GEOCHEMICAL CONSTRAINTS ON THE GENESIS OF THE MONTCALM GABBROIC COMPLEX AND Ni-Cu DEPOSIT, WESTERN ABITIBI SUBPROVINCE, ONTARIO

C. TUCKER BARRIE* AND ANTHONY J. NALDRETT

Department of Geology, University of Toronto, Toronto, Ontario M5S 3B1

DON W. DAVIS

Jack Satterley Geochronology Laboratory, Royal Ontario Museum, 100 Queen's Park, Toronto, Ontario M5S 2C6

Abstract

The Montcalm gabbroic complex (2702 \pm 2 Ma: U-Pb zircon), located in the western Abitibi Subprovince in Ontario, contains three lithologic units: a basal pyroxenite zone (PZ), a gabbro - anorthositic gabbro zone (GZ) and a ferroan gabbro zone (FZ). Lower PZ rocks are orthocumulates, with orthopyroxene, clinopyroxene, olivine and minor plagioclase as cumulus phases. They have Mg numbers of 68-72, and are enriched in TiO₂, P₂O₅, Zr, Y, and the REE relative to GZ cumulates, reflecting the presence of abundant interstitial liquid near the margin of the complex. They are *LREE*-enriched, with La_N/Yb_N in the range 2.4-3.8, and are slightly depleted in Ta, Nb, Ti, Zr, and Hf compared to MORB or primitive mantle. Upper PZ rocks have coarse-grained and pegmatitic textures, with cumulus clinopyroxene, orthopyroxene and plagioclase that are partly or completely replaced by postcumulus hornblende, plagioclase and Fe-Ti oxides. Pyroxenite and gabbro pegmatite dikes with either sharp or gradational contacts are common in the upper PZ. Systematic enrichments in V, Cu, Ni, Co, Au and S and, to a lesser extent, the REE are found in upper PZ rocks. They are attributed to concentration by a zone-refining process, whereby partial melting of hot (supersolidus?) pyroxenite was fluxed by a volatile-rich fluid medium, possibly derived from contemporaneous felsic magmatism (granodiorite dike: 2700⁺⁵₋₄ Ma: U-Pb zircon). GZ rocks are composed of plagioclase - clinopyroxene meso- to adcumulate, with local plagioclase subporphyritic intervals. GZ whole-rock Mg numbers range from 73 to 81, and have low incompatible trace-element, sulfur and PGE contents, consistent with low amounts of trapped liquid and sulfur-undersaturated conditions during GZ formation. The Montcalm deposit (3.56 million tonnes, 1.44 wt.% Ni and 0.68% Cu, 50 ppb total PGE) is located within GZ cumulates at the northern extent of the complex. High Pt/Ir values and low PGE contents in the Ni-Cu deposit and lower PZ rocks are consistent with their derivation from a primitive magma that had experienced 1) olivine and chromite fractionation, with Ir behaving compatibly in the crystallizing phases, accompanied by 2) continual removal of trace amounts of sulfide. The main event of sulfide segregation may have occurred in a different part of the magma chamber or at depth, in a lower crustal chamber. The deposit was then tectonically emplaced into its present location from a predominantly pyroxenitic host during the late stages of consolidation.

Keywords: Montcalm gabbroic complex, Abitibi Subprovince, Ontario, nickel, platinum, magmatic sulfide, zone refining.

SOMMAIRE

Le complexe gabbroîque de Montcalm, dans le secteur Ouest de la sous-province de l'Abitibi en Ontario, a un âge U-Pb obtenu sur zircon de 2702 \pm 2 Ma, et comprend trois unités lithologiques, une zone inférieure de pyroxénite (PZ), une zone de gabbro et de gabbro anorthositique (GZ), et une zone de gabbro riche en fer (FZ). Les roches près de la base de la zone PZ sont des orthocumulats d'orthopyroxène, de clinopyroxène et d'olivine, avec plagioclase accessoire. Ces roches ont une valeur de Mg# [100Mg/(Mg + Fe)] entre 68 et 72, et sont enrichies en TiO₂, P₂O₅, Zr, Y et les terres rares comparées aux cumulats GZ; ces caractères sont l'expression d'une fraction importante de liquide interstitiel près de la bordure du massif. Elles sont enrichies en terres rares légères (2.4 <La_N/Yb_N <3.8) et légèrement appauvries en Ta, Nb, Ti, Zr et Hf comparées aux basaltes MORB et au manteau primitif. Plus haut dans l'unité PZ, les roches ont une texture grossière à pegmatitique, et sont des cumulats de clinopyroxène, d'orthopyroxène et de plagioclase qu'ont remplacé à un stade postcumulus, complètement ou en partie, hornblende, plagioclase et oxydes de Fe-Ti. Les filons de pyroxénite et de gabbro pegmatitique y sont répandus et montrent une éponte soit franche, soit floue. Nous signalons des enrichissements systématiques en V, Cu, Ni, Co, Au et S, et des terres rares. Nous attribuons ces enrichissements à un processus de purification par fusion en zones, c'est-à-dire une fusion partielle d'une pyroxénite près de son solidus par l'addition d'une phase fluide, liée peut être à un magmatisme felsique contemporain (un filon de granodiorite a un âge U-Pb obtenu sur zircon de 2700⁺⁵₋₄ Ma). Les roches de la zone GZ sont des mésocumulats et des adcumulats à plagioclase + clinopyroxène qui montrent des passées localement subporphyriques à plagioclase. Leur valeur de Mg# est située entre 73 et 81; elles montrent de faibles teneurs en éléments-traces incompatibles, en soufre et en éléments du groupe du platine (EGP), ce qui concorde avec une faible proportion de liquide interstitiel et des conditions de sous-saturation en soufre. Le gisement Ni–Cu de Montcalm $(3.56 \times 10^6 \text{ tonnes}, 1.44\% \text{ en})$ poids de Ni, 0.68% de Co, 50 ppb des EGP) est situé au sein des cumulats GZ dans le secteur Nord du massif. Les valeurs élevées de Pt/Ir et les faibles teneurs en EGP du minerai et des roches près de la base de l'unité PZ seraient l'expression d'une dérivation à partir d'un magma primitif

^{*}Present address: BP Resources Canada Limited, 890 West Pender St., Ste. 700, Vancouver, British Columbia V6C 1K5.

qui aurait subi un fractionnement de l'olivine et de la chromite, le Ir ayant agi de façon compatible dans cet assemblage, et d'une perte continue de faibles quantités de sulfures. L'événement principal de séparation de sulfures pourrait avoir eu lieu ailleurs dans la chambre magmatique ou à plus grande profondeur, dans la croûte inférieure. Le gisement a ensuite été mis en place tectoniquement par le déplacement d'une roche-hôte à caractère surtout pyroxénitique au cours d'un stade tardif de la cristallisation du complexe.

(Traduit par la Rédaction)

Mots-clés: complexe gabbroïque de Montcalm, sousprovince de l'Abitibi, Ontario, nickel, platine, sulfure magmatique, affinage en zones.

INTRODUCTION

The Montcalm Ni-Cu deposit was discovered in 1976, when the first drillhole to test an airborne electromagnetic anomaly intersected 74.4 m of massive and disseminated sulfide mineralization (Blecha *et al.* 1977). Further drilling outlined 3.56 million tonnes of reserves to a depth of 300 m, with an average grade of 1.44% Ni and 0.68% Cu. The deposit is unusual in two respects. First, the sulfide mineralization is hosted within cumulate gabbroic rocks. Generally, Ni-Cu sulfide mineralization is found at the base of the host intrusion, a feature commonly attributed to gravity settling of a dense sulfide liquid through a less dense silicate liquid. Barrie & Naldrett (1989) interpreted the deposit as having been tectonically emplaced into its present location from a predominantly pyroxenitic host, during or shortly after consolidation of the Montcalm Gabbroic Complex (MGC). The second unusual feature of the deposit is its very low PGE tenor (average of 50 ppb total PGE), despite Ni and Cu contents that are considered normal for gabbro-hosted magmatic sulfide deposits (e.g., nearly two orders of magnitude lower than typical Sudbury deposits: Naldrett 1981). An initial explanation for the low tenor of the PGE at Montcalm was provided by Naldrett & Duke (1980). They modeled the average Ni, Cu and Pd contents of the deposit as a product of a sudden event of sulfide segregation from a picritic magma, after the magma had undergone continuous segregation of trace amounts of sulfide during the fractionation of olivine, clinopyroxene and plagioclase.



FIG. 1. Location map, and regional geology in the western Abitibi Subprovince. The contact with the Kapuskasing Structural Zone represents a west-dipping thrust fault.

The geology and structural history of the MGC and Ni-Cu deposit have been described in a complementary study (Barrie & Naldrett 1989). The present study uses a detailed petrographic, mineral and whole-rock geochemical traverse across the stratigraphy to interpret the magmatic and postmagmatic processes that formed the MGC and Ni-Cu deposit. High-precision U-Pb zircon ages are presented for the MGC and a granodiorite dike that cuts the Ni-Cu deposit, to place these rocks within the temporal framework of magmatism and tectonism in the southern Superior Province. In addition, neodymium isotope analyses from a regional study (Barrie & Shirey, submitted) are used to characterize isotopic signatures of the MGC parental

magma and evaluate the extent of assimilation that must have occurred during the formation of the gabbroic complex.

REGIONAL GEOLOGICAL SETTING

The Abitibi Subprovince, a major lithologic – tectonic block of the southern Superior Province, is characterized by predominantly east-trending lowgrade metavolcanic and metasedimentary rocks, and massive to gneissic intermediate and felsic plutons. The Kapuskasing Structural Zone is a northeasttrending elongate belt (500×59 km) of high-grade metamorphic rocks at the western terminus of the Abitibi Subprovince. The Montcalm area comprises



FIG. 2. Generalized geology of the Montcalm area.

a discrete assemblage of supracrustal volcanic, sedimentary and intrusive rocks, and is located along the eastern border of the Kapuskasing Structural Zone at the extreme western margin of the Abitibi Subprovince (Fig. 1).

Geological studies in the Montcalm area have been limited owing to poor access and exposure. Previous mapping by Bennett (1966a, b, 1969) has described the general geology to the south and central parts of the Montcalm area. The MGC is centrally located in the Montcalm area, within iron-rich tholeiitic basalts, and calc-alkaline andesites and dacites. Contacts with the surrounding rocks are rarely exposed. In drill core, metavolcanic rock – MGC contacts are interdigitating and gradational, indicating that parts of the MGC extend laterally into the metavolcanic suite.

Mafic metavolcanic rocks predominate to the southwest and are locally interbedded with finegrained metasedimentary rocks. Shallow northwestdipping foliations and attitudes of bedding suggest the structural influence of the Kapuskasing thrust fault to the northwest. The mafic volcanic rocks are metamorphosed to amphibolite grade within 3 km of the contact with Kapuskasing gneissic felsic intrusive rocks. The northern third of the Montcalm area consists of high-iron tholeiitic mafic metavolcanic



FIG. 3. Geology of the eastern half of the gabbroic complex, with lithologic subdivisions and Mg numbers. Bedding and foliations near vertical.

rocks interbedded with fragmental and tuffaceous calc-alkaline felsic metavolcanic rocks. Diamond drilling northwest of the MGC encountered gabbroic sills up to 40 m thick within the metavolcanic sequence. In addition, two sulfidic iron formations have been intersected by drilling along strong linear airborne magnetic anomalies (Fig. 2). To the east, the MGC is bordered by a large composite tonalite – granodiorite – granite batholithic complex. A smaller gneissic tonalite cuts the MGC along its southern margin, and ultramafic sills and dikes (clearly detected by air magnetic surveys: Fig. 2) cut the intrusion and neighboring metavolcanic rocks.

GEOLOGY OF THE MONTCALM GABBROIC COMPLEX

The MGC is a large (85 km²) subvertical, crudely layered crescent-shaped intrusion (Fig. 2). Detailed intrusion-wide lithological or structural studies are not possible, as exposures are limited to those along a river in the southern part of the intrusion, and to scattered outcrops within the intrusion. However, based on these limited exposures, the MGC can be divided into three zones: a Pyroxenite Zone (PZ), Gabbro - Anorthositic Gabbro Zone (GZ) and Ferroan Gabbro (FZ), which broadly define a NNW-SSE Fe-enrichment trend (Figs. 3, 4). Four dike suites cut the MGC, including peridotitic, pyroxenitic, gabbroic and granitic dikes. All rocks have been subjected to varying degrees of subsolidus alteration. Clinopyroxene is commonly partly or completely replaced by tremolite-actinolite and hornblende, and plagioclase is commonly altered to sericite, chlorite and clay. The following descriptions emphasize the primary cumulus and postcumulus mineralogy determined from outcrop, hand specimen and petrographic observations, and microprobe analyses of the least-altered samples.

Rock Types

The Pyroxenite Zone occurs 300 m northwest of the Ni-Cu deposit, as a lens-shaped mass up to 250 m wide and 450 m long (Fig. 4). Pyroxenitic rocks comprise 40% of the PZ. They are massive, mediumgrained clinopyroxene orthocumulates, with cumulus olivine and orthopyroxene, and rare plagioclase. Intercumulus silicates include orthopyroxene, plagioclase and oikocrystic hornblende. Pegmatitic gabbroic rocks comprise 35% of the PZ, and are more prominent near the PZ-GZ contact. They have subequal proportions of primary plagioclase, clinopyroxene and hornblende, with up to 5% magnetite and ilmenite; chlorite is commonly pseudomorphous after the silicate phases. Both of these rock types have up to 4% sulfides, predominantly pyrite and pyrrhotite, with lesser chalcopyrite and pentlandite locally. The remainder of the PZ con-



FIG. 4. Rocks of the Montcalm Ni-Cu deposit area, with Mg numbers for representative drill-core samples (projected to surface). The Ni-Cu deposit is divided into West and East Zones (hachured) by a subvertical granodiorite dike (cross pattern); a more siliceous dike borders the West Zone on its western margin (cross pattern). Line A-A' used for geochemical traverse in Figure 6.

sists of pyroxenitic and gabbro pegmatite dikes that have both sharp and gradational contacts with surrounding rocks. Pyroxenitic xenoliths are present within the Ni–Cu deposit, and within granitic rocks marginal to the MGC.

The Gabbro - Anorthositic Gabbro Zone is greater than 800 m thick and primarily composed of massive medium- to coarse-grained clinopyroxeneplagioclase mesocumulate and adcumulate. The GZ hosts the Ni-Cu deposit (Fig. 4). Poorly developed modal layering is present in approximately 5% of the drill core. Modal abundances of plagioclase and clinopyroxene vary from 30 to 65%, and intercumulus phases are generally less than 15%. Anorthositic gabbroic rocks are more abundant east of the Ni-Cu deposit. They are coarse-grained mesocumulates with greater than 65% plagioclase, and with plagioclase and clinopyroxene as both cumulus and intercumulus phases. Modal gradations are visible on a scale of meters in approximately 15% of the drill core. In comparison to the PZ, the GZ has a higher proportion of plagioclase, rare cumulus orthopyroxene, fewer intercumulus phases and is generally less altered. The contact with the PZ is marked by the appearance of plagioclase as a cumulus phase, and is gradational on a scale of meters. Gabbro pegmatite dikes are rare in the GZ, and are present only west of the Ni-Cu deposit.

The Ferroan Gabbro Zone is located in the southern two-thirds and the western "tail" of the MGC (Fig. 3). It is characterized by the presence of interstitial and cumulus magnetite, along with medium- to coarse-grained plagioclase, clinopyroxene and hornblende. Several of the outcrops have FZ dikes, or crystal mush-like FZ material that cut FZ cumulate rocks. Xenoliths of PZ cumulates are found within FZ dikes, locally. Primary modal layering is present locally, as mafic to felsic graded layers up to 1 m thick and as centimeter-thick wispy laminations of mafic minerals within the more plagioclase-rich layers.

Ultramafic, mafic, felsic and alkaline dike suites comprise fully 25% of the drill core in the vicinity of the Montcalm deposit. The ultramafic and mafic dikes may represent crystal mushes of MGC material that were mobilized during tectonism and consolidation of the cumulate rocks. A geochemical survey of these dikes indicates that in general, they do not represent compositions of the parental liquid. The geology, petrology and geochemistry of the dike

TABLE 1. U-Pb ISOTOPE DATA FOR ZIRCONS FROM MONTCALM GABBROIC COMPLEX AND GRANODIORITE DIKE SAMPLES

FRACTIONS ^a	WElGHT (mg)	U (ppm)	COMMON PE (Pg)	b <u>207Pb</u> ¢ 206Pb	<u>207Pb</u> d 204Pb	<u>208Pb</u> # 206Pb	<u>206Pb</u> ^e 238U	<u>2079b</u> e, f 235U	<u>207Pb</u> ^g 206Pb (Age)	percent discordant
MGC-1 MONTCALM	GABBROIC	COMPL	EX	•						
1. ON, +200 Ab	0.012	163	80	0.19838	155	0.178	0.51921	13.267	2701	0.24
3 grains					185			(0.60)	(0.11)	
2. ON, +200 Ab	0.020	92	30	0.18905	367	0.239	0.51670	13.191	2699.4	0.64
3 grains					589			(1.2)	(0.12)	
3. ON, +200 Ab	0.115	209	15	0.18508	3393	0.185	0.51647	13.172	2698	0.63
								(0.60)	(0.10)	
4. ON, +200	0.019	266	8	D. 18474	2156	0.204	0.51124	13.022	2696	1.54
3 grains					*			(0.80)	(0.10)	
86-220 MONTCALM	GRANODI	ORITE	DIKE							
5. ON, +200 Ab	0.019	85	9	0.18492	679	0.020	0.51745	13.190	2697	0.39
5 grains					*			(0.80)	(0.20)	
6. ON, +200 Ab	0.009	209	11	0.18580	797	0.132	0.51343	13.114	2700.3	1.31
5 grains					4115			(1.0)	(0.40)	
7. ON, +200	0.012	515	100	0.18775	341	0.123	0.47135	11.813	2669	8.1
3 grains					383			(0.80)	(0.10)	

a) All fractions are zircon populations unless otherwise indicated. ON: 0⁰ tilt, non-magnetic fraction from magnetic separator; Ab: air-abraded fraction (Krogh 1982); +200/-200: fractions larger or smaller than 200 size mesh (about 74 lm), respectively.

b) Corrected for 0.117 mole fraction common Pb in the ²⁰⁵Pb spike. Includes blank plus zircon common Pb.

c) Corrected for fractionation and blank. Pb and U fractionation correction = 0.13% per atomic mass unit. U blank = 3.8 pg (large column), 0.5 pg (small column, used for sample numbers 1,2,6); Pb blank < 8.2 pg (both columns).

d) Measured values. Numbers in brackets corrected for fractionation, blank and common lead in the spike.

(*) means all common Pb can be considered blank.

e) Corrected for fractionation, blank and common Pb using the model of Stacey & Kramers (1975)

f) Numbers in parentheses refer to percent 2-sigma error in Pb/U.

g) Numbers in parentheses refer to percent 2-sigma error in ²⁰⁷Pb/²⁰⁶Pb An error of 0.1% corresponds

to 1.6 Ma.

suites have been described by Barrie & Naldrett (1989) and Barrie (1990).

U-Pb zircon geochronology and structural history

Two samples were selected from the Montcalm area to establish the timing of tholeiitic intrusive activity and deformation, and for comparison with tholeiitic magmatism and deformation in the Abitibi and Wawa Subprovinces. A pegmatitic gabbroic segregation containing 2% quartz was selected from the GZ, well away from the upper PZ gabbro pegmatite dikes, and a second sample was collected from a 15-m wide granodiorite dike that cuts the Montcalm Ni-Cu deposit. The U-Pb data (Table 1) give ages with overlapping 2σ errors of 2702 \pm 2 Ma for the MGC, based on a four-point discordia line, and 2700 ± 2 Ma for the granodiorite dike, based on a three-point discordia line (Fig. 5). Neither sample shows signs of inheritance. The age for the MGC is younger than the U-Pb zircon age for the Kamiskotia gabbroic complex 25 km to the ESE (Fig. 1), which is 2707 \pm 2 Ma (Barrie & Davis 1990). The MGC is among the youngest tholeiitic intrusions known in the southern Superior Province, which were emplaced between 2750 and 2692 Ma. The granodiorite dike is among the oldest of the syn- to posttectonic intrusive bodies, which have U-Pb zircon ages between 2702 and 2668 Ma (Barrie & Davis 1990, Corfu *et al.* 1989, Davis *et al.* 1989, and references therein).

The MGC has been subject to at least two deformation events. The first produced a regional penetrative fabric and may have been responsible for bulk crustal rotation of the regional stratigraphy into its present subvertical position. The arcuate shape of the MGC is parallel to the regional penetrative fabric, and suggests that a broad doming to the northwest may have been coincident with or responsible for this first event. Along with four outcrops in the FZ that show facing directions from modal layering (Fig. 3). this indicates a general facing direction to the east and southeast. The second deformation event, probably related to the emplacement of the granitoid rocks to the east (2696 - 2694 Ma: Barrie & Davis 1990) and south, produced a strong flattening and elongation fabric on the eastern and southern parts of the MGC (Barrie & Naldrett 1989).

GEOCHEMISTRY

Samples representing the cumulate stratigraphy were taken from several drill holes across strike and perpendicular to the PZ – GZ contact for a petro-



FIG. 5. Concordia diagrams for the Montcalm gabbroic complex and granodiorite dike. Ages and 2σ errors calculated using the regression program of Davis (1982). a. Montcalm gabbroic complex. b. Granodiorite dike.

graphic, mineral, and whole-rock geochemical traverse across the Ni-Cu deposit (Fig. 6). The westernmost PZ, which represents the floor or the wall of the MGC, is at the base of the traverse. Results of major, trace, and rare-earth-element analyses for 20 representative samples, including 15 from the traverse, one pyroxenite xenolith and four from outcrop are included in Table 2. Concentrations of the platinum-group elements are included for 12 of these samples also. All samples weighed 1.5-2.5 kg. Drill-core samples represent 0.5-3.0 m of the section, with the coarse-grained rocks represented by longer sections wherever possible. All sample locations and additional geochemical data for the other samples in Figure 6 are reported in Barrie (1990).

Petrography and mineral chemistry of rocks on the geochemical traverse

The mode and grain size of cumulus and intercumulus silicate phases are plotted *versus* stratigraphic height in Figures 7 and 8, respectively. PZ samples are divided on the basis of textural relationships into lower and upper groups, below and above 100 m in stratigraphic height. Lower PZ rocks have orthocumulate textures that are easily discernable in hand specimen and thin section. Cumulus phases are principally clinopyroxene and orthopyroxene, with subordinate olivine and rare plagioclase. Intercumulus phases include both pyroxenes, plagioclase and minor Fe-Ti oxides. The unusually large grainsize of the intercumulus phases in sample 86-394 is due to oikocrystic hornblende. For upper PZ rocks, textural relationships that normally distinguish between cumulus and intercumulus phases become obscure with increasing grain-size. Most of these samples have large, optically continuous pyroxene grains along with oikocrystic hornblende; in addition, interstitial Fe-Ti oxides and sulfides comprise up to 5% of the mode. Textures indicating replacement of cumulus pyroxene by hornblende are evident in samples 86-399 and 86-391. Sample 86-403 is exclusively pegmatitic gabbro, with complete replacement of cumulus phases by pegmatitic hornblende, clinopyroxene and plagioclase. In the GZ, clinopyroxene and plagioclase are the cumulus phases; cumulus olivine is present in a sample at 308 m height (sample 86-428: Barrie 1990). Petrographic estimates of the mode of intercumulus phases are: 25-45% in the lower PZ, 10-30% in the upper PZ and <3-20% for the GZ. These proportions are lower than expected considering the levels of incompatible trace elements (discussed below).

The An content of cumulus plagioclase and the Mg number of cumulus clinopyroxene (microprobe data) are plotted along with normative An and whole-rock Mg numbers, corrected for their sulfide content (Fig. 9). Measured plagioclase An contents are variable but generally lower than the normative An values. In the PZ, the presence of intercumulus hornblende in several samples is not included in the normative calculation, and this tends to increase the calculated An content. Thus the trend toward normative An values of 90–100 near the top of the PZ is partly artificial. In the GZ, one sample has two core-rim pairs that indicate normal zonation, sug-

W



FIG. 6. Cross section for geochemical traverse, with traverse line (115°N, 30°E) and sample locations projected into plane of section. Labeled samples included in Table 2; geochemistry for other samples given in Barrie (1990). Sample stratigraphic height along traverse line has error estimated at \pm 10 m. Location of traverse line in Figure 4.

gesting re-equilibration with a more sodic interstitial liquid.

A comparison of clinopyroxene and whole-rock Mg numbers in the GZ reveals two important features. First, with one exception the most magnesian clinopyroxene grains have Mg numbers from 78 to 82, higher than the whole-rock values. Assuming that these represent primary, undisturbed cumulus clinopyroxene grains, their consistently high Mg number suggests a derivation from a parental liquid that did not undergo significant closed-system fractionation and Fe-enrichment. Second, reequilibration with an Fe-enriched, postcumulus silicate liquid may have affected many of the cumulus clinopyroxene grains in the GZ and the lower PZ. This is indicated by the wide range in clinopyroxene Mg numbers, with a maximum range within a sample at 203 m height (sample 86-402: Barrie 1990) from 82 to 68, and clinopyroxene core-rim pairs with consistent, normal zonation to a more hedenbergitic rim. Barnes (1986) calculated the "trapped liquid shift" for mafic minerals in the presence of variable amounts of fractionating intercumulus liquid for closed systems. He found a significant shift toward more Fe-rich compositions during postcumulus fractionation of interstitial liquid, particularly for orthocumulates with a small proportion of mafic phases. For example, a gabbronorite with a 60:40 ratio of cumulus plagioclase to pyroxene, and with

50% initial interstitial liquid, will see pyroxene Mg numbers decrease from 80 to 64 (Fig. 1 in Barnes 1986). This example may pertain to many of the GZ cumulates, which implies a relatively high proportion of original "trapped" or intercumulus liquid in the GZ. A similar conclusion was reached by Naldrett *et al.* (1970) for the basal norites of the Sudbury Irruptive, where most orthopyroxene cores have a constant Fe/(Fe+Mg) atomic ratio, yet the vast majority show a trapped liquid shift of 5–18 atomic $%_0$.

Interestingly, an adcumulate pyroxenite xenolith (sample 86–FRAG: Table 2) sampled near the Ni-Cu deposit does not show any significant zonation in clinopyroxene; nine analyses, including 3 of core-rim pairs, show Mg numbers from 75 to 80 (Barrie 1990). These values are similar to the whole-rock uncorrected Mg number of 75, or 77 if the Fe content is corrected for a petrographic estimate of its sulfide content. It would appear that this pyroxenite xenolith was derived from a part of the MGC chamber (or a separate chamber in the lower crust) that was not affected significantly by an Fe-rich postcumulus silicate liquid, in contrast to the lower PZ cumulates.

Postcumulus Fe enrichment in the pegmatitic upper PZ rocks appears to be related to volatile activity. Intercumulus Fe-Ti oxides comprise 1-4% of the mode in hornblende-bearing samples.

THE MONTCALM GABBROIC COMPLEX, ONTARIO

	85-60	86-394	86-393	86-389	86-403	86-399	86-391	86-401	86-417	85-38	86-426	86-413	86-425	86-429	86-427	86-409	86-FRAG
S102 wt %	42 3	41 7	40.9	45.6	41.2	47.7	38.4	42.2	38.2	51.0	46.9	45.7	46.4	48.1	46.4	50.1	48.7
mi02	0 74	0 53	0.56	0.70	0.34	0.52	0.34	0.49	0.48	0.21	0.16	0.21	0.18	0.14	0.20	0.25	0.27
11202	0 8	a 0	10 5	8.0	10.8	10 1	8 3	11.6	8.3	17.2	21.3	20.6	17.3	16.5	15.4	10.6	8.65
R1203	16 3	16 7	15 7	14 3	17 3	13 6	15 3	15 1	16 7	6.7	5.4	5.7	6.7	6.9	10.0	10.0	13.6
rezus	10.2	15.7	0.00	0 22	0,19	0 17	0.20	0 10	0 23	0 11	0 11	0.10	0.12	0.12	0.13	0.17	0.22
MnO	0.22	0.25	0.22	0.23	0.10	0.17	0.20	16 7	20.20	11 7	8 5	8 1	11.8	12 4	12.0	16.2	17.9
MgO	17.6	18.7	18.3	13.6	17.2	13.1	19.9	10.7	20.9	11.7	11 55	11 70	0 09	0 77	6.54	6.26	5.55
CaO	5.65	6.89	7.13	9.42	6.57	8.6/	6.8/	7.68	6.30	9.17	11.55	1 56	5.00	1 00	1.95	1.31	0.37
Na2O	0.72	0.63	0.50	1.39	0.44	1.08	0.04	0.74	0.18	1.33	1.40	1.58	1.07	1.09	0 42	0 08	0.06
K20	0.09	0.12	0.13	0.27	0.09	0.23	0.03	0.18	0.04	0.17	0.34	0.53	0.52	0.16	0.42	0.04	0.05
P205	0.10	0.10	0.09	0.10	0.03	0.06	0.05	0.03	0.04	0.03	0.02	0.04	0.02	0.01	0.02	4 22	4 20
FOI	3.85	4.85	5.16	2.62	4.93	3.85	8.27	4.70	8.08	2.77	2.98	4.54	4.08	2.55	5.20	4.25	4.39
TOTAL	98.3	99.0	99.2	96.2	99.1	99.1	97.5	99.6	99.5	100.4	98.7	98.8	97.3	97.8	98.3	99.2	99.9
T.a	5.18	5.8	6.13	5.25	3.77	3.39	1.76	0.99	0.94	2.4	3.32	2.9	2.13	1.59	1.39	2.16	1.50
Co PPm	12 5	15 4	15 7	14 4	10.9	8.2	3.6	2.1	2.9	5.4	8.0	6.9	4.6	3.2	2.6	5.5	4.4
NA	7 9	9.2	10 7	10 0	7.5	5.1	3.1	2.3	2.4	2.0	3.4	3.4	2.2	1.6	1.7	3.5	1.8
Nu.	1 09	1 0 1	2 07	2 22	1 70	1 24	0.60	0 45	0 68	0 51	0.69	0.71	0.44	0.33	0.30	0.74	0.47
Sm	1.90	1.01	2.01	2.23	1.75	0.26	0.05	0.45	0.00	0.24	0 35	0 3	0.26	0.18	0,19	0.2	0.24
Eu	0.51	0.52	0.59	0.00	0.37	0.30	0.35	0.23	0.21	0.24	0.33	0.5	0.20	01.40		0.2	
TD	0.3	0.3	0.4	0.4	0.2	0.3	0.2	0.1	0.1	0 24	ດ້າຄ	0 32	0 30	0 32	0.28	0.38	0.31
Yb	1.14	1.04	1.27	1.49	0.95	0.89	0.72	0.33	0.54	0.24	0.20	0.32	0.30	0.52	0.05	0.08	0.05
Lu	0.18	0.15	0.19	0.21	0.14	0.10	0.09	0.08	0.08	0.05	0.04	0.06	0.00	0.03	0.00		
2.	35	28	25	33	32	35	17	8	8	29	15	14	8	10	10	17	13
7	11	20	11	13	10	8	6	Å	ŝ	3	4	3	2	3	3	5	3
1	· · ·	21 4	17 6	27.0	16 3	27 2	20 8	20 8	14 4	16 6	15 9	18.9	17.1	20.3	17.4	25.2	23.1
sc	41.7	21.4	17.5	31.0	10.2	37.3	30.0	146		10.0	65	78	68	69	73	91	86
v	120	104	108	140	124	200	350	140	104	224	402	455	306	200	272	52	56
Sr	82	100	52	101	21	240	1/3	194	104	234	492	100	16	200	8	<1	
Rb	4	26	<1	17	<1	15	11	5	:::	4	12	20	741	002	575	1146	866
Cr	416	622	552	480	716	446	332	550	611	932	657	502	741	903	306	615	2300
Ni	1300	816	752	355	2088	1629	593	825	894	740	270	214	/0/	437	43 0	60.7	101 0
Co	91.9	113.3	103.0	81.0	179.5	111.6	92.0	101.7	120.6	40.3	35.0	28.7	64.2	52.2	43.4	39.7	101.0
Cu	52	73	75	87	2450	2120	297	155	65	22	37	54	185	54	92	30	
Zn	46	130	147	109	85	110			77	50	18.8	11		27	:::	38	120
s	480	520	980	480	6500	7160	3240	1120	720	100	460	240	780	60	120	<20	• • •
Mg ' *	71	73	72	68	71	71	75	72	74	80	80	76	80	80	73	78	(75)
Se ppb	340	470	510	430					81.8		<20	<20		251		· • •	
Ac pp.	196	134	152	186					830	<1	<1	<1	< 1	484	<1	<1	
ch	43.8	44 8	830	46 2					146	0.1				280	1.1	0.13	
00	40.0	~ 1	21	21					<1	< 1	<1	< 1	<1	<1	<1	<1	
08	~ ⁴	~ i	<u>`</u>	<u> </u>		• • •			0.1	<0.02	<0.02	0.05	<0.02	0.02	<0.02	<0.02	
1r	0.1	0.1	0.9	0.1	• • •	•••	•••		12	.0.02	10.04	2.55	(2	(2	<2	< 2	
Ru	6	6	44	5	•••	•••		• • •	10			21	21	0	<1	<1	
Pt	8	23	13	_ 11	• • •				, ¹ /	<u> </u>		· · · ·	2 6	3 5	q F	2.3	
Au (RNAA)	1.7	2.7	9.3	1.6			• • •	• • •	2.4	0.9	U.4	1.2	3.0	3.5			3
Au (INAA)	3	11	10	3	62	75	27		3	4	2	2	5	9		12	5
Height	25	51	68	87	106	110	132	138	151	242	325	350	360	364	377	500	•••

TABLE 2. GEOCHEMISTRY OF REPRESENTATIVE SAMPLES OF THE ROCK TYPES FOUND IN THE MONTCAIM GABBROIC COMPLEX

Major elements by XRF at X-Ray Assay Laboratories, Toronto; trace elements by XRF and NAA at the University of Toronto; PGE by RNAA at the University of Toronto; see Barrie (1990) for explanation of analytical techniques and their accuracy and precision. Mg'^{s} : Mg number calculated using mole percent MgO/ MgO + FeO, with Fe in FeO = 0.85 total Fe, less Fe in monosulfide solid solution estimated using Fe758. For sample 86-FRAG, the Mg number is not corrected for sulfide content.

Microprobe analyses of the Fe–Ti oxides indicate that the majority are either magnetite, or ilmenite containing from 2.7 to 4.6 wt.% Cr_2O_3 with negligible Mg contents (Barrie 1990). The composition of the chromian ilmenite is distinct from that of kimberlitic ilmenite, which contains >2 wt.% MgO (Mitchell 1986). In many respects, its occurrence is similar to that of unusual titanium – chromium spinels that occur in the transgressive, metasomatic ultramafic magnetite pipes of the eastern Bushveld Complex (Cameron & Desborough 1964, Cameron & Glover 1973, Viljoen & Scoon 1985); however, chromian ilmenite has not been documented in the Bushveld occurrences.

Major, trace and rare-earth-element geochemistry

For the cumulate rocks of the lower PZ and GZ, the majority of the major and incompatible trace elements plot as coherent trends on interelement variation diagrams, and are believed to represent the prealteration compositions despite subsolidus alteration and metamorphism. This immobile behavior is in accord with studies on the mobility of major and trace elements in volcanic rocks that have been subjected to greenschist-facies metamorphism and normal processes of surficial weathering (Menzies *et al.* 1979, Ludden *et al.* 1982, Beswick 1982). Variation diagrams show that the alkalis and Se, As, and Sb do not correlate well with elements of similar geochemical affinities; therefore, little emphasis is placed on these elements. Postcumulus rare-earthelement (*REE*) redistribution is evident in the predominantly pegmatitic upper PZ rocks; this is discussed below. Subsolidus chloritization has resulted in magnesium addition and silica loss in the majority of PZ rocks, and subsolidus sulfur loss is noted for several samples with concentrations of < 250 ppm S.

Selected major- and trace-element contents and trace-element ratios are plotted *versus* stratigraphic height in Figures 10 and 11. The division between the PZ and the GZ is clearly evident in the majorelement variations, and reflects the addition of plagioclase as a cumulus phase in the GZ. The major elements remain relatively constant throughout the GZ, except from 350 to 380 m, where MgO and Fe₂O₃ increase at the expense of Al₂O₃, reflecting an increase in modal clinopyroxene (Fig. 7). For the lower PZ, where primary cumulate textures predominate, the corrected Mg numbers are rela-



FIG. 7. Mode (cumulus + intercumulus) for geochemical traverse samples, based on petrographic estimations. Height refers to west - east distance along cross-section line in Figure 6. Symbols: ol olivine, opx orthopyroxene, cpx clinopyroxene, hb hornblende, plag plagioclase, S+mt sulfides + Fe-Ti oxides.

tively low, from 68 to 73. Mg numbers gradually increase up-section across the PZ-GZ contact, with values from 70 to 75 in the upper PZ steadily increasing up to 79 to 81 in the middle GZ.

The compatible trace-elements Cr, Sc and V partition into the mafic silicate and oxide phases. Wholerock Cr contents are generally lower in the PZ than in the GZ, where trace amounts of chromite are preserved locally. Chromium distribution is erratic but broadly follows the corrected Mg number, suggesting an overall trend toward more primitive compositions up-section. Scandium contents generally follow the modal abundance of clinopyroxene in the GZ. In the lower PZ, samples 1–3 have low Sc contents (17.5 to 21.7 ppm) that reflect the higher modal proportion of olivine and orthopyroxene, which have partition coefficients well below unity for Sc (Lindstrom 1976).

Vanadium appears to be a particularly sensitive indicator of volatile-related, postcumulus enrichment processes in the upper PZ. Strong enrichment in V occurs from 100 to 140 m, where, as previously men-



FIG. 8. Cumulus and intercumulus grain-size versus stratigraphic height for geochemical traverse samples, based on petrographic estimations. PZ divided into lower orthocumulates (unshaded), and upper (shaded) rocks, which are predominantly subpegmatitic to pegmatitic.

tioned, the cumulate textures are obscured by partial to complete replacement by pegmatitic phases. These samples contain 1-3% interstitial Fe-Ti oxides. The mineral-liquid partition coefficients for V between minerals and mafic to intermediate silicate melts are generally greater than unity, but they are strongly dependent on the oxygen fugacity of the system, with higher partition coefficients for more reduced systems. They range from 5 at an $f(O_2)$ of 10^{-12} bars to 0.05 at an $f(O_2)$ of 10^{-6} bars for calcic pyroxene (Lindstrom 1976); 6.3 to 13 for hornblende (Luhr & Carmichael 1980), 12 for ilmenite (Ringwood 1970), and 4.2 at an $f(O_2)$ of 10^{-13} bars to 0.11 at an $f(O_2)$ of 10^{-12} bars for magnetite (Lindstrom 1976). In samples 86-399 and 86-391, wholerock V contents are 200 and 356 ppm, respectively, yet vanadium is below detection limits (<0.5 wt.%) in microprobe analyses of pyroxene, hornblende and ilmenite. Magnetite probably is the principal Vbearing phase for these samples. Vanadium enrichment has been noted in other volatile-related systems, e.g., in the Kennedy's Vale ultramafic pegmatite

500-

body of the Bushveld Complex (Van Rensburg 1965) and in roscoeite-bearing (vanadium-bearing mica) hydrothermal veins in the Porgera porphyry Cu-Au deposit of Papua – New Guinea (Henry 1988).

Incompatible and immobile elements such as Ti. P, Zr, Y and La are highest in the lower PZ, then decrease through the upper PZ to the PZ-GZ contact, and with few exceptions remain low throughout the GZ. High values in the lower PZ are consistent with a higher proportion of trapped liquid near the margin of the complex. Variations in La and Sm in the GZ tend to parallel Al₂O₃ content, reflecting their slightly higher partition coefficients into plagioclase than Yb, Zr and Y. At 345 m, more closely spaced samples show a decrease in concentration of incompatible trace-elements, accompanied by a decrease in Al₂O₃, and increasing MgO and Fe₂O₃. These trends may reflect modal layering, with increasing clinopyroxene and decreasing intercumulus phases in the cumulates. However, the presence of cumulus olivine at 308 m suggests that magma replenishment occurred during GZ formation, which could also account for trace-element variations in the GZ stratigraphy.

Ratios of incompatible trace-element concentrations can be useful in tracking the composition of the interstitial liquid. In general, Zr/Y and chondritenormalized La/Sm and La/Yb all increase from the upper PZ to the middle GZ, and then slightly decrease. La and Sm are slightly more compatible in plagioclase than Yb, Y or Zr, so that La/Sm and La/Yb may reflect, to a certain extent, the proportion of cumulus plagioclase in addition to the composition of the interstitial liquid. All ratios suggest that the interstitial liquid becomes relatively enriched in La and Zr in the middle GZ.

Neodymium isotope geochemistry

Neodymium isotope signatures have been determined by Barrie & Shirey (submitted) for four MGC samples as part of a regional isotopic study on the evolution of the Kamiskotia - Montcalm area. The results of the analyses are reported as ϵ values corrected to the Montcalm U-Pb age, or the difference from a chondritic (CHUR) reservoir in parts per ten thousand at 2702 Ma. The 2- σ errors average ± 0.6 ϵ units. In general, positive $\epsilon_{Nd}(t)$ values reflect a long-term, light REE depletion in comparison to CHUR (e.g., the MORB mantle reservoir), whereas negative values reflect long-term light REE enrichment (e.g., old crustal rocks). Mantle-derived, uncontaminated Abitibi Subprovince rocks, such as the Alexo komatilites, have depleted $\epsilon_{Nd}(t)$ values averaging + 2.7 (corrected after Dupré et al. 1984), whereas the isotopically most enriched Abitibi rocks are found 10 and 20 km to the east of the MGC, where two granitic samples have $\epsilon_{Nd}(t)$ values of



FIG. 9. Plagioclase An contents and clinopyroxene Mg numbers versus stratigraphic height. Triangles are microprobe data: C core, R rim, unlabeled: defocussed spot analysis of core for plagioclase. Circles are normative An contents and Mg numbers adjusted for sulfide content. Microprobe data are in Barrie (1990).

+ 0.6 and -0.4 (Barrie & Shirey, submitted). MGC samples range from $\epsilon_{Nd}(t) = +3.8$ from the upper PZ, to +2.4 and +2.8 for the GZ, to +1.0 for the FZ. GZ cumulates have isotopic signatures similar to the depleted mantle elsewhere in the southern Abitibi Subprovince (Dupré *et al.* 1984, Machado *et al.* 1986). In comparison, the FZ sample is isotopically enriched and outside the analytical error. The upper PZ sample is more depleted than the depleted Abitibi mantle, and may have been subjected to *REE* mobility after crystallization (discussed below).

Base and precious metal geochemistry

Logarithmic values of S, Ni, Cu and Au are plotted *versus* stratigraphic height in Figure 12. The lower PZ has relatively constant S, decreasing Ni, slightly increasing Cu and erratic Au concentrations with height. Above 100 m these elements increase dramatically, particularly Cu and Au, which reach 2450 ppm and 75 ppb, respectively. The elevated values are found in samples where primary cumulate textures are partly or completely obscured by postcumulus pegmatitic phases. Immediately above



FIG. 10. Whole-rock major and transition-element contents versus stratigraphic height. a. Major elements (wt.%, and Mg number, corrected for sulfide (see Table 2). b. Minor (wt.%), and compatible trace-elements (ppm).

the PZ, S contents are very low in the lower GZ and then increase sporadically but consistently to 430 m. This trend is paralleled in a general sense by Ni, Cu, and Au. Metal contents normalized to S show spurious enrichments at 200 m and above 430 m due to low S contents at these levels. Anomalously low S contents may be the result of sulfide resorption into the parental magma shortly after formation (von Gruenewaldt *et al.* 1986) or into a sulfurundersaturated interstitial liquid; alternatively, they may be due to subsolidus alteration. Twelve of the samples in the traverse were selected for platinum-group element (*PGE*) analysis by radiochemical neutron activation (RNAA) using the method described in Brügmann *et al.* (1987). This method has very low detection limits (Os: 1 ppb; Ir: 0.02 ppb; Ru: 2 ppb; Pt: 1 ppb; Au: 0.02 ppb) and is ideally suited for the Montcalm suite. Samples were selected to reflect contents of primary magmatic sulfide, with the exception of sample 9, taken as an example of the upper PZ rocks that have undergone postcumulus re-equilibration with a fractionated interstitial liquid. All PZ samples regardless of texture are relatively enriched in total PGE in comparison to the GZ; however, Au is on average equally abundant in the two zones (Fig. 13). The PGE are below detection limits in all but one of GZ samples, in spite of the high sensitivity of the RNAA technique. The exception is sample 86-429, which has a low sulfur content but a high Mg number and high Cr content in comparison to other GZ samples.

THE MONTCALM NI-CU DEPOSIT

Geology

The Montcalm Ni-Cu deposit is located at the extreme northern end of the MGC (Figs. 2-4). It is composed of two subvertical sulfide-rich lenses, termed the West Zone and the East Zone, each with a maximum subsurface strike-length of 200 m, and a maximum width of 25 m (Fig. 14). The West Zone contains 1.75 million tonnes of 1.51 wt.% Ni, and 0.74 wt.% Cu: it is almost equal in size and grade to the East Zone, which has 1.81 million tonnes of 1.39 wt.% Ni and 0.61 wt.% Cu. No systematic zonation of Ni or Cu grade is present, except for possible local enrichments near the granodiorite dike, where massive sulfide generally is more highly deformed. The zones are hosted by medium- to coarse-grained gabbros of the GZ and are separated by a subvertical granodiorite dike. The wallrock gabbro contains discrete high-strain zones characterized by a well-developed flattening fabric, along with an elongation fabric locally.

Three texturally distinct types of sulfide mineralization are present. In order of decreasing abundance, these are: disseminated sulfide (10-50% sulfide by volume), massive and net-textured sulfide (>50%sulfide) and inclusion-breccia sulfide (>50% sulfide). The first two groups vary from a relatively undeformed state, with easily discernible primary igneous textures to highly foliated, locally lineated material. Foliation planes are oriented at 50° to the drill-core axis and probably represent subvertical north-trending attitudes. Disseminated sulfide generally is interstitial to altered silicate phases. In more deformed and altered rock, fine-grained sulfide phases are found within tremolite-actinolite and chlorite, which are pseudomorphous after clinopyroxene and plagioclase, respectively. In undeformed net-textured sulfide, most or all of the interstitial space is occupied by sulfide. Inclusionbreccia sulfide contains angular and rounded fragments of gabbroic, pyroxenitic and siliceous material up to 20 cm in maximum dimension. The majority of the fragments appear to be locally derived from gabbroic wallrock. However, the presence of pyroxenitic fragments (10% of the fragments) in the inclusion-breccia mineralization suggests that at least some of the fragments were derived from an ultramafic part of the intrusion, or from a magma chamber in the lower crust.

Mineralogy

The Ni-Cu deposit has a relatively simple mineralogy of pyrrhotite, pentlandite and chalcopyrite, with minor magnetite, pyrite and violarite. In undeformed net-textured sulfide, pentlandite exsolution "flames" are preserved within pyrrhotite. Elsewhere, pentlandite occurs as euhedra surrounding pyrrhotite grains. Chalcopyrite is commonly observed as millimeter-wide veinlets that locally cut both silicate and sulfide grains, as pressure shadows to fragments in the inclusion-breccia sulfide, and as fine-grained disseminations within the altered remnants of silicate phases. Magnetite is commonly located at sulfide-silicate contacts, and may be the product of desulfurization reactions between pyrrhotite and silicate phases. The presence of pyrite may represent the local sulfurization of pyrrhotite. Violarite is found along pentlandite grain margins in highly deformed ore.

Geochemistry

Base- and precious-metal concentrations are given along with S, Se, and δ^{34} S values for 21 samples from the sulfide lenses in Table 3; interelement and correlation coefficients with distance to the nearest felsic dike are given in Table 4. These samples represent the range of compositions and textures from the West and East Zones. Average metal contents in 100% sulfide derived from these data have been presented previously (Naldrett & Duke 1980). Drill-hole locations and intervals are given in Barrie (1990).

There are few significant interelement correlations (Table 4). Sulfur correlates with Ni and Co as expected, but does not correlate with Cu. This lack of correlation may be due to the rheology contrast between chalcopyrite and Fe-Ni-Co sulfides. The more malleable chalcopyrite tends to flow under stress and separate from other sulfides (Kelly & Clark 1975). Rhodium correlates with S and Ni, and shows a weak negative correlation with Cu, implying that it may be incorporated into the structure of pentlandite but not that of chalcopyrite. None of the elements correlate with distance to the nearest felsic dike, suggesting that element mobilization due to dike emplacement was either random or not significant for this population.

S/Se ratios and δ^{34} S values have been used as indicators of sedimentary sulfide contamination in magmatic deposits. Ideally, a primitive magma should have a chondritic S/Se value of approximately 2700 (Aller 1967); values of 2000 to 10,000 are con-



FIG. 11. Incompatible trace elements *versus* stratigraphic height. a. Zr, Y (ppm) and Zr/Y. b. *REE* (ppm) and *REE* ratios.

sidered normal for uncontaminated magmatic sulfide ores (Naldrett 1981). Archean sedimentary sulfide has a variable ratio depending on the reduction state of the depositional environment, but it is generally in the range of 20,000 - >50,000 (Shegelski 1978, Green 1978). S/Se values for sulfide-oxidefacies iron formation in the Kamiskotia area average 38,500 (n = 12: Barrie 1990), and for Langmuir township 85 km to the ESE, they average 23,700 (n = 11: Green 1978). For Montcalm, the S/Se value

is 13,000 (n = 20, 1σ error = 8500), nearly within the range of normal magmatic sulfide ores.

Ideally magmatic sulfides derived from primitive sources will have chondritic δ^{34} S values of 0‰ (with respect to Canyon Diablo troilite). Biogenic fractionation of sulfur isotopes generally causes an increase in ³⁴S with respect to ³²S in sulfate and sulfide minerals, and consequently in sedimentary hostrocks. Although there is ample evidence for biogenic activity during the formation of the southern



FIG. 12. Log ppm S, Ni, Cu and Au versus stratigraphic height.

Superior Province (Wilkes & Nisbet 1985), the evidence from sulfur isotopes for this activity is ambiguous: sulfides from the Michipicoten and Woman River iron formations in the Wawa Subprovince have δ^{34} S values that range from -10 to +10‰ (Goodwin *et al.* 1976). The δ^{34} S values for the Montcalm deposit average -1.8‰ with little deviation (n = 10, $1\sigma = 1.2$), consistent with a primitive magmatic source for sulfur. It is noted that this does not rule out a sedimentary source for the sulfur.

The Montcalm deposit has average base-metal contents normalized to 100% sulfide of 4.31 wt.% Ni, 1.38% Cu and 0.24% Co (Naldrett & Duke 1980). In terms of its base-metal content, it is most similar to typical Sudbury ores, which have 3–7 wt.% Ni, 2–6% Cu and 0.15% Co in 100% sulfide. Flood-basalt-related deposits such as Noril'sk, and Minnamax and Great Lakes Nickel of the Duluth district, have similar sulfide-normalized Ni and Co contents of 3–7 and 0.15–0.20 wt.%, respectively, but they have much higher Cu contents (8–17 wt.%: Naldrett 1981).

In terms of the PGE and Au, the Montcalm deposit contains conspicuously low concentrations, nearly two orders of magnitude less than floodbasalt-related deposits (Fig. 15). There appears to be a negative Pd anomaly, and the normalized Au content is relatively enriched with respect to the PGE. The steep pattern, with much lower abundances of Os, Ir and Ru, is typical of gabbro-hosted Ni–Cu deposits. This is in comparison to Ni deposits found in komatilites, which have flatter and more chondritic



FIG. 13. Total platinum-group-element (*PGE*) and Au (ppb) concentrations *versus* stratigraphic height. Palladium included in total *PGE*; estimated as Pd_{sample} = Pt_{sample} * (Pd_{deposit}/Pt_{deposit}).



FIG. 14. Ni and Cu values (wt.%) for Ni-Cu deposit lenses. Below: location of cross-section. Modified after Teck Corporation files.

patterns. Other gabbro-hosted Ni-Cu deposits having low PGE tenors and similar PGE patterns are the deposits at Moxie (Thompson 1982, Thompson & Naldrett 1984), the Bruvann deposit (Boyd *et al.* 1987) of the Råna Intrusion, Norway, and several deposits in Svecokarelian migmatite terrain of southern Finland (Papunen 1989).

DISCUSSION

Composition of the parental magma: evidence from the lower Pyroxenite Zone

Although the lower PZ, the upper PZ and the GZ have been affected by different cumulus and postcumulus processes, they all exhibit light *REE* enrichment, which is believed to be a characteristic of the overall parental magma composition (Fig. 16). Lower PZ rocks most closely approximate a liquid composition, owing to their orthocumulate texture and their relatively high contents of incompatible elements. The *REE* patterns for lower PZ rocks (Fig. 16a) have chondrite-normalized La in the range of 21–25, La/Yb in the range of 2.4–3.8, and no significant Eu anomaly. On average, they show a slight depletion in Ta-Nb-Ti and Zr-Hf if normalized to MORB or primitive mantle values.

There are several ways for elevated REE abundances with mild LREE enrichment to occur. One possibility is partial melting of the mantle with a small proportion of garnet in the residuum, followed by olivine fractionation to increase concentrations of the incompatible elements. This proposal is not viable, as the high degree of partial melting required would consume all of the garnet in reasonable garnet peridotite compositions, and no LREE enrichment would occur. A second possibility is that metasomatic activity in the upper mantle may have added a LREE-enriched, volatile or siliceous component to the upper mantle prior to partial melting and extraction of the PZ parental liquid. This process has been envisioned for LILE and LREE enrichment, accompanied by a relative high-field-strength element "depletion", in modern continental arc settings during the generation of alkaline basalts (e.g., Pearce 1983). Selective contamination is a third possibility, with a primitive magma gaining the LREE preferentially from crustal rocks during ascent through the crust, again followed by olivine fractionation. Selective contamination is believed to be a viable method of extraction of alkalis and silica from crustal rocks (Watson 1982), but it has yet to be demonstrated for the REE. A fourth mechanism is bulk assimilation of continental crust by a primitive ultramafic magma during olivine fractionation at lower crustal levels. Using the average Archean crust of Taylor & McLennan (1985) as a contaminant, the REE abundances for lower PZ samples can be derived from a 35% partial melt of the primitive mantle, followed by 20% olivine fractionation accompanied by 20% assimilation. However, Zr, Hf and Th are too enriched in this model. Of these alternatives, the most viable explanation for LREE enrichment in the lower PZ would appear to involve metasomatism in the mantle prior to partial melting and extraction of PZ parental liquids.

TABLE 3. GEOCHEMISTRY OF MASSIVE SULFIDE SAMPLES FROM THE MONTCALM HI-Cu DEPOSIT

																										DEPOSIT	
Sample	3268	3269	3270	3271	3272	3273	3274	3275	3276	3277	3278	3279	3280	3281	3282	3283	3284	3285	3286	3287	3288		x	1-sigma	n	AVERAGE	
wt.%																						#t.%					
Ni	1.98	2.60	1.73	1.35	3.58	2.49	2.09	2.45	2.72	2.61	3.19	3,85	2.60	1.77	4.30	3.73	1.82	2.69	2.51	1.54	4.70	SE I	2.68	0.69	21	1.44	>1500
Cu	0.43	1.08	0.21	0.24	0.51	1.06	1.44	1.51	0.65	1.20	0.98	0, 20	0.44	0. 52	0.41	0, 59	1.88	0.50	1.45	1.33	0.22	Cu	0.8	0.5	21	0.68	>1500
Co	0.08	0.15	0.07	0.05	0.21	0.17	0.16	0.10	0.14	0.18	0.19	0.24	0.21	0.05	0.20	0.17	0.11	0.11	0.12	0.30	0.19	Ca	0, 15	0.08	21		
s	17.9	22.1	13.6	19.5	34. 5	30. 5	23.8	20.9	22.6	28. Q	30.6	33.6	27.3	11.8	32.5	25. 1	16.5	21.0	21. 0	26.5	30. 5	s	24.1	6.5	21		
ppm																						ppm					
Se	22	22	<13	35	20	<7	27	19	28	34	12	48	16		25	34	23	<11	23	18	34	Se	23. 5	9.8	20		
Za	40	58	24	81	24	47	69	135	66	43	35	11	38	46	32	24	57	28	45	45	11	Zn	50	27	21		
Pb	25	24	16	22	15	12	13	22	21	12	21	11	17	22	19	11	24	14	11	14	13	Pb	17. 1	4.8	21		
ppb																						ppb					
Pt	30	31	9	31	19	15	184	50	54	64	31	50	22	22	32	29	21	15	31	40	48	Pt	35.6	20.7	21		
Pđ	5	9	1	20	8	1	12	18	15	12	13	3	5	9	33	d	<1	<1	8	<1	19	Pd	9. 1	8.4	21		
Rh	1.5	1.5	1.6	1.8	2.6		1.5	1.1	1.2	<1	- 41	3.7		(1	2.6	1.3	1.4	<1	<1	1.0	4.0	Rb	<1.7	0.9	19		
Ru	3	<1	30	2	<1	4	3	- 4	- 4	5	- 4	2	4	<1	2	2	3	<1	2	<1	1	Ru	< 3. 5	6.1	21		
lr -	0.5	0.4	0.3	0.7	0,3	0.1	0.4	0.3	0.6	0.4	0.1	1.2	0.3	0.4	0.3	0.5	0.4	0.2	0.2	0.4	0.4	(r	0.4	0.23	21		
Au	39	101	26	9	56	46	31	52	64	85	27	18	19	39	28	33	31	101	40	84	19	Au	45	26. 7	21		
δ ³⁴ s					-4.7	-1.8				-0.3	-2.7	-1.3	+2. 0		-3. 1	· 1. 5		- 0. 8	•0.7		•1.2	8 ³⁴ s	-1.8	1.2	10		
\$/\$	8136	10045	10462	5571	17300	43571	8815	11000	8071	8235	25500	7000	17063		13000	7382	7174	19091	9130	14722	8971	S/Se	13037	8594	20		

Transition metals analyzed by XRF and AA by X-Ray Assay Laboratories, Toronto; PGE and Au analyzed by BAA with Ni bead preconcentration; sea Hoffmann et al. (1978) for details on technique, accuracy and precision. Ni and Cu deposit average from Teck Corporation unpublished files, (calculated for reserves >0.65% Ni equivalent value, with wit. % Cu = 0.28 wit. % Ni).

		T	ABLE 4.	CORREL	TION	COEFFICIE	ENTS (r)	FOR N	li-Cu	DEPOSIT	SAMPLES'	*
Ni												0.14
Co	0.48											0.06
Cu	-0.36	0.06										0.10
Pt	0.07	0.23	0.30									-0.36
Pd	0.38	0.07	0.05	0.53								-0.02
Rh	0.74	0.35	-0.57	0.04	0.08	3						-0.30
Ru	-0.35	-0.38	-0.23	-0.34	-0.46	-0.21						0.23
Ir	0.09	0.09	~0.35	0.30	-0.16	0.38	-0.18					~0.28
Au	-0.16	0.14	0.32	0.01	-0.08	3 -0.46	-0.03	-0.24				0.06
S	0.73	0.82	-0.14	0.19	-0.28	0.68	-0.48	0.06	~0.0	04		0.12
Se	0.39	0.27	-0.12	0.53	0.23	0.56	-0.49	0.76		26 0.3	5	-0.40
	Ni	Co	Cu	Pt	Pd	Rh	Ru	Ir	A	u S	Se	Distance (m) to nearest felsic dike

R values > 0.50 in bold type; other noteworthy values underlined.

Zone refining in the upper Pyroxenite Zone

Upper PZ rocks have textures that suggest partial or complete remelting in the presence of a volatilerich phase. These include: 1) coarse-grained and pegmatitic textures with intercumulus hornblende and Fe-Ti oxides after cumulus phases, 2) gabbro pegmatite gradational with pyroxenite cumulates; and 3) pyroxenite and gabbro pegmatite dikes. The presence of a volatile-rich phase during postcumulus cooling can lower the solidus temperature of pyroxenite cumulates and cause partial melting. The newly formed melt will migrate through the cumulates, leaving behind a residue rich in compatible elements (e.g., pyroxenite dikes), while the melt becomes increasingly enriched in incompatible elements, analogous to zone refining in the metallurgical industry (Harris 1957, McBirney 1987). Enrichment in incompatible elements will occur where the volatile-rich melt crystallizes (e.g., gabbro pegmatite dikes). As in hydrothermal systems, repeated pulses of volatile-rich melt may follow the same direction and ultimately leave a complex signature. This process is similar to infiltration metasomatism described for pegmatitic hornblendites at Duke Island in Alaska by Irvine (1974, 1987).

The origin of the volatile-rich fluids is not well understood. The pegmatitic hornblendites at Duke Island, exposed over hundreds of square meters, are most prominent near the margins (Irvine 1987), with the inference that the infiltrating fluids were derived from surrounding rocks. At the Skaergaard Intrusion and several of the Tertiary layered intrusions of East Greenland, gabbro pegmatite dikes, veins, and pods are especially abundant in the Marginal Border Series, and the volatile-rich fluids responsible for their formation are believed to be derived from adjoining country-rocks (Taylor & Forester 1979, Irvine 1987, Bird et al. 1988). This fluid infiltration would have to take place while the cumulates were still hot enough to be remelted under hydrous conditions. Geothermometers indicate that calcic amphibole + pyroxene assemblages in subsolidus pegmatitic veins up to 2 cm thick at Skaergaard formed at 525°C to 825°C, under hydrostatic conditions at 0.5 kilobars (Bird et al. 1988). Experiments on the melting of magnesian basalt with $P(H_2O) =$ P(total) indicate that at 2 and 4 kilobars, the solidus



FIG. 15. PGE and Au average abundances for Montcalm Ni-Cu deposit in comparison to typical komatiite-hosted deposits (Langmuir, Mount Edward, Kambalda), and other gabbro-hosted deposits. Modified after Naldrett & Duke (1980) and Naldrett (1981).

temperatures are 700 and 825°C (Holloway & Burnham 1972). These temperatures would represent minimum temperatures for the fluids responsible for development of the upper PZ pegmatitic rocks. Interestingly, this is within the upper limits of fluids that have evolved from granitic plutons (Burnham 1979, Beane & Titley 1981). If the contemporaneous felsic dikes that cut the GZ and PZ represent the upper reaches of a larger felsic pluton at depth, then the fluids could be derived at least in part from such a pluton.

In the upper PZ, the *REE* are lowest near the GZ and progress to higher levels down-section; this is particularly prominent for S, Cu and Au. These trends would suggest that a volatile-rich fluid originated near the PZ-GZ contact, possibly from a conduit near one of the contemporaneous felsic dikes. The migrating fluid may have caused partial melting of pyroxenite cumulates, leaving a residuum of pegmatitic pyroxenite and gabbro pegmatite depleted in incompatible elements, and precipitating an incompatible-element-enriched residuum, partly due of saturation of incompatible-element-enriched phases. Given this interpretation, a V-rich phase, probably a Fe-Ti oxide, became saturated in the volatile-rich melt before a sulfide phase that contained high Cu and Au contents.

In many respects, the upper PZ is similar to the Robie Zone of the Lac des Iles Pt-Pd-Au-Cu-Ni deposit in northwestern Ontario (Macdonald 1987). Gabbros of the Robie Zone with textures similar to upper PZ rocks host significant concentrations of Pt-Pd mineralization that has been attributed to the zone-refining process (Brügmann *et al.* 1989). Unfortunately, results of semiquantitative Pt-Pd-Au analyses for PZ pyroxenites and gabbro pegmatites do not indicate any significant enrichment like that at Lac des Iles (Barrie, unpubl. data).

High Pt/Ir values, and derivation of the metal content in the Ni-Cu deposit

The high Pt/Ir values of the lower PZ cumulates (140, n = 4) are comparable to those found in pyroxenitic and gabbroic rocks of the Thetford ophiolite (71 and 265, respectively: Oshin & Crocket 1982) and gabbros associated with Munro Township komatiites (55: Crocket & MacRae 1986). These values are significantly higher than the chondritic ratio of 1.9 (Naldrett & Duke 1980), or Pt/Ir values found in ultramafic tectonites and cumulates at Thetford (0.05-11.7: Oshin & Crocket 1982) or at Munro Township (7.8: Crocket & MacRae 1986). Furthermore, the Pt/Ir value of the Montcalm Ni-Cu deposit (90, n = 20) is similar to values for the Minnamax and Great Lakes Nickel deposits of the Duluth Gabbroic Complex (55-75: Naldrett 1981), but much higher than for komatiite-hosted deposits (3.3-14.4: Naldrett & Duke 1980). Partial melting and fractional crystallization are considered viable mechanisms to produce high Pt/Ir values (or Pd/Ir values, as Pd and Pt behave similarly) in primitive magmas and derivative Ni-Cu deposits (Barnes et al. 1986, Naldrett & Barnes 1986). In both cases, the arguments are based upon the assumptions that Ir behaves compatibly in olivine and chromite, whereas Pt and Pd are incompatible. Brügmann et al. (1987) determined an olivine - komatiitic liquid partition coefficient for Ir of about 2, and there is petrological evidence that chromite fractionation removes Ir by nucleating around laurite and Os-Ir-Ru alloys (e.g., Stockman & Hlava 1984).

It is difficult to envision partial melting from a primitive mantle as the principal mechanism to increase the Pt/Ir value at Montcalm, for two reasons. First, clinopyroxene and whole-rock Mg numbers up to 82 and HREE contents in the lower



FIG. 16. *REE* diagrams, normalized to average CI chondritic values of Evensen *et al.* (1978). a. Pyroxenite Zone, with lower PZ (vertically ruled) and upper PZ (horizontally ruled). b. Gabbro Zone, with lower GZ (<300 m: vertically ruled) and upper GZ (above 300 m: horizontally ruled).

PZ suggest approximately 20-30% partial melting of a primitive mantle composition. At these amounts of partial melting, it is unlikely that sulfide would remain in the mantle as a restite phase, so that the Pt, Pd and Ir content of the melt would be controlled by their partition coefficients with mafic silicate phases. Naldrett & Barnes (1986) modeled 20 - 30% partial melting of a sulfide-free primitive mantle composition, and found Pd/Ir values of 10-20, comparable to Pt/Ir values of 5-10, given a chondritic ratio of about 2 for Pt/Pd in the mantle. The partition coefficients between sulfide liquid and silicate magma are not well known, but are believed to be very high $(>10^4)$ and similar to one another, so that sulfide derived from these magmas would have similar Pt/Ir values of 5-10. These values are much lower than those of the lower PZ cumulates and the Montcalm Ni-Cu deposit. Second, the low PGE tenor of the deposit cannot be reconciled with the base-metal tenor after segregation of an immiscible sulfide liquid from a primitive picritic magma, for any ratio of silicate magma to sulfide liquid, as pointed out by Naldrett & Duke (1980). Whereas a large batch of sulfide liquid in equilibrium with a magnesian tholeiitic melt (a low "R" factor: Campbell & Naldrett 1979) could account for the low PGEtenor, the Ni and Cu contents would be too low. Partial melting from a mantle source that had undergone a previous event of partial melting that left behind trace amounts of sulfide, as suggested for boninitic magmas (Hamlyn *et al.* 1985), could also lead to a higher Pt/Ir value; however, this scenario is not considered applicable to Montcalm in view of its tholeiitic affinities.

Fractional crystallization with continual segregation of sulfide from a primitive magma, as originally proposed by Naldrett & Duke (1980), is a reasonable alternative. They modeled the sulfide that would be in equilibrium with a magnesian tholeiitic liquid after fractional removal of 50% olivine, clinopyroxene, plagioclase, and continuous removal of trace amounts of sulfide. By this method, they achieved a sulfide liquid with 4.0 wt.% Ni, 1.3% Cu and 17 ppb Pd in 100% sulfide, very similar to sulfide-



FIG. 17. Montcalm metal contents in comparison to Thetford Ophiolite Complex data (Oshin & Crocket 1982). Montcalm PZ rocks: open squares, Montcalm GZ rocks: open circles, Thetford Iherzolites, dunites, and pyroxenites: closed circles, Thetford gabbroic rocks: closed squares. a. Ni/Co versus Pt. b. Ni/Co versus Ir. c. Ni/Co versus Pt/Ir. Star represents Montcalm deposit average. d. Ni/Co versus S.

normalized values calculated for the Montcalm deposit. This model also accounts for higher Pt/Ir values, as olivine (and chromite) fractionation would deplete the magma in Ir.

A schematic illustration of this model, involving silicate fractionation accompanied by sulfide segregation from a primitive magma, is given in Figure 17, where Montcalm data are plotted along with data from from the Thetford Ophiolite, Quebec (Oshin & Crocket 1982). The Thetford suite includes upper mantle harzburgite and peridotite tectonites, in fault contact with a cumulate sequence of partly layered cumulates. The cumulates are chromite-bearing dunites at the base, overlain by pyroxenites and gabbros. Ophiolite suites including Thetford are generally regarded as the product of open-system fractional crystallization (e.g., O'Hara 1977, Pallister & Knight 1981). Ni/Co is used as a general index of fractionation for these cumulate rocks. Ni is favored over Co by 2-4 times in mafic silicates and spinel (see Irving 1978), and 3-5 times in sulfide (Rajamani & Naldrett 1978), so that Ni/Co decreases systematically with fractionation. The Montcalm traverse samples are similar to Thetford pyroxenitic and gabbroic rocks in their Pt, Ir and S contents (except for the high S content in upper PZ rocks), and their high Pt/Ir values; the Ni-Cu deposit has a similar Pt/Ir value (Fig. 17c).

Relative timing of the immiscible sulfide event during the evolution of the MGC

The timing of the immiscible sulfide event that led to the formation of the Ni-Cu deposit is constrained by the following considerations: the presence of sulfides in the PZ, but very low S and PGE concentrations in the GZ, implying sulfur undersaturation during GZ formation; similar, but slightly higher, more fractionated Pt/Ir values in the PZ than in the Ni–Cu deposit; δ^{34} S and S/Se values consistent with a magmatic derivation of sulfide; and depleted isotopic signatures for the PZ and GZ, but an enriched signature for the FZ. These considerations are consistent with the following sequence of events: 1) ponding of a primitive partial melt from the mantle in the lower crust, and fractionation of olivine, chromite and trace amounts of sulfide; 2) migration of the residual liquid from the lower crustal chamber to the MGC chamber, to form pyroxenites represented by the PZ and the pyroxenite fragments in the inclusion-breccia sulfide; 3) formation of the main immiscible sulfide liquid from the PZ parental magma, either in a lower crust chamber or the MGC chamber; 4) continued fractionation into the stability field of plagioclase, accompanied by influxes of new magma, and the formation of GZ cumulates at 2702 \pm 2 Ma; 5) assimilation of an isotopically enriched

crustal component during FZ formation; 6) emplacement of the sulfide mass into the GZ after consolidation of GZ cumulates, during tectonism and regional crustal rotation into a subvertical position; 7) emplacement of the main granodiorite dike at 2700_{4}^{+5} Ma and subsidiary felsic dikes; 8) volatile fluxing causing remelting and recrystallization of upper PZ rocks; and 9) deformation associated with the emplacement of granitic plutons to the east at 2696–2692 Ma.

CONCLUSIONS

The principal conclusions drawn from the geology, geochronology, petrology, and geochemistry of the MGC and Montcalm Ni–Cu deposit are summarized as follows:

1. The MGC was emplaced at 2702 ± 2 Ma in an active tectonic setting, and was subjected to rotation of the crust into a near-vertical position during or shortly after consolidation. The MGC and associated Ni-Cu deposit were cut by a subvertical granodiorite dike at 2700_4^{+5} Ma.

2. In the vicinity of the Ni-Cu deposit, the lower PZ orthocumulates provide the best estimate of a liquid composition. They have relatively high concentrations of the incompatible trace-elements, are *LREE*-enriched, and have Pt/Ir values similar to but slightly higher than the Ni-Cu deposit. The majority of upper PZ rocks have coarse-grained and pegmatitic textures, and have been extensively modified by postcumulus recrystallization due to a flux of volatile-rich fluids, possibly derived from contemporaneous felsic magmatism. GZ rocks are predominantly plagioclase – clinopyroxene cumulates with low levels of incompatible trace-elements and sulfur. There is limited evidence for multiple pulses of replenishing magma during GZ formation.

3. The deposit has Ni, Cu and Pt/Ir values typical for gabbro-hosted deposits, and yet a very low PGEtenor. Values of $\delta^{34}S$ and S/Se are consistent with a predominantly magmatic source for sulfur. The high Pt/Ir value and the low tenor of the PGE are consistent with sulfide segregation from a primitive magma after fractionation of olivine, clinopyroxene and probably chromite, along with trace amounts of sulfide. This fractionation occurred during or before PZ formation, as suggested by high Pt/Ir values for PZ rocks, in the Montcalm magma chamber or in a chamber deeper in the crust.

4. The parental magma was derived from an isotopically depleted mantle, typical of tholeiitic and komatiitic magma sources in the southern Abitibi and similar to the depleted MORB mantle at 2700 Ma. Assimilation of an enriched crustal component occurred during FZ crystallization.

ACKNOWLEDGEMENTS

We thank Dr. M. Blecha and Teck Corporation for access to the drill core of the Montcalm deposit and to unpublished geochemical and aeromagnetic data; Dr. A. H. Green, J. Cecchetto and Falconbridge Ltd. for logistical support; Dr. T.E. Krogh for use of the analytical facilities at the Jack Satterley Laboratory of the Royal Ontario Museum; S. Kamo for help with U-Pb chemistry; Dr. S. B. Shirey for help with Nd isotope data collection; Drs. G. E. Brügmann and M. P. Gorton for fruitful discussions about the geochemical data; Dr. R.F. Martin and two referees for their editorial and scientific reviews. This work has been supported by grants from the Geological Society of America and Sigma Xi to CTB and NSERC Grant A-4244 to AJN.

REFERENCES

- ALLER, L. H. (1967): Earth, chemical composition of, and its comparison with that of the sun, moon and planets. *In* Composition of the Earth 1 (S.K. Runcorn, ed.). Pergamon Press, New York.
- BARNES, S. J. (1986): The effect of trapped liquid crystallization on cumulus mineral compositions in layered intrusions. *Contrib. Mineral. Petrol.* 93, 524-531.
- BARNES, S.-J., NALDRETT, A. J. & GORTON, M. P. (1985): The origin of the fractionation of platinumgroup elements in terrestrial magmas. *Chem. Geol.* 53, 303-323.
- BARRIE, C. T. (1990): Petrogenesis and Tectonic Evolution of the Kamiskotia and Montcalm Gabbroic Complexes and Adjacent Granitoid - Greenstone Belt Terrane, Western Abitibi Subprovince, Ontario, Canada. Ph.D. thesis, Univ. Toronto, Toronto, Ontario.
- & DAVIS, D. W. (1990): Timing of magmatism and deformation in the Kamiskotia – Kidd Creek area, western Abitibi Subprovince, Canada. *Precambrian Res.* 46, 217-240.
- & NALDRETT, A.J. (1989): The geology and tectonic setting of the Montcalm gabbroic complex and Ni-Cu deposit. *In* Magmatic Sulphides, The Zimbabwe Volume (M.D. Prendergast & M.J. Jones, eds.). Inst. Min. Metall., London (151-165).
- BEANE, R.E. & TITLEY, S.R. (1981): Porphyry copper deposits. II. Hydrothermal alteration and mineralization. Econ. Geol., 75th Anniv. Vol., 235-269.
- BENNETT, G. (1966a): Belford Township, District of Cochrane. Ont. Dep. Mines Prelim. Geol. Map P344.
- (1966b): Montcalm Township, District of Cochrane. Ont. Dep. Mines Prelim. Geol. Map P346.

(1969): Geology of the Belford – Strachan area, District of Cochrane. Ont. Dep. Mines, Geol. Rep. 78.

- BESWICK, A. (1982): Some geochemical aspects of alteration, and genetic relations in komatiitic suites. *In* Komatiites (N.T. Arndt & E.G. Nisbet, eds.). Allen & Unwin, London (283-308).
- BIRD, D.K., MANNING, C.E. & ROSE, N.M. (1988): Hydrothermal alteration of Tertiary layered gabbros, East Greenland. Am. J. Sci. 288, 405-457.
- BLECHA, M., THALENHURST, H. & KOMURA, A. (1977): Teck's Montcalm copper nickel deposit: AEM surveys brings major discovery. *Can. Min. J.* 98(4), 21-28.
- BOYD, R., MCDADE, J.M., MILLARD, H.T. & PAGE, N.J (1987): Platinum metal geochemistry of the Bruvann nickel-copper deposit, Råna, Norway. Norsk Geol. Tidsskr. 67, 205-213.
- BRÜGMANN, G.E., ARNDT, N.T., HOFMANN, A.W. & TOBSCHALL, H.J. (1987): Noble metal abundances in komatiite suites from Alexo, Ontario and Gorgona Island, Colombia. *Geochim. Cosmochim. Acta* 51, 2159-2169.
- _____, NALDRETT, A.J. & MACDONALD, A.J. (1989): Magma mixing and constitutional zone refining in the Lac des Iles complex, Ontario: genesis of platinum-group element mineralization. *Econ. Geol.* 84, 1557-1573.
- BURNHAM, C.W. (1979): Magmas and hydrothermal fluids. In Geochemistry of Hydrothermal Ore Deposits (H.L. Barnes, ed., 2nd edition). Wiley Interscience, New York (71-136).
- CAMERON, E.N. & DESBOROUGH, G.A. (1964): Origin of certain magnetite-bearing pegmatites in the eastern part of the Bushveld Complex, South Africa. *Econ. Geol.* 59, 197-225.
 - & GLOVER, E.D. (1973): Unusual titanianchromian spinels from the eastern Bushveld Complex. Am. Mineral. 58, 172-188.
- CAMPBELL, I.H. & NALDRETT, A.J. (1979): The influence of silicate:sulfide ratios on the geochemistry of magmatic sulfides. *Econ. Geol.* 74, 1503-1506.
- CORFU, F., KROGH, T.E., KWOK, Y.Y., MARMONT, S. & JENSEN, L. S. (1989): U-Pb zircon geochronology in the south-western Abitibi greenstone belt, Superior Province. Can. J. Earth Sci. 26, 1747-1763.
- CROCKET, J.H. & MACRAE, W.E. (1986): Platinumgroup-element distribution in komatiitic and tholeiitic volcanic rocks from Munro Township, Ontario. *Econ. Geol.* 81, 1242-1251.

DAVIS, D. W. (1982): Optimum linear regression and

error estimation applied to U-Pb data. Can. J. Earth Sci. 19, 2141-2149.

- _____, POULSEN, K.H. & KAMO, S.L. (1989): New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada. J. Geol. 97, 379-398.
- DUPRÉ, B., CHAUVEL, C. & ARNDT, N.T. (1984): Pb and Nd isotopic study of two Archean komatiitic flows from Alexo, Ontario. *Geochim. Cosmochim. Acta* 48, 1965-1972.
- EVENSEN, N.M., HAMILTON, P.J. & O'NIONS, R.K. (1978): Rare-earth abundances in chondritic meteorites. Geochim. Cosmochim. Acta 42, 1199-1212.
- GOODWIN, A., MONSTER, J. & THODE, H. (1976): Carbon and sulfur isotope abundances in Archean iron-formations and Early Precambrian life. *Econ. Geol.* 71, 870-891.
- GREEN, A.H. (1978): Evolution of Fe-Ni Sulfide Ores Associated with Archean Ultramafic Komatiites, Langmuir Township, Ontario. Ph.D. thesis, Univ. Toronto, Toronto, Ontario.
- HAMLYN, P.R., KEAYS, R.R., CAMERON, W.E., CRAW-FORD, A.J. & WALDRON, H.M. (1985): Precious metals in magnesian low-Ti lavas: implications for metallogenesis and sulfur saturation in primary magmas. Geochim. Cosmochim. Acta 49, 1797-1811.
- HARRIS, P.G. (1957): Zone refining and the origin of potassic basalts. *Geochim. Cosmochim. Acta* 12, 195-208.
- HENRY, D.D. (1988): Povgeva the first fifty years. Geol. Surv. Aust. Inc. 22, 144-149 (abstr.).
- HOFFMAN, E.L., NALDRETT, A.J., VAN LOON, J.C., HANCOCK, R.G. & MANSON, A. (1978): The determination of all the platinum group elements and gold in rocks and ore by neutron activation analysis after preconcentration by nickel sulfides fire-assay technique on large samples. *Anal. Chim. Acta* 102, 157-166.
- HOLLOWAY, J.R. & BURNHAM, C.W. (1972): Melting relations of basalt with equilibrium water pressure less than total pressure. J. Petrol. 13, 1-29.
- IRVINE, T.N. (1974): Petrology of the Duke Island ultramafic Complex, southeastern Alaska. Geol. Soc. Am., Mem. 138.
- (1987): Layering and related structures in the Duke Island and Skaergaard intrusions: similarities, differences and origins. *In* Origins of Igneous Layering (I. Parsons, ed.). D. Reidel Publ. Co., Dordrecht, Holland (185-245).

IRVING, A.J. (1978): A review of experimental studies

of crystal/liquid trace element partitioning. Geochim. Cosmochim. Acta 42, 743-770.

- KELLY, W.C. & CLARK, B.R. (1975): Sulfide deformation studies. III. Experimental deformation of chalcopyrite to 2000 bars and 500°C. *Econ. Geol.* 70, 431-453.
- KROGH, T.E. (1982): Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochim. Cosmochim. Acta 46, 637-649.
- LINDSTROM, D.J. (1976): Experimental Study of the Partitioning of the Transition Metals Between Clinopyroxene and Coexisting Silicate Liquids. Ph.D. thesis, Univ. Oregon, Eugene, Oregon.
- LUDDEN, J., GÉLINAS, L. & TRUDEL, P. (1982): Archean metavolcanics from the Rouyn-Noranda district, Abitibi greenstone belt, Quebec. 2. Mobility of trace elements and petrogenetic constraints. *Can. J. Earth Sci.* 19, 2276-2287.
- LUHR, J.F. & CARMICHAEL, I.S.E. (1980): The Colima volcanic complex, Mexico. I. Post-caldera andesites from Volcán Colima. *Contrib. Mineral. Petrol.* 71, 343-372.
- MACHADO, N., BROOKS, C. & HART, S.R. (1986): Determination of initial ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd in primary minerals from mafic and ultramafic rocks: experimental procedure and implications for the isotopic characteristics of the Archean mantle under the Abitibi greenstone belt, Canada. Geochim. Cosmochim. Acta 50, 2335-2348.
- MACDONALD, A.J. (1987): The Lac des Iles platinum group metal deposit, Thunder Bay District. Ont. Geol. Surv., Misc. Pap. 126, 235-241.
- MCBIRNEY, A.R. (1987): Constitutional zone refining of layered intrusions. *In* Origins of Igneous Layering (I. Parsons, ed.). D. Reidel Publ. Co., Dordrecht, Holland (437-452).
- MENZIES, M., SEYFRIED, W., JR. & BLANCHARD, D. (1979): Experimental evidence of rare earth element immobility in greenstones. *Nature* 282, 398-399.
- MITCHELL, R.H. (1986): Kimberlites, Mineralogy, Geochemistry and Petrology. Plenum, New York.
- NALDRETT, A.J. (1981): Nickel sulfide deposits: classification, composition, and genesis. *Econ. Geol.*, 75th Anniv. Vol., 628-685.
 - & BARNES, S.-J. (1986): The behaviour of platinum group elements during fractional crystallization and partial melting with special reference to the composition of magmatic sulfide ores. *Fortschr. Mineral.* 64, 113-133.
 - ____, BRAY, J.G., GASPARRINI, E.L., PODOLSKY, T. & RUCKLIDGE, J.C. (1970): Phase layering and

cryptic variation in the Sudbury Nickel Irruptive. Geol. Soc. S. Afr., Spec. Publ. 1, 532-545.

- & DUKE, J.M. (1980): Platinum metals in magmatic sulfide ores. *Science* 208, 1417-1424.
- & VON GRUENEWALDT, G. (1989): Association of PGE with chromitite in layered intrusions and ophiolite complexes. *Econ. Geol.* **84**, 180-187.
- O'HARA, M. J. (1977): Geochemical evolution during fractional crystallisation of a periodically refilled magma chamber. *Nature* 266, 503-507.
- OSHIN, I.O. & CROCKET, J.H. (1982): Noble metals in Thetford mines ophiolites, Quebec, Canada. I. Distribution of gold, iridium, platinum, and palladium in the ultramafic and gabbroic rocks. *Econ. Geol.* 77, 1556-1570.
- PALLISTER, J.S. & KNIGHT, R.J. (1981): Rare earth element geochemistry of the Samail ophiolite near Ibra, Oman. J. Geophys. Res. 86, 2673-2697.
- PAPUNEN, H. (1989): Platinum-group elements in metamorphosed Ni-Cu deposits. *In* Magmatic Sulphides, The Zimbabwe Volume (M.D. Prendergast & M. J. Jones, eds.). Inst. Min. Metall., London (165-176).
- PEARCE, J.A. (1983): Role of sub-continental lithosphere in magma genesis at active continental margins. In Continental Basalts and Mantle Xenoliths (C.J. Hawkesworth & M.J. Norry, eds.). Shiva Publ. Ltd., Orpington, England (230-249).
- RAJAMANI, V. & NALDRETT, A.J. (1978): Partitioning of Fe, Co, Ni, and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits. *Econ. Geol.* 73, 82-93.
- RINGWOOD, A.E. (1970): Petrogenesis of Apollo 11 basalts and implications for lunar origin. J. Geophys. Res. 75, 6453-6479.
- SHEGELSKI, R.J. (1978): Stratigraphy and Geochemistry of Sturgeon Lake - Savant Lake area. Ph.D. thesis, Univ. Toronto, Toronto, Ontario.
- STACEY, J.S. & KRAMERS, J.D. (1975): Approximation of terrestrial lead isotopic evolution by a two stage model. *Earth Planet. Sci. Lett.* 26, 207-221.
- STOCKMAN, H.W. & HLAVA, P.F. (1984): Platinumgroup minerals in alpine chromitites from southwestern Oregon. *Econ. Geol.* 79, 491-508.
- TAYLOR, H.P., JR & FORESTER, R.W. (1979): An oxygen and hydrogen isotope study of the Skaergaard intrusion and its country rocks: a description of a 55-m.y. old fossil hydrothermal system. J. Petrol. 20, 355-419.
- TAYLOR, S.R. & MCLENNAN, S.M. (1985): The Continental Crust, its Composition and Evolution.

Blackwell Scientific Publ., Oxford, England.

- THOMPSON, J.F.H. (1982): The Intrusion and Crystallization of Gabbros, Central Maine, and Genesis of their Associated Sulfides. Ph.D. thesis, Univ. Toronto, Toronto, Ontario.
 - & NALDRETT, A.J. (1984): Sulphide silicate reactions as a guide to Ni–Cu–Co mineralization central Maine, U.S.A. *In* Sulphide Deposits in Mafic and Ultramafic Rocks (D.L. Buchanan & M.J. Jones, eds.). Inst. Min. Metall., London (103-113).
- VAN RENSBERG, W.C.J. (1965): The mineralogy of the titaniferous magnetite and associated sulfides on Kennedy's Vale 361 KT, Lydenburg district, Transvaal. S. Afr. Geol. Surv. Annals 4, 113-127.
- VILIOEN, M.J. & SCOON, R.N. (1985): The distribution and main geologic features of discordant bodies of

iron-rich ultramafic pegmatite in the Bushveld Complex. *Econ. Geol.* **80**, 1109-1128.

- VON GRUENEWALDT, G., HATTON, C.J., MERKLE, R.K.W. & GAIN, S.B. (1986): Platinum-group element – chromitite associations in the Bushveld Complex. *Econ. Geol.* 81, 1067-1079.
- WATSON, E.B. (1982): Basalt contamination by centrifugal crust: some experiments and models. Contrib. Mineral. Petrol. 80, 73-87.
- WILKES, M.E. & NISBET, E.G. (1985): Archean stromatolites from the Steep Rock Group, northwestern Ontario, Canada. *Can. J. Earth Sci.* 22, 792-799.
- Received July 19, 1989, revised manuscript accepted November 22, 1989.