1.3.1. : Sample Attack and Separation

For platinum determination in geological materials, sample attack will typically involve fusion or acid digestion of a sample. A separation step may be integral to the attack, as in selective leaching or fire assay abstraction into a collectors such as lead and silver.

Platinum dissolves in aqua regia and this may be used to leach available platinum from a rock sample. Any platinum contained within a silicate matrix will however only be released in a total digestion procedure, involving hydrofluoric acid, HF. The use of an organic extractant allows platinum to be separated from most other interferrent elements.

Hydrobromic acid, HBr, in combination with bromine, Br_2, is favored as a digestion medium in one procedure detailed below. Chlorination has also been proposed for the liberation of platinum (Dolezal et al. 1968).

The fire assay procedure uses a flux, the composition of which will vary depending on the overall nature of the rock sample. A typical stock flux contains litharge (54.5%), sodium carbonate (27.5%), silica (8%), borax glass

(8%), and wheat flour (2%). The first two ingredients are basic and act as oxidizing and desulphurizing agents. On reduction litharge, the least basic of the two, yields the lead used to extract the platinum. Silica's acidity is advantageous in forming silicates with metal oxides. Borax, also acidic, dissolves most metal oxides and helps lower the fusion temperature. Flour is a source of carbon, needed to reduce litharge to lead. Changes to the stock flux are often neccessary. Basic ores require a more acid flux and so the amounts of silica and borax are increased. Acid ores require a more basic flux such as provided by sodium carbonate and litharge. Reducing ores can be oxidized with addition of potassium nitrate; oxidizing ores can be reduced with an increase of carbon-containing materials such as flour. Sulphur is removed with sodium carbonate, litharge, or potassium nitrate.

4.1.3.2. : Analytical Measurement and Data Reduction

Given the low levels of occurrence that are typical for platinum-containing samples, only the most sensitive of analytical measuring techniques are of use, unless extensive preconcentration and separation procedures have been applied. Thus nuclear techniques, atomic absorption, optical emission and mass specrometry are favored. These techniques are typically calibrated with a combination of matrix-matched synthetic standards and international reference materials. Data reduction is therefore reduced to a correlation between an analyte signal and the equivalent sample concentration using a calibration curve. Such a curve is often built into the computer control program for the spectrometer.

4.1.3.3. : Methods involving Atomic Absorption Spectoscopy

The atomic absorption measurement technique generally requires the preparation of a solution sample. This allows some form of preconcentration and/or separation to be employed.

(a) Direct Acid Attack.

A good example of a method involving direct acid attack is one first applied to the determination of gold. It involves treatment with hydrobromic acid, HBr, containing free bromine, Br_2; separation and concentration by extraction into methyl isobutyl ketone (MIBK); atomic absorption measurement; and concentration calculation from a calibration curve derived from rock and synthetic standards.

25g of rock pulp are shaken with the acid reagent, gold and tellurium are separated by extraction into MIBK, and platinum reduced with stannous chloride, $SnCl_2$, to form a tetravalent platinum complex which is then extracted into MIBK. Subsequent flame AA determination of Pt has a detection limit of 100 ppb.

Attractions of this procedure are (1) the large sample size, neccessary for representative subsampling, and (2) the use of cheap and readily available equipment, apparatus, and reagents. Further details and references are given in Johnson and Maxwell (1981).

(b) Fusion followed by Acid Digestion.

The most important preconcentration and separation schemes for platinum involve fire assay. Of four possible collectors, silver is generally preferred although tin, lead, and nickel sulphide also have their merits. The

fire assay bead may be digested in acid and platinum determined by either flame or flameless AA. Details are given below.

4.1.3.4. : Methods Involving Colorimetry

The selective absorbance of certain wavelengths of light by a colored solution allows such solutions to be characterised by the absortion curves derived from the passage of visible light.

Platinum forms colored complexes with a variety of reagents, some of which produce species stable enough for quantitative analytical determination. Interferences from all of the other precious metals may occur, however these can sometimes be minimised by solvent extraction procedures which also have the benefit of concentrating the analyte species.

The tin(II)-platinum complex has been studied in detail and allows accurate determination of Pt in the 1-25 ppm range. With solvent extraction, the detection limit can be reduced to 30 ppb based on a 10g sample.

Three other colorimetric reagents are referred to in the literature, p-nitrosodimethylaniline, rhodamine 6G and reduction of phosphomolybdic acid. Details and further references are contained in Beamish and Van Loon's text and in Fletcher (1981).

4.1.3.5. : Methods Involving Optical Emission

The use of small samples of rock powder, typically 15 mg, associated with conventional AC or DC arc/spark excitation is inappropriate for the determination of ppb levels of platinum. However the use of silver beads derived from fire assay fusion, separation, and preconcentration is a most effective use for the spectrograph. A procedure developed in the Geoscience Laboratories, Ontario Geological Survey, is described below.

Most optical emission work now uses spectrometers with argon plasma sources. As with AA, a solution sample is preferred and a detection limit of 10 ppb Pt, expressed as the rock concentration, has been claimed for determinations on digestates of conventional fire assay silver beads.

4.1.3.6. : Methods Involving Neutron Activation Analysis

Instrumental Neutron Activation Analysis (INAA) depends on the measurement of gamma and X-ray emissions from radioactive isotopes produced in a sample upon irradiation by neutrons in a nuclear reactor. A characteristic gamma ray spectrum is associated with the neutron-induced radioactivity for each element which can be measured and thus yield quantitative analytical data. The method was, in part, developed by Hoffmann (1978).

Although extremely sensitive, the technique suffers from two drawbacks when it comes to the determination of platinum: (1) interferences can reduce the sensitivity; and (2) a relatively small sample size is required. Both drawbacks can be overcome by a fire assay concentration and separation step which conveniently reduces a large (10-50 g) sample to a manageable size and removes most of the host matrix.

INAA applied to platinum at the ppb level in rock samples requires a nickel sulfide fire assay preconcentration step. Neutron activation analysis of the separated sulfide provides a method suitable for geochemical exploration as well as routine rock analysis. Typically, a detection limit of 5-10 ppb is claimed for a 50g sample by commercial laboratories.

Alkali fusion followed by extraction of Pt onto a chelating resin for Ge(Li) gamma spectrometry is referred to in the text by Reeves and Brooks (1978). ^{199}Pt has a half-life of 31 minutes.

4.1.3.7. : Other Methods

Other methods such as those involving gravimetric and volumetric determinations are not considered sensitive enough for routine geochemical analysis. The reader is referred to Beamish and Van Loon (1977).

4.1.4. : Methods used by the Geoscience Laboratories, OGS

Three methods that have been used in the Geoscience Laboratories, Ontario Geological Survey are described in detail. The first is the routine method for platinum at the ppb level in rock samples; it is based on graphite furnace atomic absorption measurement. The second is a 'back-up' method, developed for optical emission measurement, no longer in routine use. The third represents the latest development, use of inductively coupled, argon plasma-mass spectrometric (ICP-MS) measurement.

4.1.4.1.0. : Fire Assay Preconcentration and Separation followed by Flameless Atomic Absorption Measurement.

Platinum, palladium and gold are determined in geological materials by flameless AAS utilizing an auto-sampling system. A 10 g subsample of -170 mesh material is used in a classical fire assay preconcentration step to produce a silver bead of approximately 15 mg. Dissolution of the silver bead is accomplished with nitric acid, silver is precipitated as the chloride with hydrochloric acid and any platinum is dissolved in the resulting aqua regia. An aliquot of the supernatent liquid is atomized in a graphite furnace and the atomic absorption signal observed as a recorder trace and compared with a standard calibration curve.

4.1.4.1.1. : Silver Bead Preparation (Sample Attack Procedure)

A 10 g, -170 mesh rock pulp subsample is mixed with 75 g of standard flux (litharge 54.6%, sodium carbonate 27.3%, silica 8.2%, borax glass 8.2%, flour 1.7%) and one drop of a 40% aqueous solution of silver nitrate is added. The silver nitrate provides the silver neccessary to ensure the quantitative abstraction of platinum into a silver bead of good form (inquarting); the bead typically weighs 15 mg. The reagents are mixed in the assay crucible, and placed in a preheated furnace at 1025^{o}C for 35 minutes. The molten charge is cast into an iron mould and the lead button broken free from the slag and formed into a rough cube. The lead cube is placed on a preheated (950^{o}C) cupel and placed in a cupellation furnace for approximately 30 minutes until all the lead has been absorbed into the cupel. The remaining silver bead is

visually inspected to ensure adequate inquarting and is then placed in a 10 x 75 mm test tube.

4.1.4.1.2. : Analytical Solution Preparation (Sample Separation Procedure)

0.5 ml of (1 + 3) nitric acid is added to dissolve the silver, followed by 0.5 ml of (1 + 3) hydrochloric acid. The contents of the test tube are well mixed and the resulting precipitate of silver chloride, AgCl, is digested by placing the test tube in an aluminum block on a hot plate until the supernatent liquid is clear and the AgCl has coagulated as a lump on the bottom of the test tube. Heating must not be so prolonged as to involve significant loss by evaporation. 1.0 ml of distilled water is added to the test tube and the contents allowed to cool. A portion of the supernatent is transferred to a sample cup for the platinum determination.

4.1.4.1.3. : Atomic Absorption (Sample Measurement Procedure)

A conventional atomic absorption spectrophotometer, equipped with a graphite furnace and auto-sampler, is used. Instrument parameters are as follows: platinum lamp current - 12 mA; wavelength - 265.9 nm; slit width - 0.7 nm; background correction - 'on'; water coolant rate 2.5 litres/minute; sample volume 20 microlitres. Furnace program steps: (1) drying: temperature 120^{o}C, ramp time 15 seconds, hold time 20 seconds; (2) charring: temperature 800^{o}C, ramp time 20 seconds, hold time 15 seconds; (3) atomization: temperature 2700^{o}C, ramp time 0 seconds; hold time 5 seconds.

4.1.4.1.4. : Data Reduction Procedure

The concentration of platinum in the sample is read from a calibration graph, derived from the analysis of a series acid matrix matched synthetic standard solutions. The net concentration is obtained by subtracting the average overall blank value, typically 0 micrograms per millilitre. The platinum content of the rock (in ppb) is calculated as:

$$Pt(ppb) = CV \times 1000/W$$

where: C = net concentration of Pt in micrograms per millilitre in solution
V = volume in millilitres of the sample solution (typically 2)
W = weight of sample in grams (typically 10)

4.1.4.1.5. : Quality Control

Accuracy of data, obtained in the manner described above, is assessed by applying the complete procedure to a series of synthetic (0.1 and 0.2 ppm solutions), in-house and international standard reference materials (e.g. Canadian Certified Reference Materials Project (CCRMP) samples PTC-1, PTM-1, PTA-1). Precision is determined from the results of replicate (20) analyses of the in-house standards. The optimal working range is 0.05 - 0.20 micrograms Pt/millilitre in solution. The determination limit, defined as three times the standard deviation of the sample blank, is 1 ppb Pt expressed as the concentration in rock.

Standards do not have a long shelf-life. They must be prepared every two weeks and stored in polyethylene containers. The following interference observations have been made for a 0.2 ppm Pt solution:

50 ppm silver reduced the absorbance reading by 5%
50 ppm gold had no effect
5 ppm Pd had no effect
50 ppm Pd reduced the absorbance by 10%.

For most typical analytical situations, with rock samples possessing less than 1 ppm total precious metals, the method is therefore interference free.

4.1.4.2. : Fire Assay Preconcentration and Separation followed by AC Arc Optical Emission Measurement.

Although recently discontinued in the Geoscience Laboratories, due to the availability of alternative instrumentation of greater analytical flexibility, this method is worthy of mention.

A silver bead, containing the platinum from one assay ton, 29.166g, of rock pulp, is prepared for each sample using the procedure described above. (An assay ton is that weight in grams which enables "micrograms of gold per assay ton of sub-sample" to be reported as "troy ounces per short ton of sample" without any numerical factoring). In addition, a blank silver bead is prepared for each sample. The silver beads are prepared for analysis by punching a small hole in them using a steel pin with a 30^{0} conical tip. Rods of pure copper, 5 mm in diameter and 50 mm long, pointed at one end, are used as electrode supports. One silver bead is soldered to the tip of each copper support to form the electrode.

A 20 second AC arc burn-time is used with a 2 mm arc gap. The optical signal generated in the arc is recorded photographically in a 3.4 m Ebert spectrograph. A calibration graph is derived from a series of synthetic standards and the intensity, measured for the sample on a microdensitometer, is converted by means of the calibration graph to a rock concentration value.

The principal analytical lines used are 306.45 nm and 265.95 nm. The optimal working range, expressed as ppb in the rock, is 10-1000 ppb. The detection limit is 1 ppb.

It should be noted that use of silver for the counter electrode greatly improves sensitivity over the more common procedure of using a graphite counter electrode. In the latter case the detection limit is approximately 100 ppb. Greater sensitivity may be achieved by the use of two sample beads in place of one sample bead and one blank.

The availability of alternate emission spectral lines for Pt allows the method to be used to determine Pt at concentrations as high as 10 ppm in the rock.

4.1.4.3. : Methods Involving Measurement by the Technique of Inductively Coupled Plasma - Mass Spectrometry.

The recently introduced technique of ICP-MS has been successfully applied to the determination of the platinum group elements in geological

samples by several workers. In the Geoscience Laboratories of the OGS development work in is progress for a method allowing the sequential determination of Pt, Pd, Ir, Rh, and Ru. Such a method will likely involve fire assay collection in a nickel bead. If Pt alone is required then the conventional silver fire assay bead collection technique is appropriate. Osmium, due to its volatility, is not readily collected by fusion procedures.

The procedure is identical to the method described in Secton 4.1.4.1. in the separation, concentration and digestion phases. The sample solution is diluted tenfold then introduced into the ICP by a conventional peristaltic pump/nebulizer system. Pt is measured at mass number 195 (194 is also acceptable) and the resulting signal intensity is turned into a concentration value using a calibration curve produced from synthetic standards and verified with the aid of international reference materials. A detection limit of 1 ppb in the rock is attainable with a linear working range to at least 1 ppm.

4.1.5. : Analytical Program Design

If a platinum occurrence is identified, the decision to undertake further exploration work can be aided by a mineralogical study. The purpose of such a study is to identify the modes of occurrence of platinum within the host medium and thus to be able to quantify the sampling procedures required. The omission of such a study may result in the collection of samples that are either too small or too large, and in sample reduction (grinding) procedures that are not appropriate for the sample. For example, samples containing platinum that is associated exclusively with nickel sulphides, do not need to be ground as finely as those in which the platinum is locked within a silicate lattice. In any extensive sampling program the cost savings and effectiveness of the program greatly outweigh the cost of an initial mineralogical study. For platinum such a study will almost certainly involve micromineralogical techniques because resolution of the order of 1 micron is required.

Three instruments are commonly associated with a micromineralogical study. These are:

(a) The ore microscope - a modified petrographic microscope with good resolution at magnifications of 1000x.

(b) The scanning electron microscope (SEM) - essentially an extension of the ore microscope, this instrument uses a scanning electron beam in place of light to provide improved resolution and hence greater magnification. An accesory energy-dispersive X-Ray sepctrometer allows elemental analysis of particles as small as 0.1 microns diameter.

(c) The electron microprobe - similar to the SEM, the electron microprobe uses an electron beam to provide high resolution imaging of an object that has been optically aligned in the instrument with the aid of a microscope. An area of a few microns is typically observed. Accessory energy-dispersive X-Ray analysis is also available.

The sample is typically presented in the form of a polished mount. The choice of instrument depends on the particle size and distribution of the platinum in the sample. Fine particles and intergrowths high in platinum require the superior resolution of the SEM; whereas low concentrations of platinum in a major mineral require the superior sensitivity of the microprobe's analyical system to be detected. Instruments that combine the advantages of both systems are becoming available and this will simplify such studies. A detailed review of this topic is given by Gasparini (1984).

4.2. A CRITIQUE OF THE NORMALISATION OF PGE TO 100% SULPHIDE (G.C. Wilson)

This section considers the preparation of chondrite- and sulphide-normalised PGE plots, taking the sulphide-bearing Grenville sample suite discussed in Section 3.2.6. as an example. The normalisation of absolute PGE and Au abundances to relatively 'primitive' chondritic meteorites was noted in Section 1.1; accepted chondrite abundances are quoted in Table 1.1. The common practice of further comparing the chondrite-normalised data to the sulphide (or chromite) fraction of the whole rock is a means of comparing the deduced magmatic (sulphide or chromite) carrier liquid of the PGE to equivalents in other intrusions. Accordingly, the weight percent sulphide or chromite in the rock must be determined in order to scale the precious metal values to the concentrations in the inferred carrier.

Two objections can be made to the universal application of this method. The first rests on the inaccuracy of scaling the PGE content of sulphide-poor samples (e.g. < 2%) to 100% sulphide. Here we reject two of the Grenville samples (Table 3.18, samples 850 and 853) as they lie below an arbitrary baseline of 2.0 wt.% total sulphide (as calculated below). The second objection is petrogenetic, and would restrict use of the method to rocks in which the primary concentrator of PGE is clearly the sulphide phase. In this context localised, late remobilization of apparently magmatic sulphides need not exclude a sample, although it must be realized (and should be demonstrable in the final data analysis) that this may lead to modified patterns due to preferential association of the relatively mobile Pd and Au with the (commonly chalcopyrite-rich) remobilizate. Sample 863 is a case in point. The gross chemistry of remobilized sulphides may be detected petrographically (Figure 3.51C). The partial decoupling of Cu from other base metals has also been demonstrated geochemically (Good, 1985). However, presence of complex discrete PGM, particularly when in the presence of volatile-rich phases (such as biotite, amphibole, apatite, graphite or carbonate), may imply other magmatic or hydrothermal processes than sulphide-silicate melt separation with subsequent scavenging by sulphides of PGE from the magma. Renormalising PGE abundance data to 100% sulphide may be very misleading in such circumstances.

Samples 858, 861A and 863 of the Raglan Metagabbro Complex are selected for recalculation to 100% sulphide. The method chosen is a variant on that described by Hoffman et al. (1979, pp.439-440). Firstly, the Ni wt.% is converted to an equivalent weight of pentlandite. Cu is converted to chalcopyrite, and remaining S to monoclinic pyrrhotite (left-over Fe^{II+} will then belong to silicate and oxide phases). Total wt.% sulphide is divided into 100 to give an 'alpha factor' by which the PGE values are multiplied to give their estimated abundances in sulphide melt.

A problem with the method outlined above, notwithstanding its complexity, is that without extensive mineral chemical data, the exact partitioning of Ni (Co), Fe and S within the pentlandite and pyrrhotite solid solution series cannot be determined (this problem applies also to Cr in chromite). Presence of pyrite may be a further complication, and the contributions of Ni from olivine, magnetite and serpentine unknown. In the case of low Ni contents and a pyrite-rich assemblage Rowell (1984) instead converted Ni to millerite, Cu to chalcopyrite and excess S to pyrite.

Potential users of this method are here offered two methods of estimation in the absence of mineral analyses and point-count modal data. The first will require only the whole-rock base metal and sulphur analyses which should accompany any complete PGE assay; the second, for pyrite-bearing samples, needs an additional petrographic estimation of the proportions of pyrite and pyrrhotite.

Method (1) : The basic method begins with the conversion of Ni to pentlandite, $(Fe,Ni)_9S_8$. A nickel content of 35.0 wt.% Ni is assumed, close to the mean for Sudbury ores (Hawley 1962) and within the commonly-determined range of 34.2-36.2 wt.% (*ibid.*, pp.51-52). The full chemistry of this idealised composition (stoichiometry $Ni_{4.606}Fe_{4.394}S_8$), and of other essential phases, is given in Table 4.1. Cu is then converted to chalcopyrite, $CuFeS_2$, and the remaining S is assigned to monoclinic pyrrhotite. This phase is assumed to have the ideal composition Fe_7S_8 (Craig and Scott 1976, pp.CS-28,29). Excess Fe^{II+} (that not locked into 1-3 sulphides) is noted for possible whole-rock silicate interpretation. The sulphide wt.% total and alpha factor are now derived, and the latter is multiplied with the chondrite-normalised data which can then be replotted.

Method (2) : For pyritic samples a visual estimate of the pyrite:pyrrhotite ratio is required. This is best done with a sawn and polished sample, on a scale appropriate to the grainsize of the sample. As this is of necessity an approximation, we neglect both the fact that the density of pyrite is some 10% greater than that of pyrrhotite, and also the problem of scaling data concerning a two-dimensional surface to a three-dimensional sample. The relative distribution of S between pyrite and pyrrhotite is estimated by multiplying the calculated modal percentages of these phases by 0.574 and 0.426 respectively (see Table 4.1). For each sulphide in turn, the equivalent amount of Fe is calculated (from the values in Table 4.1) and (Fe+S) summed to give the weight percent of the mineral in the rock. Final procedure as for method (1).

Comparative results for the two processes are given in Table 4.2, and intermediate steps in Table 4.3. The sulphur-poor sample 853 is also included, although, as noted previously, no alpha factor can be derived with confidence. Note that treating pyrite as a separate phase lowers the calculated sulphide content (and boosts the alpha factor) by about 10 ($\pm$2) percent, increasing the carry-over of remaining Fe^{II+} to non-sulphides.

In conclusion, the renormalising of precious metal data to 100 percent sulphide is conceptually simple, provided one remembers that different processes have affected different sulphide deposits, and that a flexible approach is therefore required in interpretating the resultant patterns. Although alpha factor calculation is a process amenable to on-line data reduction following PGE analysis, the (simplifying) assumptions concerning sulphide mineralogy should not be forgotten. Since modal analysis is ultimately an expensive adjunct to geochemistry, it seems preferable to rely solely on the chemical data in the calculation, and to use Method (1). This is employed for the Grenville samples in Section 3.2.6. Specifying the sequence and chemistry of sulphides employed will systematize what formerly seemed, at least to this writer, to be something of a black art.

Table 4.1 : Idealised Sulphide weight percent compositions

Sulphide	Ni	Cu	Fe	S
Pentlandite	35.00	-	31.78	33.22
Chalcopyrite	-	34.63	30.43	34.94
Pyrrhotite	-	-	60.38	39.62
Pyrite	-	-	46.55	53.45
Millerite	64.67	-	-	35.33

See text concerning choice of these compositions. Atomic weights in calculations taken from C-12 -scaled tabulation in Walker et al (1983). Relative weight percentages of S in monoclinic pyrrhotite and pyrite, compositions as quoted, summed and scaled to 100, are 42.6 : 57.4 respectively.

Some derived factors;

Pentlandite wt.% = Ni x 2.857

....then Fe = Ni x 0.908

and S = Ni x 0.949

Chalcopyrite wt.% = Cu x 2.888

.....and Fe = Cu x 0.879

and S = Cu x 1.009

Pyrrhotite wt.% = S x 2.524

Pyrite wt.% = S x 1.871

TABLE 4.2: SULPHIDE NORMALIZATION FOR GRENVILLE SAMPLES

	Analytical Data for Whole Rock				Calculated Values for Sulphide Fraction					
Sample	Ni	Cu	FeO	S ==>	Pent	Chalc	Pyrr	Py	Wt.%sul	Alpha Factor
853	0.08	0.16	10.5	0.64	0.229	0.462	1.016	-	1.71	-
858	nd	0.12	7.2	1.32	-	0.347	3.026	-	3.37	29.6
							1.807	0.904	3.06	32.7
861A	nd	0.20	15.8	2.96	-	0.578	6.962	-	7.54	13.3
							3.731	2.395	6.70	14.9
863	0.08	1.28	24.2	8.68	0.229	3.697	18.46	-	22.39	4.47
							11.99	4.788	20.70	4.83

N.B. All values in weight percent. See Table 3.18 for complete analyses. Second line entry for each of the last three samples demonstrates the effect of trying to allow for the presence of pyrite. See text for procedure, especially regarding necessary assumptions in sulphide mineralogy. Sample 853 from Lingham Lake, the others from the Raglan Metagabbro Complex.

TABLE 4.3: Fe AND S MASS BALANCE FOR GRENVILLE SAMPLES

	Analytical Data		Calculated Values									
Sample	Total Fe	Fe_2O_3 ==>	Fe^{II}_{sul}	FeO_{rock}	Fe_{pen}	Fe_{chalc}	Fe_{pyrr}	Fe_{py}	S_{pyrr}	S_{py}	S_{chalc}	S_{pent}
853	13.1	1.43	0.827	9.436	0.073	0.141	0.613	-	0.403	-	0.161	0.076
858	9.29	1.29	1.933	4.713	-	0.106	1.827	-	1.199	-	0.121	-
			1.617	5.120	-	0.106	1.091	0.420	0.716	0.483	0.121	-
861A	19.8	2.24	4.379	10.166	-	0.176	4.203	-	2.758	-	0.202	-
			3.544	11.241	-	0.176	2.253	1.115	1.478	1.280	0.202	-
863	36.1	9.21	12.338	8.327	0.073	1.125	11.14	-	7.312	-	1.292	0.076
			10.667	10.477	0.073	1.125	7.24	2.229	4.753	2.559	1.292	0.076

N.B.; Fe^{II} (analysed) quoted as FeO in fourth column of Table 4.2. 'Total Fe' is Fe_2O_3* reported by lab. Fe_2O_3 value in this table and in Table 3.18 is the true value deduced as follows;

Fe_2O_3(quoted) = Fe_2O_3 (total Fe as Fe_2O_3) - (FeO(measured) x 1.1113)

Eight columns on right-hand side of this table; mass balance for Fe and S amongst the four sulphide minerals. FeO(rock), the deduced non-sulphide component of FeO in the samples, is readily estimated;

FeO_{rock} = (total FeO in rock) - (1.2865 x Fe^{II}_{sul}),

where Fe^{II}_{sul} is the sum of all FeII in 2-4 sulphides, given in column 3. As a consistency check for the whole procedure, (Ni+Cu+Fe^{II}_{sul})+(sum of 4 columns of S components) should equal the Wt.%sul in Table 4.2.

5.0 DISCUSSION AND SUMMARY (A.J. Macdonald)

5.1 INTRODUCTION

This Open File Report has attempted to synthesise our understanding of geology pertaining to the platinum group of elements, and descriptions of mafic and ultramafic rocks within the Province of Ontario that are host, or potential host, to economically significant PGE deposits. Our data base in this field is anticipated to increase significantly in the short term; it is intended to publish updates for a number of sections in this report as the new data become available.

The objective of this section is to summarise our understanding of the processes by which economic deposits of the PGE form, to illustrate these processes, where applicable, with examples from Ontario, and to make a few generalisations about the implications for exploration for this deposit type. The following is abridged and modified from earlier sections of this report and from Macdonald (1987b).

Our understanding of PGE geochemistry has been constrained until relatively recently by the inability to analyse these elements at levels in which they typically occur in unmineralised rocks, i.e. at the part per billion level. Recent advances, particularly with the aid of radiochemical and instrumental neutron activation analysis, have now removed this obstacle, permitting accurate determination of background PGE contents of most rock types.

The most obvious characteristics displayed by the PGE are their siderophile nature and their affinity for sulphides in mafic and ultramafic rocks. Figure 5.1 gives typical means and ranges of Pt contents in mafic and ultramafic rocks. The average Pt content of carbonaceous chondrites, on the other hand, is approximately 1000 ppb, attesting to the siderophilic character of Pt. Similar data for the other PGE are presented in Section 1.1, and in Naldrett and Duke (1980), Crocket (1981) and Campbell et al. (1983). PGE contents in intermediate and felsic igneous rocks, and in metamorphic and sedimentary rocks are less well known. Crocket (1981) suggests that typical levels for individual PGE in felsic and intermediate rocks are in the sub-ppb range.

As can be seen from Figure 5.1, the average Pt content of unmineralised mafic and ultramafic rocks is approximately 10 ppb, with a range from 0.1 ppb to 500 ppb. A typical economic PGE deposit may have a mean platinum grade of between 5 and 10 ppm, which is the same order of magnitude as gold deposits. This suggests that the geologic process(es) which are responsible for formation of a PGE deposit involve enrichment factors of approximately one thousand.

Although the sulphide content of igneous rocks hosting orthomagmatic PGE deposits can be highly variable, the precious metals display a ubiquitous association with sulphides, which has led most researchers to suggest that formation of an economically significant deposit is dependent upon the segregation of immiscible sulphides, into which the PGE preferentially partition (e.g. Naldrett and Duke 1980). For sulphide to become a discrete phase within a mafic/ultramafic magma, the solubility of sulphur in the magma must be exceeded. The precipitation of an immiscible sulphide phase, which is

a critical step in the formation of a PGE deposit, may result from one or more of the following processes :

(1) assimilation of sulphur from an external source;
(2) rapid cooling of the magma;
(3) assimilation of silica;
(4) blending of two or more disparate magmas (e.g. Irvine 1975, 1977; Naldrett and Macdonald 1980; Todd et al. 1982).

Different types of PGE deposit may form as a result of each of these processes, which are discussed in detail in the following section.

5.2. PGE Deposit Types

5.2.1. Deposit Classification

Classification of mineral deposits can be approached from several perpectives: (a) associated host rock, e.g. shale-hosted Pb-Zn deposits; (b) mineralogical association, e.g. telluride-gold ores; (c) geographic location, e.g. Alpine-type chromite deposits; (d) archetypal, e.g. "Carlin"-type gold deposits; (e) tectonic setting, e.g. rift-related Cu-Ni deposits; (f) mineralisation process, e.g. exhalative massive sulphides. The optimal approach to classification of a mineralisation type, such as ores of the platinum group of elements, separates radically different classes of mineralisation into a manageable number of categories, without permitting duplication of individual deposits within two or more categories. Classification based upon the process by which the metals are concentrated, ("f" above) avoids potential duplication which can be imposed by classifications reliant upon associated host rocks, mineralogy, geography, archetype, or tectonic setting. The approach must be flexible enough to permit modification in response to an increased understanding of the processes in question.

A classification of PGE deposit types is given in Table 5.1, based upon the inferred process by which the PGE were concentrated, and whether the PGE are the primary product, a coproduct or a biproduct. This classification is subtly different from that presented in Table 1.3; both have their strengths and selection of one or another will depend upon the individual's research objectives.

5.2.2.1. CLASS 1 : Orthomagmatic.

The orthomagmatic class contains all those deposits that form solely within the magmatic environment. This includes deposits in which the PGE were concentrated during mixing of more than one magma (Subclass 1a), by contamination of a magma with various different types of material from external sources (Subclass 1b) or by deuteric processes, i.e. involving volatile-rich fluids derived from within the magma chamber from which the host rocks crystallised (Subclass 1c). Some PGE deposits may have formed from a combination of one or more of these orthomagmatic processes.

Table 1.4 gives reserves for a number of the better known PGE deposits. Past production and published reserves for the two other deposit classes in Table 1.4 are approximately two orders of magnitude less than those for the orthomagmatic class. This does not preclude, of course, significant contributions in the future from deposit types that do not currently constitute a PGE reserve.

Table 5.1 : A classification of PGE Deposits

DEPOSIT CLASS	EXAMPLES
1. ORTHOMAGMATIC	
1a. Magma Mixing	UG2@, Merensky Reef*, Platreef* BIC J-M Reef*, SIC Great Dike*, Zimbabwe Lac des Iles*, Canada
1b. Magma Contamination	Noril'sk#, USSR Sudbury#, Canada Kambalda#, Australia Thompson#, Canada
1c. Deuteric	Dunite Pipes*, BIC
2. ALLUVIAL	
2a. Placer	Choco*, Colombia Urals*, USSR
2b. Paleoplacer	Witwatersrand#, South Africa
3. HYDROTHERMAL	New Rambler#, USA Rathbun Lake#, Canada Allard Stock#, USA Kupferschiefer#, Poland Coronation Hill@, Australia

BIC : Bushveld Igneous Complex, South Africa
SIC : Stillwater Igneous Complex, USA
* : Primary Product
@ : Co-product
# : Bi-product

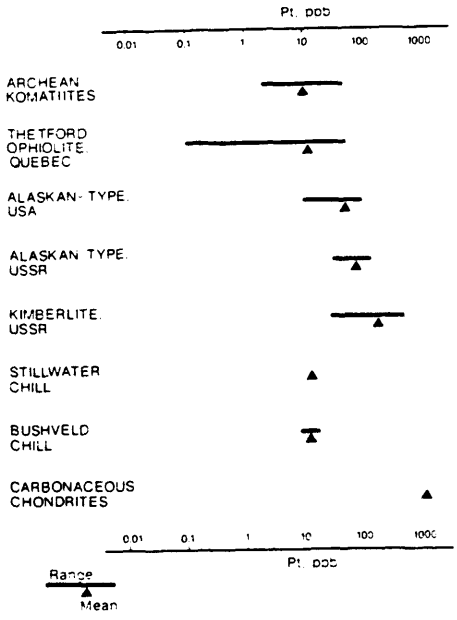


Figure 5.1 : Pt content of some mafic and ultramafic igneous rocks. Bushveld and Stillwater chills may represent magma compositions. Data from Crocket (1981), Campbell et al. (1983) and Davies and Tredoux (1985).

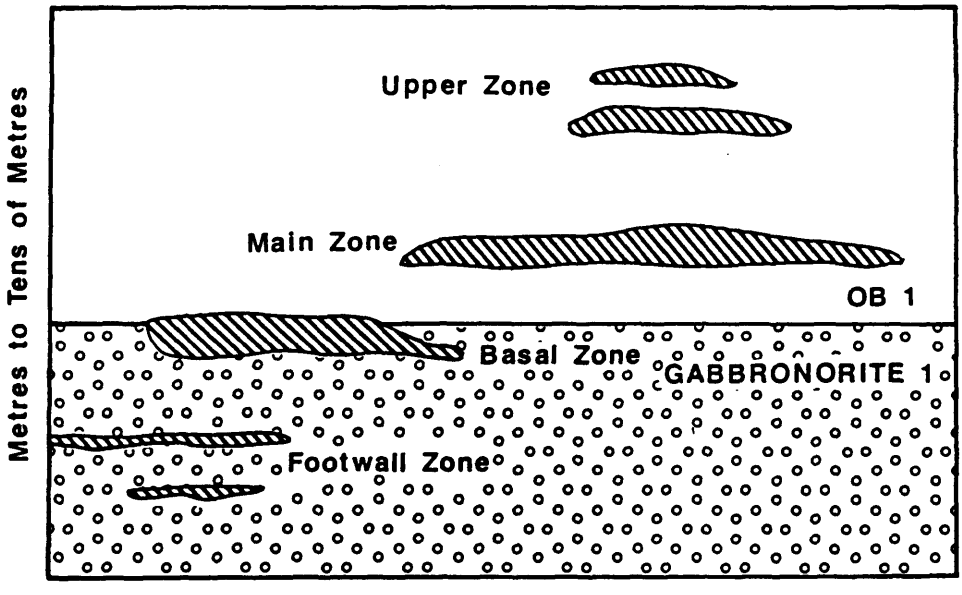


Figure 5.2 : Zones of mineralisation and stratigraphy, J-M Reef, Stillwater Igneous Complex (Raedeke and Vian, 1986).

5.2.2.2. SUBCLASS 1a : Magma Mixing

The data in Tables 1.4 and 5.1 underscore the pre-eminent position of Subclass 1a, those deposits whose formation is attributed to mixing of more than one magma. The **Merensky Reef** (sulphide), **UG2 Reef** (chromitite) and **Platreef** (sulphide) in the Bushveld Complex, South Africa, together with the **J-M Reef** (sulphide) in the Stillwater Complex, Montana, U.S.A., and the **Great Dyke** of Zimbabwe (sulphide) contain over 90% of reserves within the principal PGE deposits (Table 1.4). This percentage is likely to increase as a result of further exploration and development of the Stillwater and Great Dyke deposits.

The Bushveld and Stillwater Complexes exhibit considerable morphological, lithological, mineralogical and chemical similarities (see Figure 1.5 and Section 2.1). Stratigraphic control on mineralisation in the J-M Reef (Stillwater) is less well constrained than that of the Merensky Reef (Bushveld). Although the J-M Reef is localised generally within the vicinity of the lowest olivine-bearing rock within the Banded Series, known as olivine-bearing Zone 1 (OB1), (McCallum et al. 1980), PGE and sulphides may be found at four different stratigraphic levels in the Minneapolis Adit area (Figure 5.2, Raedeke and Vian 1986): (a) in gabbronorite, 10m below OB1; (b) across the basal contact of OB1; (c) within 3m of the basal contact, but totally within OB1; (d) within OB1, but well above the basal contact. In the last three zones sulphides are usually disseminated over 1 to 3 metres. Most commonly, mineralisation in any specific area occurs only at one stratigraphic level, although locally mineralisation may be found at up to three discrete levels. Sixty to seventy percent of the higher grade mineralisation is found at levels (b) and (c), as described by Raedeke and Vian (1986).

In a comparison of the Merensky and J-M Reefs, Campbell et al. (1983) point out a number of features common to both which must be accounted for by any genetic model:

(1) the PGE are in sulphides;
(2) the sulphides are at or near the base of cyclic (macrorhythmic) units, marked by the re-appearance of high temperature cumulus phases (chromite + olivine), and reversals in mineral fractionation trends;
(3) local discordances in the footwall rocks, known as "potholes", are present below both reefs;
(4) development of coarse grained, pegmatoidal rocks;
(5) stratigraphic level; both reefs occur about 500 m above the level at which plagioclase first becomes a cumulus phase (i.e. above the level at which the stratigraphy is first dominated by gabbroic, rather than ultramafic, rocks) - Figure 1.5.

Campbell et al. (1983) contend that any model for the origin of these deposits must account for these similarities.

The UG2 chromitite layer, which averages over 0.8 m thick (Naldrett 1981) is as little as 30 m below the Merensky Reef in the northern sector of the BIC, and as much as 400 m below in the northeastern sector. As seen in Table 1.4, the PGE resource contained in the UG2 is greater than that of the Merensky Reef. The UG2 is also noteworthy for its higher Rh grades, not only a more valuable metal but also an asset for the manufacture of three-way autocatalysts, which utilise Rh to reduce oxides of nitrogen (Robson 1985, 1986). The UG2 mineralogy, with a low sulphide, and high chromite content, caused initial metallurgical difficulties which rendered the ore difficult to

treat. By 1985 these problems were resolved and at least two of South Africa's principal PGE mining houses, Rustenburg and Western Platinum, now derive a significant proportion of their production from the UG2 Reef (Robson 1986).

The UG2 Reef is also associated with a 0.5m thick pegmatoidal, feldspathic bronzite cumulate (cf. Merensky and J-M Reefs). PGE in the UG2 Reef are present as sulphides and alloys within the chromitite, principally laurite, cooperite, braggite and Pt-Fe alloy (Gain 1980). Recently Naldrett et al.(1987) have proposed that while sulphides, with associated PGE and oxides, were deposited synchronously with the host rocks, PGE, Ni and Cu tenors were upgraded as a result of the subsolidus loss of FeS.

Much evidence is accumulating to indicate that the PGE-rich reefs in the BIC and SIC are spatially associated with mixing zones of magmas with two distinct compositions. For example, Todd et al. (1982) described two igneous suites within the SIC: rocks with an ultramafic (U) affinity, which exhibit a crystallisation order olivine, bronzite, plagioclase, augite; the second magma has an anorthositic (A) affinity with crystallisation from plagioclase, to olivine, augite and finally bronzite. Todd et al. (1982) proposed that the J-M Reef sulphides formed during mixing of the two magma types.

In the same year, Sharpe (1982) described two magma suites in chilled margins of the BIC, one with pyroxenitic affinity, the other gabbroic. Sharpe also suggested that mixing of the two magma types may have given rise to host rocks for the UG2 and Merensky Reefs.

Irvine et al. (1983) refined the magma mixing hypothesis in terms of double-diffusive convection of the two magmas (U and A) for both the Bushveld and Stillwater Complexes. Their principal conclusions are that the J-M, Merensky and UG2 Reefs owe their existence to the extraordinary composition of the Stillwater and Bushveld U-type magmas, which display an olivine-boninitic affinity, i.e. rich in SiO_2 (52-56%), MgO (12-16%), Cr (800-2000 ppm) and incompatible elements (e.g. 20-50 ppm Rb, 150-400 ppm Zr), and, most importantly, exceptionally rich in the PGE (up to 100 ppb total PGE+Au). The A-type magmas are closer to tholeiitic basalt in composition (48-50% SiO_2, 8-10% MgO), with low Cr and incompatible elements. Note that, interestingly, the specialised magma with ultramafic affinity actually has a higher silica content than the gabbroic magma. For further discussion of these magmas, refer to the review by Von Gruenewaldt et al. (1985).

Irvine et al. (1983) also point out that perhaps one of the most significant characteristics of the U-type liquids is their *low* sulphur content. The ore reefs mark the first occurrence within the stratigraphy of the BIC and SIC, with the exception of basal zones in contact with country rock, in which prominent sulphide precipitation - or, sulphide liquation, to emphasise that initial sulphide formation is as liquid droplets, rather than solid crystals - occurred on a sustained basis, permitting scavenging of available PGE by sulphides. The scavenging is a function of the strong partitioning of the PGE in favour of sulphide relative to silicate phases (Naldrett and Duke 1980). If sulphide liquation had occurred earlier in the development of the U-type liquids, then magmatic enrichment of the PGE to the observed levels would not be possible.

Sulphide precipitation in the magmatic environment, whilst being perhaps the single most important phenomenon in localising and concentrating PGE, is a

poorly understood process. A number of schemes have been proposed to account for the formation of sulphide droplets in a silicate magma:

(1) simple cooling of the magma (Haughton et al. 1974);

(2) mixing of two magmas, one primitive, the other more evolved (Irvine 1977);

(3) addition of silica by contamination (Irvine 1975; Naldrett and Macdonald 1980), discussed further under Subclass 1b.

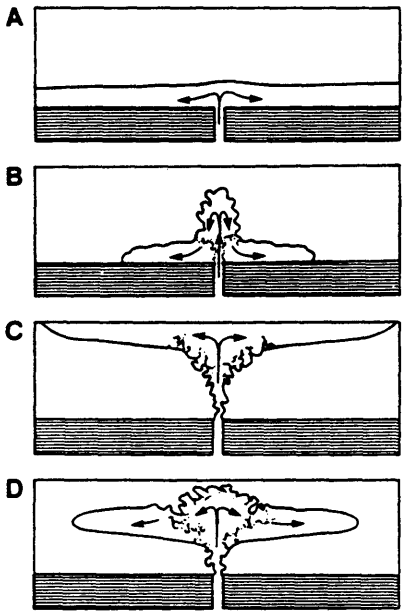


Figure 5.3 : Magma injection plumes into resident magma, with the effect of varying density difference. See text for details (after Campbell et al., 1983).

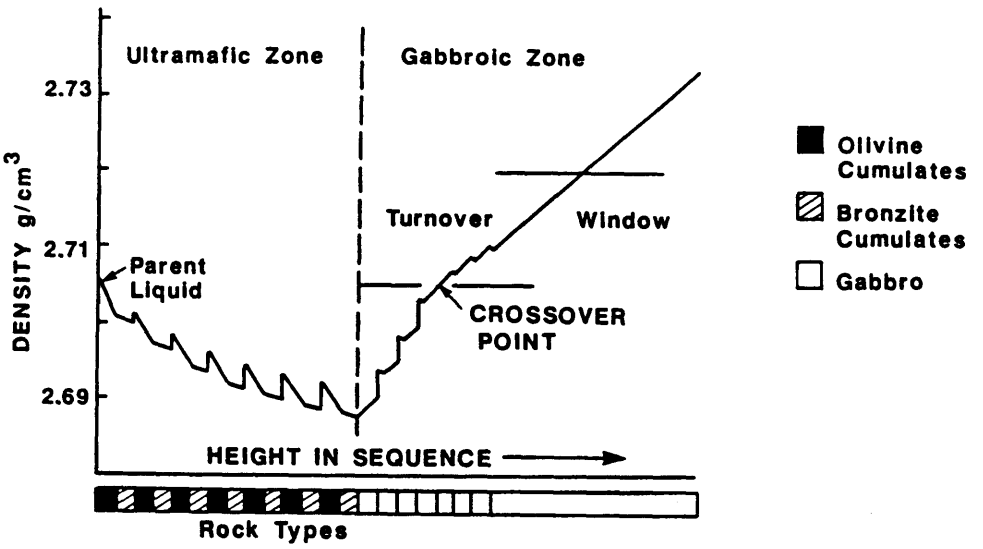


Figure 5.4 : Density variation of magma during sequential injection of primitive melts. Each cyclic unit is assumed to mark the introduction of a new pulse of magma into the chamber equal to 25% of the volume of the magma in the chamber. The turnover window is the density range in the fractionated magma for which magma turnover is possible (after Campbell et al., 1983).

As much of the gross lithological, mineralogical and chemical data for the Merensky and J-M Reefs, outlined above, are suggestive of mixing two disparate magmas, much effort has been undertaken to relate sulphide-bearing PGE mineralisation directly to the hypothesised magma mixing event. Campbell et al. (1983) presented an elegant model to relate efficiency of mixing of two magmas with stratigraphic level in the BIC and SIC. Their fluid dynamic model emphasises the control on mixing exerted by density contrasts between the magma that is resident in the chamber and the incoming, new magma pulse. Density of the resident magma will vary in sympathy with fractionation, temperature and composition. If a new pulse is more dense, it will spread along the floor of the chamber, with minimal mixing (Figure 5.3a). A dense magma jet with considerable momentum will spurt into the chamber before falling back to the floor, with only minor mixing (Figure 5.3b). If the magma pulse is lighter, it will rise through the resident magma to the roof of the chamber (Figure 5.3c), again with little mixing. If the new magma pulse has the same density as some portion of the magma chamber, it will spread across the chamber at the level in question, mixing with the resident magma (Figure 5.3d). Campbell et al. (1983) demonstrate that in magma chambers which are crystallising plagioclase - a low density mineral - the density of the remaining magma increases with fractionation. The gradual density increase of the resident magma eventually attains and exceeds that of a new magma pulse (Figure 5.4). This density crossover point is suggested by Campbell et al. (1983) to occur at the approximate stratigraphic levels of the Merensky and J-M Reefs.

Irvine (1977) and Irvine and Sharpe (1986) have also proposed that magma mixing is responsible for the formation of chromitite horizons, with attendant PGE, in layered igneous intrusions. The magma mixing model alone is capable of accounting for formation of both sulphide and oxide phases, but may also involve components of the other two hypotheses mentioned above (cooling and silica contamination): the jet of hot, incoming magma (Figure 5.3d), upon mixing with the cooler, resident magma, will itself cool, perhaps sufficiently to promote sulphide liquation. In addition, the mixing of two magmas with disparate chemical compositions can also cause sulphide to precipitate, if one has a greater silica content than the other (Irvine 1975). The chemistry of this process is described more fully in the discussion of the next Subclass, 1b.

While the points of similarity between PGE mineralisation in the BIC and SIC are best explained by orthomagmatic processes, with evidence from detailed petrography, geochemistry and radiogenic isotopes (see, for example, Von Gruenewaldt et al. 1985), the same data, when combined with additional observations, suggest that some modifications to the magma-mixing model may be required. These observations include :

(a) the close spatial association between PGE and pegmatoidal rocks;

(b) the locally transgressive nature of the reef mineralisation, often associated with "potholes" (e.g. Viljoen and Hieber 1986; Turner et al. 1985);

(c) the coexistence of hydrous silicates, such as amphiboles, micas, talc and serpentine, often Cl-rich (e.g. Johan and Watkinson 1985; Mathez et al. 1985);

(d) graphite, present in "stockworks" beneath the J-M Reef (Volborth and Housley 1984) or within potholes in the Merensky Reef (Ballhaus and Stumpfl 1985, 1986);

(e) CO_2-CH_4-H_2O-bearing and chloride-rich fluid inclusions in quartz from pegmatoids in the Merensky Reef (Ballhaus and Stumfl 1986).

At least four, fundamentally different hypotheses have been proposed to account for the pothole features which form depressions up to several hundred metres in length and 25 m deep into the footwall stratigraphy below both the Merensky and J-M Reefs. The PGE mineralisation also sympathetically drapes down into the pothole depressions (Stumpfl and Ballhaus 1986). The potholes are proposed to be slump structures over voids in the footwall (Cousins 1964; Leeb-du Toit 1986). On the other hand, Campbell (1986b) suggests that during magma mixing (e.g. Figure 5.3d) plumes of convecting magma pass downward towards the accreting crystal pile, and induce partial erosion where the down-convecting jet intersects the crystal pile.

A third proposed origin for potholes is based upon the "de-watering" hypothesis, where volatile-bearing, intercumulus liquid is displaced upward during compaction of the lower stratigraphic pile. The upward percolation of fluids could have discharged into the magma as a fumarole. Perhaps the potholes represent the egress zones of this fumarolic activity, and it has been suggested that the Merensky Reef sulphides were up-graded by PGE carried by the upward percolating fluids (Vermaak 1976; Von Gruenewaldt 1979). Instead of the fluids being derived through compaction of the lower portions of the magma chamber, Ulmer et al. (1981) propose that the fluids were released through dewatering of the underlying Transvaal sediments.

Stumpfl and Ballhaus (1986), in proposing a fourth hypothesis, reject both the magmatic erosion (e.g. Campbell 1986b) and fumerolic models (e.g. Ulmer et al. 1981) and emphasise the presence of stratigraphically-controlled mineralisation and alteration that is present within the stratigraphy around the margins of the potholes in the BIC. Turner et al. (1985) have noted similar features in the Minneapolis Adit sector of the J-M Reef, SIC. Turner et al. describe "*pothole margin mineralisation ..... concentrated in layered footwall gabbro rocks on pothole margins adjacent to the contact with the Reef package and along favourable layers marginal to pothole depressions*". The PGE mineralisation has replaced certain horizons, with fluids passing from the J-M Reef at the floor of the pothole into the marginal rocks by a diffusion mechanism. Stumpfl and Ballhaus (1986) suggest that pothole morphology and mineralogy reflect localised, elevated volatile contents during crystallisation of the magma that gave rise to the lithological units that define the potholes.

Previous understanding of the complex geometry of the Merensky Reef had been hampered by aspects of confidentiality surrounding the platinum mining industry in South Africa (Viljoen and Hieber 1986). Recently, however, a number of articles (e.g. Viljoen and Hieber 1986; Farquar 1986; Mossom 1986) have described the widespread, ubiquitous presence of complex pothole (depression) and koppie (elevation) morphologies of the Merensky Reef, with transgressive geometries of both lithological units and mineralisation, much as seen in the J-M Reef, SIC (cf. Raedeke and Vian 1986; Turner et al. 1985). The recent Bushveld descriptions emphasise an interesting association between the locations of potholes, their associated replacement pegmatites and large-scale fracture trends, possibly reflecting a regional tectonic control on these features.

A third style of PGE mineralisation in the BIC is located in the Potgietersrus Limb of the Bushveld Complex (see Naldrett 1981a). The **Platreef** mineralisation is found at the basal contact of the Bushveld Complex, and is hosted by rocks generally considered to be part of the Critical Zone (Van der Merwe 1976), the same general stratigraphic level within the BIC at which the

Merensky Reef is located. Disseminated sulphides are present sporadically within a feldspathic pyroxenite and harzburgite over a strike length of 60 km, with a thickness of up to 200 m. Less is known about this style of mineralisation than the Merensky Reef, as mining commenced on the Platreef in 1926 and terminated shortly thereafter. Recently the area has seen renewed interest, re-evaluation and detailed study. Wagner (1929) gave the original geological description, providing the basis for further work by Van der Merwe (1976), Mostert (1982), Gain and Mostert (1982), Buchanan et al. (1981), Cawthorn et al. (1985) and Barton et al. (1986). Until the work of Cawthorn et al. (1985), most authors related mineralisation to contamination or hybridisation of the Platreef host rocks by wallrock, mainly dolostone from the adjacent Transvaal sediments. On the basis of geochemical and isotopic constraints, however, Cawthorn et al. (1985) and Barton et al. (1986) developed an hypothesis for contamination of the mafic magma by rheomorphic influx of a felsic magma, probably generated by partial melting of the immediate floor rocks, banded tonalite gneisses; these felsic fluids mixed with the BIC magma, and may have promoted sulphide liquation and PGE scavenging. Barton et al. (1986) point out, however, that formation of an immiscible sulphide liquid predated contamination of the BIC magma by rheomorphic felsic magmas, and suggest that initial sulphide liquation was in response to a new influx of BIC magma, a process similar to that described for the Merensky Reef. It appears possible, therefore, that the mineralisation was modified subsequently by processes related to influx of a felsic magma. As understanding of the Platreef mineralisation evolves, the popularity of the sediment-contamination theory is waning, with the bulk of the new evidence indicating that blending of ultramafic, mafic and felsic magmas appears to have been responsible for the observed features. Mixing in the Potgietersrus limb is, therefore, a more complicated process than that invoked for the Merensky and J-M Reef mineralisation. In the latter, specialised magmas of ultramafic and mafic affinities - possibly differentiates from the same parent magma, in a master chamber at depth - have mixed. In the Platreef, however, an additional magmatic component of melted country rock gave rise to felsic magmas which entered the Bushveld magma chamber, to mix with the mafic/ultramafic magmas therein.

Cabri and Naldrett (1984) suggested that the **Lac des Iles** (Section 3.1.4.2) deposit in Northern Ontario, Canada, is a Platreef-type of PGE deposit, based upon mineralogy and metal contents. Recent geological data support this hypothesis (Macdonald 1987a). Several sulphide zones with anomalous PGE grades (up to 1000 ppb total PGE+Au) are found in gabbroic rocks contaminated by felsic magmas, which formed by rheomorphic melting of country rock. Higher grades of PGE mineralisation at Lac des Iles, up to 15,000 ppb PGE+Au, are related to intrusion of an ultramafic liquid into, and blending with, a more evolved, iron-rich, anorthositic gabbro. The orthomagmatic mineralisation experienced considerable remobilisation due to influx of deuteric fluids, locally concentrating the noble metals into transgressive gabbro pegmatites, which may carry up to 37,000 ppb PGE+Au.

The Great Dyke in Zimbabwe represents a highly significant PGE resource, estimated to contain at least approximately 8000 tonnes of PGE (as reported in Naldrett et al. 1987), or approximately 50% of the estimated Merensky Reef reserve (Table 1.4). Worst (1960), Wilson and Wilson (1981), Wilson (1982) and Prendergast (1987a,b) described the geology of the Great Dyke, which is a complex of four, sub-parallel, narrow, layered mafic-ultramafic intrusions. The lower ultramafic series consists of chromitite, dunite, harzburgite, olivine-bronzitite, bronzitite and websterite, with at least fourteen cycles

of magma replenishment. The overlying mafic sequence consists of olivine gabbro, norite and gabbronorite in three cycles.

Little is available in the literature on the stratiform Main Sulphide Zone (MSZ) of the Great Dyke, although it has been known and explored for over 60 years. The MSZ, unlike the Merensky and J-M Reefs, is hosted by ultramafic rocks, just below the contact between the Main Websterite of the ultramafic series and the lowermost olivine gabbro of the mafic series (Prendergast 1987a,b). The MSZ is hosted by bronzitite, several metres stratigraphically below the Main Websterite, and exhibits three principal features : (1) considerable stratigraphic continuity; (2) characteristic vertical metal profiles; (3) systematic lateral variations in width of mineralisation, sulphide content, intermetallic ratios and PGE content when normalised to 100% sulphide (Prendergast 1987a,b). Prendergast (1987b) considers that the MSZ mineralisaton of the Great Dyke resulted from a combination of magma replenishment, convective overturn, and magma cooling.

With the resurgence of interest in the PGE during the latter half of this decade, much new information on the MSZ is anticipated, as a result of not only academic research possibilities offered by the recent availability of diamond drill core that penetrated the MSZ, but also by aggressive exploration and development by the many mining companies with interests in Zimbabawe.

A final class of orthomagmatic, PGE-bearing sulphide deposits is found within so-called **"Alaskan/Ural - type"** intrusive complexes (Table 5.1). While these are commonly referred to as "zoned, mafic/ultramafic complexes", Irvine (1974) observed that zoning may not be concentric, continuous or even present. Where zoning *is* present, Taylor (1967) describes the most common form as: a small dunite or peridotite core, surrounded by hornblendite or hornblende pyroxenite, that sometimes contain units of olivine pyroxenite. Gabbro or norite occur marginally and are sometimes missing.

The intrusions tend to be small, commonly less than 2 km in diameter, with Union Bay in Alaska, at 10-15 km in diameter, being one of the largest examples of Alaskan/Ural intrusive complexes identified (Laznicka 1985). In both Alaska, U.S.A., and the Ural Mountains, U.S.S.R., the intrusive complexes are in linear, tectonic belts, and were intruded after peak metamorphism and after the bulk of tectonism.

The Alaskan/Ural intrusions are most commonly tholeiitic, and locally appear to be comagmatic with tholeiitic, partly subaerial, basalt to basalt-andesite flows. The country rock intruded by the complexes is variable; most commonly, coextensive gabbro and diorite, but locally tonalite and other "basement" units comprise the wall rocks (Laznicka 1985). The relative age relationships between the gabbros and the Alaskan/Ural intrusions are equivocal (e.g. McTaggart 1971), although most authors consider the gabbros to be slightly older (Laznicka 1975). Exactly the same problems have been encountered in Ontario: Pye (1968) described contradictory field relationships observed at Lac des Iles, discussed further in Section 3.1.4.2.

While little PGE production has been derived from this type of igneous association, Alaskan/Ural complexes have been identified as the probable source rocks for placer Pt production from, for example, the Choco district of Columbia, Goodnews Bay in Alaska, Tulameen, British Columbia and in the Ural Mountains (Section 5.2.3.1). Considerable evaluation of potential bedrock sources of PGE in this environment is currently underway.

Examples of Alaskan/Ural mafic/ultramafic igneous complexes in Ontario have been hypothesised in at least three locations. McTavish (1986) has suggested that the several mafic/ultramafic intrusions associated with the Quetico Fault Zone (Section 3.1.5), may exhibit affinities with this igneous type. Both Naldrett and Brugmann (1987) and Sutcliffe (in Goldie 1987) have suggested that the Lac des Iles mafic/ultramafic complex (Section 3.1.4.2) may be analagous to Alaskan/Ural intrusions. Ultramafic/mafic intrusions, and associated PGE-Ni-Cu sulphides, in the Werner-Rex Lake fault zone (Carlson 1958; Lawson and Zuberec 1987) may also be of this type.

5.2.2.3 SUBCLASS 1a : Summary.

While various competing hypotheses continue to support, on the one hand, magma mixing and, on the other, deuteric concentration of PGE to form the Merensky/UG2/J-M Reefs, the following observations are generally accepted:

(a) Mixing of two discretely different magmas (U and A) occurred at the stratigraphic levels occupied by the Reefs;

(b) Effects of a conspicuous deuteric component within the magma are manifest in the Reefs' host rocks as hydrous silicates, pegmatoidal layers and cross-cutting pegmatite dikes, locally abundant graphite in potholes and complex fluid inclusions trapped in quartz.

It is also generally agreed (dissenters include Ulmer et al. 1981) that the fluids responsible for the variable textures and compositions in the Reefs' host rocks are deuteric in origin; that is, the fluids are derived from within the parent magma, retaining the integrity of the orthomagmatic hypothesis (Table 5.1). Until conclusive evidence is available to the contrary, the optimal working hypothesis for the origin of the UG2, Merensky and J-M Reef mineralisation invokes magma mixing of two specialised magmas, with some degree of deuteric effect upon (a) silicate crystallisation, and (b) subsequent, local redistribution of the PGE-bearing sulphides.

In other deposit types whose formation is attributed to mixing of magmas, such as the Platreef and Lac des Iles, contamination by rheomorphic, felsic melts appears to have modified both magma chemistry and the geometry of mineralised zones. Mineralisation containing higher grades of PGE are, however, related to blending of mafic and ultramafic magmas; simple mixing of felsic and gabbroic magmas does <u>not</u> appear to be a critical factor in the formation of economically significant PGE mineralisation in this deposit type.

5.2.2.4. SUBCLASS 1b : Magma Contamination

The second subclass of orthomagmatic, PGE-bearing sulphide deposits is found within mafic/ultramafic intrusions and extrusions in which sulphur saturation has been achieved by addition to the magma of external material, i.e. wallrock contamination.

In 1959, Sullivan suggested that Ni deposits in the Manitoba Nickel Belt, Canada, formed by "sulphurisation", the reaction of sulphur, from an external source, with metals (e.g. Fe, Ni) in the magma. Naldrett (1966) proposed a similar process for Fe-Ni sulphides in the Porcupine District of Ontario.

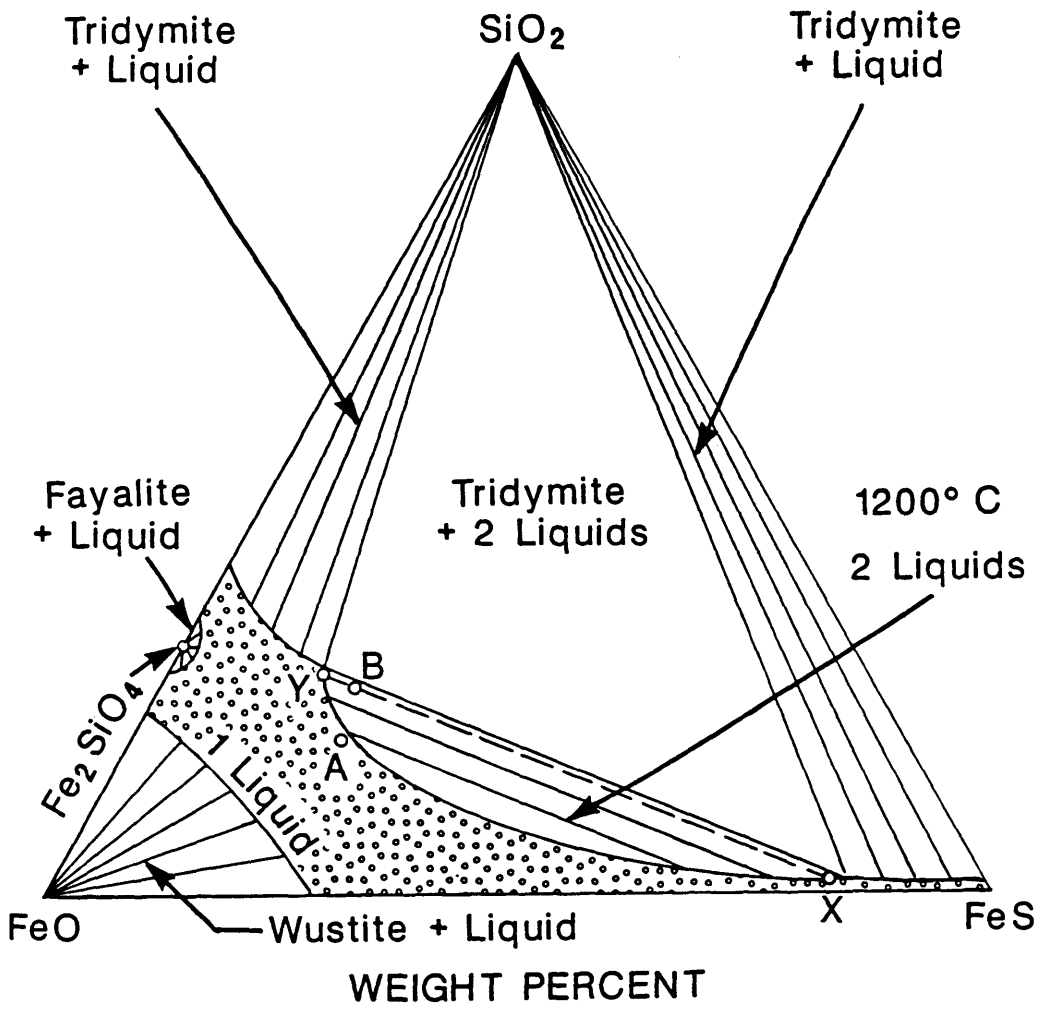


Figure 5.5 : The effect of silica contamination upon an FeO-FeS melt. See text for details (after Naldrett and Macdonald, 1980)

Irvine (1975) described an elegant model for the origin of stratiform chromite and sulphide layers in large, layered igneous intrusions, where addition of silica from an external source can initiate precipitation of chromite and/or liquation of sulphide. In 1977, however, Irvine also demonstrated how the same phenomena may result from the mixing of two magmas, discussed in the previous section.

The **Sudbury** deposit in Ontario is Canada's principal PGE resource (Table 5.1). For a recent synthesis of Sudbury geology, see Pye et al. (1984) and Section 3.2.3. in this report. A number of features of the Sudbury ores and host rocks led Naldrett and Macdonald (1980) to propose that contamination of the mafic magma by relatively silica-rich wallrock was the cause of sulphide liquation, as outlined in Section 3.2.3. The chemical effect of silica-contamination is shown in Figure 5.5. The FeO-SiO_2 side of the ternary is equivalent to silicate melts and the FeS apex is equivalent to sulphide magmas. A magma at a composition indicated by Point A is a one phase, homogenous FeO-SiO_2-FeS liquid. If SiO_2 is added such that the composition changes to that of, for example, Point B, the magma now consists of a two phase, silicate-rich liquid (Y) and co-existing sulphide liquid (X).

The **Noril'sk-Talnakh-Kharaelakh** Ni-Cu-PGE camp in Siberia, is the Soviet Union's premier source of the PGEs (Table 5.1). The geology of the Noril'sk area is described by Smirnov (1966), Bazunov (1976), Glaskovsky et al. (1977), and is summarised by Naldrett and Macdonald (1980). The Ni-Cu-PGE mineralisation has been described recently by Godlevsky and Likhachev (1986). Sulphur isotopic data for the Noril'sk area ($\delta^{34}S$ = +7 to +10) are consistent with sulphur assimilation from sulphate-bearing, Devonian evaporites that were intruded by the Permian and Triassic gabbro-dolerite host rocks for the mineralisation (Godlevsky and Grinenko 1963; Kovalenko et al. 1975).

Komatiite-associated Ni-Cu sulphide deposits, such as at **Kambalda**, Australia, and **Thompson**, Manitoba, are important hosts for sulphide deposits containing significant PGE content. At Kambalda, for example, the ores contain 2.96% Ni, 0.22% Cu, 0.07% Co, 8.09% S, 1141 ppb PGE, 339 ppb Au and 1170 ppb Ag (Hudson and Donaldson 1984). Until recently, all components of these ores were generally considered to be solely magmatic in origin, modified by metamorphism and deformation (e.g. Groves et al. 1979; Barrett et al. 1977; Marston and Kay 1980). Lesher and Groves (1986), on the other hand, suggest that the sulphur is externally derived and present arguments that the sulphide ores exsolved from komatiitic magmas *in situ*, in response to assimilation of country rocks during emplacement. They point out that the sulphide deposits show a marked spatial association with sulphidic sediments.

Many of the Abitibi Greenstone Belt Ni-Cu deposits, described in Section 3.1.7, may be of this type, with potential, therefore to host economically recoverable PGE, as at Kambalda and Thompson. Work in progress (Good 1987) is designed to test this hypothesis.

5.2.2.5. SUBCLASS 1b : Summary

Contamination by wallrock is an effective process for initiating sulphide liquation, whether the contaminant be sulphur itself, or silica in the form of assimilated sediments, or as a granitic melt. Sulphide deposits may be expected, therefore, at contacts between mafic/ultramafic bodies and their country rocks, where chemical interaction between the two has occurred. This association is relatively common in Ontario; marginal sulphide deposits

are prominent at Lac des Iles (Macdonald 1985) and in the Coldwell Complex (Dahl et al. 1986). The PGE tenor of this type of sulphide deposit is a function of (a) the amount of magma available for PGE scavenging by sulphide, and (b) the PGE content of the magma. At Lac des Iles, for example, sulphide deposits associated with country-rock contacts tend to contain < 1000 ppb (Pt + Pd + Au) (Macdonald et al. 1987).

5.2.2.6. SUBCLASS 1c : Deuteric Processes

While the deuteric component of mineralisation in the Merensky, UG2 and J-M Reefs is still controversial, some PGE deposits are contained within features that demonstrably transect stratigraphy within the layered intrusions. Perhaps the most well-known of these are the **dunite**, or hortonolite (olivine with 50-70% fayalite) **pipes** (Viljoen and Scoon 1985). The pipes are commonly contained within envelopes of olivine dunite and olivine-bronzite-plagioclase pegmatoid (Wagner 1929). These bodies have not provided large tonnages: the largest is the Driekop Pipe, up to 25 m in diameter, and mined through a vertical depth of 200 m (Schiffries 1982). Grades, on the other hand can be spectacularly high, up to 2000 ppm total PGE, although average mining grades are substantially less : the Onverwacht Pipe averaged approximately 10 ppm, the Driekop Pipe contained 6 ppm total PGE (Wagner 1929).

Where a dunite pipe cuts across an easily identifiable stratigraphic marker, such as a chromitite layer at the Onverwacht Pipe (Wagner 1929) disrupted blocks of chromitite are found within the pipe, more or less at their projected stratigraphic level (Figure 5.6). The layered rocks around a pipe locally form collapse structures, with layering becoming subvertical at the pipe contact (Schiffries 1982).

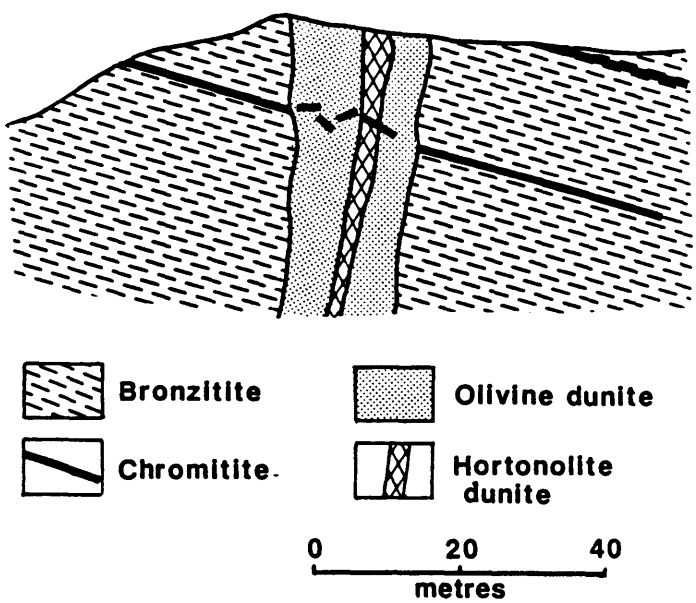


Figure 5.6 : Dunite pipe transecting stratigraphy, Onverwacht, Bushveld Igneous Complex. Note rafts of chromitite within pipe at approximately same stratigraphic level as chromitite seam outside pipe (after Stumpfl and Rucklidge, 1982).

The dunite pipes do not reflect intrusion of an olivine-rich magma; rather, the presence of chromitite slabs within pipes suggests an infiltration metasomatism, or replacement phenomenon (Stumpfl and Rucklidge 1982; Schiffries 1982). Schiffries (1982) proposes that a channelled, high temperature chloride solution is responsible for reacting with the noritic host rock, resulting in a dunite. The replacement process involves desilication of pyroxene, and production of an iron-rich olivine (Schiffries 1982).

Wagner (1929) noted that not all dunite pipes are mineralised. Stumpfl and Rucklidge (1982) draw attention to the presence of graphite and pegmatoidal textures, seen also in the Merensky Reef, implying that there may be some relation between pipe and reef formation.

Desilication of pyroxene may be a common phenomenon in other intrusions. An example may be the classic "pillowed troctolite" exposure in the Stillwater Complex, described by Hess (1960), containing elliptical masses of plagioclase-olivine rock (troctolite) in an anorthositic matrix. According to a model proposed by McCallum (1977), the troctolite "clumps" are the vestiges of original gabbro (cumulus plagioclase and augite) included within anorthosite; the original augite has been replaced by olivine.

Boudreau and McCallum (1986) describe transgressive sulphide zones on Picket Pin Mountain in Anorthosite Subzone II, the thickest anorthosite member (600m) of the Stillwater Complex, approximately 3 km stratigraphically higher than the J-M Reef. The cross-cutting sulphide zones pass upward into conformable sulphide-bearing zones (1% pyrrhotite, pentlandite and chalcopyrite), that contain approximately 800 ppb total PGE+Au. Boudreau & McCallum (1986) infer that the transgressive sulphide zone reflects a fluid conduit for upward percolating fluids to feed a stratabound sulphide deposit. Perhaps the Picket Pin mineralisation can be considered to be an intra-magma chamber, exhalative deposit!

The Lac des Iles deposit exhibits many features indicative of the effects of deuteric fluids, including: alteration of pyroxene to fibrous amphibole, known as uralite, and alteration of plagioclase to chlorite, epidote and sericite, i.e. sausseritisation (Pye 1968); pegmatoidal comb layering; pegmatoidal, miarolytic cavities; and transgressive gabbroic pegmatite dikes (Macdonald 1987a). These phenomena increase in abundance in the vicinity of mineralised zones at Lac des Iles, within the unit mapped as 'varitextured gabbro' by Macdonald (1985). Highest grades of the PGE are also localised within pegmatoidal and pegmatitic units (Macdonald 1987a), suggesting at least an association between PGE concentration and deuteric activity. Similar miarolytic features have been described in the Coldwell Complex, Marathon, Ontario, by Dahl et al. (1986) and Watkinson et al. (1986), where PGE mineralisation also shows a prominent spatial association with zones exhibiting the effects of deuteric activity.

5.2.2.7. SUBCLASS 1c : Summary.

Deuteric and sub-solidus phenomena may be significant processes, especially in large magma chambers, causing considerable modification to original magmatic mineralogy, chemistry, and morphology of lithologies and mineralisation. Alteration and replacement features are beginning to receive considerable attention within mafic and ultramafic intrusions, such as the Bushveld, Stillwater and Lac des Iles complexes. PGE-bearing sulphide

mineralisation can, it appears, form within this deuteric, late-stage period in the development of a mafic/ultramafic magma body. To date, however, only relatively small mineralised bodies, such as the dunite pipes, are considered to owe their genesis to solely deuteric processes. An understanding of the effects of late-magmatic fluids is, however, crucial to explain fully all features observed in the much more voluminous "reef"-style of mineralisation.

5.2.3.0. CLASS 2 : Alluvial Deposits
5.2.3.1. SUBCLASS 2a : Placer Deposits.

Platinum was "discovered" by Spanish Conquistadors in Colombia in the mid 16th Century. A detachment of troops moving along a drainage system in northwest Colombia, found gold and grains of an unknown, heavy, silvery mineral in the banks of a river that, subsequently, became known as the Rio Platino del Pinto. As the unknown metal had an extremely high melting point, it was regarded as useless and a hinderance to the refining of gold, and was contemptuously dubbed "platino", meaning silver of poor quality. The **Choco** district of Colombia has been a source of alluvial PGE since this time, although it has long since ceased to be significant, contributing approximately 0.5% of total supply to the Western world (Robson 1985)

The **Goodnews Bay** alluvial deposits in Alaska yielded just over 3 tonnes of PGE between 1927 and 1982, and are currently under re-evaluation (Robson 1986). This deposit, like many other alluvial placer deposits such as those in Colombia, is associated with "Alaskan/Ural-type" ultramafic complexes (Naldrett 1981). Similar placers are present down stream from the **Tulameen** ultramafic/mafic complex in British Columbia (Racevic and Cabri 1976). The weathering process enriched the Pt/(Pt+Pd) ratio in the placer, with respect to the source, as palladium is more easily dissolved and removed in the weathering environment (Naldrett 1981). "Alpine-type" ultramafic bodies are also commonly the source for placer PGE, such as in the Ural Mountains of the USSR (Mertie 1969). Perhaps not surprisingly, placer PGE in the Urals are also associated with "Alaskan/Ural-type" zoned mafic/ultramafic complexes (Naldrett 1981). To date, no significant PGE placers have been encountered in Ontario.

5.2.3.2. SUBCLASS 2b : Paleoplacers.

The **Witwatersrand** paleoplacer in South Africa, discovered in 1892, comprises PGE-bearing auriferous-uraniferous conglomerates within the Witwatersrand Supergroup. Pretorius (1975) presents a comprehensive summary of the geological environment of mineralisation in the Witwatersrand conglomerate.

Although the PGE are only a trace constituent of the Witwatersrand (less than 10 ppb), the PGE are collected as a bonus during extraction of gold from crushed ore. Annual production of the PGE, since 1921, was in the range of 150-210 kg until 1965, after which time production figures were not released, for security reasons (Reimer 1979). It is estimated, however, that annual production of the PGE in recent years has risen to 350 kg, giving a total of about 12 tonnes from this one deposit, or 10% of the PGE produced from conventional placer sources (Reimer 1979).

5.2.3.3. CLASS 2 : Summary.

Placer deposits of the PGE are spatially associated with mafic/ultramafic complexes, most commonly of the "Alaskan/Ural-" or "Alpine-type" of mafic/ultramafic intrusions. The only known paleoplacer PGE deposit of economic significance, the Witwatersrand, may have resulted from greenstone belt erosion, although arguments still rage as to the origin of other constituents, such as gold (cf. Skinner and Merewether 1986).

5.2.4. CLASS 3 : Hydrothermal PGE Deposits

Hydrothermal PGE deposits form from epigenetic fluids, whose compositions are, as yet, not well constrained, in a wide variety of geological environments; including: (1) associated with shear zones cutting mafic/ultramafic host rocks; (2) associated with alkaline porphyry copper-precious metal deposits; (3) in late diagenetic flow of metal-bearing brines in carbonaceous sediments. This deposit type is generally rich in platinum and palladium, with respect to the other PGE (Naldrett 1981). Hydrothermal PGE deposits have yet to contribute significantly to global PGE production, although this may be a function of lack of exploration for this deposit type.

5.2.4.1. SUBCLASS 3a : Shear Zone-related.

The **Rathbun Lake** PGE-bearing Cu-Ni sulphide deposit (Section 3.2.2) is located within the Wanapitei gabbronorite intrusion in Central Ontario (Dressler 1982). At Rathbun Lake, the ratio (Pt+Pd)/(Os+Ir+Ru) of >1000 is much higher than for the orthomagmatic J-M Reef (250) and Merensky Reef (12.5) (cf. Naldrett 1981); this is taken as supportive evidence for a hydrothermal origin (Rowell and Edgar 1986). The massive sulphide body at Rathbun Lake is, however, of insignificant size, measuring 14m long and 0.3 to 0.6m wide. Unfortunately, the occurrence is no longer exposed and its association with a fault can only be inferred (Rowell and Edgar 1986). This leaves open the possibility that the deposit may be the result of orthomagmatic, deuteric activity, as suggested by Dressler (1982).

Recently, Hulbert (1986) has described PGE-bearing, uraniferous veins in the Beaverlodge area of Northern Saskatchewan. Veins at, for example, the **Nicholson Number 2** deposit, are spatially associated with a mafic intrusion. Hulbert (1986) reports that PGE grades appear to decrease with increasing distance from the mafic rocks, which may therefore, have been the source from which hydrothermal fluids leached PGE.

5.2.4.2 SUBCLASS 3b : Alkaline Porphyry Deposits.

The alkaline suite of porphyry copper deposits has been known for some time to be enriched in precious metals. Kesler (1973), for example, proposed a porphyry copper-gold subclass of the porphyry copper family and Finch et al. (1983) noted, in addition, a significant enrichment of PGE within copper mineralisation in this subclass. Werle et al. (1984) described the syenitic **Allard Stock**, an epizonal Laramide intrusion at the southwestern end of the Colorado Mineral Belt, 25 km northwest of Durango, Colorado. A porphyry copper/precious metals deposit is hosted within the Allard Stock, containing typically 0.6% Cu, 2-20 ppm Ag, 10-200 ppb Au, 3 ppm Mo and 100-170 ppb total

PGE. Werle et al. (1984) conclude that fractionation of magma and volatiles in the parent magma chamber of the Allard Stock concentrated H_2O, CO_2 (up to 10% CO_2 is present in the syenitic rocks, and CO_2-bearing fluid inclusions are present in both host rocks and veins), F and S. The volatile-, base- and precious metal-bearing fluid phase was responsible for breccia and vein mineralisation, precipitating metallic minerals, calcite, fluorite and quartz.

5.2.4.3. SUBCLASS 3c : Late Diagenetic/Epithermal.

In contrast to Subclasses 3a and 3b, the hydrothermal, stratabound Kupferschiefer Cu-Ag (Pb-Zn) deposits show no spatial or temporal relationship with igneous activity. **Kupferschiefer** mineralisation is at the contact between Lower Permian volcanic rocks and rift-filling red beds, and Upper Permian marine carbonates, evaporites and red beds, with the largest and richest deposits being found in Southwest Poland. Most recent studies have indicated that the Kupferschiefer mineralisation is epigenetic, deposited from late diagenetic, convecting fluids (Jowett 1986).

At the Lubin and Polkawice Mines in Poland, Kucha (1982, 1983) described Pt-rich (>10 ppm) shales that were mapped along strike lengths in excess of 1.5 km. Maximum values of >200 ppm Pt have been found over 50m strike lengths, associated with the contact zone between white, oxidised sandstone, and black, reduced shale, containing thucholite, ketones, kerogen, phenols, tertiary alcohols and aromatic hydrocarbons. Kucha (1982) suggests that the precious metals are concentrated in the shale, during late diagenetic fluid flow, by a process of auto-oxidation and desulphurisation of the organic matter. Kucha further suggests that the PGE may act as catalysts in this reaction. As far as this author is aware, Kucha's high PGE analyses have yet to be duplicated by other researchers (E.C. Jowett, NATO Post-Doctoral Fellow, Cornell University, Oral Communication, 1987).

A second interesting polymetallic, PGE-bearing deposit, not obviously related to felsic intrusions, has been described recently at **Coronation Hill**, in the Northern Territory of Australia (Needham and Stewart-Smith 1987). The Coronation Hill Mine is one of a suite discovered in the South Alligator Valley district, mined for uranium in the mid-1950s to 1960s. The uranium deposit is hosted by highly faulted conglomerate, altered volcanic rocks and carbonaceous schist. Needham and Stewart-Smith (1987) interpret the deposit to be allied to the class of epigenetic, sandstone-hosted uranium deposits, with uranium-enriched felsic volcanic rocks as the metal source, sandstone beds as fluid conduit, and carbonaceous schist acting as reductant. The precious metal mineralisation (PGE+Au) is finely disseminated in felsic volcanic rocks, altered to quartz, sericite and chlorite, immediately to the east of the open cut from which uranium was produced. The gold is very fine grained, not visible to the naked eye, and also not associated with any prominent quartz veining. Only minor uranium mineralisation is found directly associated with the precious metals. Felsic dikes locally intrude the host rocks. A joint venture between BHP Minerals Limited, Noranda Pacific Limited and EZ Industries Limited discovered the precious metal mineralisation in 1985 and report that of 177 two metre core assays, 163 gave gold values greater than 1 g/t, averaging 0.61 g/t Pt, 1.15 g/t Pd and 7.72 g/t Au (Noranda Pacific Limited, Quarterly Report, December 31, 1985). It is presently unclear whether the spatial association between precious metal and uranium mineralisation is purely fortuitous. The exploration companies believe that the precious metal mineralisation is epithermal in nature, related to sub-aerial, acid volcanism.

5.2.4.4. CLASS 3 : Summary.

While hydrothermal PGE deposits are less well understood than the more extensively described orthomagmatic deposits, and few examples of this class of PGE deposit have been identified in Ontario, at least three distinct categories are currently identified elsewhere: (a) those associated with epigenetic fluid flow in mafic/ultramafic rocks, (b) precious metal-enriched (PGE, Au, Ag), porphyry copper deposits, of alkaline affinity, (c) carbonaceous, shale-hosted deposits, related to diagenetic fluid flow. As research progresses, other subclasses of the hydrothermal PGE deposit type will undoubtedly be identified.

5.3 Implications For Exploration

The current domination of global PGE markets by deposits of the orthomagmatic class suggests that, based upon "track record", this deposit type remains the optimal exploration target. Subclass 1a is currently the **most** desirable target within the orthomagmatic deposit class, as the PGE are a primary product, rather than a biproduct of less economic, base-metal mining. Utilising an understanding of Bushveld and Stillwater mineralisation, the following criteria can be regarded as positive indicators for mineralisation:

(1) large, compositionally stratified, mixed mafic and ultramafic, layered intrusive complex;

(2) zones of mixing between liquids of different U- and A-type affinities (Todd et al. 1982; Irvine et al. 1983), within the mafic portions of the intrusive complex, rather than the lower ultramafic zone. *Nota bene*: the MSZ in the Great Dyke is an exception, located within ultramafic host rocks, several metres **below** the contact with the mafic series;

(3) sulphides, typically only 1-2%, in zone of mixing.

Magma mixing in the BIC and SIC has been documented in the context of chemical and isotopic signatures (e.g. Irvine et al. 1983; Sharpe et al. 1986). Field expressions of the proposed mixing phenomena are complex (e.g. Turner et al. 1985) inasmuch as the geology within the zones of mixing can be highly variable on all scales, contrasting with the relative uniformity of layered rocks stratigraphically above and below the mineralised units. Detailed mapping of the Minneapolis Adit in the Stillwater Complex reveals such complexity on a small scale that certain packages of rocks are mapped collectively as "Mixed Rock" (Bow et al. 1982). Mixed Rock is an complex igneous breccia, with a matrix of plagioclase cumulate gabbro, containing 20-40% amoeboidal olivine, associated with clusters of pegmatoidal, poikilitic crystals of bronzite and augite. The rock also contains boulders of olivine cumulate, plagioclase-olivine cumulate (troctolite) and plagioclase cumulate.

Macdonald (1985, 1987a) has mapped rocks of similar complexity hosting PGE mineralisation at Lac des Iles, Canada. In contrast with the relatively monotonous gabbroic rocks that comprise the bulk of the intrusive complex hosting significant PGE at Lac des Iles, the immediate host rocks are highly complex: a wide (500m) zone of texturally and compositionally variable lithologies - from fine grained to pegmatoidal pyroxenite, norite, gabbro, quartz gabbro to anorthosite - is cored by an igneous breccia, up 100m wide that is spatially associated with the higher grades of PGE+Au. The breccia has a gabbroic matrix, with clasts, up to in excess of 3m in long dimension,

of gabbro, pegmatoidal gabbro, anorthosite and pyroxenite. The breccia is cut by gabbro pegmatite dikes, locally containing up to 37,000 ppb total PGE+Au. Mineralisation at Lac des Iles is spatially, and probably genetically, related to a pyroxenite that has intruded and locally blended with the anorthositic gabbro host (Macdonald 1987a).

While deposits that formed in response to magma mixing exhibit evidence of at least a partial role played by deuteric fluids, it is by no means certain that this is an **essential** component of the mineralisation process; suffice to say that deuteric effects are not considered deleterious to economic potential.

The renewed interest in PGE mineralisation, driven by political and market forces, may result in the discovery of potentially economic concentrations of the PGE in unconventional geologic settings. For example, the Kupferschiefer-style mineralisation was not widely recognised until 1982. The PGE-black shale connection may be worthy of further investigation in, for example, the Central African Copper Belt, the shale-hosted copper deposits of Oklahoma, etc. Possible analogues in Ontario should not be discounted. The relatively recent (1985) discoveries of PGE mineralisation associated with apparently epithermal gold mineralisation at Coronation Hill, in Australia's Northern Territory, suggests that the numerous deposits of this type, in a similar gelogical environment, warrant a closer inspection for PGE content.

The association of PGE deposits with CO_2-rich, alkaline igneous intrusions is also in need of further description. Intrusions with alkaline affinities, such as the Coldwell Complex near Marathon, Ontario, host PGE deposits of economic interest (e.g. Dahl et al. 1986). The alkaline intrusion-hosted deposit type may have to be expanded or redefined to include carbonatite bodies: the pyroxenite-syenite-carbonatite complex at Phalaborwa, in northeastern South Africa, for example, in addition to supporting apatite and vermiculite mines, contains one of the most efficient open pit copper mines in the world, producing 100MT of ore per annum, grading 0.48-0.57% Cu. The composition of recoverable precious metals is dependent largely upon copper content (typical concentrate contains 45% $\pm$ 15 Cu). The following composition of anode slimes is typical: 3.5 kg/t Au, 85 kg/t Ag, 0.45 kg/t Pt, 0.55 kg/t Pd and 0.025 kg/t Rh (Verwoerd 1986). The Ontario Geological Survey is currently (1987) re-analysing samples collected from carbonatite complexes throughout the Province to assess their potential as a PGE resource.

5.4 Conclusions

Deposits of the platinum group of elements form in three fundamental environments: (a) as an integral component of orthomagmatic processes, including mixing of magmas, wallrock contamination of magmas and by deuteric processes; (b) by alluvial concentration of degraded source material - most modern placers being derived from mafic/ultramafic complexes of the "Alaskan/Ural-" or "Alpine-type" ; (c) by hydrothermal transport, related either to leaching of PGE from mafic/ultramafic host rocks, or to alkaline porphyry copper and/or epithermal precious metal mineralisation, or to late-diagenetic fluid flow in sedimentary basins. While the diverse geological environments within Ontario preclude none of these deposit types, PGE mineralisation formed in the orthomagmatic environment provides the most attractive target for exploration, taking into account the economic advantages of this deposit type and the dominance of Precambrian over younger terrains in Ontario.

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7.0 SELECTED ANNOTATED BIBLIOGRAPHY OF PGE IN ONTARIO (G.C. Wilson)

The following bibliography contains annotated summaries of 182 journal articles, reports and books dealing mainly or tangentially with PGE in Ontario. An earlier compilation (Wilson 1985a) treated 78 items in similar fashion; the newer entries are designated by the term '** PGE'. Almost all references deal explicitly with PGE geology and/or mineralogy; a few geological references concerning favourable environments for PGE are also included.

Edited from original 'MINLIB' computer database, (c) Turnstone Geological Services Ltd, Toronto, 1983-1987. The increasing number of 1-column articles in trade journals is represented by a few items only, and the choice is governed by inclusion of geological data, reserves and grades. Many of these short items occur in the 'Northern Miner' and, from September 1986 on, can be accessed via computer link to the 'Infoglobe' system in Toronto.

As in the body of the report, PGE and PGM refer respectively to platinum group elements and minerals.

Abel,MK, Buchan,R, Coats,CJA and Penstone,ME
Copper mineralization in the Footwall complex, Strathcona Mine, Sudbury, Ontario.
Can.Mineral. 17, 275-285 (1979).
Sudbury Ontario Canada - Footwall complex - Cu - Ni - Ag - sulphides - chalcopyrite - cubanite - zoned veins with pentlandite and pyrrhotite concentrated on the footwall - wallrock alteration a few mm thick near veins - hornblende epidote garnet pyrosmalite etc - origin by entry of high-temperature Cu-rich liquid into fractures in dilatant zone - besides the Ni Cu ore in a late granite breccia the Copper Zone veins occur in the brecciated 'feldspathic gneiss complex' - veins have extremely sharp contacts and are almost pure massive sulphide - altaite - veins rich in Ag Bi Pb Te but not ** PGE - zoned deposits.

Anon
Production decision soon on Fleck's platinum bet.
Northern Miner 72 no.17, 11 (7 July 1986).
Marathon, Ontario, Canada - Coldwell complex - ** PGE - metallurgical testing of deposit indicates best recoveries for Pt and Pd of 84.5 and 87.7% respectively.

Anon
Teck takes option on Fleck's platinum bet.
Northern Miner 72 no.29, 1,6 (29 Sept. 1986).
Ontario, Canada - ** PGE project in Coldwell Complex near Marathon - deposit reserves at 47 MT grading 0.07 oz/T Pt plus Pd and 0.45% Cu - tests indicated respective recovery of these metals at levels of 84.5, 87.7 and 85 percent.

Barnes,S-J
The origin of the fractionation of platinum group elements in Archean komatiites, of the Abitibi greenstone belt, northern Ontario, Canada.
PhD thesis, University of Toronto, 231pp. (1983).

Ontario, Canada - Archean Abitibi greenstone belt - ** PGE analysis and geochemistry - ** PGE patterns - Os Ir Ru Rh Pt Pd Au - komatiites - olivine and chromite - crystal fractionation - PGE fractionation explicable by variation in timing of S saturation in magmas of different deposits, allowing variable prior removal of Ir group (refractory) PGE as alloys (perhaps nucleated on olivine and chromite) prior to S saturation - Alexo, Hart, Dundonald and Texmont deposits - petrography and photomicrographs - spinifex textures - dendritic, skeletal and hopper habits in magmatic silicates - Fe Ni S plots of sulphides in the four deposits - late hydrothermal (carbonatization) effects may have a secondary influence on Pd and Au distributions - methodology for INAA of PGE - REE - other minor and trace elements.

Barnes,S-J and Naldrett,AJ
The fractionation of the platinum-group elements at the Alexo komatiite, Abitibi greenstone belt, Northern Ontario.
Abs. Fourth Int. Platinum Symposium, Can.Mineral. 23, 295 (1985).
** PGE fractionation, Alexo komatiite, Abitibi greenstone belt, Ontario, Canada - variable PGE fractionation amongst ore types explained by crystallization of monosulphide solid solution from a sulphide liquid - extreme enrichment of Pd over Ir (normal Pd/Ir for komatiites is 5-10, Alexo ore types vary from 44-193) - PGE fractionation is greater for lower Mg contents - perhaps in olivine-rich melts the siderophile Ir formed small metal particles, upon which olivine nucleated 'and settled Ir out of the melt'.

Barnes,S-J and Naldrett,AJ
Variations in platinum group element concentrations in the Alexo mine komatiite, Abitibi greenstone belt, northern Ontario.
Geol.Mag. 123, 515-524 (1986).
Alexo komatiite, Timmins area, Ontario, Canada - Archean Abitibi greenstone belt - ** PGE - trace elements - Os Ir Ru Rh Pt Pd Au - PGE fractionation in sulphides; massive, net-textured and disseminated sulphides - Ni Cu Co - mass balance calculation explains element distributions (Pd/Ir ratios) in terms of crystallization of mss from a sulphide liquid, with no need to invoke remobilization of Pt Pd Ni Co - INAA and AAS - PGE data on standard SARM-7 - PGE patterns - sulphide ore genesis - Re does not necessarily mobilize in the same patterns as PGE and base metals.

Barnes,S-J, Gorton,MP and Naldrett,AJ
Platinum group elements in Abitibi komatiites associated with nickel sulphide deposits.
OGS Misc.Pap. 98, 1-12 (1981).
Ontario, Canada - PGE Au Ni Cu Co S analysed in samples from 4 nickel sulphide deposits, and in samples of spinifex-textured ultramafic flows thought to represent magmatic liquids from the deposits - 3 deposits (Dundonald, Hart and Texmont) have PGE distributions appropriate for komatiites, one (Alexo) has a tholeiitic distribution - no other significant difference seen between the deposits; PGE pattern at Alexo due to differentiation after formation of the parent melt, rather than a different source material or different extent of partial melting in the mantle - large tabulations of analytical data (INAA etc), including Ru Rh Pd Pt Os Ir - REE - etc - the Alexo liquid may have undergone significant crystal fractionation of chromite, a known PGE-bearing phase.

Borthwick,AA
The Geology and Geochemistry of the Big Trout Lake Complex, N.W. Ontario.
MSc thesis, University of Toronto, 200pp. (1984).
Big Trout Lake layered intrusion, Ontario, Canada - local geology, petrography, photomicrographs - olivine, pyroxene, plagioclase, serpentine, chromite - sulphide occurrences, incl. one rare instance of sulphide inclusions in chromite (pp.34-35) - ilmenite intergrowth with pyroxene (p.38) - gabbro lithologies - glomeroporphyritic anorthosite - whole-rock analyses; anorthosite, gabbro, peridotite - REE - evidence for two ultramafic magmas (p.90) - magma mixing inducing supercooling and formation of re-entrant olivine grains and sulphide droplets - liquid immiscibility - magma chamber processes - crystal chemistry of chromite and possibility of incorporating 'OPMs' - Os Ir Ru (pp.164-9) - - INAA method for ** PGE in chromitites (pp.170-171).

Borthwick,AA and Naldrett,AJ
Platinum group elements in the layered intrusion at Big Trout Lake.
OGS Misc.Pap. 103, 12-19 (1982).
Ontario Canada - layered intrusion - PGE contents of first two cycles - cumulus olivine and chromite - PGE within each cycle show a distinct differentiation trend - Pt Pd Ru Ir Os Au Ni Cu Cr S - the (Pt+Pd)/(Ru+Ir+Os) ratio increases from base to top of each cycle - the PGE in sulphides are more akin to those in gabbro-related massive Ni-Cu sulphide ore than those of enriched Merensky-type ores.

Borthwick,AA and Naldrett,AJ
Platinum-group elements in layered intrusions.
OGS Misc.Pap. 121, 13-35 (1984).
Ontario,Canada - Big Trout Lake intrusion; peridotite overlain by anorthosite - the lower peridotite can be subdivided into lower and upper units by major element and REE patterns; lack of systematic major element and PGE trends suggest periodic magma influxes - uniformity of the upper unit suggest crystallization as a closed system, 'except for magma influxes marked by resorbed, re-entrant olivine' - maps - mineralogy, petrography and geochemistry - PGE concentration falls rapidly in the layer of re-entrant olivine, indicating a stagnant layer in the magma chamber - net-textured sulphides at Big Trout Lake are depleted in Os Ir Ru - these were removed from the magma by chromite fractionation before sulphide precipitation - this subgroup of PGE are referred to as OPM (osmium-platinoid metals) - chromite influences Os Ir Ru and maybe Rh - sulphides influence Pt Pd Au to a greater extent - illustrated by PGE plots normalised to 100% chromite and 100% sulphide respectively - REE - PGE patterns.

Borthwick,AA and Naldrett,AJ
Platinum Group Elements in Layered Intrusions: the Geology and Geochemistry of the Big Trout Lake Layered Intrusion.
OGS OFR 5584, 34pp. plus 2 appendices (1986).
Big Trout Lake layered intrusion, Ontario, Canada - peridotite overlain by anorthosite - magma chamber processes - peridotite divisible into lower and upper sections - ** PGE concentrations - low Os Ir Ru in net-textured sulphides may be due to PGE removal by chromite fractionation - cumulates - REE - support for two ultramafic magmas - resorbtion of olivine - magma mixing - sulphide chemistry - PGE patterns - twin appendices are 1984 MSc thesis and 1984 paper on fire assay / INAA methodology for PGE and Au analysis in chromitites.

Boyle,RW
The Geochemistry of Gold and its Deposits.
GSC Bull. 280, 584pp. (1979).
Abundance of Au in the upper crust is about 5 ppb - Au/Ag ratio is about 0.1 - prospecting - geochemistry - massive review - native Au contains PGE, perhaps Pd more than others - it is possible that PGE may be found in tellurides of Au and other elements in Au deposits - in general there are low PGE contents in Au deposits and vice versa - some contact metamorphic deposits may contain elevated levels of both, usually possessing more Pd than Pt - some Au-bearing Cu ores have high PGE levels - the Witwatersrand and Bushveld of S.Africa - Sudbury, Ontario, Canada - possible supergene oxidation and mobility of PGE, especially Pd Ru Os - remobilised PGE probably do not travel far, being susceptible to reduction by organic matter, sulphides etc (pp.163-165) - 'the native platinoids appear to be uncommon hypogene minerals in auriferous deposits' (p.169) - the Cuniptau mine, Ontario, carries Cu Ni Pt Au in a shear zone (pp.164,196).

Boyle,RW
Gold, silver, and platinum metal deposits in the Canadian Cordillera - their geological and geochemical setting.
In 'Precious Metals in the Northern Cordillera' (Levinson,AA editor), Assoc.Expl.Geoc., 1-19 (1982).
W.Canada - Au Ag and PGE deposits - Au placers - only one PGE placer (Tulameen, BC) has been worked in W.Canada - exploration geochemistry - types of PGE deposit include disseminated PGM in layered intrusions, hortonolite-dunite pipes, disseminated PGM in pegmatitic basic and ultrabasic phases with sulphide and chromitite segregations, Ni-Cu ores of Sudbury (Ontario) type, skarns, lodes of other metals (Cu, Pb, Ag and Au), pegmatites, U ores, porphyry Cu ores, Kupferschiefer-type ores, quartz-pebble conglomerates, Tertiary and other conglomerates, gossans and placers.

Breaks,FW, Osmani,IA and Dekemp,EA
Opapimiskan Lake project: Precambrian geology of the Opapimiskan-Forester Lakes area, district of Kenora, Patricia portion.
OGS Misc.Pap. 132, 368-378 (1986).
Ontario, Canada - Opapimiskan Lake - North Caribou Lake Archean greenstone belt - maps - spinifex texture in autobrecciated komatiite - field geology - polysutured textures on surface of ultramafic metavolcanics - metasediments - BIF - anorthositic gabbro - Eyapamikama Lake clastics - Karl Lake mafic-ultramafic intrusive - talc pseudomorphs after olivine preserved as nodules 2mm to 4cm in diameter - structural geology - low Pt Pd Au values associated with Karl Lake complex - ** PGE - trace elements in Musselwhite Au showing - locally high Au As F.

Bright,EG
Whitestone Lake area, district of Parry Sound.
OGS Misc.Pap. 132, 131-135 (1986).
Ontario, Canada - area of the Grenville N. of Parry Sound - map - local geology - three major lithotectonic domains are recognized; Britt, Ahmic and Parry Sound - amphibolite, gneiss - anorthosites - oikocrystic intrusives - layered intrusions may have some potential for Ti V ** PGE - magnetite and ilmenite - metagabbro and metapyroxenite.

Brooker,EJ and Eagles,TE
Isotope ratios and trace elements in gold and base metal occurrences in Ontario: an application of plasma mass spectrometry.
OGS Misc.Pap. 131, 20-24.
Geochemical analysis - ICP mass spectrometry - REE - ** PGE - Pb isotopes - oxide molecular interferences on REE - 'under ideal conditions approximately 65 to 70 elements can be detected by ICP-MS' - routine Pb isotope analysis with 1o/oo precision has yet to be attained.

Brown,MR
Platinum producer likely.
Northern Miner 72 no.4, 1-2 (07 April 1986).
** PGE - Pt Pd production likely from Lac des Iles layered intrusion, Ontario, Canada - Ni Cu Au - grades and expectations.

Brugmann,GE, Arndt,NT, Hofmann,AW and Tobschall,H-J
Precious-metal abundances in komatiites and komatiitic basalts: implications for the genesis of PGE-bearing magmatic sulfide deposits.
Abs. Fourth Int. Platinum Symposium, Can.Mineral. 23, 297-298 (1985).
Archean komatiite flow from Alexo, Ontario, Canada and Phanerozoic komatiite from Gorgona Island, Colombia are analysed for Au - ** PGE - Pd Ir Os Ru - Cu and Ni - MgO content of the komatiitic suites range from 11-31 wt.% - lithophile element variations can be explained by olivine fractionation (- REE - Ti Zr Al Cr) - Ir Os Ru are more compatible than Au and Pd with respect to olivine and interelement ratios depend on 'the degree of melting required to generate the silicate host-liquid and the amount of fractionated olivine at the time of sulfide segregation'.

Burrows,AG and Rickaby,HC
Sudbury nickel field restudied.
ODM Ann.Rep. 43 pt.2, 49pp. (1934).
Sudbury, Ontario, Canada - history and topography - Ni Cu ** PGE production - local geology - greenstones - sediments - 'eye and eyebrow structures' (pp.13-17) of quartz in rhyolite - staurolite in metasediments - Snider, Waters and McKim townships - metabasites - Copper Cliff arkose - flow structures in rhyolite - Ramsay Lake conglomerate - Wanapitei quartzite - Nickel Irruptive - dyke-like quartz-diorite 'offsets' from the norite (pp.26-30) - granite - uralitic diabase - Creighton, Frood, Stobie, Garson, Falconbridge Mines - Ni Cu sulphide ores - OGS map 43d of Sudbury Ni area - map 43e of Falconbridge Mine.

Cabri,LJ
Some observations on the geochemistry of the platinum-group elements.
Trans.Geol.Soc.S.Afr. 77, 65-67 (1974).
PGE and PGM at Sudbury, Ontario, Canada and at Noril'sk and Monchegorsk, USSR - distribution of Pt and Pd between phases; current data suggest that significant quantities of PGE are unlikely to occur in solid solution in sulphides of Cu Ni deposits at Sudbury and Noril'sk - Pd is lower in placers than in Cu Ni sulphide ores, perhaps partly due to its greater solubility - presence of silicates and chromite in Pt nuggets from the Tulameen district of BC indicate a dunitic source for the placer PGM.

Cabri,LJ
Mineralogy and distribution of the platinum-group in mill samples from the Cu-Ni deposits of the Sudbury, Ontario, area.

In 'Precious Metals' (McGachie,RO and Bradley,AG, editors), Pergamon Press, 23-34 (1981).
Sudbury, Ontario, Canada - the principal PGM are michenerite, sperrylite and moncheite - less common phases include insizwaite, froodite, sudburyite, kotulskite, merenskyite, hollingworthite and irarsite - PGE Bi Te As Sb Te Sn S - arsenic - PGE refining/recovery - EPM,SEM - Pt Pd Rh occur as solid solutions in cobaltite and gersdorffite; unlike the common sulphides, PGE concentrations in sulpharsenides proved adequate for direct analysis.

Cabri,LJ
Relationship of mineralogy to the recovery of platinum-group elements from ores.
In 'Platinum-Group Elements: Mineralogy,Geology and Recovery' (Cabri,LJ editor), CIM Spec.Vol. 23, CIM, Montreal, 233-250 (1981).
PGE minerals - PGE refining/ecovery - Pt Ir Os Ru Rh Pd - deposits of Alaska, USA - Bushveld, S.Africa - Witwatersrand placers - the Merensky Reef - the Stillwater complex in Montana - the Lac des Iles complex in Ontario, Canada - Sudbury - Noril'sk USSR etc - also on chromite deposits, plus porphyry Cu Mo ore, the Palabora carbonatite, laterites and gossans - mineralogy and recovery methods.

Cabri,LJ and Laflamme,JHG
Sudburyite, a new palladium-antimony mineral from Sudbury, Ontario.
Can.Mineral. 12, 275-279 (1974).
Sudbury, Ontario, Canada - ideally PdSb, sudburyite occurs as small, often elongate inclusions (= < 18 x 100um), commonly in cobaltite or maucherite - PGE - Pd Sb Pt Ni Te Bi mineralogy - Frood and Copper Cliff mines - Sb-rich michenerite - EPM.

Cabri,LJ and Laflamme,JHG
The mineralogy of the platinum-group elements from some copper-nickel deposits of the Sudbury area, Ontario.
Econ.Geol. 71, 1159-1195 (1976).
PGE - Sudbury, Ontario, Canada - South Range rich in As and Sb, North Range rich in Sn (as constituents of PGE minerals) - Pt - sulphide liquid immiscibility - Cu rich liquid - EPM of Cu Ni ore for PGE - arsenic.

Cabri,LJ and Laflamme,JHG
Mineralogy of samples from the Lac des Iles area, Ontario.
CANMET Rep. 79-27, Ottawa, 20pp. (1979).
Ontario, Canada - PGE in samples containing low-grade disseminated Cu Ni sulphides; chalcopyrite and pentlandite are the main Cu and Ni species, although Ni occurs in 13 minerals, exclusive of the PGM - main PGM are braggite phases, kotulskite, isomertieite, merenskyite and sperrylite - Pd Pt Te As Sb S - arsenic - Pd also occurs in solid solution in pentlandite, Au and melonite (NiTe2) - EPM and standards and chosen X-ray lines - colour photomicrographs of siegenite, millerite, moncheite, stillwaterite etc.

Cabri,LJ and Laflamme,JHG
Mineralogy and distribution of platinum-group elements in mill products from Sudbury.
In 'Applied Mineralogy' (Park,WC, Hausen,DM and Hagni,RD editors), conf. proc., Met.Soc. of AIME, pp.911-922 (1984).
Sudbury, Ontario, Canada - ore microscopy, EPM, PIXE and bulk analysis of

concentrate from Clarabelle primary mill, Copper Cliff - ** PGE balance - some 91% of the Pt can be accounted for, 83% occurring in sperrylite - less than half the Pd is accounted for; the main host phase idenified is michenerite - Rh occurs largely in solid solution and as hollingworthite inclusions in sulpharsenides - - Ir also seems closely associated with sulpharsenides - little is known of Ru and Os distributions - SEM photographs - gersdorffite, cobaltite, irarsite, moncheite etc.

Cabri,LJ and Naldrett,AJ
The nature of the distribution and concentration of platinum-group elements in various geological environments.
Proc.27th IGC, Vol. 10, Mineralogy, pp.17-46, VNU Science Press (1984).
A non-genetic two-fold classification of PGE deposits, according to their chalcophile (sulphide association) and siderophile (oxide/silicate association) tendencies - deposits range in age from Triassic to Archaean - sulphide association include Sudbury (Ontario,Canada), Merensky Reef (Bushveld,S.Africa) and Noril'sk (USSR) - the oxide/silicate association includes various chromitite and Ti magnetite -related deposits and the ultramafic pegmatite 'pipes' of the Bushveld - Pt Pd Rh Ru Ir Os - Au - distribution data for PGE between sulphides and other phases - EPM and PIXE data - J-M Reef of the Stillwater, Montana,USA) - mineralogy of Noril'sk-Talnakh, the Platreef, the UG-2, Kambalda-type ores (komatiite-related, Australia and elsewhere) etc - Lac des Iles,Ontario - pentlandite as a common, significant host for PGE - chromite-bearing Alpine-type ores tend to have high Ru Os Ir relative to Pt Pd Rh - a useful review and summary of PGE deposits, combining data on mineralogy, grainsize and grades (as available).- placer PGE.

Cabri,LJ, Harris,DC and Gait,RI
Michenerite (PdBiTe) redefined and froodite (PdBi2) confirmed from the Sudbury area.
Can.Mineral. 11, 903-912 (1973).
Michenerite from the Vermilion and Frood Mines, Sudbury, Ontario, Canada - PGM - PGE - Pd Bi Te - froodite - EPM, XRD and optical properties - photomicrographs.

Cabri,LJ, Laflamme,JHG and Stewart,JM
Temagamite, a new palladium-mercury telluride from the Temagami copper deposit, Ontario, Canada.
Can.Mineral. 12, 193-198 (1973).
Ontario Canada - Pd Hg Te - inclusions of the telluride Pd3HgTe3 occur (max. size 115 microns) occur in chalcopyrite, associated with merenskyite and/or stuetzite and/or hessite - optical properties - reflectance - EPM - unnamed Pd Hg Ag telluride - massive chalcopyrite ore - PGE.

Cabri,LJ, Laflamme,JHG, Stewart,JM, Rowland,JF and Chen,TT
New data on some palladian arsenides and antimonides.
Can.Mineral. 13, 321-335 (1975).
EPM and XRD data for PGM in the Pd As Sb system - arsenic - PGM include stillwaterite, palladoarsenide, sperrylite and mertieite II - PGM from Sudbury, Ontario, Canada and the Stillwater layered intrusion, Montana, USA - ore microscopy - photomicrographs - phase diagrams - PGE.

Cabri,LJ, Laflamme,JHG, Stewart,JM, Turner,K and Skinner,BJ
On cooperite, braggite and vysotskite.
Amer.Mineral. 63, 832-839 (1978).
The Pt Pd S system - three phases in the solid solution braggite series - vysotskite may be defined as having less than about 10 mol.% PtS - it is formed at lower (submagmatic) temperatures than the other two PGM, perhaps by liquid immiscibility or solid-state reaction - phase diagrams, EPM, XRD - photomicrographs - samples from the Stillwater layered intrusion, Montana, USA, the Bushveld complex, S.Africa and the Lac des Iles complex, Ontario, Canada - also reported in GAC/MAC Abs.w.Progs. 3, 376 (1978) - PGE.

Cabri,LJ, Blank,H, El Goresy,A, Laflamme,JHG, Nobiling,RI, Sizgoric,MB and Traxel,K
Quantitative proton microprobe analyses of major sulphides in ore deposits of the Sudbury area.
GAC/MAC Prog.w.Abs. 8, A9 (1983).
PIXE of Sudbury sulphides - chalcopyrite pentlandite and pyrrhotite - the Se and Zn contents - detection limits for Pd Rh Pt Ir - these PGE were not detected - limits varied from 5-60 p.p.m. - Ontario Canada.

Cabri,LJ, Blank,H, El Goresy,A, Laflamme,JHG, Nobiling,RI, Sizgoric,MB and Traxel,K
Quantitative trace-element analyses of sulfides from Sudbury and Stillwater by proton microprobe.
Can.Mineral. 22, 521-542 (1984).
Sudbury, Ontario, Canada - Stillwater complex, Montana, USA - PIXE - no PGE found in Sudbury sulphides, down to detection limits of 1.2 to 3 ppm for Pd and Rh and 50-60 ppm for Pt - Stillwater pentlandites contain PGE in solid solution; 1870-13600 ppm Pd - <26 to 110 ppm Rh - <14 to 80 ppm Ru - chalcopyrite, pentlandite and pyrrhotite from both complexes contain Se in solid solution - Sudbury chalcopyrite also contains Zn in amounts from <35 to 2570 ppm, heterogeneously distributed - SEM and EPM data - PGE distribution within sulphides - Lac des Iles.

Campbell,IH and Barnes,SJ
A model for the geochemistry of the platinum-group elements in magmatic sulphide deposits.
Can.Mineral. 22, 151-160 (1984).
PGE - partition coefficients (D) for Pt and Pd between silicate and sulphide liquids - liquid immiscibility - if D is very high the sulphide liquid depletes the silicate melt in PGE - estimated D values for various sulphides vary from 300 for those associated with komatiites to 1000 for those related to flood basalts and over 100,000 for the Stillwater (Montana USA) J-M Reef and the UG-2 chromitite of the Bushveld, S.Africa - Sudbury, Ontario, Canada - Pt in silicate rocks may be used in exploration for deposits rich in Ni and Cu - silicates hosting such deposits should have low Pt and Pt/Ni, but normal or only slightly depleted Ni: for this to be valid D for Pt must be high.

Carlson,HD
Geology of the Werner Lake-Rex Lake area.
ODM Ann.Rep. 66 Pt.4, 30pp. (1958).
Area some 50 miles N. of Kenora in N.W. Ontario, Canada - Precambrian granites, tonalites, mafic intrusives and metasediments - quartzite - granulite - garnet - amphibolite - schist -

peridotite - pyroxenite - hornblendite - fault zones - exploration for Ni Co Cu sulphide ore - sulphide showings, some with sulphide in later pegmatite (p.24) - ** PGE traces (p.24); individual Pt grades not given; 0.07 oz/T total - OGS maps 1957-2/3.

Chyi,LL and Crocket,JH
Partition of platinum, palladium, iridium and gold among coexisting minerals from the deep ore zone, Strathcona Mine, Sudbury, Ontario.
Econ.Geol. 71, 1196-1205 (1976).
RNAA of Pt Pd Ir Au - pyrrhotite, pentlandite, chalcopyrite and magnetite - Sudbury, Ontario, Canada - Pt and Pd reach ppm levels in chalcopyrite and pentlandite, whereas Au and Ir values do not exceed 15 ppb, except for the Au content of pentlandite which averages 118 ppb - Pd and Au are concentrated into pentlandite, and Pt and Ir are associated with chalcopyrite - except for Ir, magnetite is depleted in precious metals with respect to all sulphides - Pd probably resides in pyrrhotite at magmatic temperatures, until pentlandite exsolution below 300C - chalcopyrite may be derived both by exsolution from pyrrhotite solid solution and by direct magmatic crystallization; Pt distribution should accordingly be influenced by both processes - Cu Ni Fe S - liquid immiscibility - PGE.

Clark,WB
Platinum.
Min.Info.Serv. 23 no.6, 115-122 (1970).
Review of ** PGE - Pt Pd Ir Os Ru Rh - map of Pt recovery in California, USA, as a byproduct of placer Au operations - uses - PGM - Pt in California - Sudbury, Ontario, Canada - Bushveld, S.Africa - analysis for PGE - metals recovery, markets and prices in 1969 - see also Carlson,CA et al, for ** PGE in podiform chromites in California and Oregon; USGS OFR 85-0442, 15pp. (1985).

Coats,CJA and Snajdr,P
Ore deposits of the North Range, Onaping-Levack area, Sudbury.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 327-346 (1984).
Sudbury, Ontario, Canada - local geology - norites and sublayer - Sudbury breccia - diabase - contact metamorphism - Footwall Breccia - whole rock analyses - sulphide ores - many mines - Ni Cu - minerals in Strathcona copper zones (p.341) - ** PGE Au Ag - McCreedy West - Pt Pd Rh Ru Ir - xenoliths - zoned metals.

Cochrane,LB
Ore deposits of the Copper Cliff Offset.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 347-359 (1984).
Sudbury, Ontario, Canada - Copper Cliff - offset dykes - Cu Ni sulphide ore - quartz diorite - xenoliths - ** PGE - Pt Pd Ru Rh Ir Ag - sketch maps - local geology - Sudbury breccia - the 120 and 810 ore bodies.

Conrod,DM and Naldrett,AJ
Petrology, geochemistry, isotopic studies, and platinum group element potential of the Nipissing diabase.
OGS Misc.Pap. 127, 206-222 (1985).

Two sites of the Nipissing diabase in Ontario, Canada, on the Montreal River in the Cobalt area and south of Lake Wanapitei, near Sudbury; Cross Lake, Portage Bay, Bonanza Lake - diabase, hypersthene gabbro, gabbronorite - differentiated phases; quartz diorite, granodiorite, syenogranitic pegmatite - EPM data on orthopyroxene and on olivine Ni contents - note on age dates - maps - petrography - modal analyses - varied texture diabase - ** PGE potential to be assessed by NAA of samples.

Cousins,CA
Notes on the geochemistry of the platinum group elements.
Trans.Geol.Soc.S.Afr. 76, 77-81 (1973).
PGE geochemistry - chromites - sulphides - Pd Pt Ir Ru Os Ir Au - Merensky Reef, Bushveld, S.Africa - Sudbury, Ontario, Canada - Great Dyke of Rhodesia - Noril'sk, USSR - alluvial PGE - strong affinity of PGE for S As - arsenic - Zimbabwe.

Cousins,CA and Vermaak,CF
The contribution of southern African ore deposits to the geochemistry of the platinum group metals.
Econ.Geol. 71, 287-305 (1976).
S.Africa - chromite - PGE probably occur in Cr spinels as discrete inclusions, without appreciably substituting for base metal cations within the lattice - secondary mobilization of PGE causes 'Sudbury trend' enrichment in Pd - freshwater placers are enriched in Pt - marine placers show concentrations in Os and Ir - leached metals such as Pd end up in deep-water sediments - map of PGE distribution in southern Africa - brief review of deposits from Archean to Tertiary - PGE geochemistry; ionic radii, geochemical cycle, occurrence (with table of analyses) in Merensky Reef, UG-2 chromitite, dunite pipes, Palabora carbonatite, the Great Dyke of Rhodesia, Sudbury (Ontario, Canada) etc - Zimbabwe - Bushveld, S.Africa.

Craig,JR and Vaughan,DJ
Ore Microscopy and Ore Petrography.
Wiley, 406pp. (1981).
Textbook - ore microscopy - microscopes - optical properties - ore textures - ore petrography - replacement textures, intergrowths, twin crystals - colloform banding - exsolution 'flames' etc - the Ni Cu ores of Sudbury, Ontario, Canada - layered intrusions - magmatic ores - Cr - Fe Ni Cu - Fe Ti - PGE - diagnostic table of approx. 100 of the more common ore minerals - many examples - a wide range of ore types and associations is reviewed.

Crocket,JH
Platinum-group elements in mafic and ultramafic rocks:a summary.
Can.Mineral. 17, 391-402 (1979).
PGE - Pd - Ir - S - sulphides - distribution in rocks, chromite and silicates - peridotites - Alaska, USA - USSR - kimberlite - Bushveld, S.Africa - Rhum, Scotland, UK - TVD - fractional crystallization - Pt - olivine may concentrate Ir, although the Ir may really be in chromite inclusions - Pd and Ir are very low in MORB relative to other basalts - komatiite - kimberlite - dunite - Ontario, Canada - Ir Ru and Os may be concentrated in early products of fractional crystallization.

Crocket,JH and MacRae,WE
PGE distribution in komatiitic and tholeiitic volcanic rocks from Munro

Township, Ontario.
Abs. Fourth Int. Platinum Symposium, Can.Mineral. 23, 300-301 (1985).
Munro township, Ontario, Canada - peridotitic komatiite flows - ** PGE - Pt Pd Ir Au by RNAA - fractionation trends; Pt Pd Au preferentially into the melt, and Ir into a solid phase (probably olivine) - these trends are much weaker in tholeiitic than in komatiitic flows - Pd may be preferentially partitioned into liquid immiscible sulphide relative to Pt.

Crocket,JH and MacRae,WE
Platinum-group element distribution in komatiitic and tholeiitic volcanic rocks from Munro Township, Ontario.
Econ.Geol. 81 no.5 (A Third Issue Devoted to Platinum Deposits), 1242-1251 (1986).
Munro township, Ontario, Canada - Archean Abitibi greenstone belt - Pyke Hill, Fred's Flow, Theo's Flow - ** PGE - fractionation of PGE in komatiites - spinifex-textured rocks - Ir thought to be coprecipitated with olivine or pyroxene, whereas Pt and Pd 'are rejected from the structures of these minerals'.

Crocket,JH and Teruta,Y
Pt, Pd, Au and Ir of Kelley Lake bottom sediments.
Can.Mineral. 14, 58-61 (1976).
Sudbury, Ontario, Canada - ** PGE - Pt Pd Au Ir in recent sediments - fallout from metal refining - environmental geochemistry - analyses as high as 1.8 ppm Pt.

Dahl,R, McGoran,J and Watkinson,DH
The Coldwell complex platinum-group-element deposit: 1. Geological relationships of layered gabbroic host rocks.
GAC/MAC Prog.w.Abs. 11, 61 (1986).
Ontario, Canada - 1100 Ma Coldwell complex, Proterozoic layered intrusion near Marathon - ** PGE deposit of 47 MT grading 0.02 oz/T Pt - 0.054 oz/T Pd - 0.42% Cu - PGE-rich sulphide assemblages spatially related to K-rich pegmatitic units - S-bearing metavolcanics assimilated by volatile-rich gabbroic magma? - PGE-related sulphides are rich in chalcopyrite and cubanite rather than pyrrhotite.

Davis,GC
Little Stobie Mine: a South Range contact deposit.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 361-369 (1984).
Sudbury, Ontario, Canada - Little Stobie Mine - Footwall Complex - sulphide ores - pyrrhotite, chalcopyrite, pentlandite - - pyrite and cubanite locally abundant - Sublayer - Number 1 and 2 ore bodies - ** PGE - Cu Ni Co S Pt Pd Au - norite.

DeYoung,JH, Sutphin,DM, Werner,ABT and Foose,MP
International Strategic Minerals Inventory Summary Report - Nickel.
USGS Circ. 930-D, 62pp. (1985).
Mineral economics - world distribution of Ni deposits - Sudbury, Ontario, Canada - New Caledonia - Kambalda, western Australia - reserves - production - tabulated review of many countries - notes on other commodities in the deposits, e.g. ** PGE, Au and Cr - bibliography.

Douglas,RJW (editor)
Geology and Economic Minerals of Canada.
GSC Econ.Geol.Rep. 1, 2 vols, 838pp. (1976).
Canada - review of geology and mineral deposits - a third volume is a folio of charts and maps - Muskox layered intrusion, NWT - Ni - Sudbury, Thompson - Co Cr Ti Cu Zn Pb - Au Ag and ** PGE.

Dressler,BO
Geology of the Wanapitei Lake area, District of Sudbury.
OGS Rep. 213, 131pp. (1982).
Sudbury, Ontario, Canada - Archean - Huronian and older rocks are cut by Nipissing diabase intrusives (2160 Ma), the Sudbury Nickel Irruptive (1840 Ma) and Proterozoic olivine diabase (1290 Ma) - Sudbury structure - Onaping Formation - impact origin has also been proposed for the Lake Wanapitei structure - iron formation - BIF - granites and diabases - Huronian metasediments; Mississagi, Serpent and Lorrain Formations - clastic dyke (p.26) - petrography of Nipissing gabbro, pegmatitic gabbro, granodiorite etc - PGE notes (pp.45,55,100,101) - deformation lamellae of plagioclase from the Onaping tuff (p.68) - Sudbury breccias - the Irruptive; norite, micropegmatite - photomicrographs - dolomite porphyroblasts in arkose (p.79) - Lake Wanapitei crater (pp.80-86); suevite - economic geology; Cu Fe Ni Cu etc - massive sulphide in Nipissing gabbro - Cu and Au in quartz-carbonate veins in Huronian Supergroup and in nearby Nipissing intrusives - ** PGE from the massive sulphide near Rathbun Lake; grab samples upto 0.98 oz/T Pd and 1.08 oz/T Pt - other Au and U occurrences - OGS maps 2450/2451 - age dates.

Dunning,GR
The Geology and Platinum-Group Mineralization of the Roby Zone, Lac des Iles complex, Northwestern Ontario.
MSc thesis, Carleton University, 129pp. (1979).
Lac des Iles mafic-ultramafic complex, Ontario, Canada - three intrusions recognized, from earliest to latest; western gabbro, eastern gabbro, and the ultramafic body - cumulates - layered intrusions - 2-pyroxene geothermometer - other mafic bodies nearby; Legris Lake, Shelby Lake, Wakinoo Lake, Demars Lake - Lac des Iles gabbro, clinopyroxenite, websterite, peridotite, anorthosite and norite - geophysics - ground magnetic survey of eastern gabbro - Cu Ni Fe ** PGE mineralization in the Roby Zone - petrography - shear zones in western gabbro - pyrite, magnetite, chalcopyrite, pentlandite, pyrrhotite, millerite, violarite, vysotskite, sphalerite and galena - EPM data - PGM - braggite, kotulskite, vysotskite, merenskyite, a Ag Pd Te phase, stibiopalladinite.

Dunning,GR, Watkinson,DH and Mainwaring,PR
Correlation of platinum group elements, copper and nickel with lithology in the Lac des Iles complex, Canada.
Proc. Internatl. Symp. on Metall. of Layered Mafic-Ultramafic Intrusions, Internatl.Geol.Correl.Prog.Proj. 109, 83-102 (1981).
Ontario, Canada - ** PGE Cu Ni in Lac des Iles intrusion - Archean complex containing at least 3 variably altered and metmorphosed layered intrusions - the earliest and most westerly contains PGE and disseminated Cu Ni sulphides - cumulates - 12 PGM identified - minimum reserves for deposit are 7 MT averaging 6.85 g/T combined PGE plus Au - totally altered gabbro and clinopyroxenite have the highest PGE contents - evidence for magmatic precious metals and

subsequent redistribution - vysotskite, braggite, kotulskite; the most abundant PGM - deuteric-hydrothermal processes - deformation.

Evans,AM
An Introduction to Ore Geology.
Elsevier, 231pp. (1980).
Textbook - numerous examples, maps and sketches of deposits - ore forming processes reviewed - geothermometry, geobarometry - paragenesis - zoned deposits (Variscan - Cornwall, England, UK - Missouri, USA) - sulphides - metallogeny - classification of ore deposits - Cr - ** PGE - chromite - Bushveld, S.Africa - the Cu Ni Fe sulphide deposits; Kambalda and the Yilgarn Block, Australia - Sudbury, Ontario, Canada - carbonatites - Palabora.

Fenwick,KG and Scott,JF
1975 report of the North Central Regional Geologist.
ODM Misc.Pap. 64, 39-54 (1976).
Ontario, Canada - U - barite - industrial minerals - base metals - Lac Des Iles Cu Ni Pd Pt deposit; substantial sections with ** PGE grades of >0.10 to >0.20 oz/ton - bibliography.

Fenwick,KG and Scott,JF
1976 report of the North Central Regional Geologist.
OGS Misc.Pap. 71, 38-56 (1978).
Ontario, Canada - industrial minerals - amethyst mining - the Prairie Lake carbonatite complex; U and Nb - Pd predominates Pt at Lac des Iles ** PGE deposit (p.44) - bibliography - chromite deposit near Obonga Lake - Cr - Gordon Lake serpentinite N. of Kenora is also anomalously Cr-rich.

Fenwick,KG, Larsen,CR, Scott,JF, Mason,MK and Schnieders,B
1979 report of North Central Regional Geologist.
OGS Misc.Pap. 91, 38-61 (1980).
Ontario, Canada - Coldwell complex contains deposit of >30 MT grading 0.45-0.50% total Cu with significant Pt and Pd values - ** PGE - Au prospecting in Atikokan area.

Finn,GC, Edgar,AD and Rowell,WF
Petrology, geochemistry, and economic potential of the Nipissing Diabase.
OGS Misc.Pap. 103, 43-58 (1982).
The Wanapitei intrusion is a Nipissing-type diabase N.E. of Sudbury, Ontario, Canada - mostly gabbronorite with minor felsic phases in its upper regions - EPM reveals inverse cryptic layering, with increasing Mg/(Mg+Fe) in pyroxene and increasing An content in plagioclase with height - distinct breaks in differentiation trends indicate at least four cycles in the intrusion - the Mg Ca Ni Cr Cu contents rise upwards - layered intrusion - slight Au Pt Pd enrichment found within gabbronorite and 'poorly defined shear zones of altered gabbronorite within the intrusion' - the enrichments are in sulphide-bearing samples, for which maximum values were 2.1 ppm Au, >10 ppm Pt, >10 ppm Pd and 7 ppm Ag - PGE.

Fleischer,M, Pabst,A, Mandarino,JA, Chao,GY and Cabri,LJ
New Mineral Names.
Amer.Mineral. 61, 174-186 (1976).
Discussions of 54 reported new occurrences and/or supposed new species of PGM - 31 from China, 15 from Talnakh, USSR - all six

PGE reported from 2 PGM in New Guinea - native Ru from Japan - sudburyite from Sudbury, Ontario, Canada - 3 more PGM from S.Africa and a PGM intergrowth from the Stillwater, Montana, USA.

Fortescue,JAC and Webb,JR
An orientation geochemical study at the Lac des Iles complex, district of Thunder Bay.
OGS Misc.Pap. 132, 217-219 (1986).
Lac des Iles layered intrusion, Ontario, Canada - geochemical exploration - humus - geobotanical exploration for ** PGE - maps - program initiated to analyse Pd and Pt contents of humus.

Fyfe,WS, Kronberg,BI, Long,DF, Murray,F, Powell,M, Try,C, van der Flier,E, Winder,CG and Brown,JR
Stratigraphy and geochemistry of northern Ontario carbonaceous deposits: Onakawana lignites.
OGS Misc.Pap. 113, 63-81 (1983).
Ontario Canada - lower Cretaceous Mattagami Formation - coal:lignite - trace element analysis by SSMS - elements which may be concentrated in lignite include V Sr Ba Zr (U Th) - ESCA - the lignites formed in a weathering environment with predominant kaolin-gibbsite - some concentration in Au Pd Pt was noted on NAA of some samples - PGE.

Fyfe,WS, Kronberg,BI, Murray,FH, Van der Flier,E, Winder,GC and Long,DGF
Geochemistry of Northern Ontario lignites.
Abs. OGS Geoscience Research Seminar and Open House '84, 10 (1984).
Ontario Canada - trace element analysis of some 60 elements in coals and related sediments in N.Ontario - U Th B Zr Mo Sn Ge Ga and some REE are depleted by as much as a factor of 10 relative to crustal mean - REE - strongly depleted elements include Cr Mn Rb F - Au in the analysed rocks is in the range 1-96 ppb - Pt values are 5-100 ppb - Pd is present at 5-250 ppb - Ir values are 0.1-0.2 ppb - 50 samples analysed - 'the range of values does suggest that Au-Pd-Pt are mobile in this environment' - PGE.

Fyon,JA and Crocket,JH
Exploration potential for base and precious metal mineralization in part of Strathy Township, Temagami area.
OGS OFR 5591, 46pp. (1986).
Ontario, Canada - two volcano-sedimentary terrains, the Older and Younger Volcanic Complexes are structurally juxtaposed in the Temagami area - the Younger is divided into lower and upper tholeiitic basalt cycles with an intervening calc-alkaline cycle (incl. felsic pyroclastics) and some clastic sediments - oxide facies BIF occurs at top of both Older and Younger complexes - felsic pyroclastics in Younger complex may have good potential for massive sulphide mineralization - REE - volcanic stratigraphy - maps - structural geology - an ultramafic 'fragmental' occurs in the West Pit of the Sherman Fe Mine - ultramafic rock fragments in calcite matrix (p.5) - pillow lava, conglomerate, turbidite sediments - felsic volcanic vents - layered mafic intrusion (pp.16-17,30) is zoned from marginal diorite through pyroxenite and gabbro to anorthositic gabbro - zoned intrusion - ** PGE potential, and some PGE recovery from area in past - shear zones in intrusion have quartz veins with sulphides - greenschist to amphibolite grade metamorphism - hydrothermal alteration - silicification and Fe carbonate - types of showings include chloritized shear zones with arsenopyrite - pyrrhotite - pyrite

and Au potential.

Geul,JJC
Geology of Devon and Pardee townships and the Stuart location.
ODM Geol.Rep. 87, 52pp. (1970).
Ontario, Canada - incl. OGS map 2207 - area about 40 miles S.W. of Thunder Bay - Proterozoic sediments; Animikie age - turbidites - greywacke - cut by Keeweenawan age mafic intrusions, including sills, dykes and 'a crosscutting trough-shaped body of olivine leucogabbro, called the Crystal Lake Gabbro', the latter of age comparable to the Duluth intrusion - Cu Ni Fe deposits - Crystal Lake Gabbro - troctolite - chromite - Great Lakes Nickel Corp. deposit with Cu and Ni plus 'low values' in Pt Pd Au - suggested magmatic origin by sulphide liquid immiscibility - PGE - use of 'syngenetic' to refer to primary magmatic ore, and 'epigenetic' to refer to 'pyritic calcite-filled breccia and shear zones' - possible 'epigenetic silver mineralization' postulated at 'the intersection of black carbonaceous shales...with diabase dikes and sheets' - Ag - sulphide ores.

Green,AH
Evolution of Fe-Ni sulfide ores associated with Archean ultramafic komatiites, Langmuir township, Ontario.
PhD thesis, University of Toronto, 355pp. (1978).
Timmins area, Ontario, Canada - Archean Abitibi greenstone belt - Ni sulphide deposits associated with ultramafic komatiites - magmatic origin supported - local geology - stratigraphy - Langmuir deposit lies on S.E. flank of Shaw Dome - deposit geology - petrography, ore textures, photomicrographs - BIF - whole-rock analyses - komatiite chemistry - trace elements - igneous rock classification - deformation in area concentrated along shear zones (pp.77-78) - wallrock alteration - chlorite, serpentine, talc, carbonate - metamorphic grade (pp.86-89) - spinifex textures - ore controls - ore mineralogy (3 gradational assemblages) - pyrrhotite - pentlandite - pyrite - chalcopyrite - chromite - magnetite - millerite - Cu Ni Co S analyses - ** PGE - data for Se Zn Pb As - arsenic - Os Ir Ru Rh Pt Pd Au - sulphide chemistry - S/Se ratios - S isotopes - reviews of komatiites and associated sulphide deposits - comparison with Australian deposits - Kambalda etc - and deposits from Zimbabwe, Africa - INAA and EPM.

Green,AH and Naldrett,AJ
The Langmuir volcanic peridotite-associated nickel deposits: Canadian equivalents of the Western Australian occurrences.
Econ.Geol. 76, 1503-1523 (1981).
Ultramafic-hosted Ni deposits in the Archean Abitibi greenstone belt, Ontario, Canada - host rocks are Mg rich volcanic and subvolcanic ultramafics with spinifex-textured tops - at least one deposit (Dumont) is in a dunitic intrusion, and others (Dundonald) are partially hosted in sulphidic iron formations - Langmuir 1 and 2 deposits described in detail; magmatic origin supported by 'regular sequence through the basal ultramafic flow of massive ore overlain by net-textured ore, then by barren peridotite, and, lastly, by a spinifex-textured cap..' - ratios of S to Se and S isotope data may indicate assimilation of sulphide-rich cherty iron formation - BIF - other modifications of magmatic character include shearing, brecciation and greenschist facies metamorphism - similarity to Windarra deposits of W.Australia - analytical data - Fe Ni S -

S Se - PGE - Os Ir Ru Rh Pt Pd - Au - PGE patterns similar to Kambalda and Mount Edward in Australia.

Gronlie,A
Platinum-group minerals in the Lillefjell Klumpen nickel-copper deposit, Norway.
Terra Cognita 6 no.3, 560 (1986).
Norway - Lillefjellklumpen Ni Cu deposit - Grong district, 5 km N. of the Skorovas Mine, 200 km N.E. of Trondheim - Caledonides - gabbro - massive sulphide ore - 5.8 ppm ** PGE, 4.9 ppm being Pt and Pd - Pt/Pd ratio is 0.6 - normalized Au and PGE pattern is similar to the Kanichee intrusion (Temagami, Ontario, Canada) - although the Norwegian deposit has lower absolute PGE values.

Guilbert,JM and Park,CF
The Geology of Ore Deposits.
W.H. Freeman and Co., 4th edition, 985pp. (1986).
Major textbook on economic geology - note on mineral economics - deposit classifications - chromitites and ** PGE deposits in layered intrusions - Bushveld complex, S.Africa - Sudbury, Ontario - anorthosites - Ti - diamonds and kimberlites - carbonatites - Palabora Cu P Fe deposit - Cu Ni sulphide deposits - ophiolites - many other examples of many deposit types - bibliographies.

Guindon,DL and Nichol,I
Speciation of free gold in glacial overburden.
OGS OFR 5444, 15pp plus figures and tables (1983).
Compilation of analytical data on native gold - besides Au and Ag some 529 EPM analyses revealed detectable amounts of only 5 other elements; Cu Hg Pb Pd Fe - ** PGE - samples from mines and prospects in Ontario (and Quebec), Canada - most samples from the Timmins, Kirkland Lake, Larder Lake, Matachewan and Matheson areas - literature review of trace elements in Au - no As or Zn detected, although up to 10 wt.% arsenic is present in native Ag of the Ross Mine - microinclusions may account for some of the values, particularly when values exceed the maxima found for the majority of the samples (0.17% Cu, 0.7% Hg, 0.1% Pb, 0.07% Pd, 0.1% Fe) - analyses with >0.2% Cu or >0.1% of Pb, Pd or Fe are suspect in this regard - some Hg-rich analyses (mostly from the Kirkland Lake area) may reflect inclusions of coloradoite - Au in ultramafics has the highest Hg and Cu contents overall, but relatively lower Pb - analyses and fineness quoted for a number of sites and mines, including Kerr Addison, Ross etc.

Hak,J, Watkinson,DH and Jonasson,IR
New microprobe data on platinum-group minerals and their relationships to metamorphism and deformation of host Ni-Cu sulfide deposits.
Abs. Fourth Int. Platinum Symposium, Can.Mineral. 23, 304-305 (1985).
EPM of ** PGE, Au and Ag minerals from 12 Ni Cu deposits in Canada - Ontario, Manitoba and Quebec - 'in strongly metamorphosed and oxide-rich deposits, the PGM, often with Ag minerals, occupy pressure shadows of magnetite' - Pt Pd As Co - sperrylite - arsenic - petrography - microstructural geology.

Hawley,JE
Lead and zinc deposits, Dorion and McTavish townships, Thunder Bay district.
ODM Ann.Rep. 38 Pt.6, 59-85 (1929).

Area E. of Nipigon Station, about 30 miles N.E. of Thunder Bay, Ontario, Canada - Archean and Proterozoic geology - granite, granite gneiss and metasediments, late diabase sills - Pb and Zn deposits - mine descriptions include the Dorion and Ogema Mines - the Wright shaft (p.79) was reported to contain Au and Pt 'but it is questionable whether the latter was found' - ** PGE.

Hawley,JE
The Sudbury Ores: their mineralogy and origin.
Can.Mineral. 7, 1-207 (1962).
Sudbury, Ontario, Canada - descriptions of over 60 minerals - ores found to be magmatic, derived from the magma of the 'Nickel Irruptive' - liquid immiscibility and sulphide segregation - some post-magmatic effects, e.g. 'late-stage pseudo-eutectic intergrowths of arsenides and sulphides' (seen as quantitatively unimportant) - PGE minerals - Pt Pd As Bi - sperrylite, michenerite, froodite - ore petrography - analyses of pyrite, pentlandite etc - minerals of Cu Fe Ni S Co Ag etc - 96 photomicrographs - also granites (Creighton,Murray) and breccias (pp.8-17) - Au Ag and PGE (pp.122-128, 179-181) - some breccia zones are linear, others are branching and ramifying - the matrices may be enriched relative to the hostrocks in Na or in K - and in V Cr Mn Co Ni Mo Pb and free carbon (upto 0.57%) - H2O levels are however low, perhaps due to later metamorphism by the intrusives - the PGE recoveries (most-least) are in order Pt Pd Ru Rh Ir - Os has been detected but not recovered (volatile oxide loss) - byproduct Au and Ag are recovered in a 1:31 ratio - Ag content of sulphides - there is a 'late' ore assemblage of Cu Ni As Bi Te Pb and precious metals - arsenic - native Ag and electrum seem to be the latest minerals - the ore paragenesis also includes heazlewoodite, native Bi, parkerite, hessite and maucherite - arsenic - pyrite - pyrrhotite, pentlandite, chalcopyrite, cubanite and pyrite - also ilmenite, magnetite, gersdorffite, niccolite and maucherite - Ni Cu Fe S As - arsenic - heazlewoodite (?), bornite, valleriite, stannite, violarite, sphalerite, millerite - ** PGE minerals such as sperrylite, michenerite, froodite - Pt Pd Bi - native Au and Ag - hessite - galena, native Bi - quartz, carbonates, biotite, amphibole - Se - Pt Pd Rh - Sb Te - petrography - ore textures.

Hawley,JE and Rimsaite,Y
Platinum metals in some Canadian uranium and sulphide ores.
Amer.Mineral. 38, 463-475 (1953).
Lead button fire assay / spectrographic analysis of ** PGE - Canada and Insizwa, ** S.Africa - Pd Pt Rh Ru Ir Os - large samples - Athabasca, Saskatchewan U ore; one unusual sample with high Pd Pt - also analysed; Ni sulphide ore from Sudbury, Ontario - Rankin Inlet, NWT - Duluth gabbro, Minnesota, USA - Lynn Lake, Manitoba - with few exceptions these samples had 1 ppm Pd, often much more - pyrrhotite, chalcopyrite - Cu and Au ores from Quebec, Ontario and Manitoba, and arsenides from native Cu deposits of Michigan - Pd Pt Rh in samples from Noranda, Powell-Rouyn, Flin Flon, Bruce Mines, Hollinger (Timmins) etc - PGE generally detectable in chalcopyrite in the small non-nickeliferous deposits on the N. shore of Lake Huron - Phanerozoic sulphide from Eastern Townships and Buchans, Newfoundland - PGE commonly detectable in bulk samples at low levels, e.g. 30 ppb Rh and 6 ppb Pd in Hollinger pyrrhotite - 'all nickeliferous ores tested indicate the presence of platinoids'.

Hawley,JE, Lewis,CL and Wark,WJ
Spectrographic study of platinum and palladium in common sulphides and arsenides of the Sudbury district, Ontario.
Econ.Geol. 46, 149-162 (1951).
Sudbury, Ontario, Canada - ** PGE - Pt and Pd in sulphides - pyrite, pyrrhotite, pentlandite, chalcopyrite - and in niccolite, gersdorffite and maucherite - occurrence of Be in arsenides - - beryllium, arsenic - probable early inclusions of PGM such as sperrylite in sulphides.

Hodgkinson,JM
Geology of the Kashabowie area.
ODM Geol.Rep. 53, 35pp. (1968).
Ontario, Canada - plus OGS maps 2127/2128 - area about 60 miles W. of Lakehead in the Thunder Bay district - Precambrian geology; Archean and Proterozoic - Shebandowan Lake area - acid metavolcanics; agglomerate, tuff - rhyolite - basic metavolcanics - pillow lavas - boudinage in metasediments (photo on p.10) - granites and syenites - various Cu Ni Au showings - some Ni Cu sites have associated Co and Pt (pp.25-27) ** PGE.

Hodgson,CJ
Precambrian Lode Gold Deposits.
Cordilleran Section of GAC, Short Course No.6, 70pp. (1985).
Review of Precambrian Au deposits - Au reserves as a function of age dates (p.4) - Archean greenstone belts - classification of deposits - structural geology - shear zones - Quebec, Ontario and NWT, Canada - Australia - saddle reefs - production from Canadian Au mines - hydrothermal alteration - data on Au and ** PGE (p.46) - genetic models - bibliography.

Hoffman,EL
The Platinum Group Element and Gold Content of some Nickel Sulphide Ores.
PhD Thesis, University of Toronto, 177pp. (1978).
Geochemical analysis - INAA and Ni sulphide fire assay method for ** PGE - samples from Sudbury, Ontario, Canada, and from the Manitoba Nickel Belt - Pt Pd Ru Rh Ir Os Au - Cu -rich stringers in the Levack breccia are enriched in Pd and Cu and depleted in Os Ir Ru Rh Ni relative to the granite breccia ores of the Main Ore Zone at Sudbury - Levack West Mine, North Range - at the South Range, the ores of the No.2 orebody of the Little Stobie Mine are enriched in Rh Ru Pd Ir Os relative to the No.1 orebody; this is attributed to two separate pulses of Sublayer sulphide material - at the Pipe 2 Mine in Manitoba hydrothermal activity may account for some high Ir Rh Pt Pd Ni As values in some vein and shear zone samples - arsenic - PGE and sulphide liquid immiscibility - preparation of fire assay beads - INAA procedure.

Hoffman,EL, Naldrett,AJ, Alcock,RA and Hancock,RGV
The noble-metal content of ore in the Levack West and Little Stobie mines, Ontario.
Can.Mineral. 17, 437-451 (1979).
INAA - fire assay - PGE - Rh - Ru - Pd - Pt - Ir - Os - Au - ores of Sudbury area - association of Rh Ru Ir Os with Ni mineralization - and (lesser) affinity of Pd Pt Au for Cu ore - Ontario, Canada - Levack West mine in the North Range - Little Stobie mine in the

South Range - at Levack West norite of the Main Sudbury Irruptive overlies the footwall, which consists of brecciated granodiorite, gneiss and migmatite - 2 ore zones: the main ore zone is a mineralized granite breccia in an embayment of the footwall - it grades into the footwall ore zone, fracture fillings in Levack breccia.

Hudson,DR, Robinson,BW, Vigers,RBW and Travis,GA
Zoned michenerite-testibiopalladite from Kambalda, Western Australia.
Can.Mineral. 16, 121-126 (1978).
Kambalda, Australia - Ni - Pt - PGE - EPM - Sudbury, Ontario, Canada - USSR - where Ni sulphide mineralization is cut by Au Te quartz carbonate veins at Kambalda odd Pb Bi Ag Pd tellurides occur (altaite,rucklidgeite..) - higher Bi % toward margins of zoned grains: hydrothermal growth / exsolution? - zoned crystals.

Hutchison,CS
Economic Deposits and Their Tectonic Setting.
Macmillan Press Ltd, 365pp. (1983).
Textbook on mineral deposits - mineralization and plate tectonics - comparison of oceanic and continental crust (p.11) - ophiolites - chromitites - Cr - Zambales ophiolite, Philippines - Cyprus - Kupferschiefer - Zechstein - black shales - Hg deposits (Almaden, and Idria in Yugoslavia, and New Almaden, California, USA) - layered intrusions - Sudbury, Ontario - Bushveld, S.Africa - Ni Cu Cr ** PGE - Great Dyke, Zimbabwe, Africa - alkaline igneous rocks - carbonatites - Nb etc.

Innes,DG and Colvine,AC
The regional metallogenetic setting of Sudbury.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 45-56 (1984).
Sudbury, Ontario, Canada - review of local geology - Ni Cu ** PGE deposits - Huronian sediments - Nipissing diabase - Archean and Proterozoic geology - metallogenetic provinces.

Innes,DG and Debicki,RL
1975 report of the Sudbury resident geologist.
ODM Misc.Pap. 64, 101-116 (1976).
Ontario, Canada - locations of many mines in Sudbury area - Cu Ni ** PGE and other products mined - bibliography - notes on assessment work.

Irvine,TN
Western Lac des Mille Lacs area.
ODM Geol.Rep. 12, 24pp. (1963).
Area W.N.W. of Kashabowie, N.W.Ontario, Canada - incl. OGS map 2022 - aeromagnetic map - Archean and Proterozoic stratigraphy - Couchiching (?) paragneiss forms the putative base of the succession - porphyritic basalt with saussuritized plagioclase phenocrysts - mafic intrusives; peridotite, hornblendite, diorite - granitic rocks - Keweenawan diabase dykes - Ni Cu sulphide showings in the mafic intrusives sometimes return Pt and Pd values (p.21) - ** PGE.

James,RS
New data on the geology of the ore zone, Kanichee intrusion, Temagami, Ontario.

GAC/MAC Prog.w.Abs. 11, 85 (1986).
Layered intrusions - Kanichee intrusion, Temagami, Ontario, Canada - mineralized dunite/peridotite - zoned intrusion - Ni Cu ** PGE mineralization - border phase indicates high Mg basalt parent of possible komatiitic affinity - skeletal clinopyroxene crystals.

James,RS and Hawke,D
Geology and petrogenesis of the Kanichee layered complex, Ontario.
Can.Mineral. 22, 93-109 (1984).
Temagami greenstone belt, Ontario, Canada - the Kanichee layered intrusive contains 5 cycles of cumulates - an ultramafic apophysis contains sulphide ore - the host peridotite has been altered to serpentine, talc,chlorite - igneous hornblende amphibole is a common accessory in all 5 cycles - in cycle 1 it is a cumulus phase in clinopyroxenite - sulphides also occur throughout, but are most common at the base, in cycle 1, the ore zone - Ni Cu PGE ore - carbonate-quartz veins with pockets,lenses and bands of sulphide are largely restricted to altered peridotite - chalcopyrite is the main ore in the veins, whereas pyrrhotite normally dominates the disseminated sulphides - the Ni Cu Au and PGE were remobilised by hydrothermal processes and deposited in the veins in cycle 1 - Pt etc.

Jonasson,IR, Eckstrand,OR and Watkinson,DH
Preliminary investigations of the abundance of playinum, palladium and gold in some samples of Canadian copper-nickel ores.
GSC Pap. 87-1A, 946pp. in 2 vols., 835-846 (1987).
** PGE and Au abundances in samples from many mines and occurrences - a total of some 50 occurrences, with 24 elements tabulated - Pt Pd Au were determined by an AAS method - ultramafic-hosted Ni Cu deposits sampled include Renzy Mine, Quebec, Canada (Grenville deposit, best values in one sample; 210 ppb Pd and 700 ppb Au) - Kanichee Mine, Temagami, Ontario - Marbridge and Expo-Ungava Mines, Quebec - Sothman, Textmont (Fatima) and Alexo deposits near Timmins - Lakemount property, Wawa - Shebandowan, Norpax and Gordon lake mines, Ontario - sites in Manitoba and NWT, including Thompson and Moak Lake - Muskox layered intrusion - Rottenstone area, Saskatchewan - the Turnagain property and the Giant Mascot Mine in BC - data also provided on heavy mineral concentrates of these sites and on samples from mafic-hosted Ni Cu deposits, such as the Goodwin Lake gabbro, New Brunswick - sites in Ungava - Macassa property in Limerick township, Ontario - Calumet Island - Nimitz prospect in Best township - Dumont nickel - Great Lakes Nickel - Sudbury mines - the Mortimer, Strickland, Emo and Kenbridge properties in Ontario - Lynn Lake, Manitoba - Rivett Lake, NWT - Wellgreen Mine in the Yukon - and for the E and L property, Nickel Mountain, BC.

Keays,RR
Palladium and iridium in komatiites and associated rocks: application to petrogenetic problems.
In 'Komatiites' (Arndt,NT and Nisbet,EG editors), George Allen and Unwin, 435-457 (1982).
W.Australia - Munro township, Ontario, Canada - spinifex-textured komatiites have uniform Pd (9.2 ppb) and Ir (1.47 ppb) contents, and their contents of Pt Ru Os are estimated at 8.2, 5.5, 2.7 ppb respectively - sulphide-poor dunitic komatiites (MgO>40%) have higher Ir (7.08+/-0.86 ppb) and lower, variable Pd (2.2+/-1.9 ppb) - 'spinifex-textured komatiites have the lowest and most primitive Pd:Ir ratios' (about

6.3) 'of any magma type' - mantle derivation - magma evolution - S in magmas - significance of Ir contents of olivines as a guide to the intratelluric (phenocryst) vs. in-situ crystallization origin of the crystals - PGE.

Keays,RR
Archaean gold deposits are their source rocks: the upper mantle connection.
In 'Gold '82: the Geology, Geochemistry and Genesis of Gold Deposits' (Foster,RP editor), A.A. Balkema, Rotterdam, 19-51 (1984).
Archean greenstone belts - 'the only Au which is of economic importance is readily accessible Au that is associated with highly reactive sulphides' - PGE Au Ni Cu are significantly retained by high-Mg lavas because of their high temperature of generation (c.1600C c.f. the usual c.1200C) - such magmas (komatiite, picrite, high-Mg basalt) only become S-saturated just before eruption, hence the metals are not lost in liquid immiscible sulphide droplets which remain at depth - high Au contents of sulphidic Au-associated interflow sediments may be due to seawater exchange with such melts and their volcanic products - major Au deposits are associated with rift systems allowing surfacing of 'high temperature, S-undersaturated (and therefore precious metal-enriched) high-magnesium melts' - picrites from Disko Island, W. Greenland and from Gorgona Island, Colombia, S.America - komatiites from Ontario, Canada, ** S.Africa, Zimbabwe and Australia.

Keays,RR and Crocket,JH
A study of precious metals in the Sudbury nickel irruptive ores.
Econ.Geol. 65, 438-450 (1970).
Sudbury, Ontario, Canada - NAA of Ru Pd Os Ir Au - Cu Ni sulphide ores of the Strathcona Mine and elsewhere - analyses mostly of separates of pyrrhotite and chalcopyrite - Pd and Au average 962 and 39 ppb respectively in the footwall chalcopyrite at Strathcona; PGE enriched in footwall and in deep ore zone - in contrast Ru Os Ir reach maximum values (76,25,57 ppb) in pyrrhotite of the hanging wall breccia ores - mine section - PGE distribution suggestive of fractionation between pyrrhotite solid solution and a sulphide melt - Ir Ru Os as sulphides in melt? - in contrast, Pd probably occurs as discrete inclusions within chalcopyrite, not in solid solution - Falconbridge, Frood and Creighton mines.

Kerrich,R
Archean gold-bearing chemical sedimentary rocks and veins: a synthesis of stable isotope and chemical relations.
OGS Misc.Pap. 97, 144-167 (1981).
Quebec,Ontario and NWT Canada - Archean greenstone belts - hot reducing fluids may be critical to other metals enriched in Au veins, such as Cr Ni W Pd Pt - ** PGE - relative enrichment of rather immobile elements over base metals may be due to relatively low water/rock ratios in metamorphism.

Kerrich,R, Hutchinson,RW and Hodder,RW
Field relations and geochemistry of Au,Ni, and Cr deposits in ultramafic-mafic volcanic rocks.
OGS Misc.Pap. 87, 84-94 (1979).
Ontario Canada - Au Ni Cr deposits in Archean greenstone belts - analyses of Au Ag Pd contents of Timmins area rocks - 'no primary rock type is intrinsically favourable for gold' - carbonate (ankerite) layers

are all low in Cr and Ni, so they are 'unlikely to represent carbonatized ultramafic flows' - banded quartz-tourmaline and quartz-fuchsite mica veins were also examined - dravite and Cr mica - fuchsite has 2370-8460 ppm Cr and 160-2500 ppm Ni - in contrast to the low Ni and Cr in the stratiform carbonate levels are much higher in the 'highly altered' (H/A zone) rocks at Dome - O isotopes - PGE.

Kimberley,MM
Origin of stratiform uranium deposits in sandstone, conglomerate, and pyroclastic rock.
In 'Uranium Deposits, their Mineralogy and Origin' (Kimberley,MM, editor). MAC Short Course Handbook 3, 523pp., 339-381 (1978).
Sedimentary, stratiform U deposits - review of deposits - Witwatersrand, ** S.Africa - Elliot Lake, Ontario, Canada - Serra de Jacobina, Brazil, S.America - Mount Eclipse, Australia - deposits in Italy and Austria - U-bearing Quaternary volcanics, Italy - U Th - silicification - pyrite-marcasite lenses - Permian mineralization in Austro-Italian Alps - Niger, Africa - Colorado Plateau, USA - Utah, Arizona, New Mexico - comparison of Witwatersrand and Elliot Lake - pyrite, uraninite, gold, hydrocarbons - Au - C - mid-Precambrian ores - thucholite, zircon, chromite - REE - ** PGE - PGM occur in Wits. in commercial amounts, but not at Elliot Lake - Ce in Elliot Lake uraninite - bibliographies.

Knopf,A
A gold-platinum-palladium lode in southern Nevada.
USGS Bull 620-A, 18pp (1915).
Boss Mine, Yellow Pine mining district, Clark County, Nevada, USA - mining Au ore locally remarkably rich in Pt and Pd - map with list of 30 local mines - deposit originally located for Cu - chrysocolla and other oxidized Cu minerals - two samples showing many oz/T of the metals; sample 2 assayed 99.08 oz Pt, 111.0 oz Au and 16.0 oz Pd - local rocks are stratified dolomites of mid-Carboniferous age, folded and faulted - main ore deposits in area are carbonate-hosted Pb Zn - some Au deposits in area; Keystone Mine the largest - close association of Au with quartz monzonite porphyry dykes - at the Boss Mine the country rock is black, fetid Carboniferous dolomite - a small quartz porphyry body is visible 600 feet N. of the mine - the ore bodies are 1)oxidized Cu shoots, and 2)Au Pd Pt shoots - these are fine-grained siliceous ores with minor Bi plumbojarosite - no fixed metal ratios; overall Pt>Pd? (p.5) - analysed Au has 2.2% Ag - only known sulphide; chalcocite - hydrothermally replaced deposit, now highly oxidized - supergene concentration of noble metals is suspected - Cu Fe Pb Bi and precious metals - comparison with other deposits in Wyoming, USA / Ontario, Canada, etc - ** PGE.

Lightfoot,PC, Conrod,D, Naldrett,AJ and Evensen,NM
Petrologic, chemical, isotopic, and economic potential studies of the Nipissing diabase.
OGS Misc.Pap. 130, 87-106 (1986).
Nipissing diabase - rocks from Cobalt to Sault Ste. Marie, Ontario, Canada - tholeiitic rocks and more felsic differentiates - rift-related suite with potential for Ni Cu Co ** PGE mineralization - maps - petrography - 2 photomicrographs - sill-like intrusions - Cross Lake sill - Bonanza Lake - Basswood Lake - Bruce Mines - quartz diabase - gabbronorite - pyroxenes - hypersthene,

inverted pigeonite - granodiorite - EPM - compositions of plagioclase, olivine and orthopyroxene - trace elements - Zr Y Sr Rbb Nb - REE - REE patterns - trace element data normalized to MORB averages - fractional crystallization superposed on earlier mixing/contamination processes.

Linhart,E and Sutcliffe,RH
Petrological and economic geological studies on the northern Lac des Iles complex, district of Thunder Bay.
OGS Misc.Pap. 132, 80-81 (1986).
Lac des Iles layered intrusion, Thunder Bay district, Ontario, Canada - ultramafic rocks - dunite, wehrlite, websterite and clinopyroxenites - ** PGE - Au Pt Pd sample analyses - clinopyroxenite underlies almost 70% of the mapped 2.5 x 5 km area in the northern ultramafic centre of the complex - chalcopyrite is the most abundant sulphide - a new ** PGE occurrence was discovered, and a new occurrence of chromite on the large island in the N.W. part of Lac des Iles.

Macdonald,AJ
The Lac des Iles platinum group metals deposit, Thunder Bay district, Ontario.
OGS Misc.Pap. 126, 235-241 (1985).
** PGE at Lac des Iles, layered intrusion, Ontario, Canada - Pd Pt Cu Ni Au deposit - PGE mineral economics - maps - geology of gabbro complex - exploration geophysics; aeromagnetic data - gabbro megabreccia - cumulates - varitextured gabbro - 'alteration intensity, particularly of pyroxene, by uralitization increases in zones of mineralization'.

Mackasey,WO
Geology of Dorothea, Sandra, and Irwin Townships, District of Thunder Bay.
ODM Geol.Rep. 122, 83pp. (1975).
E. shore of Lake Nipigon, Ontario, Canada - Archean and Proterozoic geology - metavolcanics - tuff breccia - pillow lava - pyroclastics, some with flame structures due to shearing - metasediments - conglomerate and iron formation - BIF - serpentinized peridotite - porphyritic diabase ('greenspar') - faults - carbonate zones, some with Au - reports of Cu Mo ** PGE - Pd but no Pt - some high grade grab samples - Au in pyrite (pp.67-70) - OGS map 2294 - pyrite.

Martins,JM
Report of activities 1983, Sudbury resident geologist area, northeastern region.
OGS Misc.Pap. 117, 191-201 (1984).
Sudbury,Ontario, Canada - map (p.194) showing 16 producing mines in the Sudbury mining camp, producing Ni - Cu - Pt - Se - Te - Co - Au - Ag - Fe - PGE.

Mertie,JB
Economic geology of the platinum metals.
USGS Prof.Pap. 630, 120pp. (1969).
PGE review - worldwide survey of deposits - two bibliographies with 'foreign' and USA entries; approx. 450 and 150 references respectively - until approx. 1920 all PGE recovery was from placers - properties of Pt Ir Os Ru Rh Pd - Au and Ag - world production of PGE, 1950-1966 - PGE minerals and alloys - occurrence of PGE in Canada; most recovery from the Sudbury area,Ontario - general geology - three types of PGE deposit; total mean PGE grades in the order of 0.02

oz/ton - different metals concentrated into different hosts, e.g. Rh in pyrrhotite, the principal overall PGE carrier - Pt elsewhere in Canada (pp.25-32); Ontario, Manitoba (Thompson etc), Quebec, NWT, BC, Yukon - many other countries.

Meyer,W, Campbell,RW, Adlington,R and Toews,FH
Sudbury resident geologist area, northeastern region.
OGS Misc.Pap. 128, 256-272 (1986).
Ontario, Canada - Au study in area E. of Wanapitei Lake; Scadding Twp. - Huronian sediments and Nipissing diabase - Scadding mine - hydrothermal alteration - other subjects; Temagami magnetic anomaly - geophysics - Sudbury-Espanola area precious metal study - ** PGE occurrence in Curtin Twp. lies within sill-like Nipissing diabase body (pp.260-261) - Groundstar Mine - Golden Rose and McMillan Au mines.

Milne,VG
Geology of the Kukatush - Sewell Lake area, district of Sudbury.
ODM Geol.Rep. 97, 116pp. (1972).
Ontario, Canada - incl. OGS maps 2230 and 2231 of Reeves and Sewell, Penhorwood and Kenogaming townships - also colour charts of Reeves Mine, Dunvegan Mines Ltd site, and Radio Hill Fe deposit - area some 40 miles S.W. of Timmins - Archean local geology - younger diabase dykes - stratigraphy - field geology - stretched agglomerate - tuffs - metasediments - metavolcanics - BIF - structures in BIF - chert - mafic and ultramafic intrusives - serpentinite - ribbon asbestos - carbonatization - olivine, tremolite, antigorite - hydrothermal alteration - petrography - photomicrographs - porphyry ad other granitic rocks - cleavage and kink bands - faults - Reeves asbestos deposit - prospects - Ni showings - Au prospects - pyritic shear zones - one grab sample with 2.5% Ni and 0.01 oz/ton Pt (p.81) - ** PGE.

Mohide,TP
Platinum Group Metals - Ontario and the World.
Ontario Mineral Policy Background Paper 7, Ontario Ministry of Natural Resources, 162pp. (1979).
PGE - supply and demand - world production; S.Africa, USSR, Ontario, Canada etc - Pt Pd Rh Ir Ru Os - uses, markets and prices - market economy.

Mohide,TP
Silver.
Ontario Mineral Policy Background Paper 20, Ontario Ministry of Natural Resources, 406pp. (1985).
Extensive review of Ag - precious metals - history of science/economics/ mining/uses of Ag - variations in Ag price - mineral economics and world markets - USA stockpile - forecasts for Au Ag Pt Cu - ** PGE - production of Ag Pb Zn Cu - history of the availability of the precious metals from 1757 to the present.

Moore,ES
Geology and ore deposits of the Atikokan area.
ODM Ann.Rep. 48 pt.2, 1-34 (1939).
Ontario, Canada - incl. OGS map 48a - topography - Archean geology; agglomerate, tuff, greenstone, bluish limestone, iron formation, breccia - Fe deposits - pyrite - Au mines - Elizabeth Mine; granite-greenstone

contact - lamprophyre - Rebair property - feldspar porphyry dykes - Harold Lake Mine etc - showings of Pb Zn Ni Pt - talc, soapstone and beryl - ** PGE - BIF.

Moorhouse,WW
Geology of the Eagle Lake area.
ODM Ann.Rep. 48 pt.4, 31pp. (1941).
Incl. OGS map 48d - Kenora, Ontario, Canada - area S.W. of Dryden - Archean - greenstone - pillow lavas - sediments, tuffs, granite - folding and (p.20) shearing - earliest reported Au deposits were in shear zones in granites near the contact with Keewatin lavas - Au also occurs in 'silicified shear zones or bodies of highly quartzose porphyries in the acid volcanics and porphyries...' (p.21) - norites near Straight Lake suggested for Pt searching - ** PGE (p.26).

Muir,JE and Comba,CDA
The Dundonald deposit: an example of volcanic-type nickel-sulfide mineralization.
Can.Mineral. 17, 351-359 (1979).
Timmins, Ontario, Canada - Abitibi greenstone belt - Archean - komatiitic peridotite flows - Ni sulphides in net-textured and disseminated mineralization in the olivine cumulate zones - growth by settling of sulphide droplets - liquid immiscibility - ore also semimassive in basal chill zones, and with colloform textures in interflow volcanic-sedimentary horizons - graphite - pentlandite - violarite - millerite - heazlewoodite - maucherite - Cu As - arsenic - ** PGE - texture photographs.

Muir,TL
Geology of the Morgan Lake - Nelson Lake area, district of Sudbury.
OGS OFR 5426, 203pp. (1983).
Sudbury, Ontario, Canada - area centred 25 km N.N.W. of Sudbury, in Morgan, Lumsden and Bowell townships - complex 'basement' - trace elements and variation diagrams - data on ** PGE - Pt Pd Au Ag - Ni Cu Co Pb Zn etc - mineral properties - sulphides - possible Nipissing diabase in area - cation plots - photomicrographs - Archean and Proterozoic geology.

Murray,F, Van der Flier,E, Fyfe,WS, Kronberg,BI, Long,DF, Try,C and Winder,CG
Stratigraphy and geochemistry of Northern Ontario carbonaceous deposits: Onakawana lignites.
OGS Misc.Pap. 121, 84-98 (1984).
Ontario, Canada - multi-element analyses of coals - lignites - environmental implications - SSMS, XRF and NAA data - S U Th - significant enrichment in Au Pt Pd in some samples - coals may have very high F concentrations; the lignites have very low F - some elements associated with refractory minerals are enriched; Ti - REE - Zr Th - some 'bio-essential elements' are often enriched; B Ga Ge - large tabulations of data - one lignite sample had 96 ppn Au - 35 ppb Pt - 250 ppb Pd - ** PGE.

Naldrett,AJ
The composition of Ni-sulphide ores with special reference to their PGE content.
OGS Misc.Pap. 87, 23-36 (1979).
PGE in Ni sulphide ores - relationship to partial melting of mantle source - a high degree of melting gives a flat PGE pattern, as in the case of

komatiite-related deposits - PGE contribute <3% to the value of komatiite deposits, 6-15% to the value of Sudbury ores studied, 35% to the value of Noril'sk ore and 85% to the value of the Merensky Reef ore - Ontario, Canada, USSR and Bushveld, S.Africa - analyses and PGE plots calculated to 100% sulphide - Pipe deposit, Manitoba - genesis of ores - PGE partitioning - Os Ir Ru Rh Pt Pd Au .

Naldrett,AJ
Nickel sulfide deposits: classification, composition, and genesis.
Econ.Geol.75th Anniv.Vol., 628-685 (1981).
Classification of Ni sulphide ores by lithology and tectonic situation - mineralization and plate tectonics - settings including those of Sudbury, Ontario, Canada - Noril'sk and Talnakh (USSR) - Duluth intrusion, USA - ores associated with rifting, and with komatiites and tholeiites of Archean greenstone belts - geochemistry of the ores; data on Fe S O Cu Ni Co PGE Zn Pb As Se - arsenic - S isotopes - sulphide mineralogy - Ru Rh Pd Pt Os Ir - liquid immiscibility - PGE patterns (pp.657-661) - major review.

Naldrett,AJ
Platinum-group element deposits.
In 'Platinum-Group Elements: Mineralogy,Geology and Recovery' (Cabri,LJ editor), CIM Spec.Vol. 23, CIM, Montreal, 197-231 (1981).
PGE deposits - classification - maps - Bushveld, S.Africa, Stillwater, Montana, USA, Lac des Iles, Ontario, Canada - these 3 are Merensky-type PGE-dominant deposits - in contrast, Ni Cu sulphide dominant deposits include Sudbury, Noril'sk (USSR), Duluth (Minnesota), the komatiite-associated Kambalda (Australia), Ungava (Quebec) etc - data is then given for PGE concentrations in sulphide ores - Os Ir Ru Pt Pd Rh and also Au - fractional crystallization, with Sudbury as an example - deposits very rich and poor in PGE.

Naldrett,AJ
Platinum Group Metals in Ontario.
OGS Open File Report 5380, 76pp. (1982).
Ontario, Canada - includes data from Barnes et al (OGS Misc.Pap. 98, 1-12 1982) and copies of Naldrett and Duke (1980) and Naldrett (Econ.Geol. Vol. 1981) - summary (pp.1-6); data on Ru Rh Pd Pt Os Ir Au etc - the (Pt+Pd)/(Ru+Ir+Os) ratio generally low (<2) in Archean komatiite-related deposits, high (>12) in gabbro-related deposits - deposits related to flood basalts have especially high values, and lighter than normal Pt Pd Au in the sulphides - analyses by fire assay/ INAA - the high value for Alexo (18) ascribed to an unusually fractionated komatiite melt, Pd and Pt entering partial mantle melts at an early stage - ratio values given for about 20 deposits, including Falconbridge (2.28), Great Lakes Nickel (56) and Lac des Iles (>1000) - deposits studied; Alexo, Dundonald, Hart, Langmuir, McWatters, Texmont (komatiite association) - Strathcona and Falconbridge (Sudbury) - Kanichee, Kenbridge, Montcalm, Norpax, Werner Lake (gabbro-related) - Great Lakes Nickel (flood basalt association) - Lac des Iles ('Merensky type') - and also Port Coldwell, Kidd Creek and Puddy Lake - PGE.

Naldrett,AJ
Mineralogy and composition of the Sudbury ores.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1,

603pp., 309-325 (1984).
Sudbury, Ontario, Canada - review of mineralogy; Fe Ni S and Cu Ni S ores - trace elements; Co Zn Pb As Sb Se Pt Au etc - S isotopes - photomicrographs - lists of minerals - phase diagrams - PGE plots - Strathcona, Levack West and Falconbridge Mines - volume includes map 2491 - GSC aeromagnetic map - PGE patterns - arsenic.

Naldrett,AJ
Summary, discussion, and synthesis.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 533-569 (1984).
Sudbury, Ontario, Canada - review of data on the Sudbury structure and associated Ni Cu ores - geology and geophysics - breccias - shock metamorphism - Onaping, Onwatin and Chelmsford Formations - meteorite impact controversy - norite - Sublayer - offset dykes - whole rock analyses - trace elements - REE - age dating - Sr isotopes - the Ni Cu ores - ** PGE - resume of the ores (pp.558-564) - liquid immiscibility.

Naldrett,AJ and Kullerud,G
A study of the Strathcona Mine and its bearing on the origin of the nickel-copper ores of the Sudbury district, Ontario.
J.Petrol. 8, 453-531 (1967).
Sudbury,Ontario, Canada - geology and petrology of the Strathcona Fe Ni Cu sulphide deposit - EPM of olivine and pyroxenes within xenoliths of dunite-gabbro composition, occurring within the 'xenolithic norite' and 'hanging-wall breccia' supports a cognate origin - the Nickel Irruptive may be a funnel-shaped intrusion with a zone of ultramafics near the base - Na metasomatism in the breccia - origin of the sulphide ores - exsolution - pyrrhotite and pentlandite - liquid immiscibility - petrography of norites, breccias and gneiss - silicate-sulphide textures; small-scale replacement of silicates by sulphides in the main zone but not the hanging wall - relevant description of PGE-bearing deposit, although not PGE-specific.

Naldrett,AJ and Macdonald,AJ
Tectonic settings of Ni-Cu sulphide ores: their importance in genesis and exploration.
In 'The Continental Crust and its Mineral Deposits' (Strangway,DW editor), GAC Spec.Pap. 20, 804pp., 633-657 (1980).
Review of magmatic Ni Cu sulphide deposits - such ore forms only when immiscible sulphides separate from silicate magma - liquid immiscibility - magma chamber processes - Sudbury, Ontario, Canada - Duluth complex, Minnesota, USA - layered intrusions - Noril'sk-Talnakh, USSR - mineralization and plate tectonics - rifting, aulacogenes, flood basalts - Water Hen intrusion - rifting in Afar Triangle - Red Sea - paper outlines tectonic setting of deposits which also contain high ** PGE values.

Naldrett,AJ, Innis,DG and Sowa,JM
Platinum group element concentrations in some magmatic ores in Ontario.
OGS Misc.Pap. 93, 171-178 (1980).
Ontario, Canada - PGE Au Ni Co Cu S data for sulphide ores - komatiite-related deposits have low values of (Pt + Pd)/(Ru + Ir + Os) and gabbro-related deposits have high values of this ratio - deposits associated with flood basalts have very high values of this ratio and

relatively high Pt Pd and Au contents in sulphides - the Strathcona orebody at Sudbury is markedly zoned from hanging wall to footwall: the Pt and Pd increase and Ru Ir Os decrease - the PGE at the Falconbridge deposit are in similar proportions to the hanging wall at Strathcona - Lac des Iles has extremely low Pt/Pd and high (Pt+Pd)/(Ru+Ir+Os) - plot of Pt/(Pt+Pd) vs. Cu/(Cu+Ni) - zoned deposits - Coldwell complex, Great Lakes Nickel, Kanichee, Lac des Iles, Alexo, McWatters, Werner Lake.

Naldrett,AJ, Rao,BV and Evensen,NM
Contamination at Sudbury and its role in Ore Formation.
In 'Metallogeny of Basic and Ultrabasic Rocks' (Gallagher,MJ, Ixer,RA, Neary,CR and Prichard,HM editors), Inst.Min.Metall., 75-92 (1986).
Sudbury, Ontario, Canada - Cu Ni ** PGE ores - local geology of Proterozoic mafic-ultramafic igneous complex - ore deposits associated only with those Sublayer intrusions which carry inclusions of a suite of ultramafic-mafic cumulates - high REE contents in rocks of the complex - genetic model involving assimilation of high proportions of Archean tonalite and quartz monzonite by continental basaltic parent magma - REE - geochemistry - Sr isotopes - 50% salic contamination for Main Mass, 25-75% for Sublayer - norite, gabbro, granophyre, magmatic sulphides.

Naldrett,AJ, Innes,DG, Sowa,J and Gorton,MP
Compositional variations within and between five Sudbury ore deposits.
Econ.Geol. 77, 1519-1534 (1982).
PGE in Ni sulphide ores - the ratio (Pt + Pd / Ru + Ir + Os) is <2.5 in komatiitic associations, >13 in basaltic associations - at Levack West and Strathcona there is strong zoning - Cu Ni Zn Pt Pd Au rise into the footwall and Co Rh Ru Ir and Os increase in the other direction - this is explicable by fractionation of sulphide melt, with the residual liquid being expelled into footwall - Falconbridge deposit resembles the Strathcona hanging wall - an early-crystallizing fraction:less Pt - Ontario, Canada - zoned deposits.

Naldrett,AJ, Hoffman,EL, Green,AH, Chou,C-L, Naldrett,SR and Alcock,RA
The composition of Ni-sulfide ores,with particular reference to their content of PGE and Au.
Can.Mineral. 17, 403-415 (1979).
Sulphide ores - Ni Pt PGE - Au - komatiites - Sudbury, Ontario - Pipe deposit in Manitoba - fractional crystallization - silicate:sulphide ratios - Noril'sk USSR - S isotopes influenced by evaporite - assimilation - partition coefficients - Cu - Jimberlana - Canada and Australia.

O'Neill,JJ and Gunning,HC
Platinum and Allied Metal Deposits of Canada.
GSC Econ.Geol.Ser. 13, 165pp. (1934).
Review of PGE geology and occurrence, both in Canada (pp.50-112) and around the world (pp.113-144) - Ru Rh Os Ir Pt Pd - PGE properties, uses and mineralogy (some 17 species are described) - deposit types - E.-W. catalogue of known PGE occurrences in Canada - Nova Scotia - Quebec - Ontario (Sudbury layered intrusion - Alexo Mine) - Manitoba - Saskatchewan - Alberta - BC (in particular, numerous placer sites - Tulameen area) - Yukon - NWT - worldwide; USSR, Australia, S.Africa, Rhodesia / Zimbabwe, USA, Colombia etc - production - bibliography.

Ontario Department of Mines

Lakehead-Shebandowan Sheet.
ODM Map P.177 (1:126,720) (1963).
Area W. from Thunder Bay, Ontario, Canada - OGS Map includes Kakabeka Falls, Dawson Road Lots, Pardee Twp. (Cu Ni Pt occurrence - ** PGE) etc - OGS Map.

Ontario Department of Mines
Lac des Iles Sheet.
ODM Map P.187 (1:126,720) (1963).
Ontario, Canada - OGS Map - Lac des Mille Lacs, Lac des Iles - includes gabbro and ultrabasic rocks of the Lac des Iles complex, now site of ** PGE exploration.

Ontario Department of Mines
Lac des Iles sheet.
ODM Map 2135 (1:31,680) (1967).
Lac des Iles, Ontario, Canada - Archean geology - Lac des Iles complex, since reassessed for ** PGE potential - diabase, granite, migmatite, anorthosite, gabbro, pyroxenite etc - BIF - metavolcanics and metasediments.

Ontario Department of Mines
Big Trout Lake - North Caribou Lake.
ODM Map 2292 (1:253,440) (1974).
OGS Map - Ontario, Canada - Archean basement with Proterozoic diabase and carbonatite (sovite) - Big Beaverhouse and Schryburt Lake carbonatites - mafic-ultramafic Big Trout Lake complex; gabbro, anorthosite, hornblendite - complex since reevaluated for ** PGE - showings for Ag Au Cu Nb - asbestos and arsenopyrite - Muskrat Dam Lake - Eyapamikama Lake - Opapimiskan Lake - greenstone belts.

Ontario Division of Mines
Mulcahy Township.
ODM Map 2295 (1:12,000) (1976).
OGS Map - Ontario, Canada - Archean geology in area W. of Red Lake - metavolcanics, metasediments, metagabbro, porphyry, granite, pyroxenite, serpentinite - BIF - Au Cu Ni - sulphides - area since reassessed for ** PGE potential.

Ontario Geological Survey
Sudbury Mining Area.
OGS 1:63360 map 2170 (1968).
Sudbury, Ontario, Canada - Archean and Proterozoic (Grenville) geology - location of mines of Zn Pb Cu Ag Au Ni Pt Co Se Te Fe - PGE - OGS map.

Ontario Geological Survey
Sioux Lookout - Armstrong.
OGS Map 2442 (1:253,440) (1980).
OGS Map - Ontario, Canada - Archean greenstone belts - Sioux Lookout - Lake St.Joseph - the Pashkokogan Lake to Kenoji Lake cataclastic zone - Lake of Bays batholith - Sturgeon Lake - granite, granodiorite, trondhjemite, metasediments, metavolcanics, syenite - Proterozoic Sibley Group sediments, and extensive diabase dykes and sills - many showings for Ag Au Cd Cr Cu Fe Hg Li Mo Ni Pb Pt Zn - ** PGE - sulphides - pyrite, arsenopyrite, bornite, chalcopyrite, galena, marcasite, molybdenite, pyrrhotite, pentlandite - tourmaline, graphite - hematite - magnetite - fuchsite green mica - BIF -

metasediments and metavolcanics - greenstone belts - Lewis lake batholith - mafic and ultramafic rocks - gabbro, anorthosite, diorite, pyroxenite, peridotite - Pt showing at Puddy Lake.

Ontario Geological Survey
Best Township.
OGS GDIF 158, 37pp. (1984).
Ontario, Canada - incl. 4 maps showing geophysical anomalies, property locations - area S.S.W. of Cobalt, immediately N. of Strathy Twp. - includes a large number of showings - pyrite from Northland Mine - showings for Co Cu Ni Pt Au Mo - ** PGE; Camsell occurrence (p.6).

Owen,DL and Coats,CJA
Falconbridge and East Mines.
In 'The Geology and Ore Deposits of the Sudbury Structure' (Pye,EG, Naldrett,AJ and Giblin,PE, editors), OGS Spec.Vol. 1, 603pp., 371-378 (1984).
Sudbury, Ontario, Canada - Falconbridge Mine - East Mine - ores in fault zones between the base of the Igneous Complex and the metasediments and metavolcanics of the Stobie Formation - mine sections - ore types - ** PGE - ores depleted in Ni Pt Pd Au relative to other Sudbury deposits - faults - ore mineralogy - pyrrhotite, pentlandite, gersdorffite, chalcopyrite, marcasite.

Parthe,E and Crocket,JH
Platinum Group.
In Handbook of Geochemistry Vol. II-5 (Wedepohl,KA editor), Springer-Verlag (1969 on).
PGE - Ru Rh Pd Pt Ir Os - review - crystal chemistry - isotopes - REE - abundances - Moon rocks, meteorites, rock-forming minerals - average Pd and Pt contents in common minerals are < 10 ppb - PGE occur especially in chromites and in accessory phases in granitic pegmatites, e.g. REE-rich species such as gadolinite, columbite and thortveitite; enriched in residual fluids as granitic rocks crystallize? - PGM - ore deposits (Sudbury, Ontario, Canada, Noril'sk, USSR, Bushveld, S.Africa etc).

Patterson,GC and Watkinson,DH
Metamorphism and supergene alteration of Cu-Ni sulfides, Thierry Mine, Northwestern Ontario.
Can.Mineral. 22, 13-21 (1984).
4 types of ore occur at the Thierry Mine, in the Uchi greenstone belt of N.W.Ontario, Canada - disseminated Cu Ni Fe sulphides, breccia ore, mylonite ore and bornite ore - magmatic sulphides, modified by strong shearing to form the mylonite and breccia ore - the bornite ore formed by Cu enrichment of blocks of amphibolite schist in mylonite - PGE are enriched in the mylonite and bornite ores in the shear zones - late metamorphic violarite is rich in Co - early violarite is not - a rare mineral assemblage contains species of Te Bi Ag Pt Pd and minor Au - merenskyite, native Ag, etc.

Patterson,GC, Mason,JK and Schneiders,BR
Thunder Bay resident geologist area, North Central Region.
OGS Misc.Pap. 128, 70-135 (1986).
Thunder Bay area, Ontario, Canada - lengthy tabulation of mining claim assessment work - notes on many deposits and showings - Atikokan Co / base metals / ** PGE project (pp.123-126, by

MacTavish,AD and Dutka,RJA) - Atikokan River and Quetico intrusions - sulphide occurrences in gabbros.

Pye,EG
Geology of Lac des Iles area.
ODM Geol.Rep. 64, 47pp. (1968).
Ontario, Canada - incl. OGS maps 2135,2136 - Archean area - Proterozoic sills and dykes - amphibolites, pyroclastics, volcanic breccia - metasediments and metavolcanics - conglomerate and iron formation - the Lac des Iles area contains a basic-ultrabasic complex - peridotite,serpentinite, gabbro,norite and anorthosite - disseminated sulphides - Cu Ni Pt Pd - the 'C zone' is the richest of 8 delineated mineralized zones, with about 5% sulphides in norite contained irregular anorthositic patches - sulphide of magmatic origin - no planes of weakness seen along which late solutions might have penetrated - BIF - PGE.

Ramdohr,P
The Ore Minerals and their Intergrowths.
Pergamon, 2nd Engl. edition, 2 volumes, 1205pp. (1980).
An updated version - ore petrography - photomicrography - ore textures - many mines - entries give partial outlines to mineralogy of some 3000 locations - entries on PGE phases include native metals and alloys; Pt Pd Ir Os Fe - photos of samples from the Urals, USSR - sulphides; Pt Pd Ru Ni S etc; braggite, cooperite, laurite - other PGM such as sperrylite, michenerite, froodite - As Bi - arsenic - native Ag (pp.313-321), native Au (pp.321-334) etc - samples from Ontario, Canada, etc - bibliography of some 800 references - 637 figures, mostly photomicrographs - reflectivity data updated in appendix. .

Robinson,DJ and Hutchinson,RW
Evidence for a volcanogenic-exhalative origin of a massive nickel sulphide deposit at Redstone, Timmins, Ontario.
In 'Precambrian Sulphide Deposits' (Hutchinson,RW, Spence,CD and Franklin,JM, editors), H.S. Robinson Memorial Vol., GAC Spec.Pap. 25, 791pp., 211-254 (1982).
Timmins area, Ontario, Canada - Redstone Archean volcanogenic stratabound Ni sulphide deposit, on southern flank of Shaw dome - Ni deposit located in dacitic tuff of Deloro Group, which is overlain by komatiitic flows (with spinifex tops) of the Tisdale Group - main sulphide layer occurs at komatiite-tuff contact - deposit characterized by heterogeneous distribution of ** PGE, Au Ni and Cu - volcanic exhalative model for deposit - local geology - whole-rock analyses - EPM of chlorite, Ca amphibole, serpentine and talc - sulphide-facies BIF - biotite mica - analyses of Ni Cu Rh Ru Pd Pt Ir Os Au As in sulphide assmblages - arsenic - relative PGE abundance is Pd>Pt>Ru>Au>Os>Ir>Rh - sulphide zones generally enriched in Rh Pd Au and depleted in Os Ir Ru Pt relative to chondritic abundances - hydrothermal alteration - petrography, photomicrographs, ore textures.

Robson,GG
Platinum 1985.
Johnson Matthey, London, 72pp. (1985).
Metal markets - useful review of ** PGE production and economics - data on Pt Pd Rh Ru Ir Os - uses - occurrence; S.Africa, Sudbury, Ontario, Canada - Noril'sk, USSR - Stillwater

complex, Montana, USA - Bushveld complex - reserves - supply and demand - prices - defence stockpiles; USA, Japan and Europe - history of PGE production - physical properties.

Rowell,WF
Platinum Group Elements and Gold in the Wanapitei Nipissing-type Intrusion, Northeastern Ontario.
MSc thesis, University of Western Ontario, 86pp. (1984).
Ontario, Canada - ** PGE and Au - Lake Wanapitei - Portage Bay - PGE and Au enrichment in small Cu Ni sulphide deposit at south end of Rathbun Lake - hydrothermal deposit; in sulphide zone only plagioclase and pyroxene relicts remain of original gabbronorite host mineralogy - gangue dominated by chlorite, quartz, biotite - main sulphides - pyrite and chalcopyrite - accessory millerite, violarite, arsenopyrite, magnetite, pyrrhotite, PGM - merenskyite, kotulskite, sperrylite and native Au - ore textures - most PGM occur in gangue, often in clusters of up to 15 grains - PGM associated with sulphides either border chalcopyrite or occur as exsolved blebs in chalcopyrite or pyrite - Nipissing diabase intrusions - local geology - Au Pt Pd in gabbronorite - petrography and photomicrographs - PGE patterns - O isotopes - hydrothermal fluids - EPM and INAA data.

Rowell,WF and Edgar,AD
Petrology,geochemistry and economic potential of the Nipissing gabbro, Ontario.
In Geoscience Research Seminar December 6-7,1983, Abstracts, OGS, 19 (1983).
Nipissing gabbro - Ontario, Canada - Cu rich massive sulphide lens - rich in Pt and Pd - EPM - As - PGE minerals mostly discrete, not as inclusions in sulphides - very low in Ir - probably deposited from hydrothermal fluid at 400 C - highest Au in rock with least S - O isotopes - geothermometer - arsenic.

Rowell,WF and Edgar,AD
Petrology,geochemistry, and economic potential of the Nipissing gabbro.
OGS Misc.Pap. 113, 153-157 (1983).
Ontario, Canada - Au Pt and Pd - Nipissing gabbro - significant values were only found in sulphide-bearing gabbronorite samples from the S. end of Rathbun Lake - Pt and especially Pd are associated preferentially with chalcopyrite, and Au and Ir are most abundant in pyrrhotite - in PGE OFR.

Rowell,WF and Edgar,AD
Petrology,geochemistry, and economic potential of the Nipissing gabbro.
OGS Misc.Pap. 121, 5-12 (1984).
Ontario, Canada - PGE and Au concentrated in a small Cu Ni sulphide deposit in a 'Nipissing-type intrusion', the Wanapitei intrusion - this paper describes the Rathbun Lake deposit's PGE and Au content - sulphide samples average 9% Cu - 0.5% Ni - 9.7 ppm Pt - 20.8 ppm Pd - 3.05 ppm Au - 'Pd resides in merenskyite and to a lesser extent kotulskite, while Pt is concentrated in sperrylite' - the intrusion is ring-shaped, and cuts Gowganda Formation greywacke - it is approx. 98% gabbronorite - its mineralogy is 'still pristine except in a few areas of localized hydrothermal activity' - hydrothermal Pt - the Rathbun Lake sulphide deposit was worked almost 70 years ago, so only dump samples are available - all 16 sulphide-bearing samples

examined show a degree of hydrothermal alteration - secondary assemblage includes sulphides (chalcopyrite - pyrite), chlorite, quartz, sericite and biotite - most PGM grains occur in gangue, not in sulphide - EPM of PGM - Bi Te As Sb - arsenic - ore textures - millerite - violarite - deposit has higher Cu/(Cu+Ni) than other Cu-Ni-PGE deposits - steep PGE plot (calc. to 100% sulphide) - the (Pt+Pd)/(Os+Ir+Ru) ratio is 626 - O isotope data - hydrothermal fluid 'was at least partially of meteoric origin and at a temperature of 300 to 400C' - PGE patterns.

Rowell,WF and Edgar,AD
Genesis of platinum-group elements and gold in a hydrothermal sulfide occurrence in a Nipissing intrusion, Northeastern Ontario.
Abs. Fourth Int. Platinum Symposium, Can.Mineral. 23, 313 (1985).
Rathbun Lake, Ontario, Canada - Pt Pd Au in Cu Ni sulphide occurrence in Nipissing diabase -type intrusion near Lake Wanapitei - ** PGE - apparent hydrothermal Pt - pyrite - chalcopyrite - native Au - merenskyite - kotulskite - sperrylite - mineralogy and paragenesis of PGM.

Rowell,WF and Edgar,AD
Platinum-group element mineralization in a hydrothermal Cu-Ni sulfide occurrence, Rathbun Lake, northeastern Ontario.
Econ.Geol. 81 no.5 (A Third Issue Devoted to Platinum Deposits), 1272-1277 (1986).
Ontario, Canada - Pd Pt Au concentrated in hydrothermal Cu Ni sulphide occurrence near Rathbun Lake - Wanapitei intrusion is about 98% medium-grained gabbronorite - extensive hydrothermal alteration to chlorite, quartz, epidote, sericite and biotite - shear zone - massive mineralization - pyrite and chalcopyrite are main sulphides - ** PGE - PGM include bismuthian merenskyite, with lesser kotulskite, michenerite and temagamite - sperrylite - EPM - petrography - 2 photomicrographs - PGE plot - Nipissing diabase -type intrusion - Te Bi As Hg Sb - arsenic - Ni Cu S - Pt and Pd seem more mobile than Rh Ru Ir Os in this setting.

Rucklidge,JC
Electron microprobe investigations of platinum metal minerals from Ontario.
Can.Mineral. 9, 617-628 (1969).
EPM of PGM - Pt Pd Rh Ir Ni Te Bi As S - arsenic - hollingworthite, irarsite and michenerite - hessite - Ag - tellurbismuth - Pd melonite - Ni merenskyite - XRD - PGE - samples from Ontario, Canada localities; Werner Lake, Strathcona, Falconbridge (Sudbury).

Sage,RP
Geology of the Cargill Township Carbonatite Complex.
OGS OFR 5400, 46pp. (1983).
Ontario, Canada - intrusion with outer pyroxenite rim carrying minor Cu Ni sulphide mineralization, and a carbonatite core with calcitic, dolomitic (rauhaugite) and sideritic phases - intrusion age dated at 1740 Ma - apatite-rich residuum generated by Cretaceous weathering - apatite reserves calculated at 62.5 MT grading 19.6% P2O5 - P - residuum also carries Nb - REE - vermiculite, clays and sands - industrial minerals - complex emplaced on regional faults of the Kapuskasing subprovince, and then split in two along later faults, generating distinctive aeromagnetic pattern - drill core sampling - petrography - local geology - Archean gneiss, fenitized

against western part of complex - Cargill and Cumming townships - mafic-ultramafic rocks (pp.12-21); these include clinopyroxenites, hornblendite, carbonatite and hybrid rocks - alkaline samples contain 5% or more magnetite - zoned crystals; clinopyroxene - some magnetite primary, some secondary after silicates - pyrrhotite -rich sulphides (? liquid immiscibility involved in origin) rarely reach 15% of samples - biotite, apatite, calcite - phlogopite in sovite of the core is often zoned - clinohumite - REE occur in crandallite-rich layer overlying the residuum - Ni Cu but no ** PGE detected in assay of sulphide samples - pyrite, pyrrhotite, chalcopyrite - compilation of whole-rock analyses, trace element and EPM data.

Sage,RP
Alkalic Rocks and Complexes of the James Bay Lowlands.
OGS OFR 5406, 75pp. (1983).
Ontario, Canada - some 14 pronounced aeromagnetic anomalies suggest intrusions below the Paleozoic cover of the James Bay lowlands - most have never been drill-tested - location map (p.xxii) - examples in the Martison Lake area include Niskibi Lake, Gooseberry Brook, Lawaski River, Poplar River, Little Drowning River, Kingfisher River (West and East) - some have been drilled; the Albany Forks carbonatite is an example; petrography - sovite - banded magnetite-apatite rock - O isotopes - C isotopes - one specimen of altered gabbro recovered - the Drowning River complex is 154 km N.W. of Hearst; protoclastic 'andesinite' with protoclastic texture - biotite, magnetite, olivine, clinopyroxene - possibilities for Cu Ni and ** PGE? - exploration 'is likely to be difficult and expensive' - the Mammamattawa Complex is buried deep (875') under Paleozoic cover, like some of the other complexes - Squirrel River is 76 km N.W. of Hearst - picrite to gabbro - glomeroporphyritic textures - olivine, clinopyroxene, plagioclase, biotite, magnetite, apatite - biotite often forms narrow rim completely enclosing magnetite.

Sage,RP
Geology of the Killala Lake Alkalic Rock Complex.
OGS OFR 5407, 98pp. (1983).
Killala Lake alkalic complex, Ontario, Canada - approx age date is 1050+/-35 Ma - 4 separate maps - zoned intrusive complex with silica-saturated syenite core and olivine gabbro rim sandwiching nepheline syenite - larvikite and monzonite - widespread disseminated sulphides in gabbro rim; minor Cu Ni values and ** PGE potential - Nb - minor pyrochlore in pegmatitic phases of syenite - petrography - diabase, lamprophyre and feldspar porphyry dykes - gabbro rim (pp.12-18) dominated by olivine gabbro, with minor gabbro and troctolite - possible chilled contact phase is intruded by later nepheline syenite, syenite and coarse gabbro - this fine-grained gabbro has up to 10% magnetite and 0-5% biotite - mica occurs as rims on magnetite - olivine-plagioclase and pyroxene-plagioclase grain boundaries display kelyphitic rim textures; symplectic intergrowths of light green amphibole and untwinned plagioclase - samples with 5-10% disseminated sulphide had Cu Ni values but no PGE - whole-rock analyses - AFM plots - norms - density data.

Sage,RP and Breaks,FW

Geology of the Cat Lake - Pickle Lake area, districts of Kenora and Thunder Bay.
OGS Rep. 207, 238pp. (1982).
Ontario, Canada - incl. OGS Map 2218 (compilation sheet), more detailed maps, and separate table of whole-rock analyses, trace element data and norms - Pickle Crow - metavolcanics - tholeiites - AFM plots and variation diagrams - Archean greenstone belts - metasediments - petrography and photomicrographs - laharic breccia - sulphide occurrences - BIF - porphyry - protomylonite - McVicar Lake Ni Cu prospect; ore textures; violarite in pyrrhotite host - Bamaji U occurrences - Loon Mo prospect - Sanderson Ag Au Cu Zn Pb prospect - pillow lava and tuff - mafic and ultramafic rocks - Thierry deposit has significant Pt Pd values - ** PGE (p.133) - listing of mining properties.

Sage,RP and Watkinson,DH
Alkalic rock - carbonatite complexes of the Precambrian shield of Ontario.
GAC/MAC Prog.w.Abs. 11, 122 (1986).
Most alkalic-carbonatite complexes in Ontario (Canada) are Archean to Proterozoic in age; three age date groupings; 2700-2400, 1850-1700 and 1250-900 Ma - early Paleozoic rocks occur in the Lake Nipissing area - mafic units may contain base metals and ** PGE - most carbonatites carry primary Nb - local enrichments in U P Zr - no obvious correlation of age with possible economic potential.

Sandefur,BT
The geology and paragenesis of the nickel ores of the Cuniptau Mine, Goward Nipissing district, Ontario.
Econ.Geol. 37, 173-187 (1942).
Ontario, Canada - Ni mine in Strathy township, Nipissing district - folded and faulted Keewatin lavas intruded by peridotite and (later) Keeweenawan dykes - the important Ni sulphide is the secondary phase violarite; perhaps one of the first Ni deposits mined 'in which secondary enrichment has played an important role' - 'the largest ore bodies occur in a shear zone' - it seems that the best ore was localized by well-developed, pre-mineral fractures' - altered volcanics - serpentinized pre-Algoman peridotite carries the massive sulphides - the older lavas are schistose near the contact - the intrusive contains small pyrite crystals (the later dykes do not) - the peridotite is largely altered to chlorite, talc,serpentine, magnetite and amphiboles, with some relict Ti augite between serpentinized olivines - petrography of local rocks, gangue and ore - photomicrographs - pentlandite is the most abundant Ni-bearing mineral; pentlandite and pyrrhotite are commonly altered to violarite - three generations of magnetite - two grains of sperrylite were found - arsenic - As Pt - magnetite and chromite are the only metallic minerals left from the original peridotite - deformation postdating the alteration of the peridotite opened channels for later ore fluids - summary history of peridotite; intrusion - alteration - deformation - sulphide deposition - supergene formation of violarite, marcasite, hematite and calcite (and oxidation of sulphides to form a gossan 'which first attracted attention to the property') - pyrite - PGE.

Savitsky,E, Polyakova,V, Gorina,N and Roshan,N
Physical Metallurgy of Platinum Metals.
Mir Publishers, Moscow, translated from 1975 Russian edition, distributed by Pergamon Press, 395pp. (1978).

Metallurgy of Pt Pd Rh Ir Ru Os - PGE alloys - phase diagrams - occurrence, production and prices of PGE - composition of commercially refined metals - metal recovery flowsheet (Sudbury, Ontario, Canada; pp.20-21) - PGE isotopes - electronic structure - neutron capture cross sections - thermal, electrical, magnetic and optical properties - deformation, strength, creep, single crystal growth - metallography - photomicrographs - alloy textures - etching agents - SEM and FIM images - many binary systems described - some ternary systems, e.g. Ps Bi As - arsenic - Ru W Re - unusual systems such as PGE C alloys; graphite precipitates - solubility of H in PGE - uses; alloys for thermocouples, catalysts, electrical contacts, magnets - bibliography of 522 references - index.

Sawkins,FJ
Metal Deposits in Relation to Plate Tectonics.
Springer-Verlag, 325pp. (1984).
Mineralization and plate tectonics - textbook review in terms of convergent and divergent environments, collisional settings, etc - includes a)Ocean-type crust; spreading systems - Salton Sea - Troodos ophiolite,Cyprus - Samail (Semail) ophiolite,Oman - chromite - Cr - Greece and Zimbabwe -
b)Hotspots, anorogenic magmatism etc; Sn of Brazil and Nigeria - anorthosites with Fe - Ti - Grenville province - layered intrusions - Bushveld - Stillwater,Montana, USA - Sudbury, Ontario - carbonatites; Kola, USSR - Palabora - layered intrusions -
rifting environments and anorogenic sites - mantle hotspots - mineralization in Cr PGE Cu Ni - mafic rocks with relatively high initial Sr isotope ratios - Dufek intrusion in Antarctica also hotspot-related (pp.167-173)? -
c)Early rifting; hydrothermal Cu deposits; Messina,S.Africa - breccia pipes - Oslo graben and Mo - stratiform Cu deposits - Zambia, the Kupferschiefer and Zechstein of Germany - Roan of Zambia, Africa - magmatic Cu Ni deposits; Noril'sk-Talnakh USSR - Mississippi Valley type Pb Zn deposits - MVTs - Alps - Ireland -
34pp. of references.

Shklanka,R (editor)
Copper, nickel, lead and zinc deposits of Ontario.
ODM MRC 12, 394pp. (1969).
Ontario, Canada - Cu Ni Pb Zn deposits reviewed - inventory includes >1600 deposits - many mines - Alexo Mine (pp.116-117); metabasalts intruded by ultramafic sills, the thickest of which, the Dundonald sill, is a layered intrusion 2400 feet thick - pyrrhotite, pentlandite, lesser chalcopyrite and heazlewoodite - Abitibi Archean greenstone belt - Long Lake Grenville Pb Zn deposit (pp.133-134) occurs in marble; sphalerite with minor galena - chalcopyrite - pyrite - in veins and lenses up to 140 feet long and 14 feet wide - the Cuniptau (Trebor) Mine in Temagami; Cu Ni Pt Au Ag Pd - ** PGE - Strathy Twp. - the Raglan Ni prospect (p.227); pyrrhotite and chalcopyrite in metagabbro over a length of about 500 feet and a width of some 15-100 feet at surface - Norrie prospect, on N.E. shore of Net Lake in Strathy Twp., occurs in a silicified, quartz-veined mafic intrusive - a last example, the Lac des Iles prospect (pp.331-332) contains eight known mineralized zones, the predominant host rock being norite with segregations of anorthosite; some 5 vol.% sulphides in mineralized area (zone 'C' is the most important).

Smirnov,VI, Ginzburg,AI, Grigoriev,VM and Yakovlev,VF
Studies of Mineral Deposits.
Mir Publishers, Moscow, English trans. of Russian edition (1981), 288pp. (1983).
Review of mineral deposits - 36 chapters devoted to different commodities; many metals covered - metallogeny - many USSR examples - Fe ores; magmatic ores, carbonatites, volcanogenic, sedimentary and Precambrian deposits - Mn nodules and other Mn ores - Cr ores, incl. the Bushveld, S.Africa - magmatic and placer Ti ores - ores of V - Mg - Al - Ni ores, incl. Noril'sk, Talnakh, Sudbury (Ontario, Canada) and New Caledonia - Co - PGE, etc.

Smith,AR and Sutcliffe,RH
Geology of the Tib gabbro, Lac des Iles aea, district of Thunder Bay.
OGS Misc.Pap. 132, 76-79 (1986).
Ontario, Canada - Archean layered intrusion in Wabigoon subprovince - anomalous ** PGE contents - map - igneous layering - sulphide mineralization in Kuhner occurrence; coarse to pegmatitic rocks on S.W. margin of the Tib gabbro - pyrrhotite - chalcopyrite - pyrite - host rocks are melagabbronorite to norite - Ni Cu Pt Pd Au values - intrusion has approximate exposed area of 25 km2 - the body is divisible into four zones - gabbronorite, gabbro and orthopyroxenite, websterite, anorthosite, magnetite cumulate - tonalites in area are divided into those older and younger than the gabbro.

Stumpfl,EF
Some aspects of the genesis of platinum deposits.
Econ.Geol. 57, 619-623 (1962).
Pt - Driekop, Bushveld, S.Africa - dunite pipes - Sb - Bi - As - S - PGE in discrete phases, not in sulphides alone - Noril'sk USSR - hydrocarbons - relatively low temperature hydrothermal possibility - Sudbury, Ontario, Canada - arsenic.

Stumpfl,EF
Distribution, transport and concentration of platinum group elements.
In 'Metallogeny of Basic and Ultrabasic Rocks', Inst.Min.Met., 379-394 (1986).
Review of aspects of the geochemistry of ** PGE - recent sediments - Mn crusts and Mn nodules - PGE in Kupferschiefer-type deposits - hydrothermal fluids - Pt and Pd in Mn nodules - the Zechstein - PGE in Archean greenstone belts - Kambalda, Australia - Merensky Reef, UG-2 and Platreef, Bushveld, S.Africa - Great Dyke of Zimbabwe, Africa - Sudbury, Ontario, Canada - Stillwater complex, Montana, USA - graphite, volatiles and mafic pegmatoids - petrography and photomicrographs - EPM of Bushveld silicates - potholes - fluid inclusions - 46 references.

Stumpfl,EF and Tarkian,M
Platinum genesis: new mineralogical evidence.
Econ.Geol. 71, 1451-1460 (1976).
Bushveld, S.Africa - Pt reefs contain braggite, cooperite, laurite, sperrylite, Pt Fe alloy and minor Pt Pd Bi Te phases - pipe deposits contain Pt Fe alloy, sperrylite, geversite and Rh Ir As S phases - Sudbury (Ontario,Canada) and Stillwater (Montana,USA) deposits are rich in compounds of Pd Pt Bi Te and S - Pd preferentially associates with sulphides in the early stages and forms discrete PGE phases later in

the magmatic cycle - serpentinization is important in converting silicate Ni into sulphide Ni, and in extracting PGE from major phases and localising them into minor PGM.

Sutcliffe,RH
Mulcahy Lake gabbro: a well-preserved layered intrusion in the Wabigoon subprovince.
In Abs. OGS Geoscience Research Seminar and Open House '84, 14 (1984).
Ontario, Canada - Mulcahy Lake gabbro - tholeiitic layered intrusion 45 km S.W. of Dryden - two sequences resulting from separate magma pulses, each crystallizing from the base upwards with Fe enrichment trends; the 'lower and middle zones' - cumulates with a 'roof zone' of intermediate pyroxene hornfels - igneous layering - magma chamber dynamics - sulphides at the lower zone-middle zone boundary; potential PGE exploration target.

Sutcliffe,RH
Geology of the Mulcahy Lake gabbro intrusion.
OGS Misc.Pap. 119, 33-37 (1984).
Layered intrusion 45 km S.W. of Dryden, Ontario, Canada - bulk composition is Fe-rich tholeiite - cryptic and rhythmic layering - Ni and Cu prospects - sketch map - petrology - Cu Ni PGE potential - deformation zones within the intrusion are locally carbonatized and contain quartz veins; Au potential?

Sutcliffe,RH
Regional geology of the Lac des Iles area, district of Thunder Bay.
OGS Misc.Pap. 132, 70-75 (1986).
Ontario, Canada - several Archean mafic-ultramafic intrusions in the Lac des Iles area have ** PGE potential - local geology - Lac des Iles layered intrusion - Tib gabbro - Demars Lake intrusion (small zoned intrusion with websterite core and gabbro/pyroxenite margin) - gabbroic rocks at Wakinoo Lake - Dog River, Taman Lake and Buck Lake intrusions - intrusions in the region are emplaced into older tonalitic host rocks - net veining textures suggest magma mixing involved in adjacent tonalitic and mafic rocks in some locations; skeletal hornblende crystallization may be indicative of such processes - breccias - Cu Ni Pt Pd Au values - structural geology.

Sutcliffe,RH
Mafic intrusive suites hosting platinum group element occurrences in the Thunder Bay area.
In Abs. OGS Geoscience Research Seminar and Open House '86, 4 (1986).
** PGE - Ontario, Canada - Lac des Iles - Crystal Lake gabbro - Lac des Iles is one of several late Archean ultramafic to mafic tholeiitic intrusions along the Wabigoon-Quetico subprovince boundary; PGE mineralization within zones of gabbro, gabbronorite and websterite at Lac des Iles - Crystal Lake and the Coldwell complex are later (Proterozoic) intrusives - PGE at Crystal Lake are related to coarse pegmatitic olivine gabbro near the base of the intrusion.

Sutcliffe,RH and Sweeney,JM
Geology of the Lac des Iles complex, district of Thunder Bay.
OGS Misc.Pap. 126, 47-52 (1985).
Lac des Iles layered intrusion, Ontario, Canada - Archean

Wabigoon subprovince - exploration history and general geology - gabbros - ** PGE Cu Ni mineralization - rheomorphism with net veining of tonalite back-intruded into amphibolite dyke - mineralization related to late pegmatitic gabbro and intrusion breccia.

Sutcliffe,RH and Sweeney,JM
Precambrian geology of the Lac des Iles complex, district of Thunder Bay.
OGS Map P3047, 1:15,840 (1986).
Lac des Iles layered intrusion, N.W. Ontario, Canada - with notes - mafic to ultramafic suite - Cu Ni Pt Pd mineralization - ** PGE - exploration history - local geology - gabbro, gabbronorite, serpentinite - sulphides - mafic pegmatoids - websterite, peridotite, wehrlite, clinopyroxenite, hornblendite.

Sweeny,JM and Sutcliffe,RH
Geology and platinum group element mineralization of the Roby zone, Lac des Iles complex.
OGS Misc.Pap. 132, 82-84 (1986).
Ontario, Canada - Lac des Iles layered intrusion - map - gabbros - magma mixing - ** PGE mineralization - volatiles, magma mixing, redistribution of magmatic sulphides by volatile-rich pegmatitic phases are processes linked to development of mineralized zones.

Talkington,R and Watkinson,DH
Precious-metal distribution trends in the Lac-des-Iles complex, Northwestern Ontario.
GAC/MAC Prog.w.Abs. 7, 83 (1982).
Archean sulphide-bearing layered basic complex - magmatic and hydrothermal sulphides and PGE - Pd Pt Te Bi - most PGE are associated with secondary sulphides and silicates - Lac des Iles, Ontario, Canada.

Talkington,RW and Watkinson,DH
Trends in the distribution of the precious metals in the Lac-des-Iles complex, Northwestern Ontario.
Can.Mineral. 22, 125-136 (1984).
N.W.Ontario, Canada - sulphide-bearing layered intrusion - magmatic sulphide and PGE mineralization commonly associated with mafic cumulates - later hydrothermal fluids have however been active in altering primary silicates, redistributing Cu Ni sulphides and producing PGE-bearing minerals of Te Bi As S - Pt and Pd tend to be concentrated at low concentrations of Cu Ni and Au - most PGE minerals are linked with secondary silicates and sulphides - highest PGE values are found in rocks formerly rich in pyroxene, now mainly composed of amphiboles - Lac des Iles - arsenic.

Talkington,RW, Watkinson,DH, Whittaker,DJ and Jones,PC
Platinum-group minerals and other solid inclusions in chromite of ophiolitic complexes: occurrence and petrological significance.
Tscher.Min.Pet.Mitt. 32, 285-301 (1984).
Small (<250 um) randomly-orientated inclusions in chromites of ophiolites and other mafic-ultramafic rocks - silicates are modally the most abundant type - PGM include sulphides rich in Ru and Os-rich alloys - chemistry and random orientation of PGM argue against exsolution origin - trapping during chromite formation is preferred - one possible origin of silicate inclusions involves incomplete breakdown of a Cr pargasite amphibole to give chromite, olivine, liquid and

vapour - preferred explanation is again trapping - overall, chromite preipitates on fO2 increase in magma: volatiles and S locally concentrate - some PGE alloys converted to sulphides? - trapping of inclusions - accumulation of chromitite - zoned crystals - chromite from Big Trout Lake, Ontario, Canada.

Watkinson,DH and Dunning,G
Geology and platinum-group mineralization, Lac-des-Iles complex, Northwestern Ontario.
Can.Mineral. 17, 453-462 (1979).
Ontario, Canada - complex of mafic cumulates in granitic rocks of Wabigoon Belt - 2 units - E. gabbro is oxide-rich and sulphide-poor, W. gabbro is coarser and pegmatitic, and includes a minor layered anorthosite, layered and steeply-dipping with Cu Ni Fe sulphides and PGE minerals - vysotskite Pd Pt Ni S - kotulskite Pd Pt Te Bi - most Cu S Ni and PGE are in the first intrusive phase of the complex, the 'W. gabbro' liquid - sulphides precipitated in orthopyroxene cumulate - late fluids generated pegmatite and hydrothermal alteration, especially in rock rich in clinopyroxene - Pd Cu and Fe migrated, but only on a centimetre scale - Pd occurs most commonly with Ni minerals - area underwent amphibolite to greenschist metamorphism in Kenoran event, but primary textures and minerals still visible - sulphide liquid precipitated PGE in mss which exsolved pyrrhotite pentlandite chalcopyrite - Lac des Iles.

Watkinson,DH, Dahl,R and McGoran,J
The Coldwell complex platinum-group-element deposit: 2. Relationships of platinum-group-elements to pegmatitic biotite-bearing gabbro and the role of a fluid phase.
GAC/MAC Prog.w.Abs. 11, 142 (1986).
** PGE in Coldwell Complex layered intrusion near Marathon, Ontario, Canada - Pt Pd Rh enrichment in ore assemblages of chalcopyrite - cubanite - pentlandite - pyrrhotite - pyrite - PGM identified; merenskyite and hollingworthite - sulphide assemblages are often in contact with biotite in which EPM reveals high contents of Ti Na F Cl - mineralogy and petrography - apatite, albite, granophyric intergrowths - mafic pegmatoids - inference of hydrothermal processes.

Watkinson,DH, Jones,PL and Marshall,D
Platinum group elements in the Eastern gabbro, Coldwell complex, Northwestern Ontario.
OGS Misc.Pap. 121, 36-41 (1984).
Ontario,Canada - Coldwell Complex layered intrusion - magnetite-bearing layered gabbro was sampled and analysed for Pt Pd Au Cu Ni Co S - 'no concentrations were found except in heterogeneous, marginal gabbro at the base of the section exposed on Highway 17' - results compatible with bulk of PGE being scavenged by S near the base of the complex, little PGE remaining when a later magma influx arrived and formed the layered series - map analyses - gabbro - augite syenite - pegmatitic pods - igneous layering.

Watkinson,DH, Whittaker,PJ and Jones,PL
Platinum group elements in the Eastern Gabbro, Coldwell Complex, Northwestern Ontario.
OGS Misc.Pap. 113, 183-191 (1983).
Ontario, Canada - PGE concetrations in the Coldwell Complex are associated

with chalcopyrite/pyrrhotite/cubanite/pentlandite in massive gabbroic rocks near the country rock boundary - much of the sulphide-bearing gabbro contains inclusions, biotite and pegmatitic pods - layered gabbro occurs above the massive unit - Cu Ni Pt Pd - hollingworthite occurs (Rh As S) as does merenskyite (a Pd Bi Te mineral) (photo) - arsenic.

Watkinson,DH, Hak,J, Morton,P and Johan,Z
Merenskyite from the Shebandowan nickel-copper mine, Northwestern Ontario.
Can.Mineral. 16, 659-663 (1978).
Ontario, Canada - Ni Cu sulphide - EPM - PGE Pd Pt Bi - exsolution - Shebandowan greenstone belt - BIF - greenschist metamorphism - no evidence for hydrothermal effects in PGE, although silicate and sulphide have been subject to serpentinization / metamorphism - sulphide solid solutions - photomicrographs - ore textures.

Watson,RJ
Platinum-bearing nickel-copper deposit on Lower Shebandowan Lake, district of Thunder Bay.
ODM Ann.Rep. 37 pt.4, 128-149 (1929).
Shebandowan district, Ontario, Canada - sheared peridotite hosts ore in metasedimentary-metavolcanic terrain - sulphide replacements along a zone about 1 mile long and 100 feet wide in Discovery Bay area - local geology - 'graphite' locally abundant in the 'greenstones' - granite, porphyry, diabase - maps - the sulphide zone is highly sheared, with late sulphides, calcite, dolomite - serpentinized olivine - petrography and photomicrographs - Ni values only in sheared peridotite - pyrite, pyrrhotite, chalcopyrite and polydymite - small seams of magnetite may cut sulphides - Cu Ni data, plus Au Pt Pd values - ** PGE - minor Co - highest assaying sample quoted (oz/T) at 0.083 Au, 0.04 Pt and 0.11 Pd.

Whittaker,PJ
Chromite deposits in Ontario.
OGS Open File Report 5306, 152pp. (1980).
5 areas of Ontario,Canada - chromite deposits; layered, disseminated and podiform - industrial grades - Cr geochemistry - study areas; 1)Puddy-Chrome Lakes, 50 km W. of Lake Nipigon; shearing - alteration - serpentinization - chromitite - Cr / Fe ratio highest found in the deposits (2.38-2.56, mean 2.45) - magnetite with Ni - Alpine-type intrusion - 'hot mantle diapirs' - petrography and photomicrographs - 2)Big Trout Lake, 420 km N.E. of Red Lake; gabbro - anorthosite - ultramafic (pyroxenitic) xenoliths - serpentinite - chromite textures - crystal cavities, silicate inclusions - possible PGE in sulphides (droplets, and interstitial between chromite grains) by analogy with Bushveld (Hiemstra 1979) - EPM of chromite; Cr/Fe 1.21 max, mean 0.88; large amounts of chromite but relatively low grade Cr - 3)Crystal Lake gabbro, 47 km S.W. of Thunder Bay; phase layering, 3 zones in gabbroic intrusion, the middle zone of greatest economic significance (Great Lakes Nickel Corp. Cu Ni deposit) - pegmatitic patches - anorthosite - petrography - lithologic and perhaps genetic similarity to the Duluth complex, USA - 4)Shebandowan Cu Ni deposit; serpentinized peridotite intruded sill-like into metavolcanics - 5)accessory chromite in komatiitic flows; Timmins area as example; Langmuir Ni sulphide deposit.

Whittaker,PJ
Chromite deposits in Ontario.
OGS Study 55, 97pp. (1986).
Exploration for Cr in Ontario, Canada - chromite - Cr in plutonic, hypasbyssal ad extrusive environments - Big Trout Lake - Puddy-Chrome Lakes - Crystal Lake gabbro - Shebandowan (Hagey township) - Dundonald township - Archean Cr deposits - metallurgical uses and mineralogy of chromite - survey of rock types - Nipissing diabase appears to have slightly lower Cr contents than other mafic rocks (pp.7-8) - maps and deposit descriptions - petrography and photomicrographs - layered intrusions - chromite, serpentine, lizardite, magnetite, bastite, antigorite - EPM of chromite - Cr : Fe ratios - whole-rock analyses - possible ** PGE content of Cr-rich rocks - Cr Ni Cu plots - Timmins area, Abitibi greenstone belt - deposit classification.

Whittaker,PJ
Platinum group elements and their potential in Ontario.
Abs. OGS Geoscience Research Seminar and Open House '86, 3 (1986).
Ontario, Canada - ** PGE potential of the province briefly reviewed - magmatic and hydrothermal processes - high PGE concentrations may occur in secondary vein-filling situations, e.g. Pt in chalcopyrite; Kanichee deposit is an example of Pt enrichment in secondary chalcopyrite veining - weak hydrothermal alteration along veins - Rathbun Lake as another example.

Wilkinson,SJ
Geology and Sulphide Mineralization of the Marginal Phases of the Coldwell Complex, Northwestern Ontario.
MSc thesis, Carleton University, 129pp. (1983).
Coldwell complex - alkaline layered intrusion near Marathon, Ontario, Canada - gabbros of the initial intrusive cycle define the base of the intrusion and contain sulphide mineralization, primarily in a xenolith-rich 'heterogeneous gabbro' within the massive gabbros - magnetite layers at the base of the layered gabbro unit host less extensive zones of sulphide enrichment - pyrrhotite, chalcopyrite, cubanite and minor pentlandite are the main sulphides - ** PGE occur in a Pd -rich PGM assemblage; hollingworthite, merenskyite - sulphide precipitation thought to be a response to assimilation of wall rocks - Middleton, Coubran Lake and Bamoos Lake map areas - maps - alkalic-carbonatite complexes in Ontario - age dates for the complex cluster in the 1100-1000 Ma range - field geology - Archean host rocks - gabbro and syenite lithologies - petrography and photomicrographs - cumulus, intercumulus and deuteric minerals - miarolitic cavities occur in mineralized zones (p.66) - pyrite - selenides occur; clausthalite - Se - Pt Pd Rh Ru Ir Os Au - petrogenesis - magma chamber processes - liquid immiscibility and sulphides - mss - magnetite and sulphide localization - volatiles and alteration concentrated in the heterogeneous gabbro - EPM data - olivine and clinopyroxene.

Wilkinson,S and Colvine,AC
Sulphide mineralization in the marginal phases of the Coldwell alkalic complex.
OGS Misc.Pap. 82, 210-215 (1978).
Coldwell complex - layered intrusion - Marathon area, Ontario, Canada - reserves >50 MT grading 0.4%% Cu with significant ** PGE content -

gabbro and syenite lithologies - chalcopyrite and pyrrhotite occurrences in gabbros of the Coubran Lake, Bamoos Lake and Middleton areas - mineralization in concentrations in heterogeneous gabbro (most important; sulphide deposition perhaps induced by contamination of gabbroic magma by wall rock assimilation), and also in magnetite-rich layers in layered gabbro, and in magnetite-rich layers in syenites.

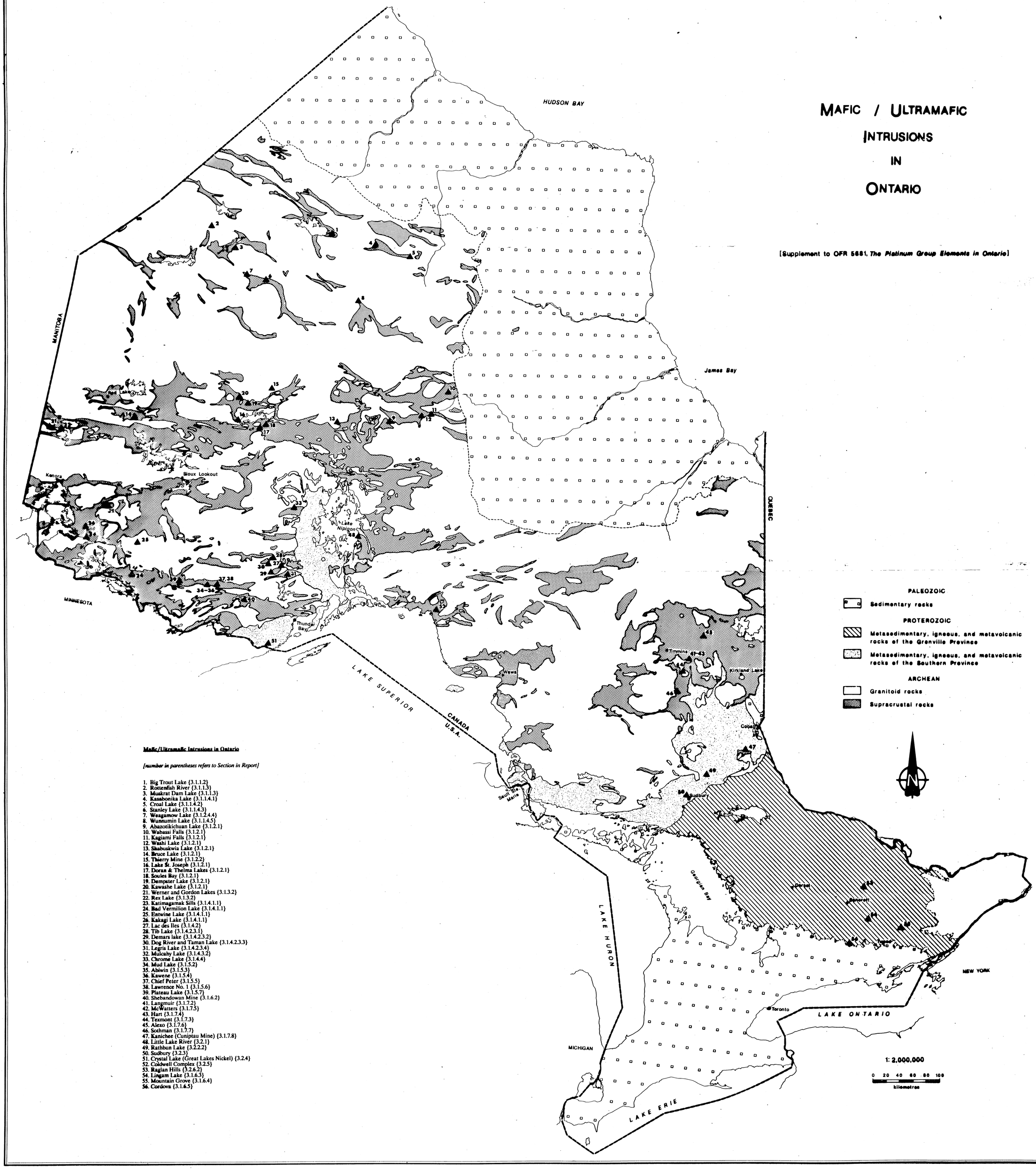
Wilson,GC
The role of free carbon in metallic mineral deposits.
Univ. of Toronto IsoTrace Rep. 1985-1, 58pp. (1985).
Review of the occurrence of free C in ore deposits - graphite - hydrocarbons - emphasis on precious metal mines - PGE - hydrothermal Pt and Pd - Au - active carbon - kerogen - thucholite - anthraxolite - bitumens - Au mines incl. those in Nevada, USA and Ontario, Canada - graphite - pyrite - graphite in layered intrusions - Bushveld, S.Africa and Stillwater complex, Montana - serpentinization - Cl and Pt - massive sulphides - Zechstein Cu deposits - Mississippi Valley deposits - MVTs - Pb Zn - U deposits - Hg - Ag - 'coal blend' - graphite veins, such as those in Sri Lanka - black shales - fluid inclusions - hydrothermal fluids - C isotopes - bibliography with 250 references.

Wilson,GC
An Annotated Bibliography of the Platinum Group Elements.
OGS OFR 5559, 308pp. (1985).
Extensively cross-referenced bibliography listing some 320 references on ** PGE - over 200 keywords are indexed - PGE geology and mineralogy - Pt Os Ir Ru Rh Pd etc - many geographic entries, e.g. to layered intrusions such as the Bushveld, S.Africa, the Stillwater complex, Montana, USA - many entries for Sudbury and elsewhere in Ontario, Canada.

Wilson,GC
An Annotated Bibliography of the Platinum Group Elements.
OGS OFR 5559, 308pp. (1985).
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MAFIC / ULTRAMAFIC INTRUSIONS IN ONTARIO

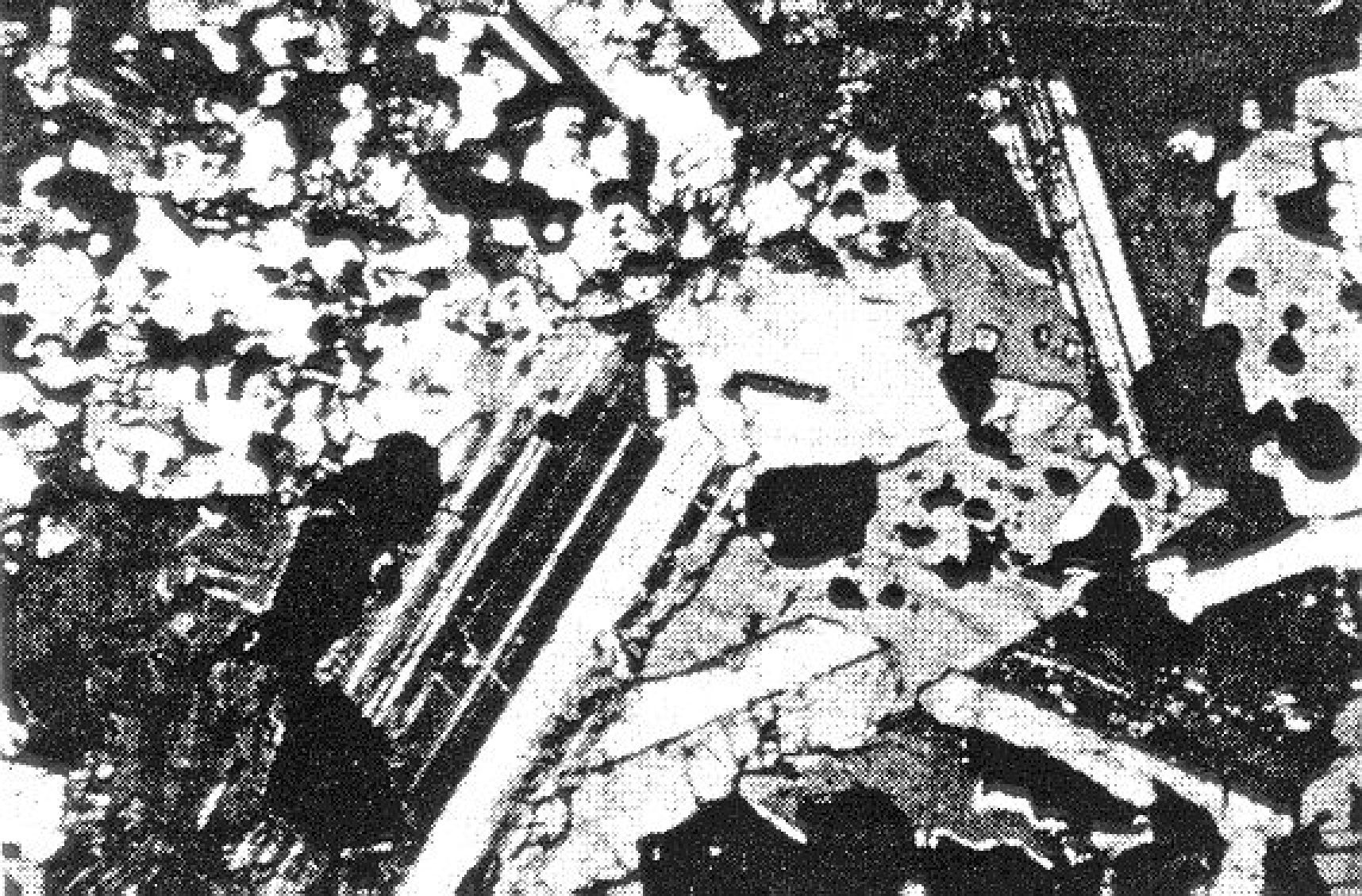
[Supplement to OFR 5681, *The Platinum Group Elements in Ontario*]



Mafic/Ultramafic Intrusions in Ontario

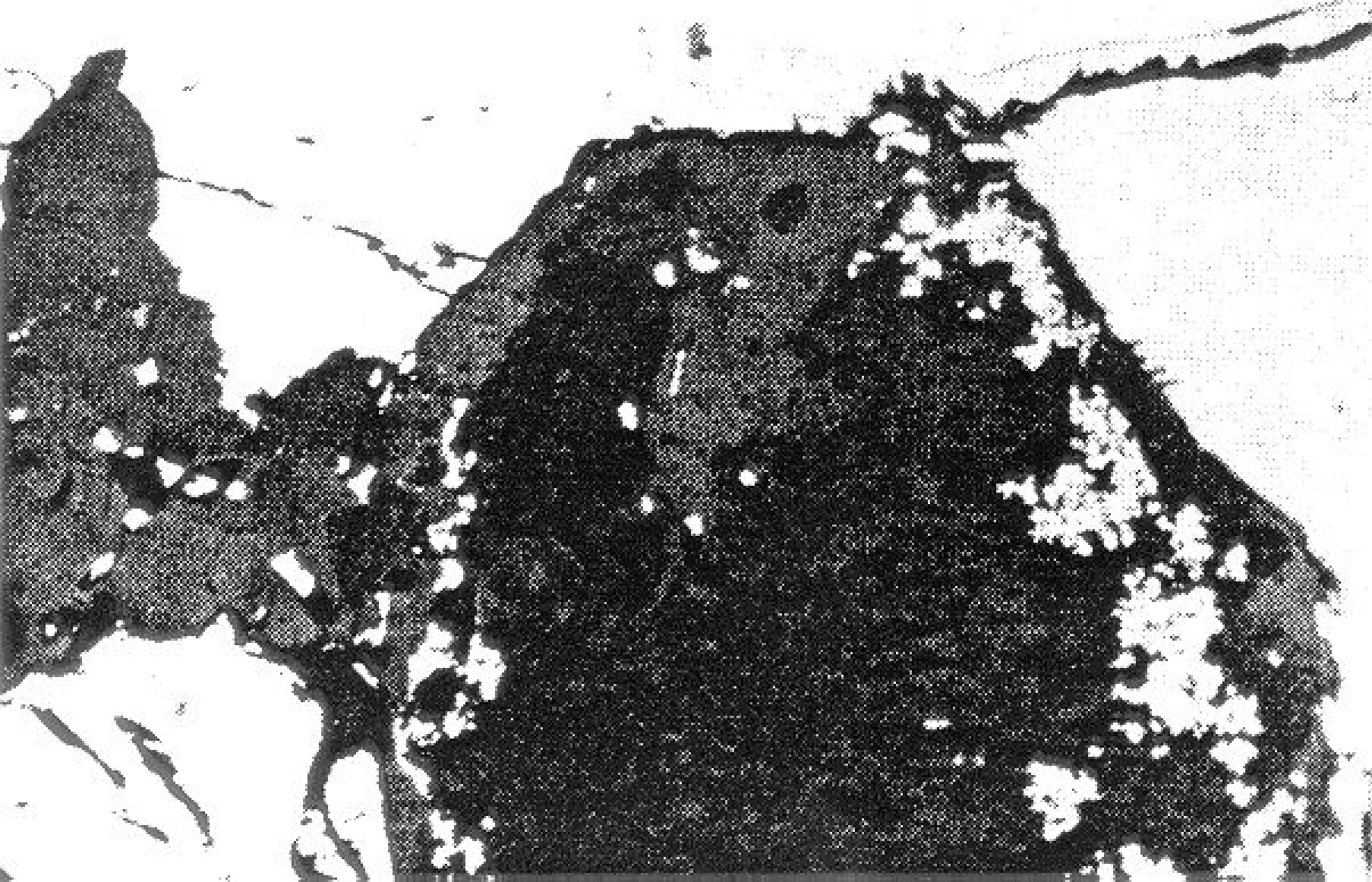
[number in parentheses refers to Section in Report]

1. Big Trout Lake {3.1.1.2}
2. Rottenfish River {3.1.1.3}
3. Muskrat Dam Lake {3.1.1.3}
4. Kasabonika Lake {3.1.1.4.1}
5. Croal Lake {3.1.1.4.2}
6. Stanley Lake {3.1.1.4.3}
7. Weagamow Lake {3.1.2.4.4}
8. Wunnumin Lake {3.1.1.4.5}
9. Abazotikichuan Lake {3.1.2.1}
10. Wabassi Falls {3.1.2.1}
11. Kagiami Falls {3.1.2.1}
12. Washi Lake {3.1.2.1}
13. Shabuskwia Lake {3.1.2.1}
14. Bruce Lake {3.1.2.1}
15. Thierry Mine {3.1.2.2}
16. Lake St. Joseph {3.1.2.1}
17. Doran & Thelma Lakes {3.1.2.1}
18. Soules Bay {3.1.2.1}
19. Dempster Lake {3.1.2.1}
20. Kawashe Lake {3.1.2.1}
21. Werner and Gordon Lakes {3.1.3.2}
22. Rex Lake {3.1.3.2}
23. Katimagamak Sills {3.1.4.1.1}
24. Bad Vermilion Lake {3.1.4.1.1}
25. Entwine Lake {3.1.4.1.1}
26. Kakagi Lake {3.1.4.1.1}
27. Lac des Iles {3.1.4.2}
28. Tib Lake {3.1.4.2.3.1}
29. Demars lake {3.1.4.2.3.2}
30. Dog River and Taman Lake {3.1.4.2.3.3}
31. Legris Lake {3.1.4.2.3.4}
32. Mulcahy Lake {3.1.4.3.2}
33. Chrome Lake {3.1.4.4}
34. Mud Lake {3.1.5.2}
35. Abiwin {3.1.5.3}
36. Kawene {3.1.5.4}
37. Chief Peter {3.1.5.5}
38. Lawrence No. 1 {3.1.5.6}
39. Plateau Lake {3.1.5.7}
40. Shebandowan Mine {3.1.6.2}
41. Langmuir {3.1.7.2}
42. McWatters {3.1.7.5}
43. Hart {3.1.7.4}
44. Texmont {3.1.7.3}
45. Alexo {3.1.7.6}
46. Sothman {3.1.7.7}
47. Kanichee (Cuniptau Mine) {3.1.7.8}
48. Little Lake River {3.2.1}
49. Rathbun Lake {3.2.2.2}
50. Sudbury {3.2.3}
51. Crystal Lake (Great Lakes Nickel) {3.2.4}
52. Coldwell Complex {3.2.5}
53. Raglan Hills {3.2.6.2}
54. Lingam Lake {3.1.6.3}
55. Mountain Grove {3.1.6.4}
56. Cordova {3.1.6.5}



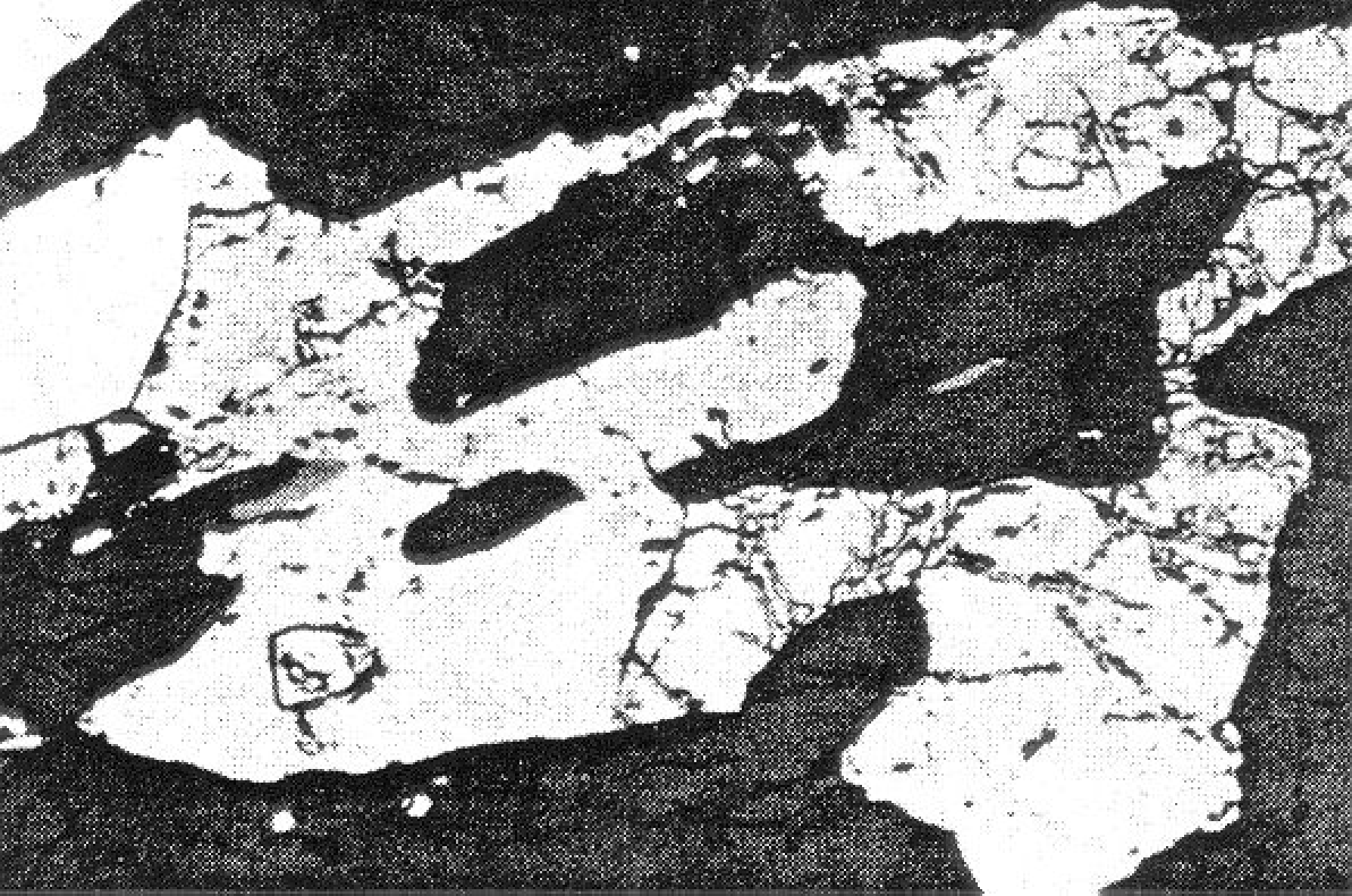


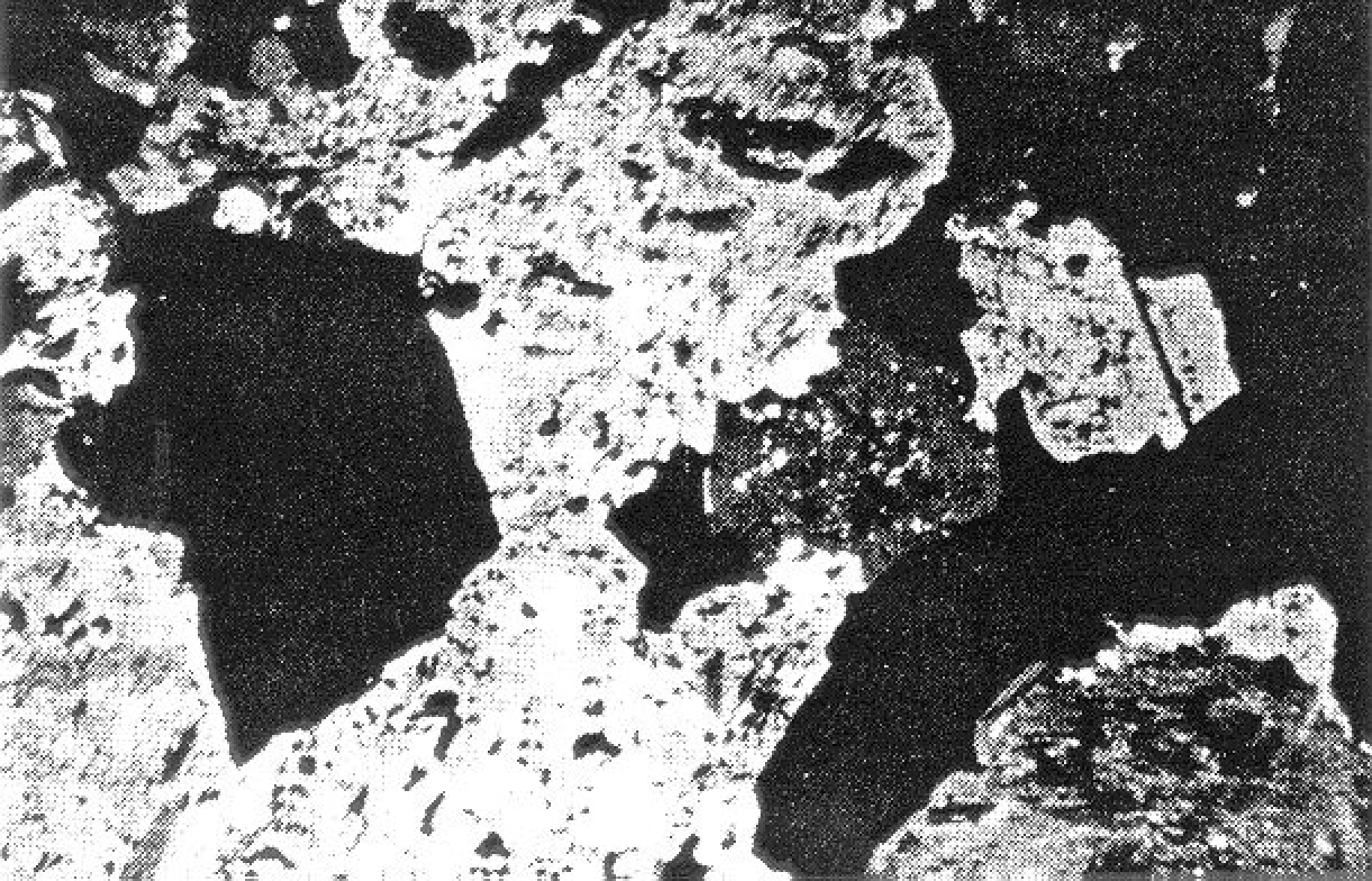


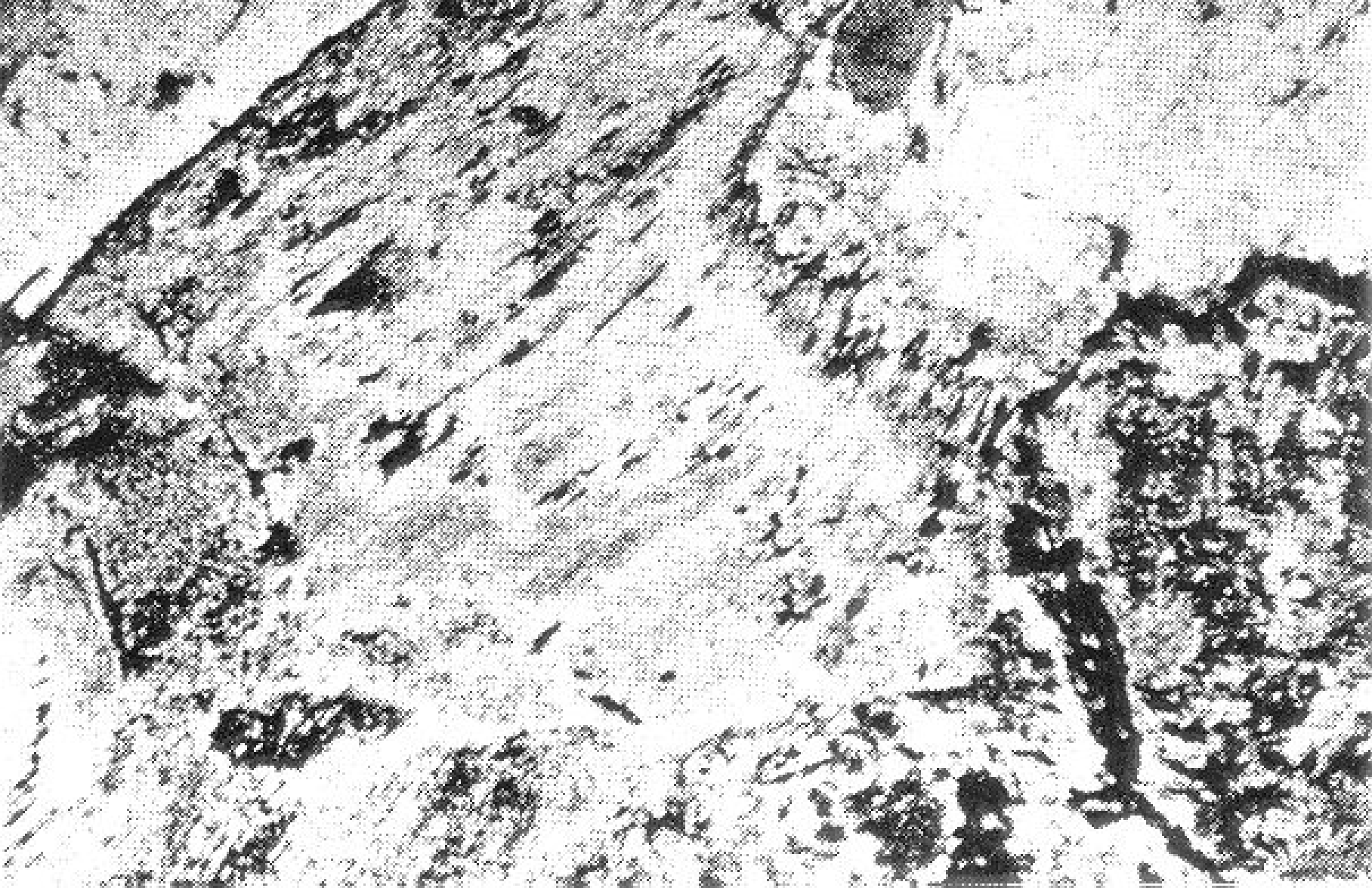


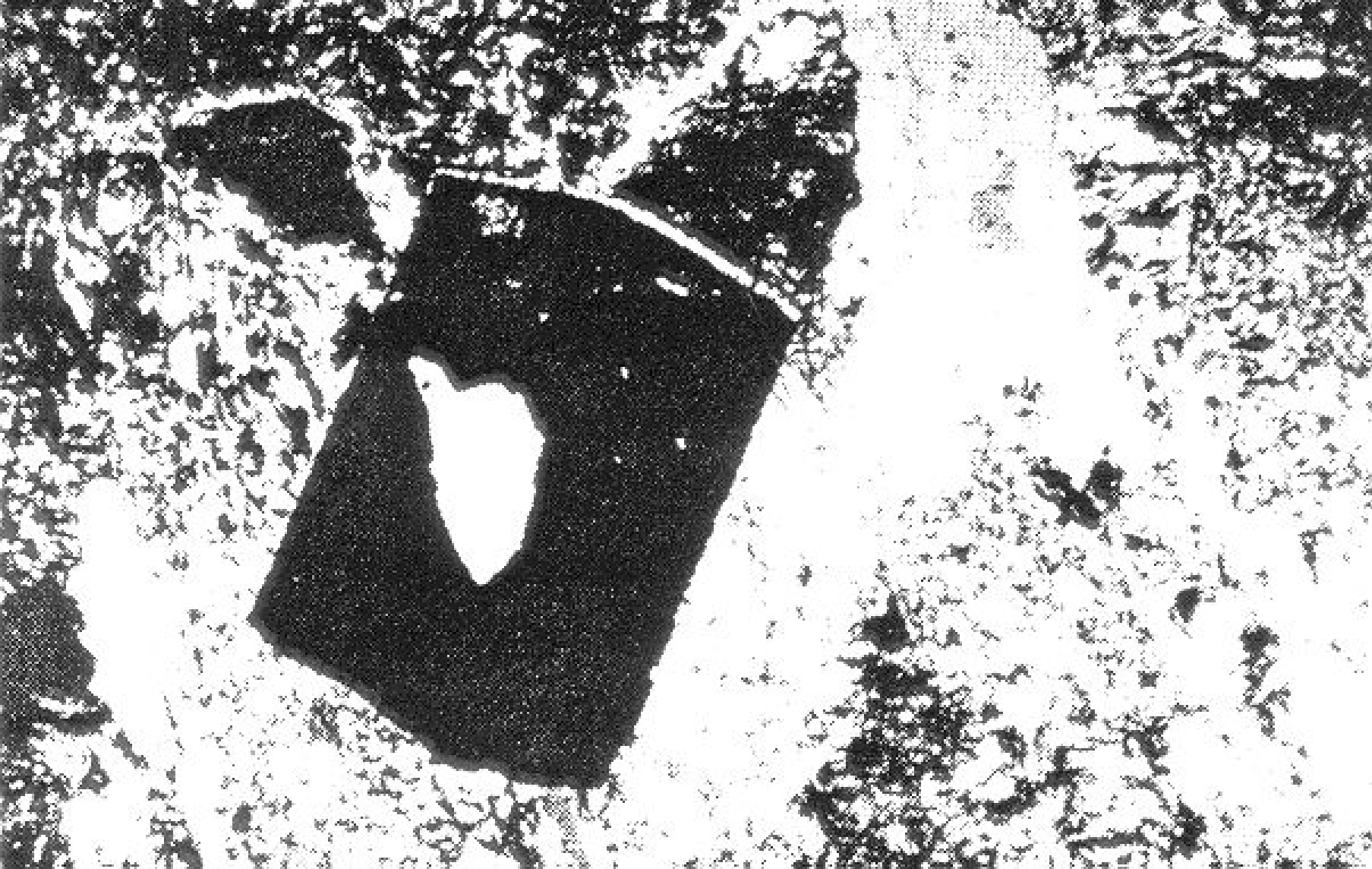


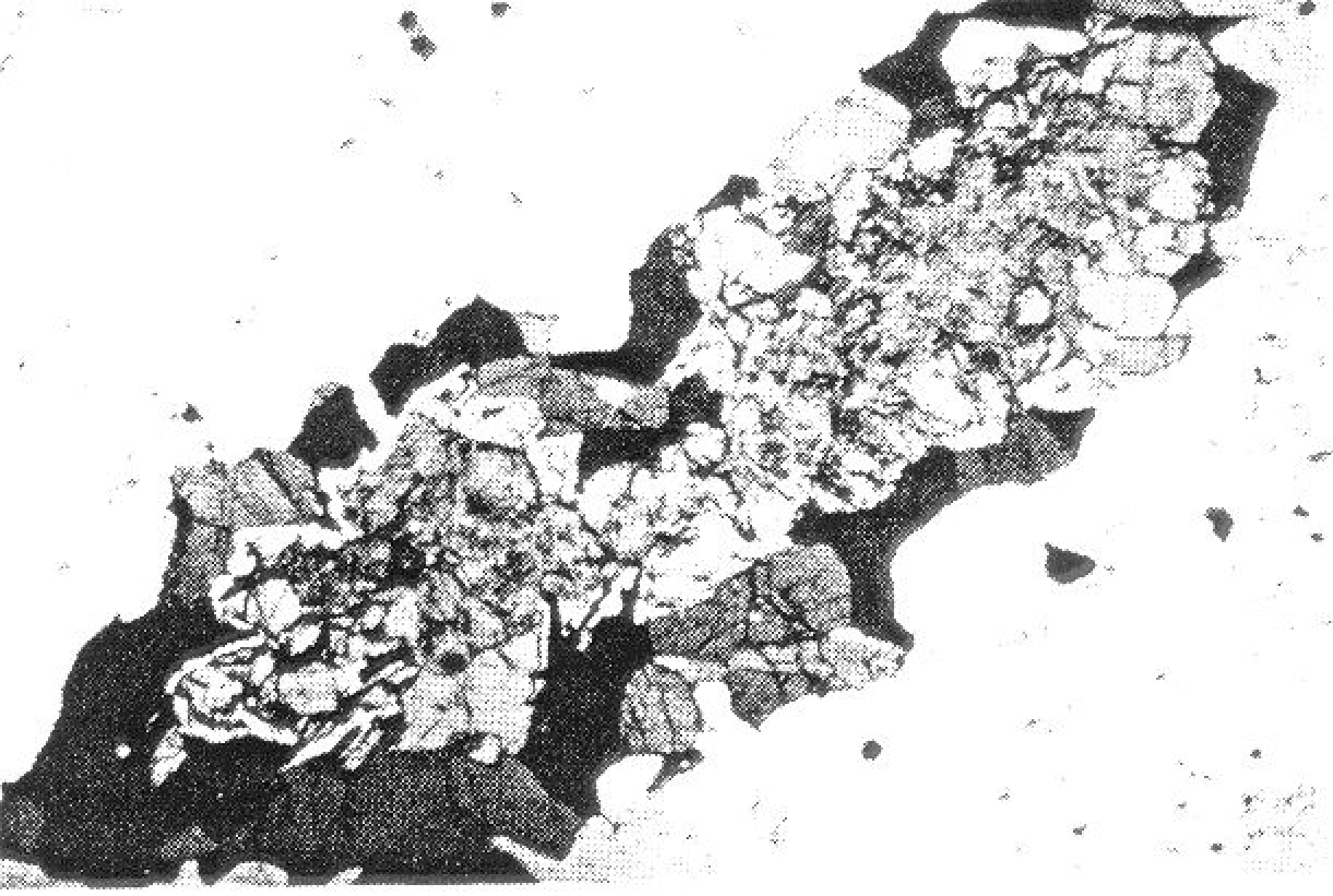


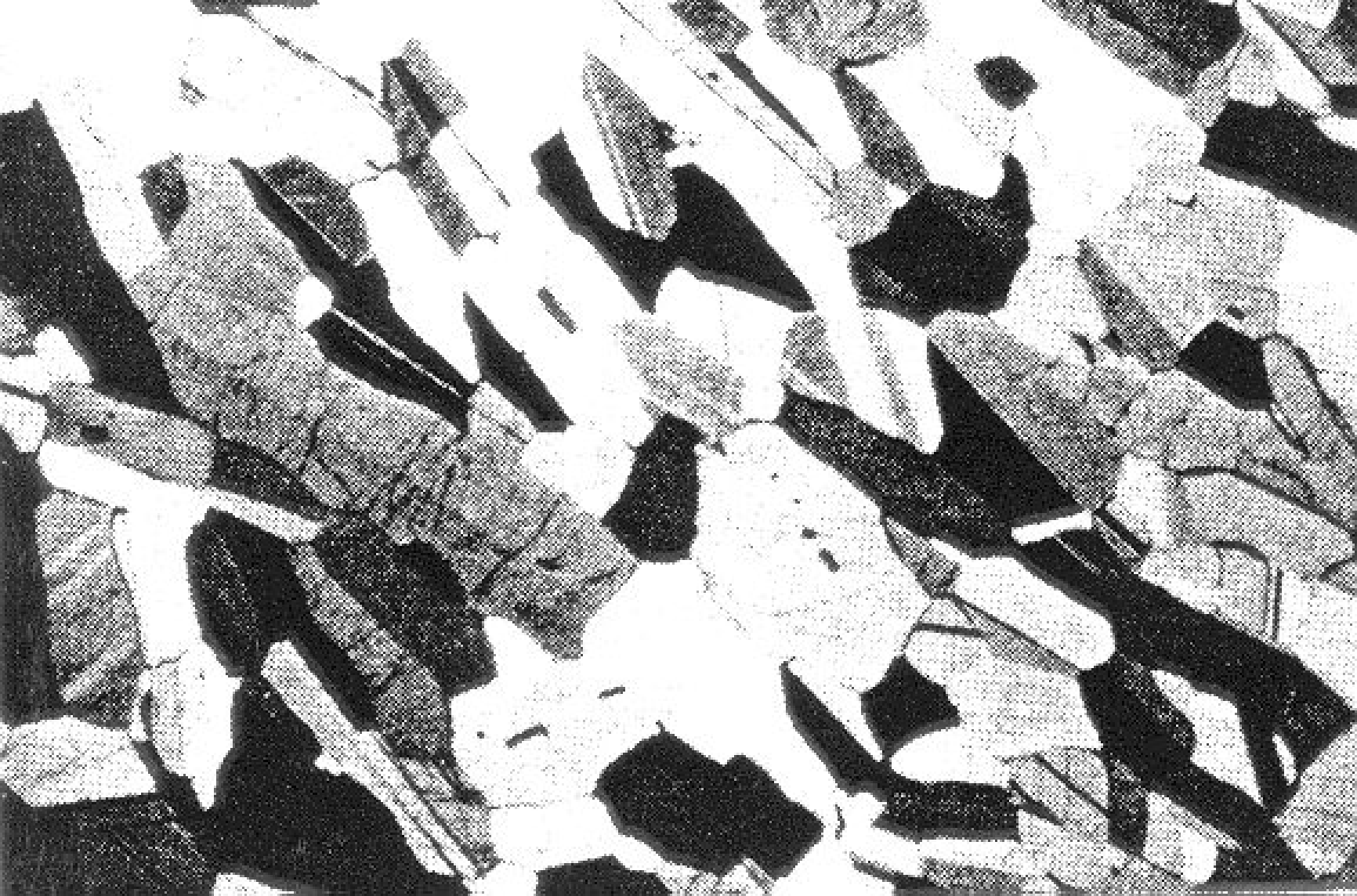




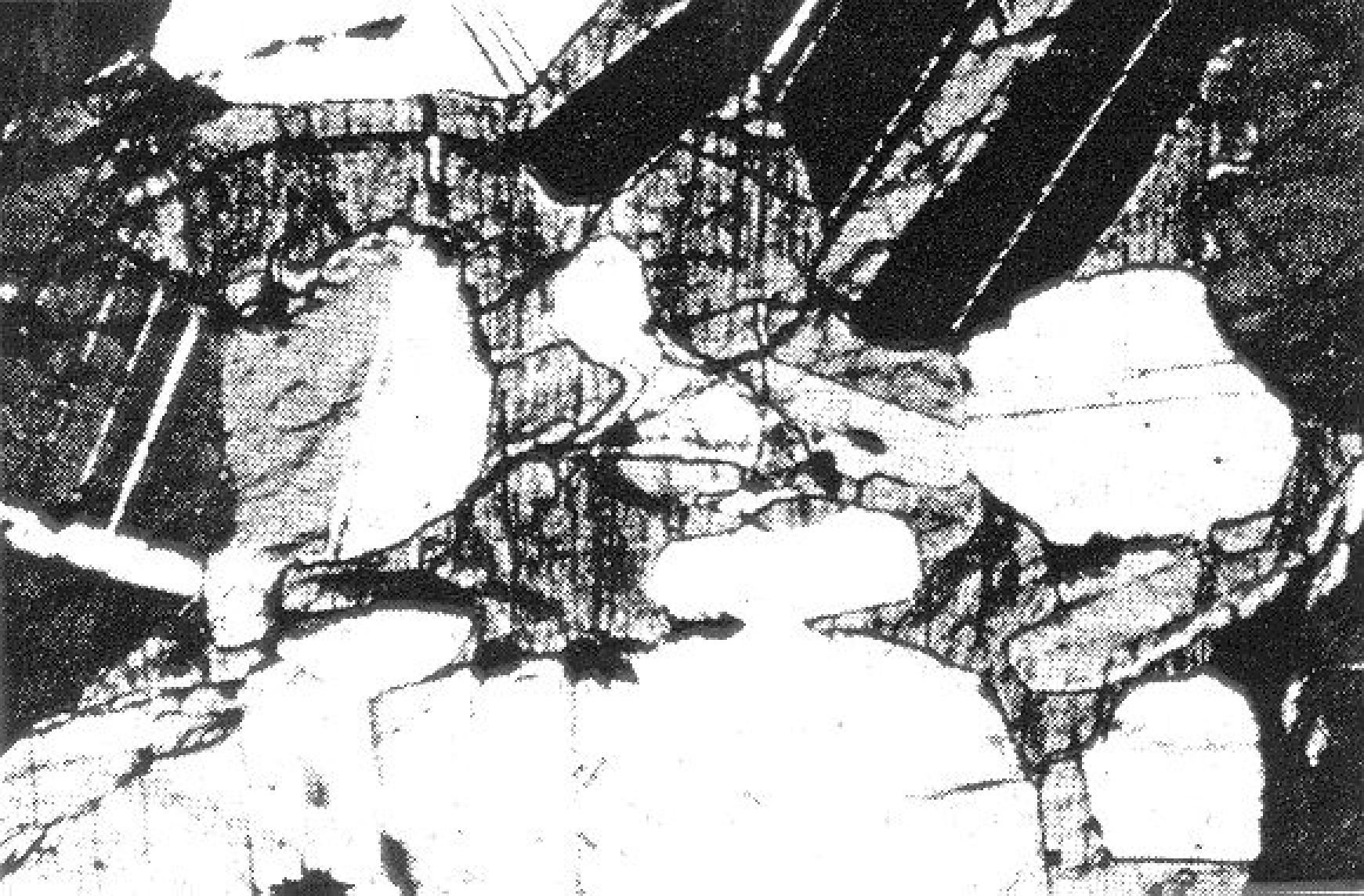


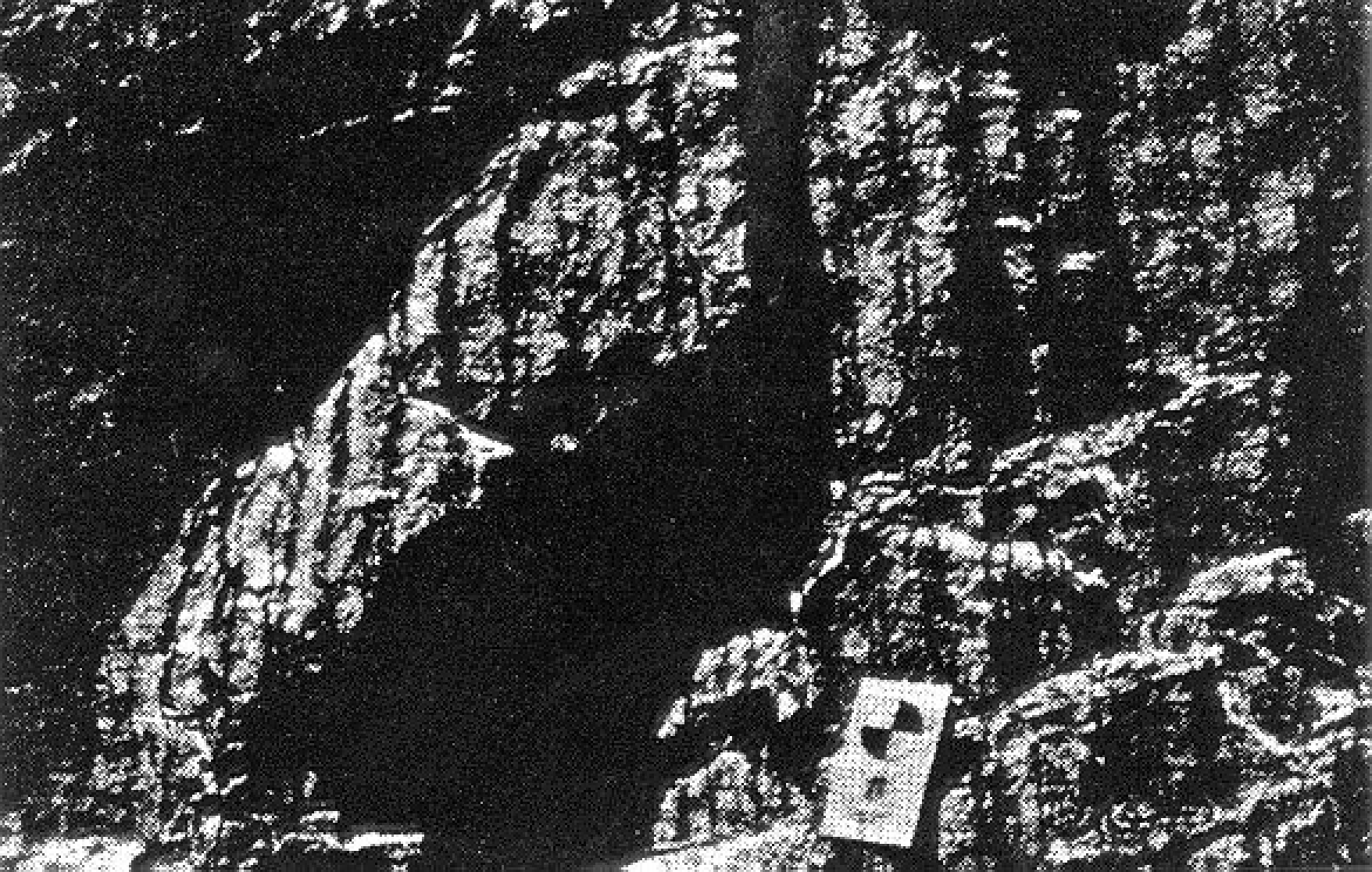


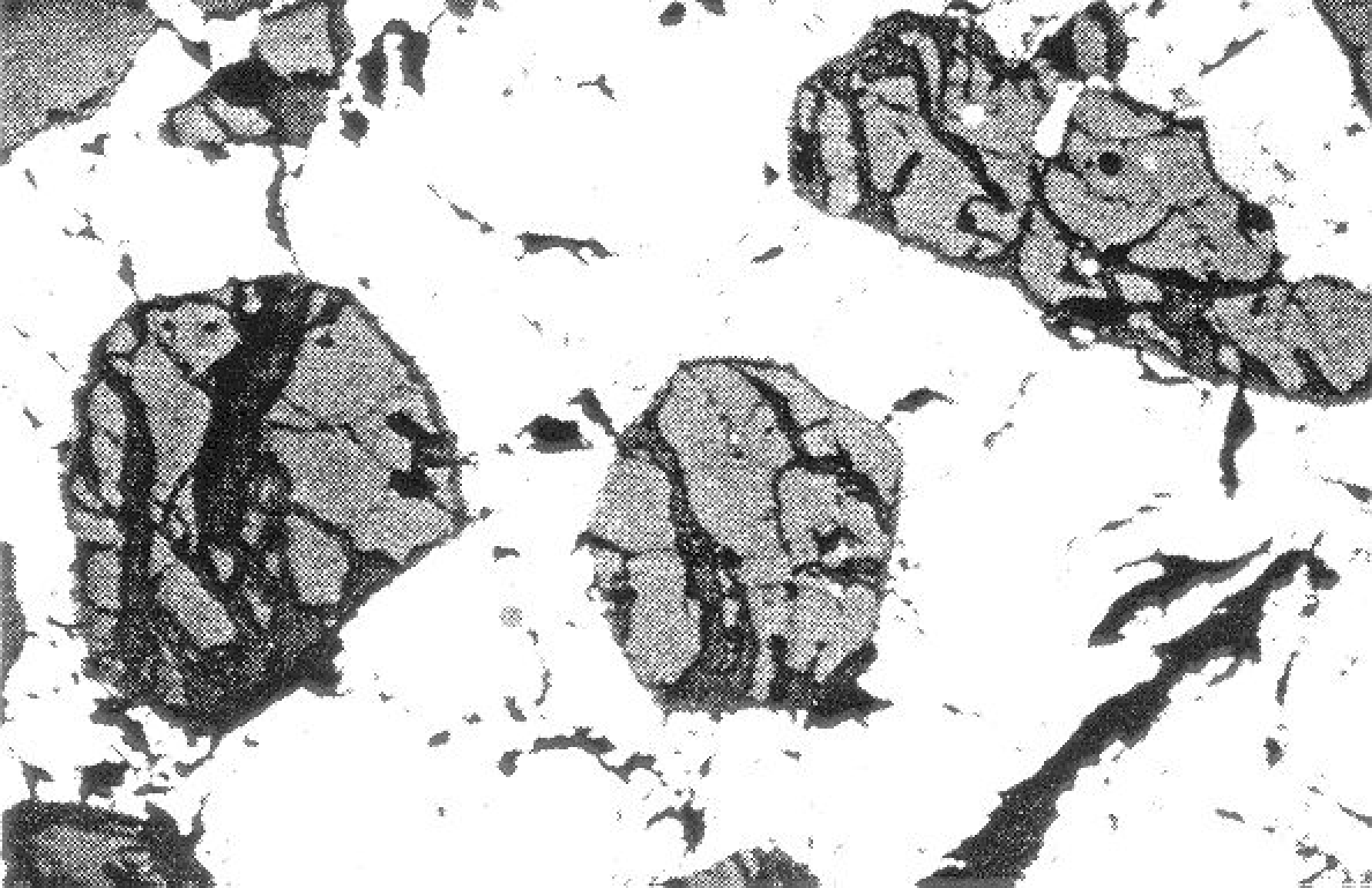


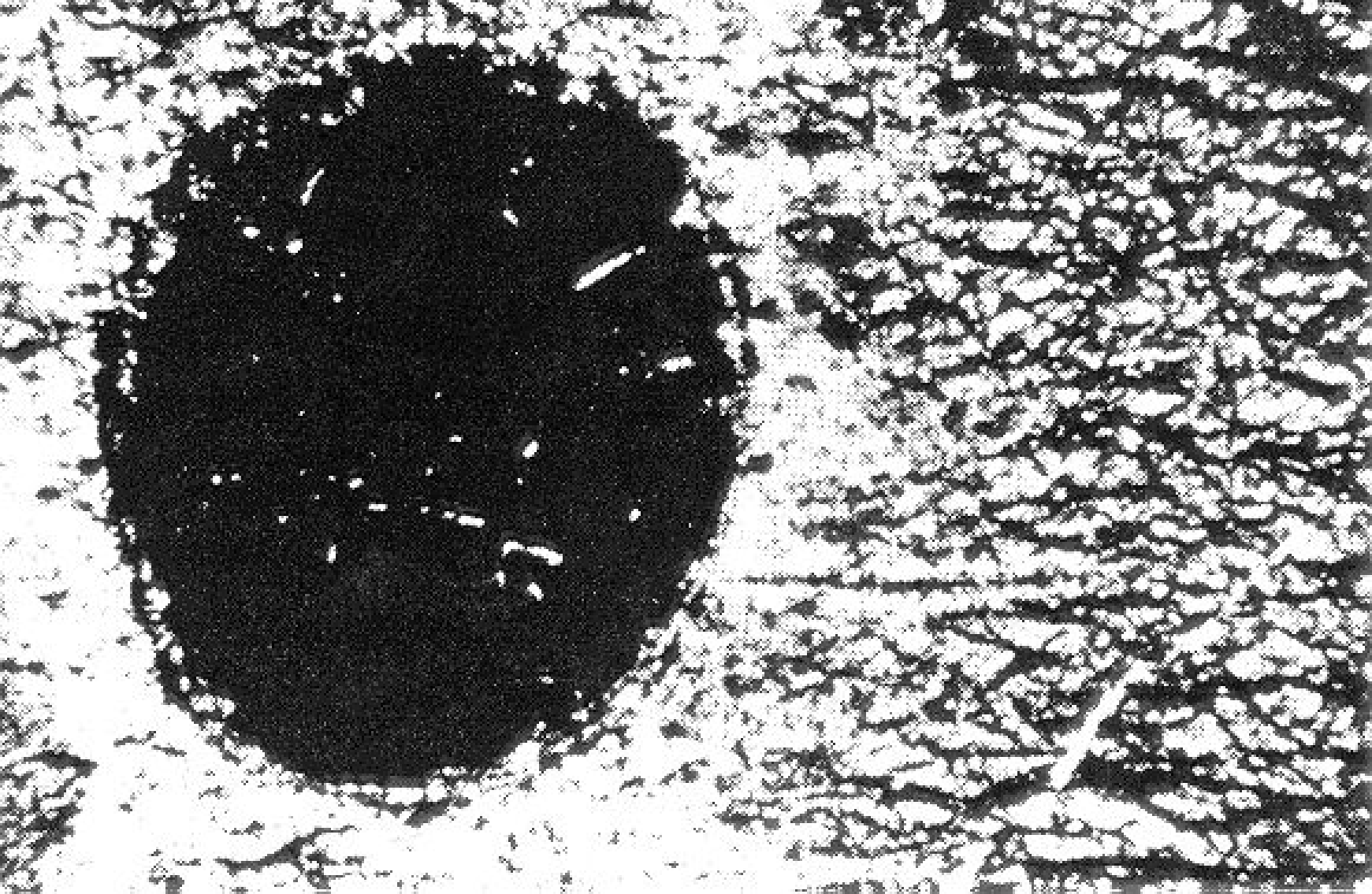


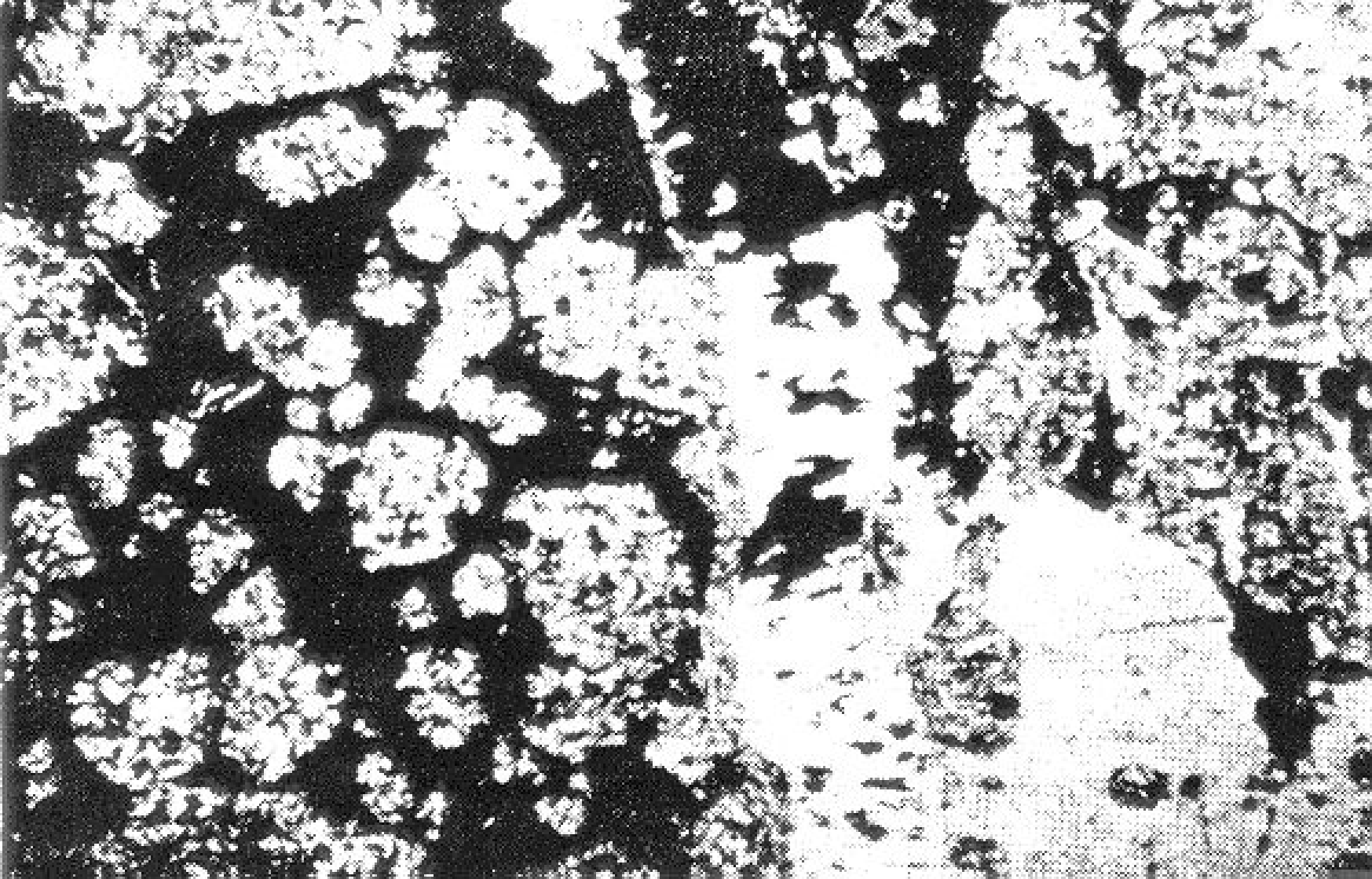


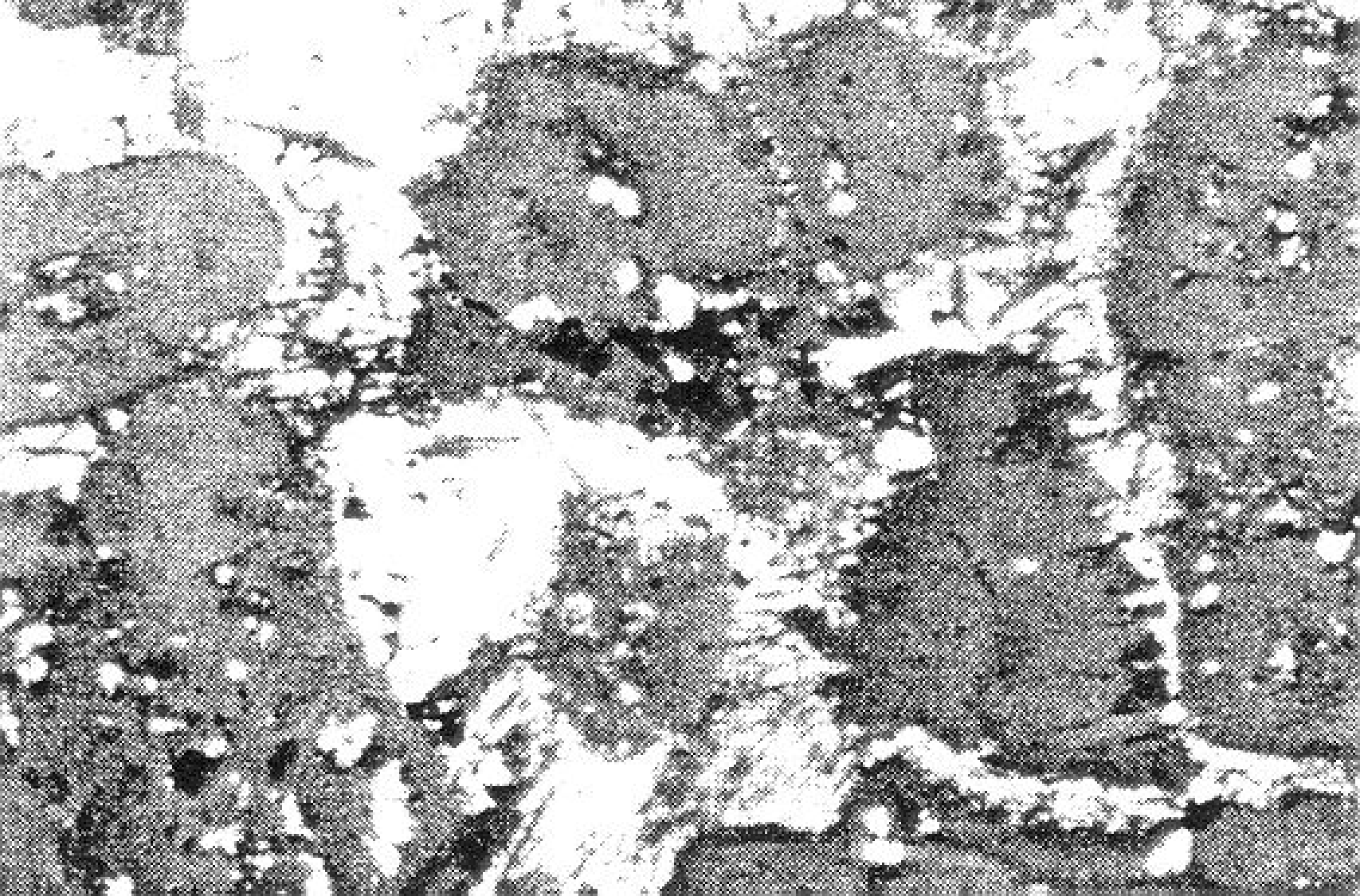










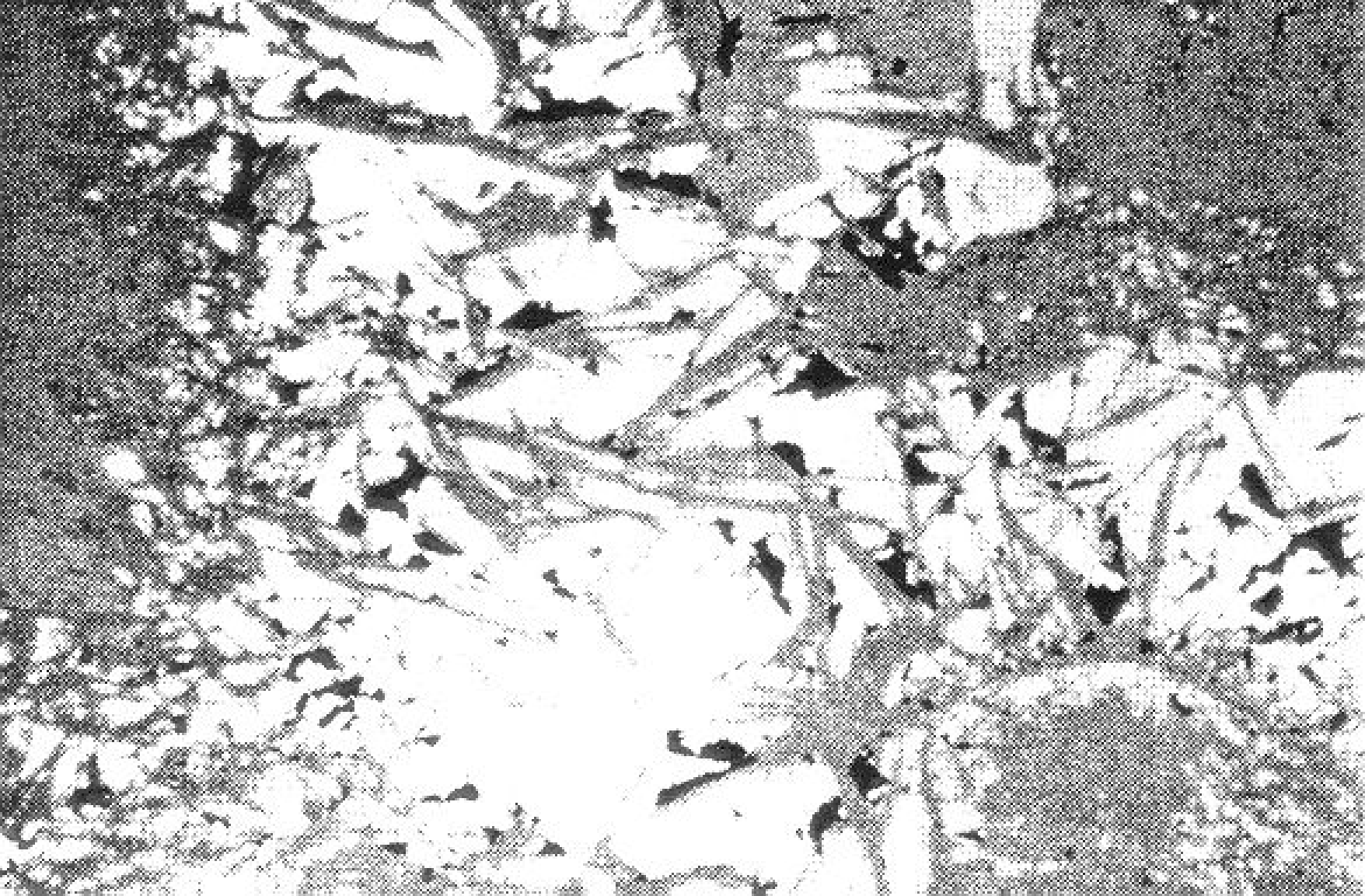




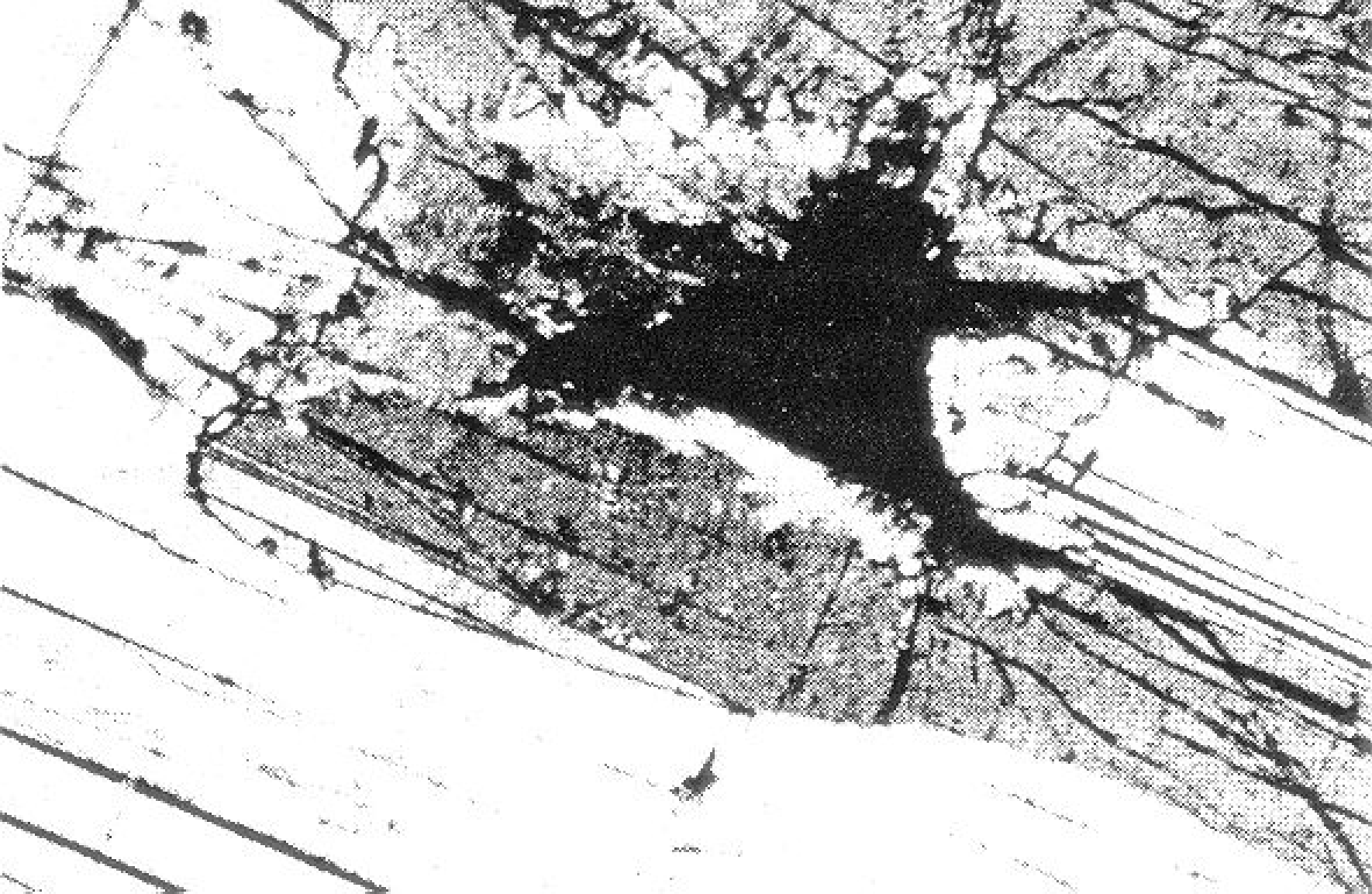




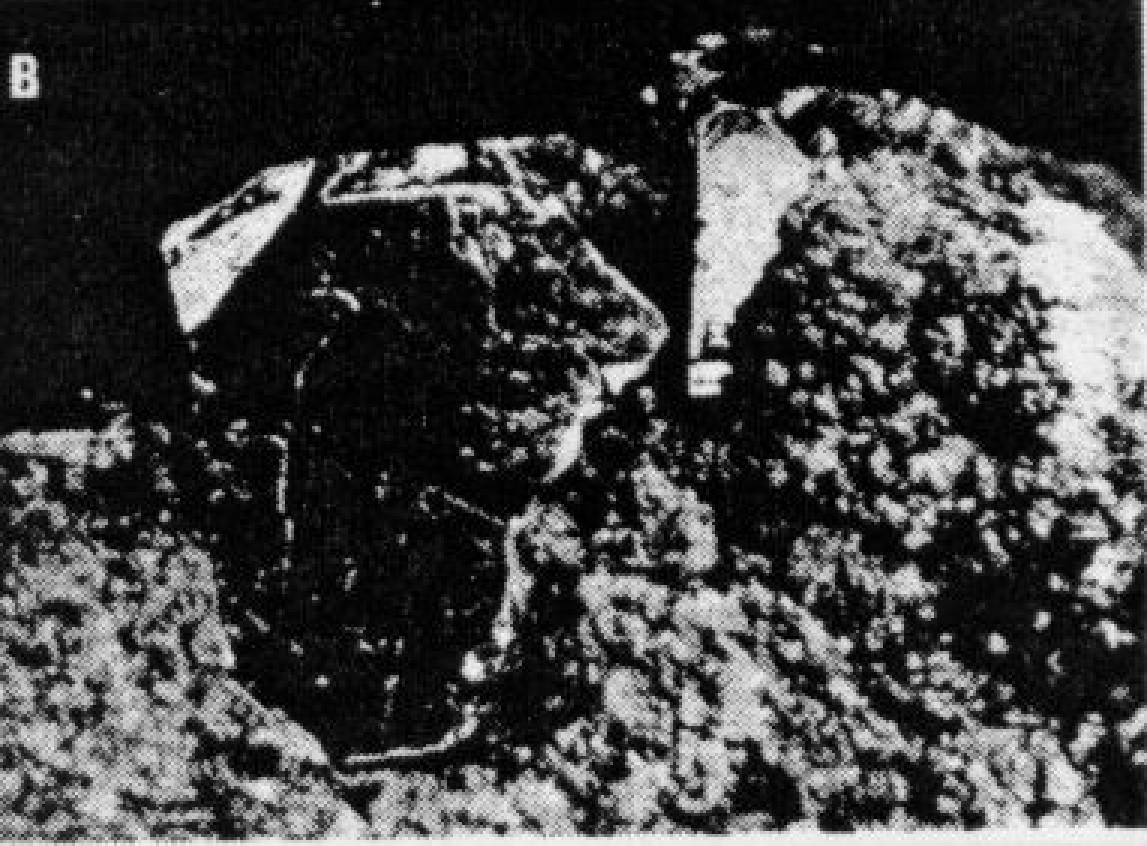


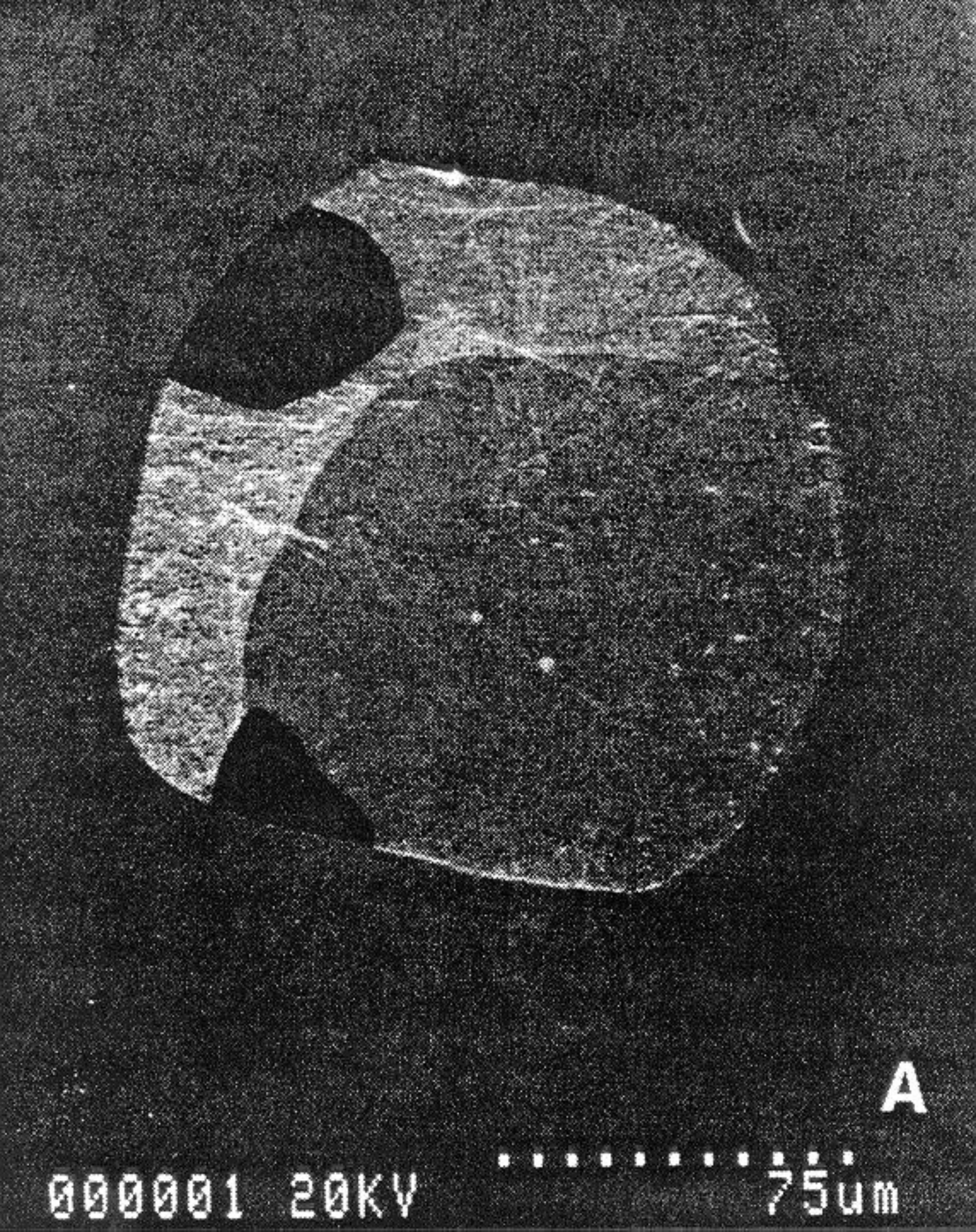


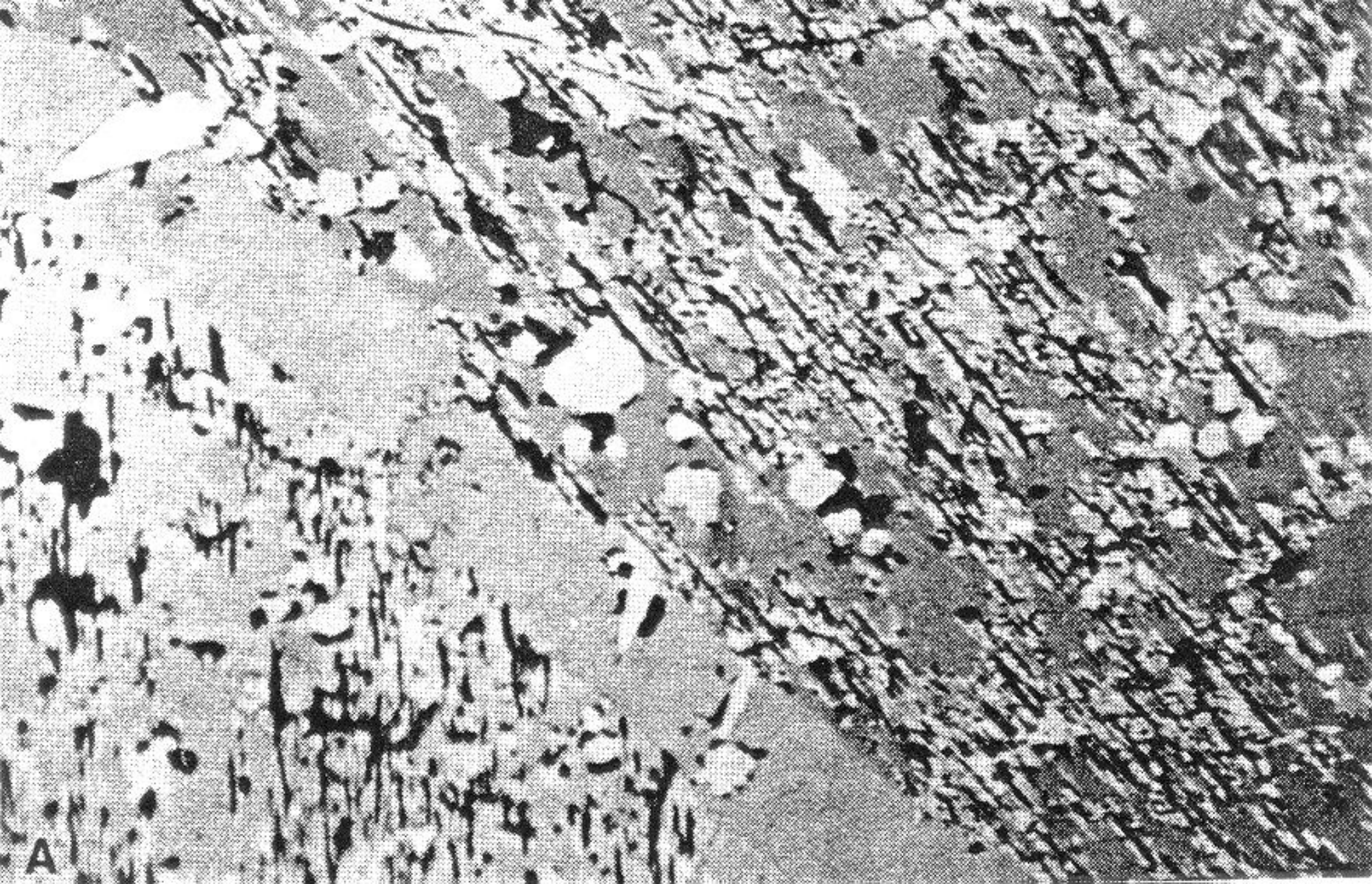


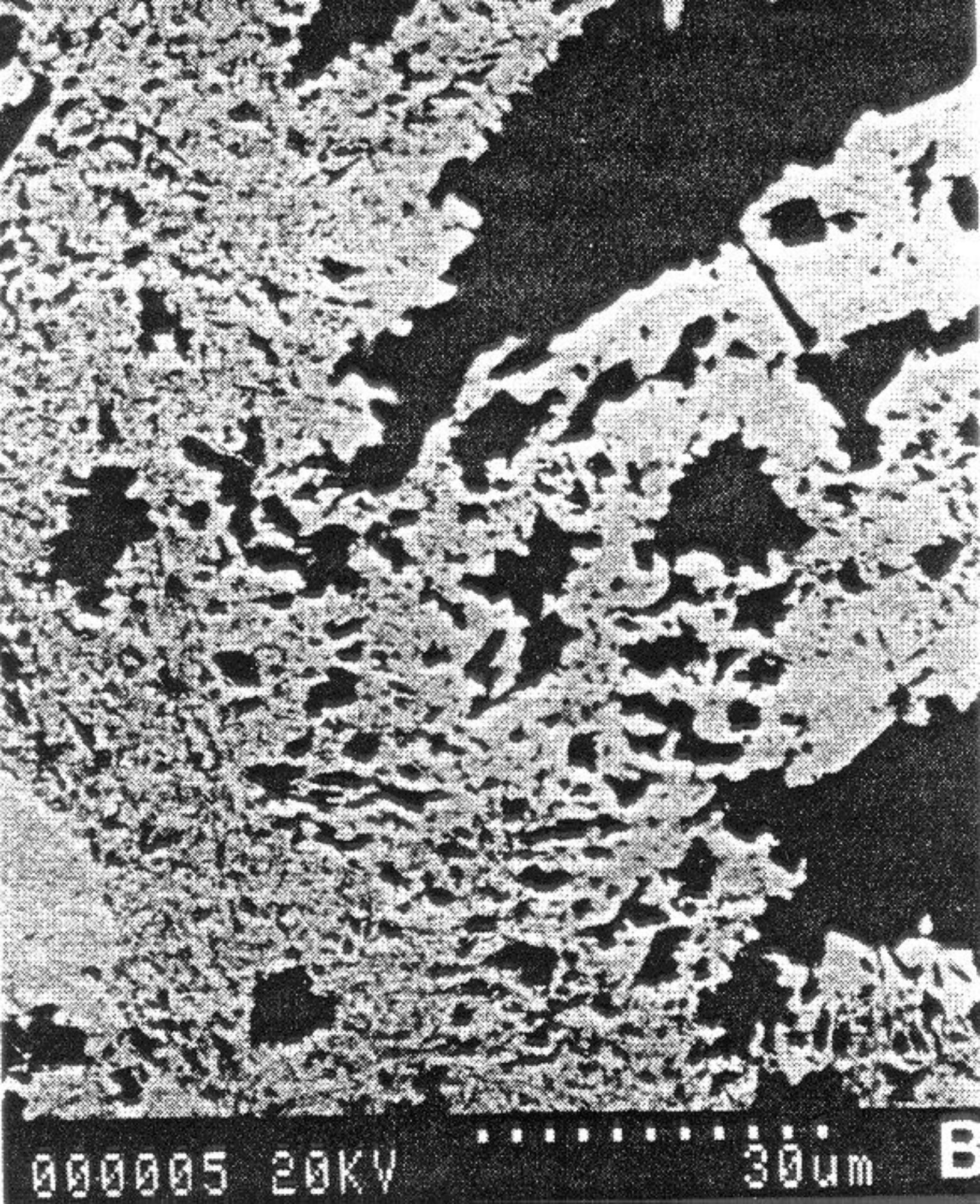





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