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ONTARIO GEOLOGICAL SURVEY

Open File Report 5705

Platinum Group Element Distribution in the Kanichee Intrusion District of Nipissing

by

D.J. Good

1989

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V.G. Milne

V.G. Milne, Director
Ontario Geological Survey

FOREWORD

Exploration interest in the Platinum Group Elements was renewed in the mid-1980's by anticipation of increased demands and concern over security of supply. In Ontario, this renewed interest was focused on mafic and ultramafic intrusive rocks of the Superior Province. One commonly used exploration model was developed on the hypothesis that the Platinum Group Elements were concentrated by magmatic processes during the crystallization of these intrusive rocks.

The Kanichee Intrusion in Strathy Township, which is one of these mafic - ultramafic plutons, has long been known as a host of sulphide mineralization. This report presents the results of a brief assessment of the potential of the Kanichee Intrusion, and others like it, to host concentrations of the Platinum Group Elements. It identifies geochemical signatures that might prove useful in exploration for other PGE-bearing sulphide deposits similar to that in the Kanichee Intrusion.

V.G. Milne
Director, Ontario Geological Survey

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ABSTRACT

The Kanichee Intrusion is composed predominantly of layered olivine plus clinopyroxene cumulates. Minor gabbro occurs at the top and at the margin of the intrusion. Previous studies of the intrusion were equivocal in establishing its magmatic parentage. However, the Mg Number, abundance of PGE and TiO_2, and the pattern of chondrite-normalized REE of the intrusion, determined in this study, are all compatible with an HREE- and Al_2O_3-depleted magma of komatiitic affinity.

A significant amount of Cu-Ni-precious metals is concentrated in vein sulphides at the north end or base of the intrusion. The vein sulphides, which represent remobilized magmatic sulphides, were compared to komatiite-associated, magmatic sulphides to identify relationships which could be used to determine the processes and conditions involved during remobilization. Analytical data show that Pd and Pt are enriched in the vein sulphides relative to Os, Ir, Ru, and Rh. The Pd/Ir ratio in the vein sulphides ranges between 12 and 485, and the chondrite-normalized ratios of Os and Ru to Ir are less than 1. When compared to komatiite-associated magmatic sulphides, these observations indicate that all of the PGEs are mobile during remobilization. However, Pd and Pt are fractionated from the Os group of elements, and Ir is fractionated from Os and Ru.

The relative mobilities, within the ore zone, of the trace elements As, Sb, S, Se and Bi and of the metals Cu, Ni, Au, and PGE were determined. From greatest to least, the relative mobility of the trace

elements is As > Bi> S = Se > Sb. The relative mobility of the metals is Pd > Cu = Au > Pt > Ir = Ni.

The extremely mobile nature of As in the system responsible for mineralization at Kanichee has enriched the As concentration in the unmineralized peridotite in the vicinity of the ore zone by up to 20 times. The exploration for an extension of the vein sulphides at Kanichee or in other komatiitic intrusions could be enhanced by exploring for the associated As halo.

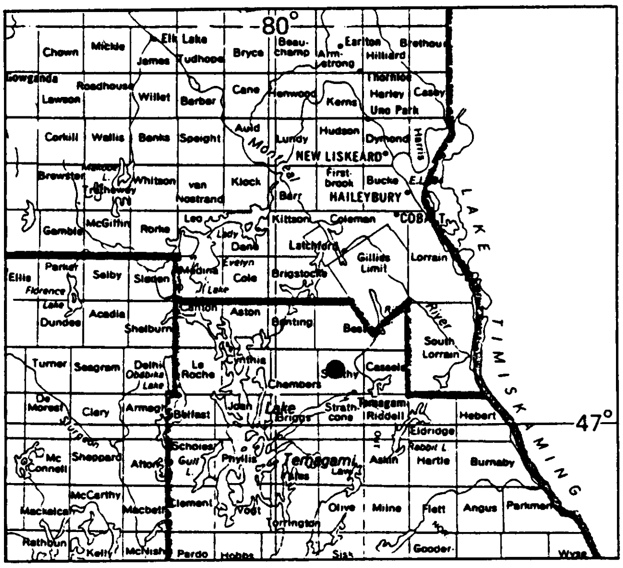
PLATINUM GROUP ELEMENT DISTRIBUTION IN THE KANICHEE INTRUSION, DISTRICT OF NIPISSING

by

D.J. Good[1]

INTRODUCTION

The Kanichee ultramafic/mafic layered intrusion is located 6.5 km northeast of the Town of Temagami in Strathy Township, northeastern Ontario (Figure 1).



Scale : 1:1 584 000 or
1 inch to 25 miles

Figure 1. Location of the Kanichee Intrusion.

In plan view, the exposed portion of the intrusion is approximately 1070 m thick and 760 m wide. Igneous layers in the

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Manuscript approved for publication by V.G. Milne, Director, Ontario Geological Survey, January 16, 1989.

intrusion face southeast, strike approximately northeast and dip steeply south. The intrusive body as a whole plunges to the southeast (James and Hawke 1984). At the north end or base of the intrusion, a significant amount of Cu-Ni-precious metals is concentrated in vein sulphides.

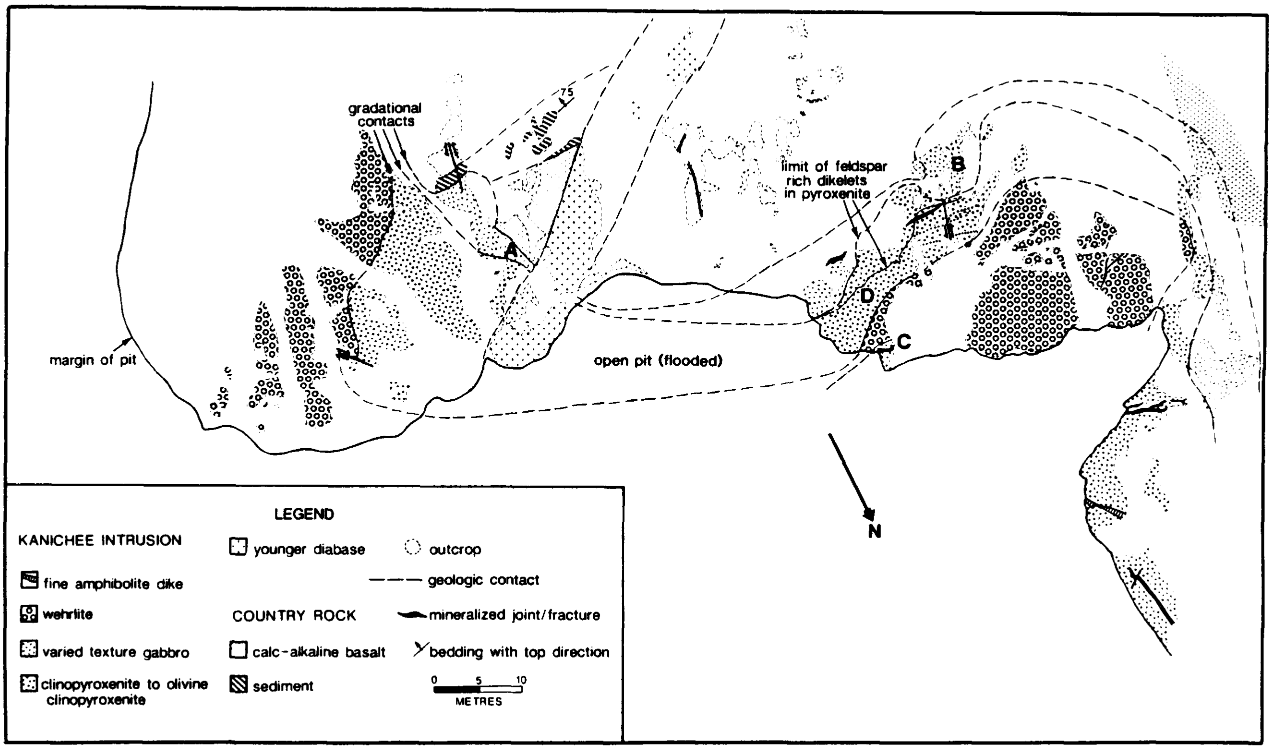

Figure 2. Geology of outcrop around the south edge of the open pit.

The composition of the parent magma of the Kanichee Intrusion had not been satisfactorily determined during previous studies. In fact, previous workers (*e.g.* Hawke 1982, James and Hawke 1984) provide contradictory evidence as to whether the magma was tholeiitic or komatiitic. The first objective of this study, therefore, was to classify the intrusion, based upon major and trace element and REE and PGE data for unmineralized and relatively unaltered samples. This classification was essential to the second part of the study, in which the Cu-Ni-precious metal vein-sulphide mineralization at the base of the intrusion was compared with sulphides from magmas of the same type.

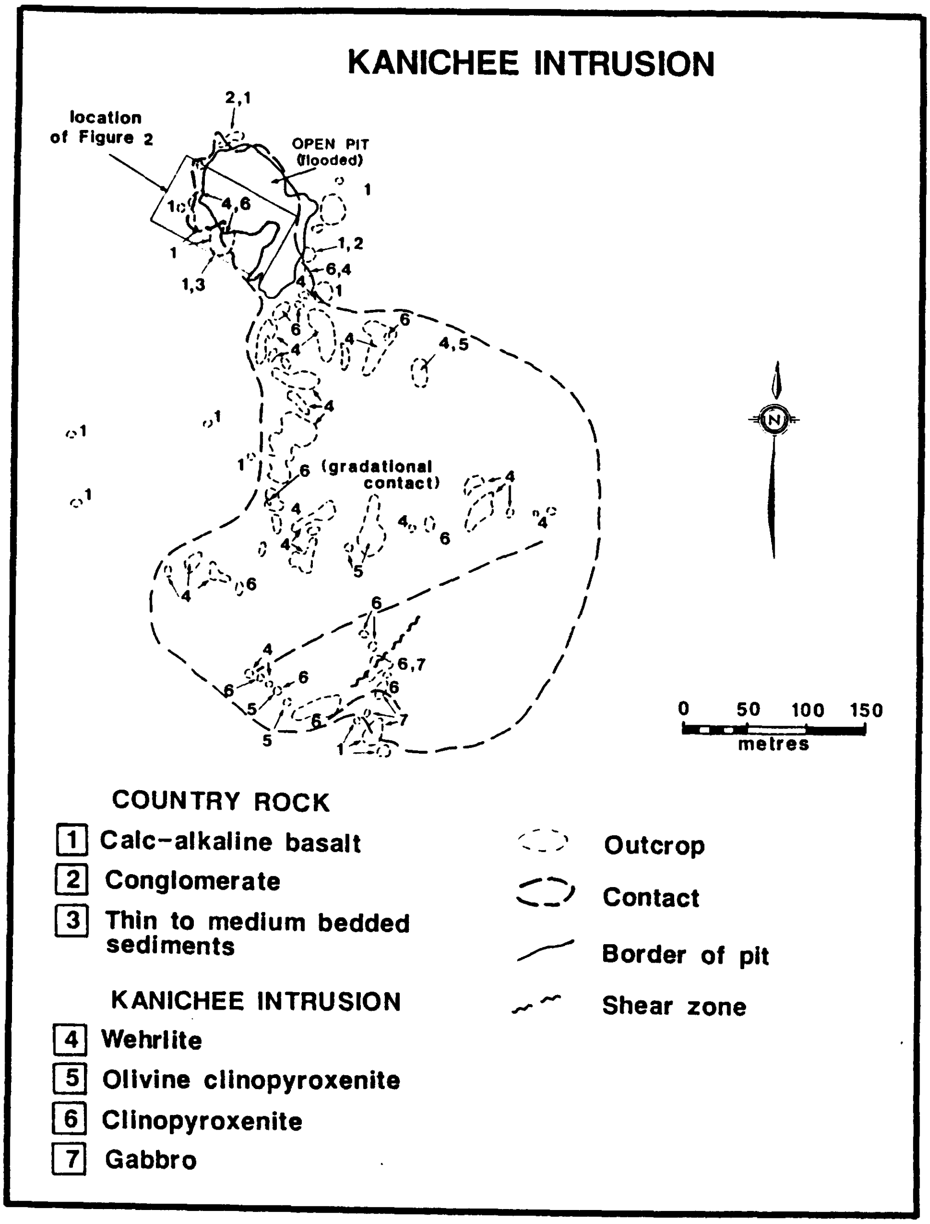

Figure 3. Geology of the Kanichee Intrusion.

For this study, new outcrop along the southwestern edge of the open pit, exposed by overburden removal, was mapped at a scale of 1:250 (Figure 2), and the rest of the intrusion was mapped at a scale of approximately 1:4800 (Figure 3). Twenty-seven samples were analyzed for major, trace, REE, and Platinum Group Elements (PGE).

PREVIOUS WORK

The Kanichee (also known as the Cuniptau or Ajax) Intrusion has been the focus of several studies. It was examined during regional mapping projects by Moorhouse (1942) and by Bennett and Innes (1971). Bennett (1978) described some petrology of the intrusion. A mineralogical study of two hand specimens of sulphide ore from the intrusion was conducted by Cabri and Laflamme (1974). The petrology and geochemistry of the intrusion were described by Hawke (1982) and James and Hawke (1984).

MINE PRODUCTION

The deposit was mined in 1936 by Cuniptau Mines Limited (Thomson *et al.* 1957) and, between 1974 and February 1976, by Ajax Minerals Limited (Canadian Minerals Yearbook 1974, 1975, 1976).

Cuniptau Mines Limited produced a total of 45 tonnes of copper, 29.7 tonnes of nickel, 1,151 grams of gold, 28,304 grams of silver, 2,572 grams of platinum and 6,106 grams of palladium from 3,010 tonnes milled.

Ajax Minerals Limited excavated an open pit to a depth of 35 m and produced a total of 1,404 tonnes of copper and 617 tonnes of nickel from 251,437 tonnes of ore (Canadian Minerals Yearbook 1976). The average grade was 0.72% copper and 0.50% nickel. Documentation of precious metal production by Ajax Minerals Ltd. is unavailable, but the average assays of mill concentrate for 1974 and 1975 contained 11,140 ppb Pd, 2,023 ppb Pt, 2,049 ppb Au, 2.84% Ni and 9.56% Cu (Naldrett and Cabri 1976, p. 1145).

REGIONAL GEOLOGY

The Archean metavolcanic-metasedimentary stratigraphy in Strathy Township strikes northeast, faces south, and consists of two mafic to felsic cycles (Bennett 1978). These cycles are equivalent to the Lower Volcanic Group and Middle Volcanic Group described by Fyon and O'Donnell (1987). The Kanichee ultramafic/mafic body intruded interlayered conglomerate and calc-alkaline metavolcanic flows and pyroclastic rocks near the top of the Lower Volcanic Group (Fyon and O'Donnell 1987).

ACKNOWLEDGEMENTS

Assistance in the field and some independent mapping were provided by B. Sifrer. Dr. R.S. James, Professor, Laurentian University, is thanked for his contributions to the geological map around the open pit. Dr. J.A. Fyon, Ontario Geological Survey, is thanked for his input to the project. Dr. A.J. Naldrett, Professor, University of Toronto, and Dr. R.G.V. Hancock, Supervisor, Slowpoke Facility, University of Toronto, provided technical support in the preparation of PGE analyses. Mr. Eric Quaisar of Diepdaume Mines Limited is thanked for his permission to work on the property. Mr. B. Paterson, Ministry of Natural Resources, Temagami, provided assistance for overburden stripping.

PETROLOGY OF THE INTRUSION

The intrusion is predominantly ultramafic, with minor gabbroic components. Ultramafic layers comprise cumulate assemblages of olivine, clinopyroxene and minor igneous hornblende and chromite, and range in composition from dunite to clinopyroxenite. Hawke (1982) outlined 5 igneous cycles based on the geochemical and mineralogical trends of 44 samples collected on two traverses across the intrusion, and of 17 samples collected in the vicinity of the open pit. Cycles 1 to 4 of Hawke (1982) consist of a wehrlite or dunite base that grades upward to an olivine clinopyroxenite or clinopyroxenite top. Only cycle 5 exhibits the complete suite of rock types from dunite to gabbro.

A thin layer of gabbro is present at the contact with the surrounding calc-alkaline metavolcanic rocks near the open pit (Figure 2). It is not known whether this marginal gabbro is present elsewhere at the intrusion-country rock contact, due to poor outcrop exposure.

A geologic map (Figure 2) of the exposed outcrop around the open pit, compiled in part from previous work by Professor R.S. James of Laurentian University, indicates conformable layering of wehrlite and clinopyroxenite. Additional mapping over the rest of the intrusion (Figure 3) has outlined several thin, discontinuous layers of clinopyroxenite, ranging in thickness from less than 1 m to greater than 15 m, within the wehrlite. These clinopyroxenite layers have gradational contacts with the enclosing wehrlite. Similarly, layers of wehrlite and thin layers of plagioclase-bearing clinopyroxenite or melagabbro are found within the clinopyroxenite unit of cycle 5. It is evident, therefore, that layering in the intrusion is more complex than Hawke (1982) suggested.

The petrology of the intrusion is described in detail by Hawke (1982) and James and Hawke (1984) and the reader is referred to these sources for more complete descriptions.

Dunite in the Kanichee Intrusion consists of greater than 90 per cent fine grained cumulate olivine, minor cumulate chromite and minor intercumulus clinopyroxene. Minor intercumulus igneous hornblende is found locally in dunite of each cycle (Hawke 1982). In hand sample, the dunite is black.

Wehrlite consists of 40 to 90 per cent fine grained cumulus olivine, 10 to 60 per cent fine to medium grained clinopyroxene and minor chromite and primary hornblende. In hand sample, the wehrlite is dark grey to black.

Clinopyroxenite is medium to coarse grained, equigranular and contains up to 10 per cent fine grained olivine. Olivine clinopyroxenite is similar to clinopyroxenite, but contains up to 40 per cent fine grained olivine. Unaltered clinopyroxenite is light green in colour with a light orange-brown weathered surface. Where clinopyroxenite has been altered to amphibolite, it is dark green to black and has a green weathered surface.

In all rock types, olivine varies in grain size from less than 1 mm to 3 mm, but averages less than 1 mm. Olivine is completely altered to serpentine, and the serpentine is locally altered to tremolite (Photo 1) or talc (Photo 2).

Photo 1. Pseudomorph of clinopyroxene oikocryst altered to very fine, fibrous talc (light grey), with included olivine pseudomorphs which have been altered to serpentine, followed by tremolite. The opaque mineral is magnetite. The long dimension of the photo is 4.2 mm.

Clinopyroxene crystallizes as a post-cumulus phase in the dunite and wehrlite, but is a cumulate phase in the olivine clinopyroxenite and clinopyroxenite. It is intercumulus and fine grained in the dunite, but in wehrlite it forms coarse oikocrysts. Cumulus clinopyroxene is fine to medium grained, short prismatic, subhedral, and equigranular. Clinopyroxene is partially altered to tremolite, serpentine, talc or chlorite and commonly exhibits a sequence of reaction products. In Photo 1, the clinopyroxene has first been altered to serpentine and then to talc. In Photo 2, the clinopyroxene has been altered to tremolite and serpentine. Hawke (1982) stated that alteration of clinopyroxene is more intense in the lower portion of the intrusion, close to the ore zone, than in the upper cycles.

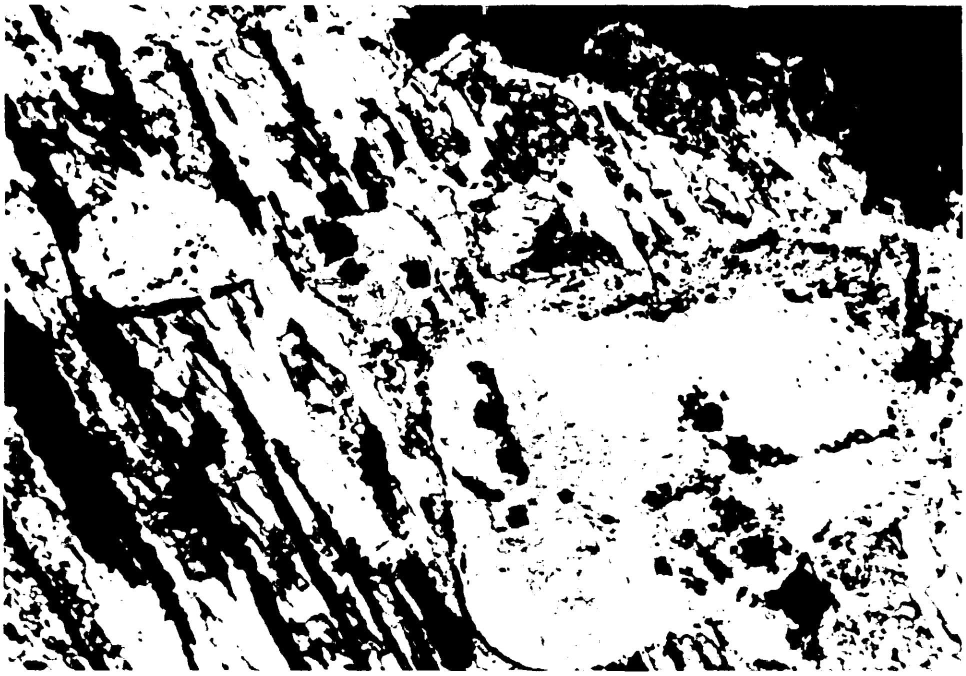

Photo 2. Pseudomorph of clinopyroxene oikocryst altered to serpentine and amphibole, with included olivine pseudomorphs which have been altered to serpentine, followed by talc. The long dimension of the photo is 4.2 mm.

Primary hornblende is brown, fine to medium grained, and intercumulus to olivine in the dunite and wehrlite. It is most abundant (up to 17 per cent) in the peridotites near the base of the intrusion, near the ore zone, and is a cumulate phase in unit 1C (hornblende clinopyroxenite) of Hawke (1982). In wehrlite, hornblende is commonly intergrown with clinopyroxene and forms 3 to 4 mm oikocrysts which include olivine. Clinopyroxene locally has rims or cores of the brown hornblende, possibly indicative of late magmatic equilibration. As seen in thin section, hornblende is weakly altered, relative to clinopyroxene, but it is locally partially altered to tremolite and chlorite.

The gabbro at the top of cycle 5 of Hawke (1982) is coarse grained, and consists of partially altered plagioclase, up to 10 mm in length, clinopyroxene, which is intensely altered to tremolite, and minor (1 per cent) igneous brown hornblende (Hawke 1982). Hawke (1982) reported granophyric intergrowths of quartz and plagioclase toward the top of cycle 5.

Gabbro also occurs at two points along the contact between the intrusion and the country rock (A and B, Figure 2). At point A, the contact between the gabbro and the calc-alkaline basalt is well exposed. At the contact, the gabbro decreases in grain size from medium to fine, and becomes more leucocratic over approximately 1 metre. Textures within 5 cm of the contact suggest partial assimilation of the calc-alkaline basalt. The contact is gradational and irregular. Embayments of the gabbroic material in the basalt are observable on the scale of millimetres.

At point B, the gabbroic unit is heterogeneous in both composition and grain size. These variations are irregular and observable over distances of millimetres to metres. The composition ranges from melagabbro to leucogabbro, and the grain size ranges from less than 1 mm to 3 to 5 mm. However, approaching the contact with the pillowed calc-alkaline basalt, grain size decreases to 1 mm. The contact is sharp.

SULPHIDE MINERALIZATION

Based on field observations, there are four settings for Fe-Ni-Cu sulphide mineralization:

1. sulphide-carbonate-quartz or sulphide-carbonate-talc-serpentine veins. The veins fill joints and faults, predominantly at the north end, or base, of the intrusion.

2. disseminated, fine to coarse blebs of sulphide within a halo marginal to mineralized joints and faults.

3. fine, disseminated to net-textured sulphides within the peridotite at the base of the intrusion and near the ore zone. These are presumably of magmatic origin, but are possibly hydrothermally modified.

4. trace amounts of fine, disseminated sulphides within the peridotite of cycles 2 to 5 of Hawke (1982), away from the ore zone and its associated alteration.

The sulphide veins (type 1) are associated with calcite, talc, serpentine, quartz, chlorite or tremolite. Sulphide minerals present in the veins are chalcopyrite, pyrrhotite, pentlandite, and minor pyrite, sphalerite, galena, mackinawite, violarite and covellite.

The orientations of joints in one outcrop (point C, Figure 2) were measured to determine the spatial relationships among barren, sulphide-bearing, and silicate- or calcite-bearing joints. The data (Figure 4) indicate two dominant sets of mineralized joints that trend northeast and northwest. The joint surfaces are moderate to steeply dipping; however, a very shallow-dipping, sulphide-mineralized joint occurs close to outcrop C. There does not appear to be any difference in orientation between barren and mineralized joints.

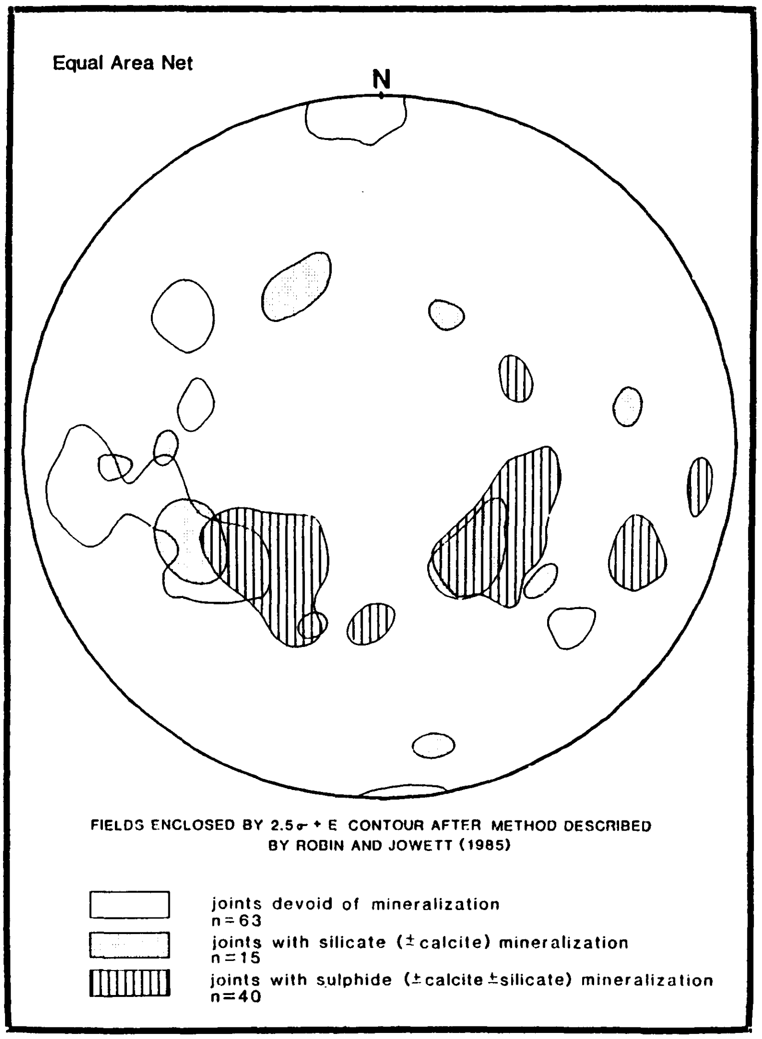

Figure 4. Contoured equal area stereographic plot of poles to joints in Outcrop D, Figure 2.

Type 2 mineralization consists of chalcopyrite, pyrrhotite, pentlandite and pyrite. On a thin section scale, these sulphides are associated with the most hydrothermally altered areas. For example, in a sample of wehrlite consisting of serpentinized pseudomorphs of olivine and fresh intercumulus clinopyroxene, the sulphides are commonly located in patches surrounded by chlorite or fibrous serpentine. The typical width of a sulphide halo is unknown, since most of the ore zone has been excavated. However, the halo to one, 1-3 cm thick, sulphide vein in outcrop C (Figure 2) is 10-30 cm thick.

Type 3 mineralization consists of pyrrhotite, pentlandite, and chalcopyrite. These sulphides, which presumably segregated from the silicate melt, are interstitial to cumulate olivine and should be representative of the sulphides from which the vein sulphides were derived. However, owing to the extent of hydrothermal activity which led to the precipitation of the sulphide-carbonate veins, it is likely that the compositions of the primary sulphide minerals were modified.

Type 4 sulphides, which include pyrrhotite, pentlandite and chalcopyrite, are located interstitial to olivine in dunite and wehrlite of cycles 2 to 5. This type of mineralization was considered to be the least altered in the intrusion.

The textures and modes of occurrence of the four types of sulphide mineralization suggest that types 1 and 2 contain remobilized magmatic sulphides, whose compositions are different from their magmatic precursors. The compositions of sulphides in type 4 mineralization are believed to be those of the unaltered magmatic sulphides, and the sulphides in type 3 mineralization are believed to be magmatic sulphides that have been hydrothermally altered during the emplacement of the vein sulphides. Comparisons of the different types of mineralization should, therefore, reveal something of the conditions and processes of remobilization. However, such comparisons require an understanding of the magmatic parentage of the Kanichee Intrusion in order to model the compositions of the original magmatic sulphides.

GEOCHEMISTRY OF THE KANICHEE INTRUSION

In previous publications, the magmatic parentage of the Kanichee Intrusion was a point of debate. Hawke (1982) showed that two diagrams commonly used to separate rocks of tholeiitic origin from those of komatiitic origin provide contradictory evidence. On a plot of Al_2O_3 vs FeO/FeO+MgO (weight per cent), the olivine plus clinopyroxene cumulates in the Kanichee Intrusion lie within the field of tholeiites and the gabbro plots in the field of komatiites. However, on a plot of TiO_2 vs MgO (weight per cent), the olivine plus clinopyroxene cumulates plot within the field of komatiites. Hawke (1982) concluded that the magma was intermediate between komatiitic and tholeiitic end members.

James and Hawke (1984) determined the composition of the initial magma by using a mass balance calculation for the proportions of rock types in cycle 5. They concluded that the magma was of tholeiitic origin, because the Al_2O_3/TiO_2 and CaO/Al_2O_3 ratios of their model composition (approximately 10 and 1.1, respectively) were consistent with a high-magnesium, tholeiitic magma. This calculation assumes that the sequence of dunite to gabbro in cycle 5 represents the end product of the complete crystallization of a primary magma, and does not take into account the cumulates of cycles 1 to 4 and the resulting fractionated liquid. Nor does it take into account the expected variation in thickness of each unit of cycle 5 in the third dimension. The possibility that too much or too little gabbro, and therefore plagioclase, was used in the calculation would give erroneous Al_2O_3 concentrations. This, in turn, would result in misleading Al_2O_3/TiO_2

TABLE 1. Whole rock major and trace element analyses of samples from the Kanichee Intrusion.

Sample No.	167	168	169	170	171	172	174	175	176	203	204	211	213	214	267	269	270
Rock Type	per	per	per	per	per	olcpx	olcpx	weh	weh	dun	cpx	gab	cpx	olcpx	weh	weh	weh
SiO_2	41.20	42.50	44.60	44.70	40.40	47.40	46.20	39.70	40.90	38.40	49.90	47.70	51.30	47.20	44.30	41.80	42.50
TiO_2	0.50	0.53	0.56	0.57	0.49	0.69	0.72	0.51	0.60	0.22	0.50	0.82	0.59	0.46	0.60	0.57	0.58
Al_2O_3	4.67	4.91	5.21	5.27	4.51	5.53	6.14	5.07	4.77	2.09	3.64	13.20	3.99	2.91	5.47	5.83	5.59
Fe_2O_3	16.40	15.20	13.30	13.60	17.40	12.70	13.40	15.30	15.10	16.60	10.80	13.10	10.00	12.50	15.50	15.70	15.50
MnO	0.17	0.16	0.09	0.08	0.12	0.20	0.25	0.16	0.15	0.21	0.19	0.22	0.17	0.16	0.13	0.15	0.15
MgO	25.50	25.40	24.20	24.20	26.10	19.80	17.90	24.90	26.00	30.20	20.30	9.99	16.00	21.90	22.40	23.50	23.50
CaO	3.64	3.82	2.67	2.41	1.88	9.02	9.92	5.08	4.15	2.32	9.85	10.40	12.30	10.60	4.96	4.81	4.37
Na_2O	0.00	0.09	0.00	0.00	0.26	0.06	0.25	0.14	0.00	0.03	0.00	1.29	0.69	0.04	0.08	0.00	0.00
K_2O	0.04	0.05	0.02	0.02	0.03	0.05	0.08	0.05	0.05	0.02	0.02	0.26	0.05	0.02	0.05	0.04	0.04
P_2O_5	0.01	0.01	0.03	0.02	0.01	0.05	0.05	0.02	0.04	0.00	0.02	0.04	0.02	0.03	0.04	0.03	0.04
CO_2	1.07	0.74	2.28	2.11	0.60	0.11	0.80	1.81	0.95	0.33	0.17	0.20	2.10	0.61	0.21	0.79	0.46
S	0.76	0.34	1.11	1.31	0.80	0.04	0.02	0.19	0.22	0.17	0.01	0.06	0.06	0.01	0.76	0.15	0.21
LOI	7.70	7.20	6.70	6.70	8.20	4.00	4.10	8.40	7.50	9.30	3.50	2.90	3.70	4.30	5.40	7.00	6.90
TOTAL	99.80	99.90	97.40	97.60	99.40	99.50	99.00	99.30	99.30	99.40	98.70	99.90	98.80	100.10	98.90	99.40	99.20
Nb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Rb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sr	33	37	71	64	23	31	39	57	42	18	23	322	43	23	28	45	39
Y	8	10	8	9	8	16	14	10	12	4	4	13	10	9	9	12	11
Zr	48	51	52	52	44	58	58	53	52	29	34	86	40	34	47	56	55

Notes:

Major elements in weight percent; trace elements in ppm; Fe_2O_3 = total Fe; nd = not detected.

All sample numbers are preceded by 87DJG-; dun = dunite, cpx = clinopyroxenite, gab = gabbro, weh = wehrlite, olcpx = olivine clinopyroxenite.

Samples 167 to 171 are peridotite with disseminated to net-textured sulphides, and were collected from the rubble pile.

and CaO/Al_2O_3 ratios. Conclusions based on this model composition, therefore, are unreliable.

Major and trace element analyses of twenty-seven samples of the Kanichee Intrusion were completed to provide data to re-evaluate its magmatic parentage, and allow further study of the sulphide mineralization.

ANALYTICAL METHODS AND SAMPLE SELECTION

All of the samples were analyzed for major and trace elements (Cu, Ni, Pt, Pd, Au, S, Se, Sb, Bi, and As) at the Geoscience Laboratories, Ontario Geological Survey. The resulting data are reported in Tables 1 to 4. Pt, Pd and Au concentrations were determined by ICP/MS methods. The complete spectrum of PGE (Os, Ir, Ru, Rh, Pt, and Pd) and Au were also determined by the author using the fire assay/INAA (induced neutron activation analyses) technique (after Hoffman 1978), and these values are reported in Tables 3 and 4. Three samples were analyzed for REE by the Geoscience Laboratories, Ontario Geological Survey, and are reported in Table 2.

Sample groups 87DJG-161 to 166 and 87DJG-166 to 171 were collected from the rubble pile on the north side of the open pit. Samples in the first group contain calcite, quartz, talc, serpentine and sulphide (type 1 mineralization), and were broken from large blocks. The second group was selected from large blocks of peridotite containing disseminated to net-textured sulphide (type 2 mineralization). Sample groups 87DJG-172 to 176 and 87DJG-267 to 270 were collected from the outcrop along the south edge of the open pit (Figure 2). The sample group comprising

87DJG-203, 204, 211, 213, 214, and 215 was selected from the remainder of the intrusion, away from the ore zone (Figure 3).

RESULTS

Major Elements

Hawke (1982) showed that the major element geochemistry of the intrusion was controlled by variations in the abundance of olivine and clinopyroxene. Figure 5 is a plot of SiO_2 against Mg Number (atomic per cent $Mg/Mg+0.9Fe_{total}$) and demonstrates how the compositions of olivine

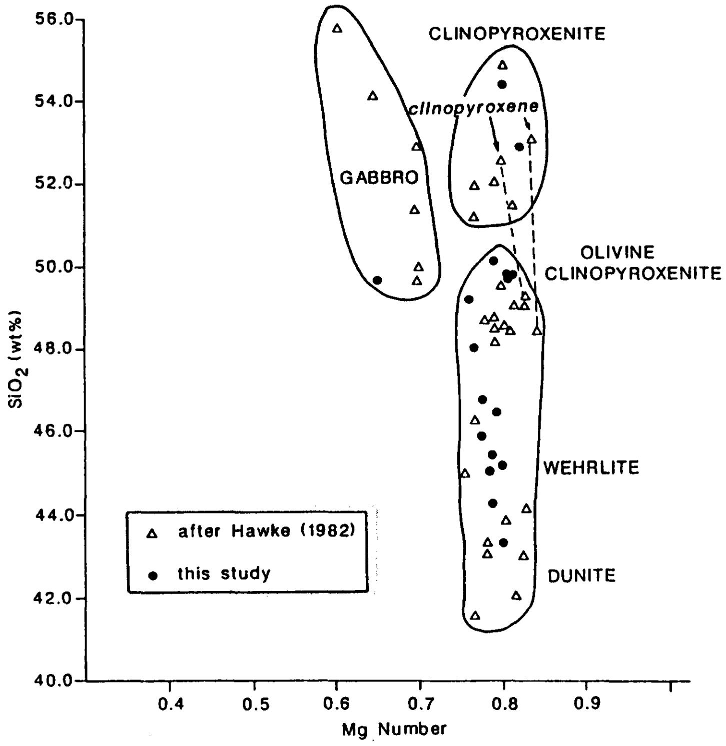

Figure 5. Mg Number (atomic per cent Mg/Mg+Fe) versus atomic per cent SiO_2 for samples of the Kanichee Intrusion from this study and from Hawke (1982).

and clinopyroxene also control the whole rock geochemistry. In Figure 5, samples of clinopyroxenite, olivine clinopyroxenite, wehrlite, and dunite, from both this study and from Hawke (1982), lie along a near-vertical line. For two samples the composition of clinopyroxene in olivine clinopyroxenite is joined to the respective whole rock compositon (after Hawke 1982). There is no fresh olivine available, but its forsterite content is probably close to the whole rock Mg Numbers plotted for dunite. Therefore, the near-vertical line for the rock types is analogous to a mixing line which joins the compositions of clinopyroxene and olivine.

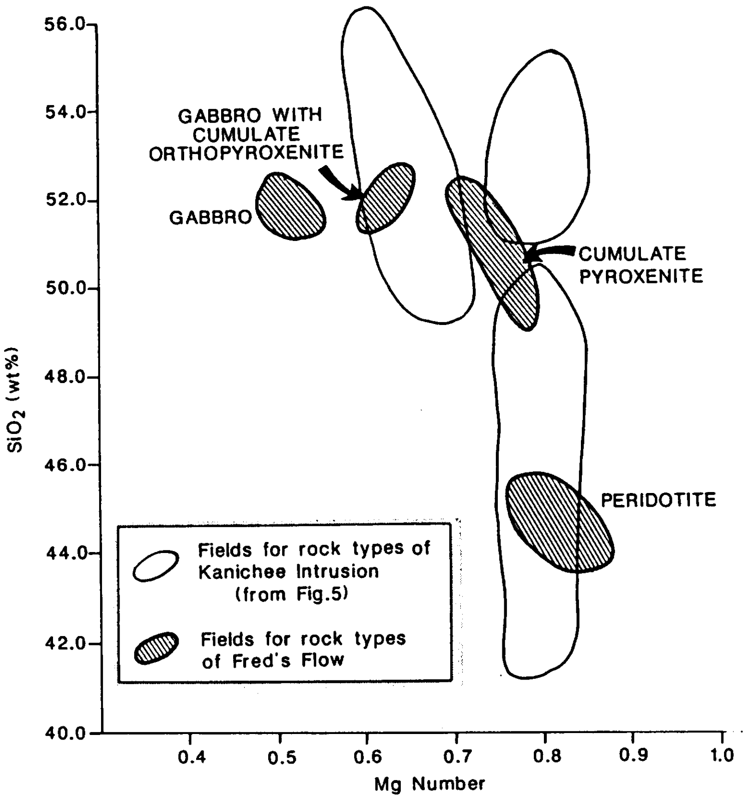

Figure 6. Mg Number (atomic per cent Mg/Mg+Fe) versus atomic per cent SiO_2, showing the overlapping fields from Fred's Flow (Arndt 1977) and from the Kanichee Intrusion.

In Figure 6, the fields for rock types at Kanichee are compared to those of a differentiated komatiite, Fred's Flow (after Arndt 1975). The high Mg Numbers of samples from Kanichee and their similarity to compositions from Fred's Flow are considered to be good evidence that the Kanichee Intrusion crystallized from a komatiitic melt.

Rare Earth Elements

The chondrite-normalized abundances of rare earth elements in three samples from the Kanichee Intrusion - a dunite (87DJG-203), a clinopyroxenite (87DJG-204), and a gabbro (87DJG-211) - are given in Table 2 and are plotted in Figure 7. The REE are approximately 2.7 to 3

Table 2. Rare earth element analyses of samples from the Kanichee Intrusion.

Sample No.	203	204	211
Rock Type	dun	cpx	gab
La	1000	960	2700
Ce	2500	2600	6800
Nd	1900	1800	5400
Sm	570	610	1800
Eu	230	160	740
Gd	650	790	2400
Tb	110	130	380
Dy	710	910	2300
Er	410	520	1300
Tm	60	80	190
Yb	350	520	1100
Lu	60	90	170

Notes:
All sample numbers are preceded by 87DJG.
All values are ppb.

times more abundant in the gabbro than in the peridotites, and the patterns are parallel. The clinopyroxenite is slightly enriched in the HREE relative to the dunite, due to the slightly higher ratio of Lu to Ce partition coefficients (D_{Lu}/D_{Ce}) for clinopyroxene than for olivine (after Arth 1976). The pattern exhibited by the dunite is probably

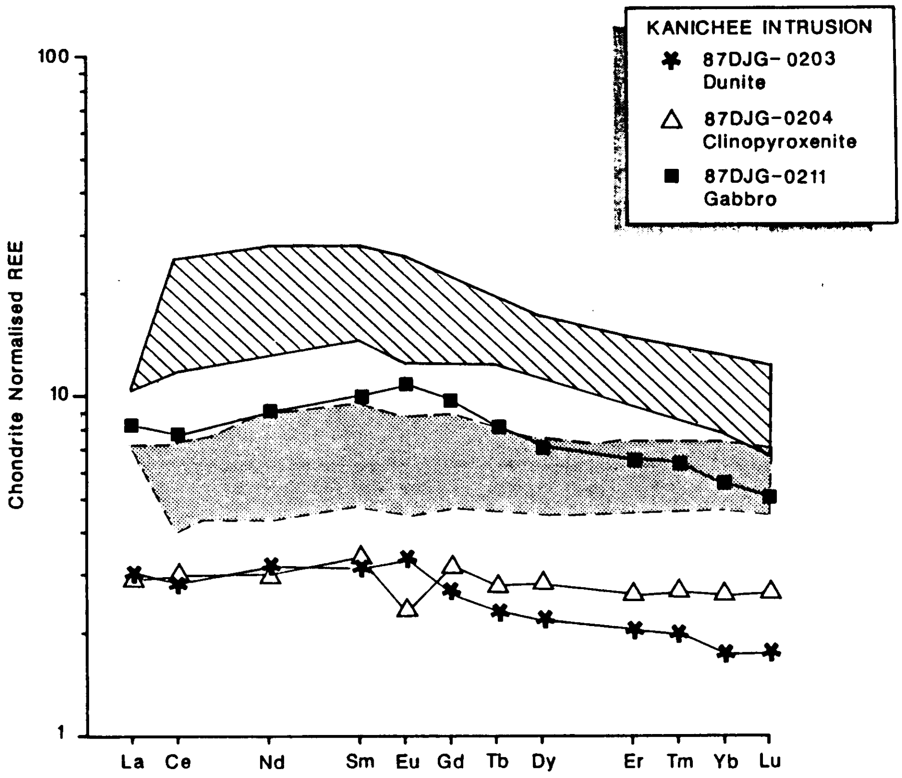

Figure 7. REE patterns for samples of dunite, clinopyroxenite and gabbro located away from the Kanichee ore zone. The hachured area represents the range of REE patterns for 4 tholeiites in Munro Township, Ontario (see Figure 8a), and the shaded area is the range of REE patterns for 6 komatiites from Munro Township and the Barberton Mountain Land (see Figure 8b).

closest to that of the melt. Also shown on Figure 7, for comparison, are the ranges of REE in 4 tholeiites from Munro Township in Ontario and 6 komatiites from the Barberton Mountain Land.

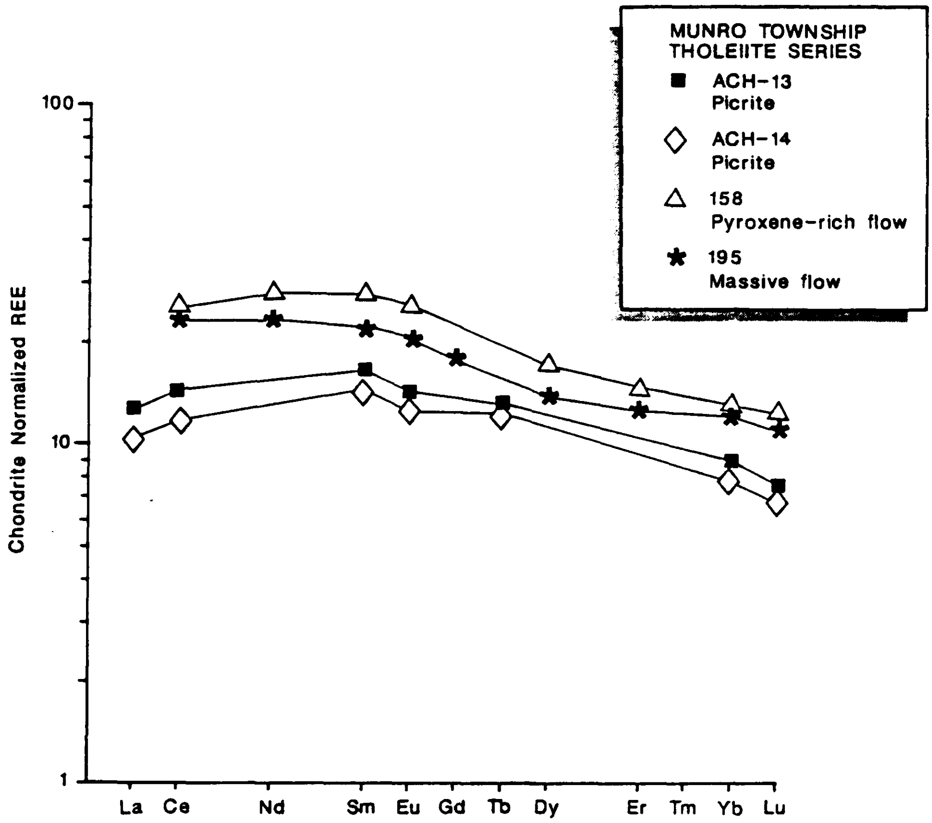

Figure 8a. REE patterns for tholeiitic rocks from Munro Township, Ontario (after Arth et al. 1977 and the Basaltic Volcanism Study 1981).

The chondrite-normalized abundances of REE in these same tholeiitic and komatiitic rocks are plotted on Figures 8a and 8b for purposes of discussion. Figure 8a gives data for 4 rocks of tholeiitic affinity from Munro Township (after Arth *et al.* 1977). These data for tholeiitic rocks are shown as a hachured area on Figure 8b, on which are plotted the REE patterns for 6 rocks of komatiitic affinity from both the Barberton Mountain Land (after Sun and Nesbitt 1978) and Munro Township (after Arndt 1975).

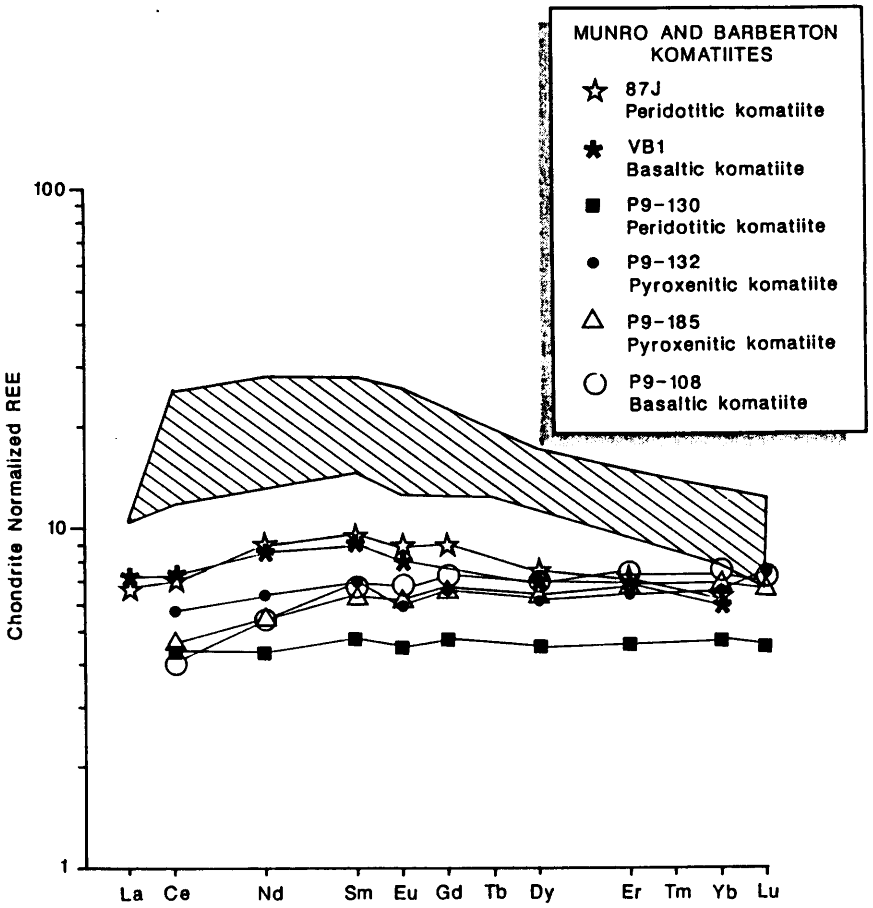

Figure 8b. REE patterns of komatiitic rocks from Munro Township, Ontario (after Arndt 1975) and from the Barberton Mountain Land (after Sun and Nesbitt 1978). Also shown is the range of REE patterns for tholeiitic rocks from Munro Township (Figure 8a).

The REE patterns of the Kanichee samples in Figure 7 are similar to those for both the tholeiitic and the komatiitic rocks. The tholeiitic samples (ACH-13 and ACH-14, Figure 8a) are picritic and contain 1.7 and 1.45 times as much Ce and Lu, respectively, as is found in the Kanichee gabbro. Two of the komatiite samples plotted on Figure 8b (87J, termed peridotitic komatiite by Sun and Nesbitt (1978), and VB1, termed Badplaas type basaltic komatiite by Viljoen and Viljoen

(1969)) contain concentrations of Ce and Lu which are more similar to those of the Kanichee Intrusion. However, because the Kanichee samples are cumulates, their absolute abundances of REE cannot be used to characterize the parent magma. However, the chondrite-normalized patterns can be used to describe the composition of the melt. These patterns (Figure 7) are compatible with either a komatiitic or tholeiitic magma.

MAGMATIC PARENTAGE

As just discussed, the rare earth element data are compatible with either a komatiitic or a tholeiitic magma, whereas data obtained from the major element analyses, in particular the TiO_2 concentrations and Mg Numbers, suggest that the Kanichee Intrusion crystallized from a komatiitic magma. The Al_2O_3 concentrations of the Kanichee samples are depleted relative to typical komatiites, and might therefore indicate a tholeiitic parentage. Sun and Nesbitt (1978) noted that samples of komatiites from the Barberton Mountain Lane (87J and VB1, Figure 8b) were similarly depleted in Al_2O_3 as well as in HREE, relative to other komatiitic rocks. They suggested that this could result from crystal fractionation of up to 20 per cent garnet (with 20 per cent Al_2O_3) from a komatiitic magma, either prior to or during its ascent from the mantle. A similar genesis is envisaged for the magma which crystallized the Kanichee Intrusion, which is considered to have been komatiitic and not tholeiitic.

TABLE 3. Trace element and Platinum Group Element analyses of samples from the Kanichee Intrusion.

Sample No.	167	168	169	170	171	172	174	175	176	203	204	211	213	214	267	269	270
Rock Type	per	per	per	per	per	olcpx	olcpx	weh	weh	dun	cpx	gab	cpx	olcpx	weh	weh	weh
S	0.76	0.34	1.11	1.31	0.80	0.04	0.02	0.19	0.22	0.17	0.01	0.06	0.06	0.01	0.76	0.15	0.21
Cu	1580	630	4400	5450	1535	166	151	335	361	470	12	136	455	230	2790	87	181
Ni	2520	610	2500	2800	2400	950	780	1570	1640	1690	1280	122	510	810	1960	1230	1480
As	14	27	4.5	8	72	54	2.5	62	45	3.5	nd	15	4.5	3	25	120	74
Bi	2.7	0.6	7.3	5.2	3.6	0.3	0.2	0.5	0.6	0.3	0.2	0.2	0.1	0.1	2.3	0.6	0.8
Sb	0.7	0.5	0.2	0.2	0.7	0.2	0.2	0.5	0.7	0.4	0.2	0.2	0.6	0.1	0.4	0.3	0.4
Se	1590	569	1500	2213	1485	196	134	466	616	630	59	186	538	197	1650	443	555
Os	6.8							3.9			3			4			
Ir	5.1	2.2	1.9	1.7	3.3	0.8	0.5	3	3.9	2.7	2.9		0.2	5.8	1.3	1.5	1.9
Ru	5.3									9.5			4.9	1.3		1.9	
Rh	5.3	2.6	1.9	1.5	3.8			2	3.9	2.4	2.3		3	85	295	10	25
Pt	12	36	271	364	242	4	15	26	33	21	19	nd	2	69	600	24	50
Pd	276	72	635	701	433	2	13	30	87	43	37	nd	3	13	166	11	20
Au	31	16	121	103	55	5	5	9	8	8	3	3					

Notes:

All sample numbers preceded by 87DJG.

per = peridotite, olcpx = olivine clinopyroxenite, weh = wehrlite; dun = dunite; cpx = clinopyroxenite; gab = gabbro.

nd = not detected.

S values in weight per cent; Cu, Ni, As, Bi, and Sb values in ppm; Se, Os, Ir, Ru, Rh, Pt, Pd, and Au values in ppb.

PLATINUM GROUP ELEMENTS

As discussed in the previous section, the Kanichee Intrusion apparently crystallized from a komatiitic magma. Accordingly, the abundances and distribution of PGEs in the Kanichee Intrusion can be compared with those of komatiites elsewhere.

The chondrite-normalized patterns for the abundance of PGE in samples of peridotite from the Kanichee Intrusion are presented in Figure 9. These samples contain trace sulphides (0.01 to 0.17 weight per cent S), and were obtained away from the ore zone. The range of PGE for unmineralized samples (< 0.1 wt. per cent S) in two komatiite flows [Fred's Flow (after Crocket and MacRae 1986) and Alexo (after Brugmann

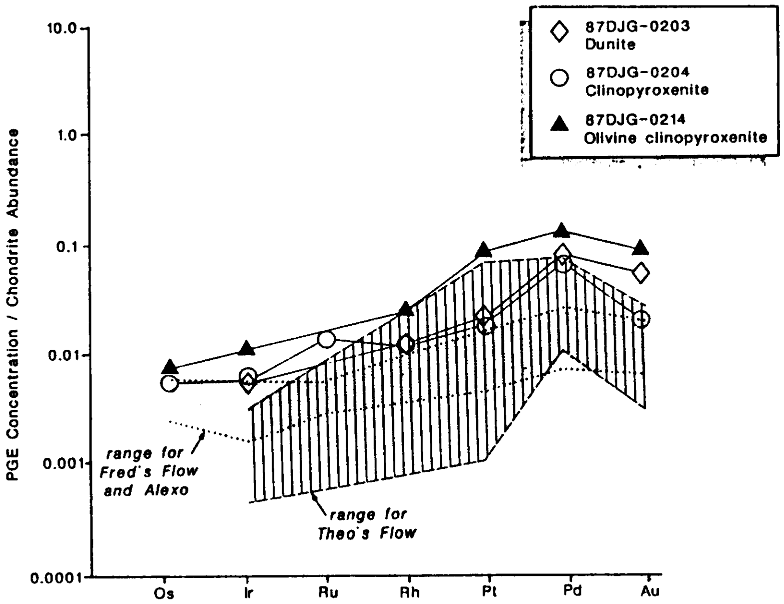

Figure 9. Chondrite-normalized abundances of PGE in samples from the Kanichee Intrusion, taken away from the open pit. Also plotted are the fields of two komatiitic flows - the Alexo Flow (after Brugmann et al. 1987) and Fred's Flow (after Crocket and MacRae 1986) - and one tholeiitic flow - Theo's Flow (after Crocket and MacRae 1986).

et al. 1987)] and one tholeiitic flow [Theo's Flow (after Crocket and MacRae 1986)] from the Abitibi Greenstone belt in Ontario are also shown on Figure 9. The PGE patterns of the Kanichee samples are similar to those of the komatiites, and are consistent with rocks derived from a komatiitic magma, although the abundances are slightly higher.

Table 4. Trace element data for samples of vein sulphides from the Kanichee Intrusion.

Sample No.	161	162	164	165	166	215	268
S	4.27	4.88	34.40	4.48	18.90	0.40	3.44
Cu	.710	.636	1.2	2.7	7.1	.107	1.0
Ni	.588	.832	7.9	.316	2.0	.120	.816
As	2.5	1	3	nd	16	17	72
Bi	5.9	6.1	10.9	3	4.7	0.4	5.4
Sb	0.5	1	0.5	0.2	0.6	0.5	2.5
Se	17.0	11.9	57	8.85	33.7	750	7.275
Os		38	67		49		5.9
Ir	4	52	108	1.5	92	5.1	8.8
Ru		60	68		73		
Rh	8	62	407		144		21
Pt	1193	649	2950	110	430	45	880
Pd	1938	1290	3635	641	2365	60	1680
Au	76	90	90	2100	150	12	100

Notes:
All sample numbers preceded by 87DJG.
nd = not determined.
S, Cu, and Ni values in weight per cent; As, Bi, Sb, and Se values in ppm; Os, Ir, Ru, Rh, Pt, Pd, and Au values in ppb.

The similarity of proportions of Pd and Ir in ores and host rock of komatiitic affinity is widely recognized (Crocket 1984). The range of Pd/Ir ratios for nine sulphide-bearing komatiites from West Australia, Zimbabwe and Canada, as summarized by Barnes *et al.* (1985), is 2.2 to 33. The average Pd/Ir ratio for the unmineralized Kanichee samples (Table 5) is 15.6 ± 6, well within this range. Since the PGE abundances and the Pd/Ir ratios in the unmineralized, unaltered Kanichee samples are similar to those of komatiites elsewhere, it is probable that the magmatic sulphides from which the vein sulphides were derived would have had compositions similar to komatiite-associated sulphides elsewhere.

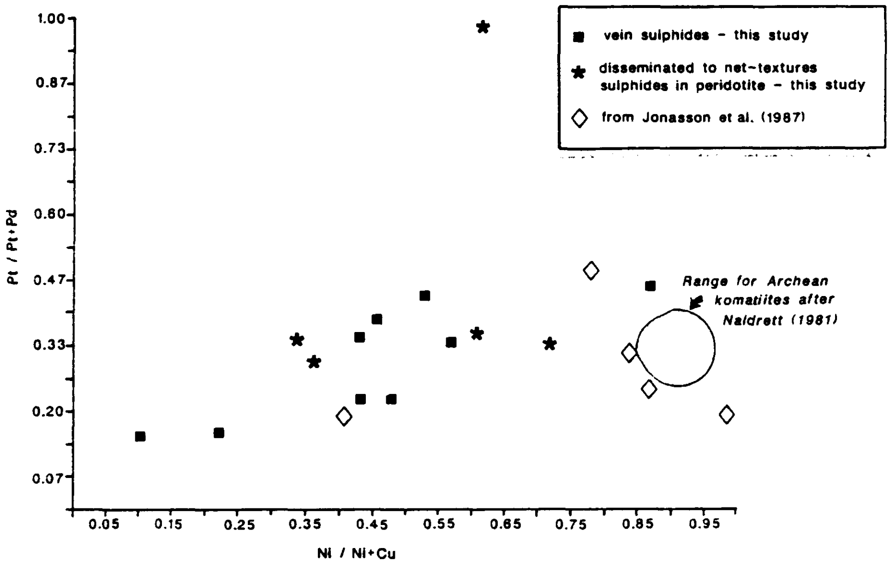

Figure 10. Pt/Pt+Pd against Ni/Ni+Cu for sulphide-bearing samples from the Kanichee Intrusion (this study and after Jonasson et al. 1987). The range for Archean komatiites (after Naldrett 1981) is plotted for comparison.

Figure 10 is a plot of Pt/Pt+Pd against Ni/Ni+Cu for samples of types 1 (vein) and 3 (disseminated to net-textured) mineralization in the Kanichee Intrusion, collected near the ore zone. Also shown are Kanichee samples analysed by Jonasson *et al.* (1987) and the range of typical sulphide-bearing komatiites (after Naldrett 1981). The horizontal and vertical scatter of the data is related to the fractionation of Cu from Ni, and of Pd from Pt, during hydrothermal mobilization and deposition of sulphides. The following discussion is intended to detail some of the effects of hydrothermal mobilization on the PGE.

In Figure 11, the range of PGE values for unmineralized samples, collected away from the ore zone, is compared to that of unmineralized samples, collected close to the ore zone. These PGE patterns can also be described in terms of inter-element ratios, as in Table 5. Both Table 5 and Figure 11 show that the abundances of Ir, Rh and Pt are essentially the same in both groups. However, the average Pd/Ir ratio and the average Pd content are slightly higher in samples from near the

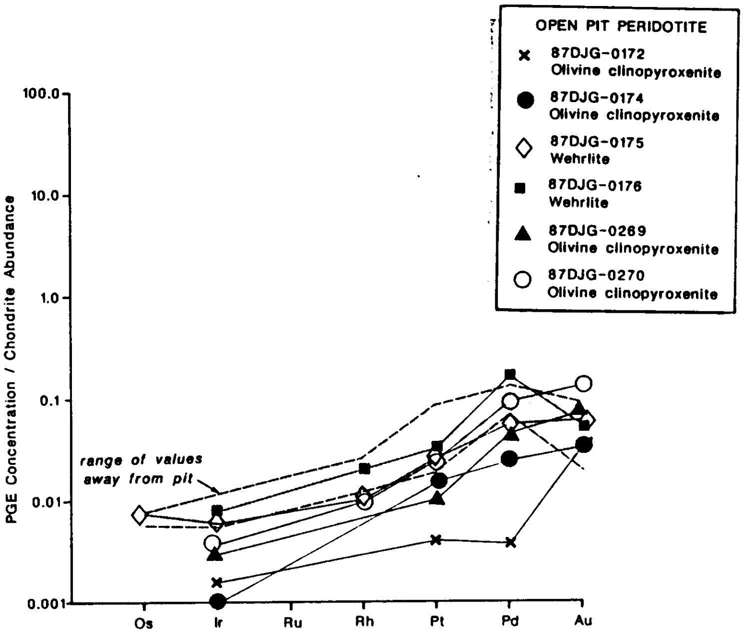

Figure 11. Chondrite-normalized abundances of PGE for unmineralized peridotite close to the ore zone at the Kanichee Intrusion. Also plotted are the fields of two komatiites (Alexo Flow and Fred's Flow) and one tholeiite (Theo's Flow). See Figure 9 for data sources, and Table 5 for comparison of inter-element ratios.

ore zone. It appears, therefore, that Pd is slightly enriched in unmineralized samples from close to the ore zone.

Table 5. Pd/Ir, Pt/Ir and Rh/Ir ratios for samples from the Kanichee Intrusion.

Sample No.	Pd/Ir	Pt/Ir	Rh/Ir
Group 1. Vein Sulphide			
87DJG-161	485	298	2
87DJG-162	25	12	1.2
87DJG-164	34	27	3.8
87DJG-165	427	73	-
87DJG-166	26	4.7	1.6
87DJG-215	12	8.8	-
87DJG-268	191	100	2.4
Group 2. Open Pit, Mineralized			
87DJG-167	54	2.4	1.04
87DJG-168	33	16	1.2
87DJG-169	334	143	1
87DJG-170	412	214	.88
87DJG-171	131	73	1.15
87DJG-267	461	227	1
Group 3. Open Pit, Unmineralized			
87DJG-172	2.5	5	-
87DJG-174	26	30	-
87DJG-175	10	9	.67
87DJG-176	22	8.5	1
87DJG-269	16	6.7	-
87DJG-270	26	13	1
Group 4. Away from Open Pit, Unmineralized			
87DJG-203	16	7.8	.89
87DJG-204	13	6.6	.79
87DJG-211	-	-	-
87DJG-213	10	15	-
87DJG-214	12	15	.84

Figures 12 and 15b show the changes in PGE concentrations for 4 samples selected from a section across a sulphide-carbonate vein, located near point C on Figure 2. The samples comprise unmineralized peridotite (87DJG-269 and 270), mineralized peridotite from the sulphide-bearing halo around the vein (87DJG-267) and the sulphide vein (87DJG-268). Within the sulphide halo, the Ir and Rh contents are unchanged from the unmineralized peridotite, but the Pd, Pt, and Au contents are enriched. In the sulphide vein, all of the PGE are further enriched, but the Pd/Ir ratio actually decreases, relative to the halo.

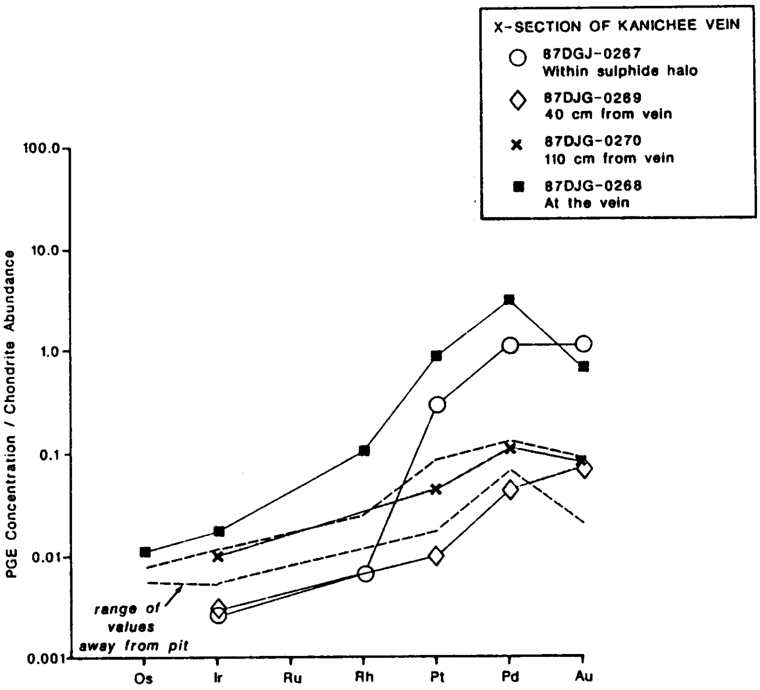

Figure 12. Chondrite-normalized abundances of PGE from samples along a cross section of a vein near Point C on Figure 2, plotted with the range of PGE abundances for samples taken away from the open pit (see Figure 9). Inter-element ratios are given in Table 5.

Figure 13 is a plot of the chondrite-normalized abundances of PGE in peridotites containing type 3 mineralization collected from the rubble pile at Kanichee. The range for unmineralized samples is shown for comparison. The abundance of Pt + Pd is higher in the mineralized samples, and is similar to the Pt + Pd content of the sulphide-bearing halo to the vein described above (sample 87DJG-267). It is apparent, therefore, that the abundances of PGE in these samples have been modified, perhaps by hydrothermal processes.

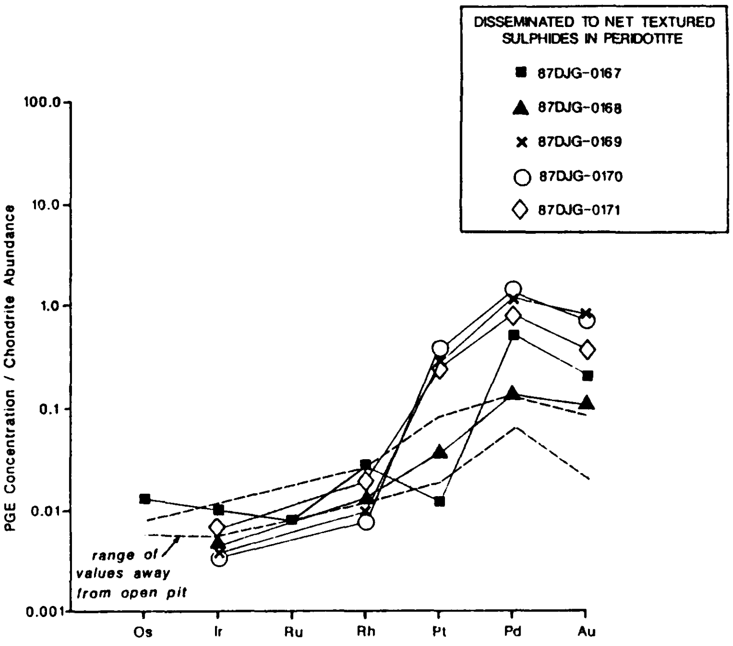

Figure 13. Chondrite-normalized abundances of PGE for samples of peridotite containing disseminated to net-textured sulphides, collected from the rubble pile at the Kanichee open pit. Also shown is the range of abundances for samples collected away from the pit (see Figure 9).

Figure 14 is a plot of the chondrite-normalized abundance of PGE in the Kanichee vein sulphides (type 1 mineralization). The range between the maximum and minimum Ir concentrations spans two orders of magnitude, whereas the Pd values vary by less than 1 order of magnitude.

The chondrite-normalized ratios of Os and Ru to Ir for the Kanichee vein sulphides (Figure 14) are less than one. These ratios are greater than one in other komatiite-associated sulphide deposits (after

Barnes *et al.* 1985). This suggests that Ir behaves differently from Os and Ru during hydrothermal mobilization.

Discussion

The fractionation of Pt and Pd from the Os-Ir-Ru-Rh group during hydrothermal mobilization of sulphides was noted by Keays *et al.* (1981) and Lesher and Keays (1984) at Kambalda, Western Australia. Similarly, Dillon-Leitch *et al.* (1986) suggested that, at the Donaldson West Deposit in Ungava, Pt and the Os-Ir-Ru-Rh group behaved coherently during metamorphic events and that Pd was preferentially mobilized from them.

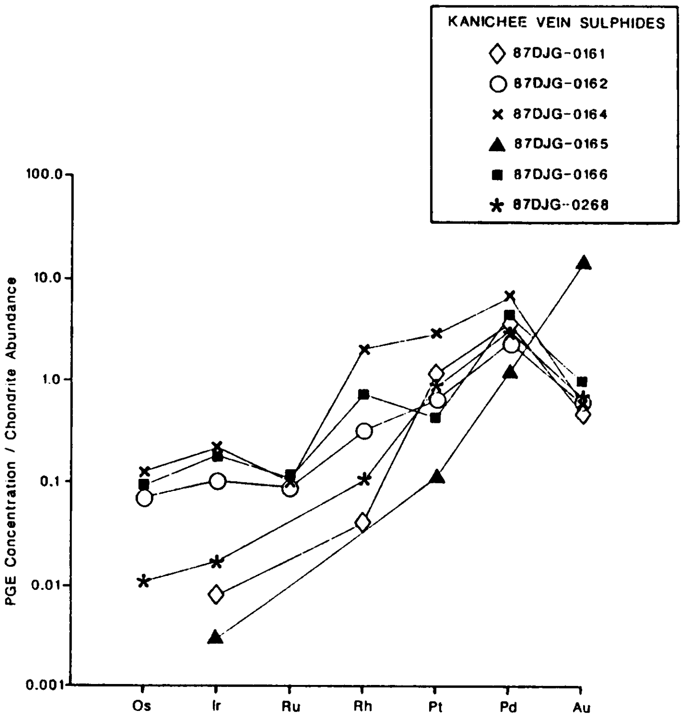

Figure 14. Chondrite-normalized abundances of PGE in samples of vein sulphides from the Kanichee Intrusion.

At Kanichee, the relative differences in behaviour among PGE during hydrothermal mobilization are further defined. The ratios for Os+Ir+Ru+Rh/Pt+Pd in the vein sulphides are much higher at Kanichee than at either Kambalda (Lesher and Keays 1984) or at Donaldson West (Dillon-Leitch *et al.* 1986). This suggests that the Os group of PGE is indeed mobile in hydrothermal fluids. Further, the evidence cited above indicates that Os and Ru are fractionated from Ir.

PLATINUM GROUP MINERALS

It has been shown that the dominant host for PGE in sulphide-bearing komatiites at Kambalda (Hudson and Donaldson 1984), and Donaldson West, Ungava (Dillon-Leitch *et al.* 1986) are complex Te-, As-, Sb- and Bi-bearing PGE minerals. The platinum group minerals common to both locales are sperrylite [$PtAs_2$], sudburyite [(Pd, Pt, Ni)(Sb, Te, Bi)], and palladian melonites [$NiTe_2$].

In their mineralogical investigation of two sulphide-bearing samples from the Kanichee deposit, Cabri and Laflamme (1974) demonstrated that the Pt and Pd were contained in michenerite [(Pt,Pd)BiTe], sperrylite [$PtAs_2$], and cobaltite [CoAsS]. In both samples, michenerite occurs as 1 to 45 micron grains disseminated in chalcopyrite, pyrrhotite, magnetite and pentlandite. Sperrylite was found in one of the samples as 1 to 10 micron grains within pyrrhotite, silicates, chalcopyrite and magnetite. The cobaltite contained small quantities of Pt (less than 0.2 wt. percent) and Pd (approximately 0.3 wt. percent).

MOBILITY OF TRACE ELEMENTS

There is a strong association between PGE and As, Sb, Bi, and Se in komatiites. Similar associations between Au mineralization and trace elements have been useful in detecting alteration halos by geochemical exploration techniques. It follows, therefore, that an understanding of the trace element distribution at Kanichee might be useful to further exploration for similar vein deposits in komatiites elsewhere.

The relative mobilities of As, Sb, Se, Bi, Ni, Cu and PGE within the ore zone at Kanichee can be determined by comparing their concentrations in peridotite away from the ore zone (background) to the concentration in (1) unmineralized peridotite in the ore zone, (2) the blebby sulphide-bearing halos marginal to sulphide veins, and (3) the sulphide veins. This was done for the sample suites previously described: the resulting analytical data are listed in Table 3.

Figures 15a and b are plots of the trace element concentrations in 4 samples across a section from a carbonate-sulphide vein in barren peridotite, located at point C on Figure 2. The range of background values is indicated at the right hand side of the figures.

As demonstrated by Figures 15a and b, all of the elements except Au are enriched in the vein relative to the host rock. S, Se, Bi, Cu, Au, Pd and Pt are enriched in the blebby sulphide halo relative to the unmineralized peridotite. As and perhaps Bi are enriched, and Cu may be depleted in the unmineralized peridotite of the ore zone, relative to the background values. The concentrations of Sb, Ir and Ni are unchanged from the sulphide halo to the unmineralized peridotite, both

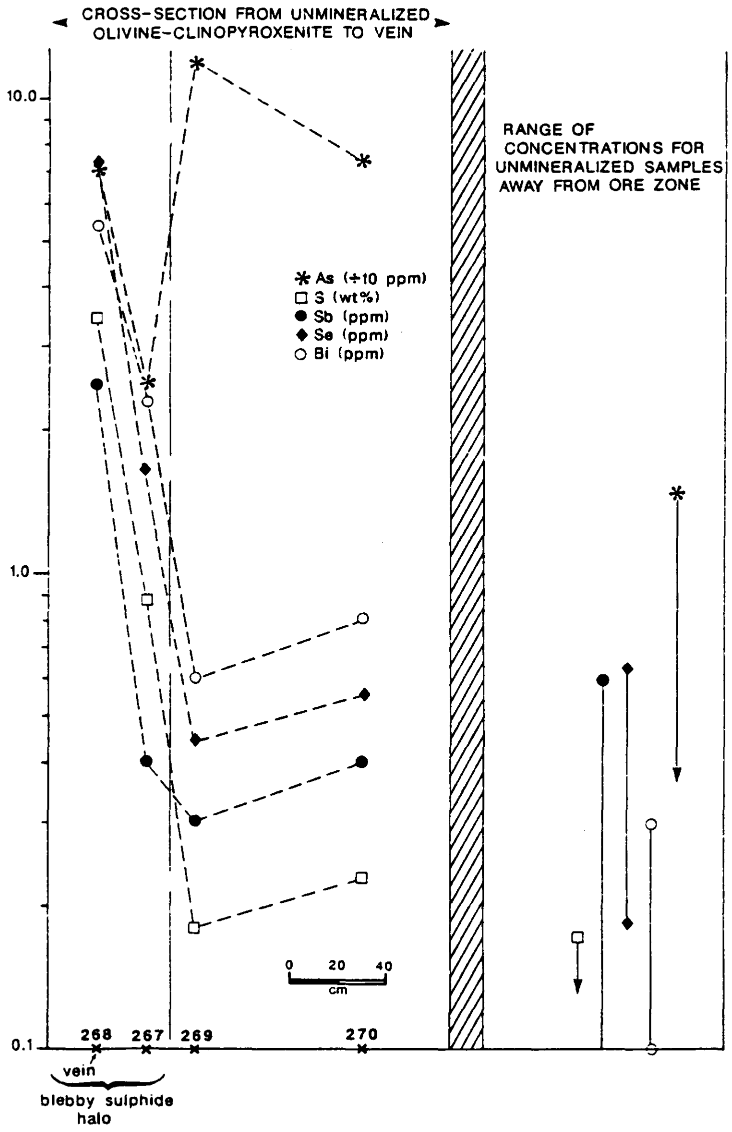

Figure 15a. Abundances of trace elements across a section from unmineralized olivine clinopyroxenite to a blebbly sulphide-mineralized halo to a carbonate-sulphide vein, near Point C on Figure 2. The range of values for unmineralized rocks away from the ore zone is shown to the right of the vertical bar.

within and away from the ore zone. As contents, although irregular, are highly enriched in the ore zone.

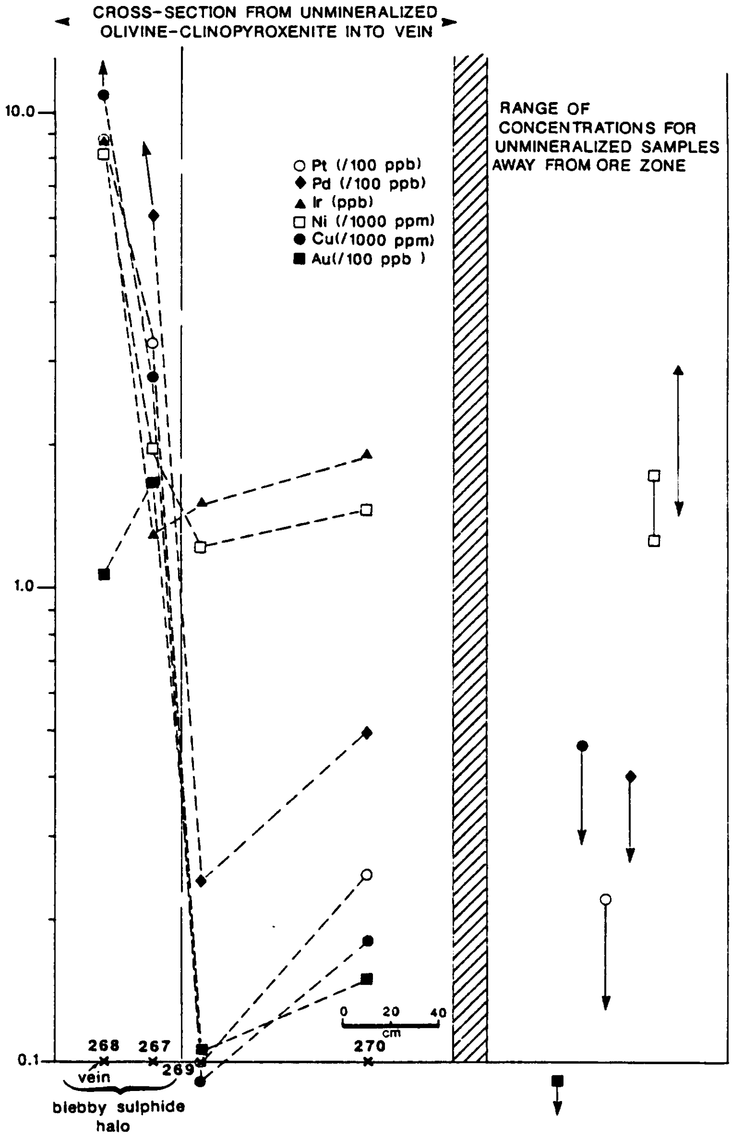

Figure 15b. Abundances of PGE, Ni, Cu and Au across a section from unmineralized olivine clinopyroxenite to a blebbly sulphide-mineralized halo to a carbonate-sulphide vein, near Point C on Figure 2. The range of values for unmineralized rocks away from the ore zone is shown to the right of the vertical bar.

The relative order of mobility of the trace elements plotted in Figure 15a, from greatest to least, is As > Bi > S = Se > Sb. Similarly, the order for the metals plotted in Figure 15b is Pd > Cu = Au > Pt > Ir = Ni.

CONCLUSIONS

The Kanichee Intrusion is interpreted to have crystallized from a magma of komatiitic affinity. The Mg Number, abundance of PGE and TiO_2, and the pattern of chondrite-normalized REE are all compatible with a HREE- and Al_2O_3-depleted magma of komatiitic affinity. This conclusion removes the uncertainty resulting from previous studies of the intrusion.

The abundances of PGE and the Pd/Ir ratio in unmineralized samples away from the ore zone are similar to those of komatiites elsewhere. The PGE concentrations of unmineralized peridotite and of peridotite containing disseminated to net-textured sulphide (type 3) mineralization in the vicinity of the ore zone were modified during the hydrothermal activity responsible for the precipitation of sulphide-carbonate-quartz veins (type 1 mineralization). The dominant effect was the enrichment of Pd with respect to the other PGE.

All of the PGE are concentrated in the vein sulphides (type 1) and were, therefore, mobile in the hydrothermal system responsible for their deposition. During either dissolution or precipitation, Pd and Pt were enriched relative to, and, therefore, fractionated from the Os group of elements. Similarly, Ir is enriched relative to, and, therefore, fractionated from Os and Ru.

The relative mobilities of As, Sb, Se, Bi, Cu, Ni, Au, and PGE within the ore zone have been determined. From greatest to least, the relative mobilities of trace elements were As > Bi> S = Se > Sb. For the precious and base metals, the order is Pd > Cu = Au > Pt > Ir = Ni.

An important implication of the relative mobilities of the trace elements relates to the use of As as a geochemical exploration tool. The extremely mobile nature of As in the system responsible for mineralization at Kanichee has enriched the As concentrations in the unmineralized peridotite in the vicinity of the ore zone by up to 20 times. The exploration for other deposits of the vein sulphides at Kanichee or in other komatiitic intrusions could be enhanced by exploring for the associated As halo.

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