

GEOLOGY AND PETROGENESIS OF THE KANICHEE LAYERED COMPLEX, ONTARIO

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ABSTRACT

The Kanichee layered intrusive complex is the largest of several mafic-ultramafic bodies in felsic and mafic metavolcanic rocks in the northern portion of the Temagami greenstone belt, Ontario. An ultramafic apophysis along the northern margin of the intrusion contains a mineralized zone of disseminated and vein pyrrhotite, chalcopyrite and pentlandite; the host olivine peridotite has been altered to various serpentine-talc-carbonate assemblages. The intrusive body consists of five cycles of cumulate rocks. In the lower four cycles, cumulus chromite, olivine and clinopyroxene form rocks ranging from dunite to clinopyroxenite. In cycle 5 a similar suite of ultramafic rocks is overlain by olivine and quartz gabbros in which plagioclase, clinopyroxene and an Fe-Ti oxide phase are the dominant minerals. Igneous hornblende is a common accessory in the ultramafic rocks of all cycles; in cycle 1, it occurs as a cumulus phase in the clinopyroxenites. The sulfide minerals occur as disseminated interstitial grains in the ultramafic rocks of all five cycles, but are particularly abundant in the olivine cumulates at the base of the complex (*i.e.*, the ore zone, cycle 1). The similarity in mineralogy and chemistry of the ultramafic rocks of the five cycles suggests that each one formed from magma of similar composition; only the final pulse of magma remained in place long enough to form fractionated liquids from which the olivine gabbro and possibly the quartz gabbro crystallized. The order of appearance of cumulate phases in each cycle and the chemistry of the parent magma (estimated from the relative proportions of rock types in cycle 5) suggest that each cycle crystallized from a high-magnesium basaltic magma belonging to Jolly's (1980) magnesian tholeiite suite.

Keywords: sill, mafic-ultramafic, layered, magmatic cycles, olivine, clinopyroxene, plagioclase, Ni-Cu, platinum-group elements, Temagami, Ontario.

SOMMAIRE

Le complexe intrusif stratifié de Kanichee est le plus grand de plusieurs massifs mafiques-ultramafiques dans les roches métavolcaniques felsiques et mafiques de la partie nord de la ceinture de roches vertes de Temagami (Ontario). Une apophyse ultramafique en bordure nord du massif renferme une zone minéralisée en pyrrhotite, chalcopyrite et pentlandite soit en filons, soit sous forme disséminée; cette péridotite à olivine est altérée en divers assemblages de serpen-

tine, talc et carbonate. Le complexe intrusif comprend cinq cycles de cumulats. Dans les quatre cycles inférieurs, la chromite, l'olivine et le clinopyroxène constituent des roches à cumulats qui s'échelonnent de la dunite à la clinopyroxénite. Dans le cinquième cycle, une suite analogue de roches ultramafiques est recouverte de gabbros à olivine et de gabbros quartzifères dans lesquels le plagioclase, le clinopyroxène et une phase d'oxyde de Fe-Ti sont les minéraux dominants. La hornblende ignée est un accessoire commun des roches ultramafiques de tous les cycles; elle forme, dans le premier cycle, une phase cumulative dans les clinopyroxénites. Les sulfures se présentent en grains interstitiels disséminés dans les roches ultramafiques des cinq cycles, mais sont particulièrement abondants dans les cumulats d'olivine de la base du complexe (c'est-à-dire, la zone minéralisée, cycle 1). Vu la similarité minéralogique et chimique des roches ultramafiques des cinq cycles, chaque cycle se serait formé à partir d'un magma de même composition; seule la dernière poussée de magma est demeurée en place le temps nécessaire pour permettre le fractionnement du liquide ainsi que la cristallisation du gabbro à olivine et peut-être aussi celle du gabbro quartzifère. L'ordre d'apparition des phases cumulatives dans chaque cycle et le chimisme du magma parent (déduit des proportions relatives des types de roche du cycle 5) montrent que chacun des cycles a cristallisé d'un magma basaltique riche en magnésium apparenté aux tholéiites magnésiennes de Jolly (1980).

(Traduit par la Rédaction)

Mots-clés: filons-couches, mafique-ultramafique, stratifié, cycles magmatiques, olivine, clinopyroxène, plagioclase, Ni-Cu, éléments du groupe du platine, Temagami, Ontario.

INTRODUCTION

The Kanichee layered intrusive complex is the largest of several sill-like mafic and ultramafic synvolcanic intrusive bodies that occur in the northern portion of the Temagami greenstone belt. Various aspects of the geology of this volcanic belt have been reported by Bennett (1978), Bennett & Innes (1971a, b), Bennett & McNally (1970a, b), Simony (1964) and Moorhouse (1942). In Figure 1, the Kanichee intrusive complex is shown to be located within mafic and felsic metavolcanic rocks in the central portion of Strathy Township, approximately 6.5 km northwest of the townsite of Temagami, Ontario. It was

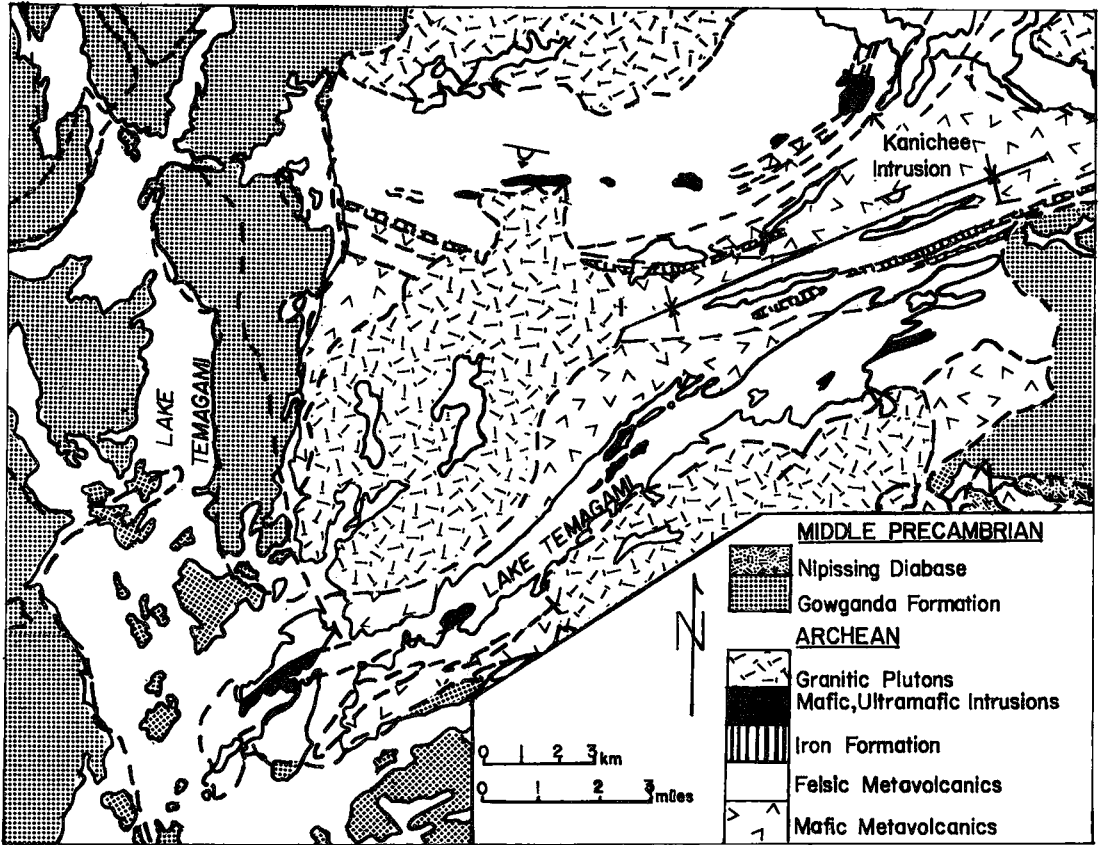


FIG. 1. Regional geological plan of the Northeast Temagami area, after Bennett (1978).

first reported in the literature by Knight (1920), who recognized a gossan zone 90×25 m at its northern extremity, that contains disseminated and vein pyrrhotite, chalcopyrite and pentlandite mineralization. This zone has been intermittently explored and mined from as early as 1910 (Bennett 1978). Most recently, in the period 1972–1975, Ajax Minerals Ltd. developed an open pit to excavate both disseminated and vein ore to a depth of nearly 35 metres. Sandefur (1943) described the geology of the intrusive complex in the immediate vicinity of this ore as well as the mineralogy and paragenesis of the mineralization. Cabri & Laflamme (1974) documented the mineral chemistry of the major ore minerals in a few typical vein-specimens from the intrusive body, and Naldrett *et al.* (1979) and Naldrett (1981) reported the concentration of Au and Pt-group metals in a variety of ore-zone specimens.

In this paper, we describe the geology and geochemistry of the layered rocks that form the intrusive body and host the Ni - Cu - precious-metal mineralization at the northern extremity of the complex.

GENERAL GEOLOGICAL FEATURES

A plan view of the geology of the Kanichee intrusive complex is illustrated in Figure 2. The dimensions of the major and minor axes of this oval-shaped body are approximately 1050 and 730 metres, respectively. A lenticular zone of quartz gabbro lies immediately south of the main portion of the complex. It is not clear whether it has a separate origin from the olivine gabbro immediately to the north. As shown in Figure 2, and in more detail in Figure 4, the ore zone (cycle-1) rocks have a clear intrusive relationship to the metavolcanic country rocks. Within this part of the complex, the contact has been observed in several places. Typically, it is either very sharp with no contact aureole, or it is the location of a talc-chlorite-carbonate zone of alteration that separates serpentinized peridotite from greenschist-facies metavolcanic rocks. The contact with the country rock has not been observed elsewhere in the complex.

In Figure 2, the layered complex is shown to consist of five magmatic cycles, each of which consists

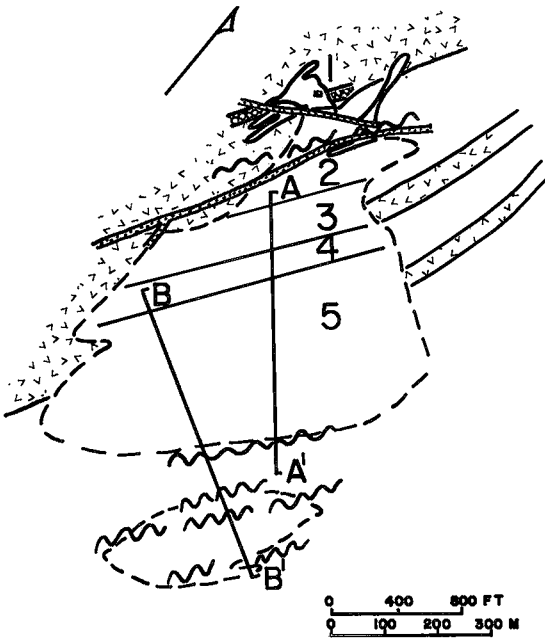


FIG. 2. Geological plan of the Kanichee layered intrusive complex. Numerals 1-5 refer to cycles of igneous rocks illustrated in sections A-A' and B-B' in Figure 3. Cycle 1 is also referred to as the "Ore Zone". Shading for metavolcanic rocks as in Figure 1. Two ages of mafic dyke-rocks are also illustrated as linear outlines of solid dots and open, cobble-like symbols. Field relations by D. Hawke.

of one or more rock types. These range in composition from dunite and olivine peridotite, in which olivine is the only major cumulus phase, to peridotite and clinopyroxenite, which are olivine — clinopyroxene cumulates. Gabbro is only found in cycle 5. The contact between cycles 1 and 2 lies within the open pit of the ore zone, but it is not accessible for observation owing to flooding. The ore zone (cycle 1) and the lower portion of cycle 2 are separated from the remainder of the complex by a fault zone whose azimuth is 050° . The boundary between cycles 3 and 4 and between cycles 4 and 5 is approximately marked by narrow (10-20 m wide) linear valleys oriented parallel to stratigraphic boundaries between felsic and mafic metavolcanic units in the country rock adjacent to the complex. The precise nature of the contact between cycles is unknown owing to lack of exposure. Within individual cycles, the rocks are typically massive and medium grained. Boundaries between recognizably distinct rock-types (*i.e.*, peridotite and clinopyroxenite) are gradational, and only rarely is centimetre-scale layering recognized.

In Figure 3, the geology is presented for the two stratigraphic sections A-A' and B-B' whose location

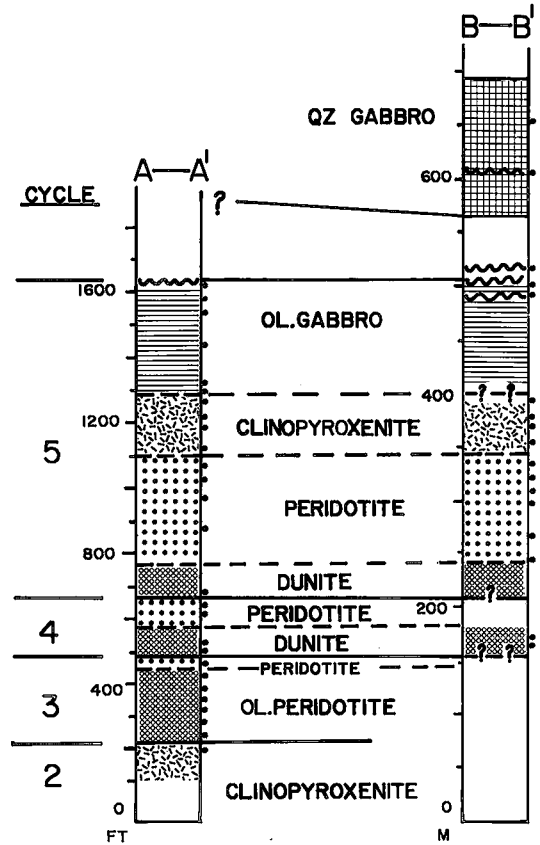


FIG. 3. Geology of the igneous cycles 2-5 inclusive as exhibited by the stratigraphic sections A-A' and B-B'. Solid dots indicate sample locations.

is shown in Figure 2. Section A-A' consists of four separate igneous cycles, each consisting of layers of one or more of dunite, olivine peridotite, peridotite, clinopyroxenite or olivine gabbro. Cycle 5 shows the widest range of rock types and can be correlated with reasonable confidence between the two stratigraphic sections. Cycles 3 and 4 appear as truncated versions of cycle 5 in that they contain only the more olivine-rich cumulate portions of cycle 5; clinopyroxenite and olivine gabbro are absent. Only the uppermost portion of cycle 2 is observed, *i.e.*, clinopyroxenite. The base of this cycle is probably represented by the peridotite that overlies cycle-1 rocks (Fig. 4).

The strike direction of the boundaries between cycles within the layered series is approximately 055° . This value has been determined by correlation of equivalent members in the two stratigraphic sections illustrated in Figure 3. From Figure 2, it is clear that the strike direction is nearly parallel to the flow contacts exhibited by the host metavolcanic rocks. The sequence of cumulus phases forming each magmatic

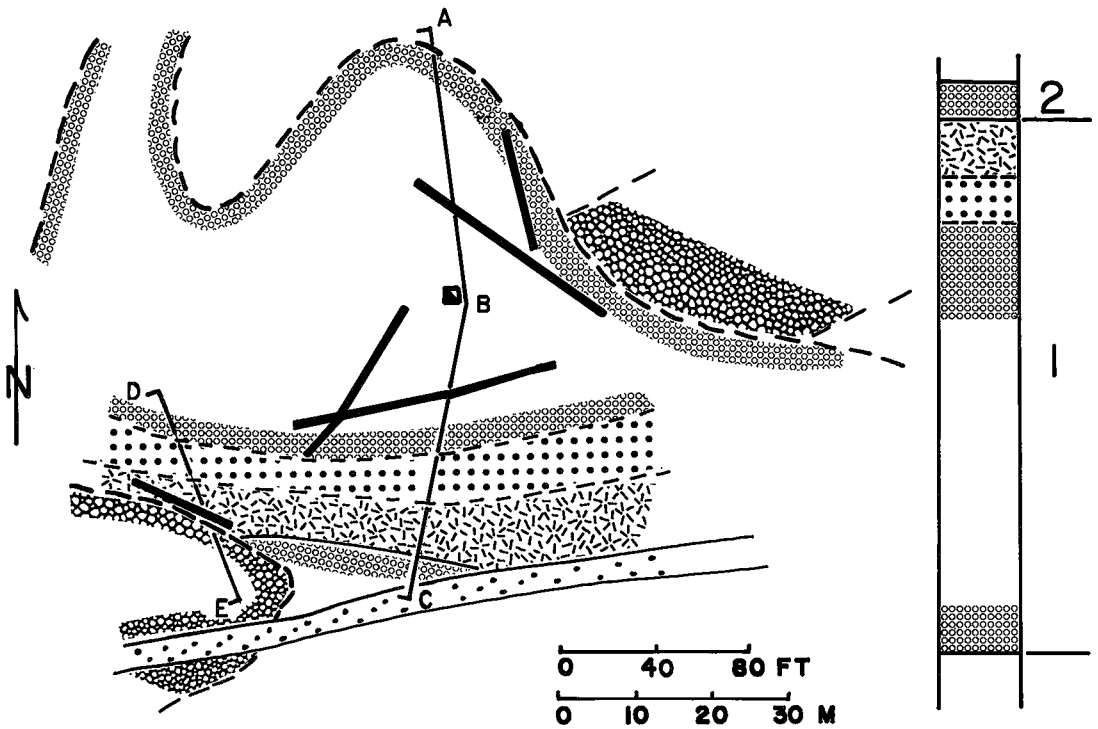


FIG. 4. Detailed geological plan of the ore zone (cycle 1). Symbols for rock units in the layered complex are as in Figure 3; those for mafic dykes are as in Figure 2. The heavy black line shows the distribution of the Cu-rich veins within the ore zone. The disseminated Ni-Cu ore is largely confined to the olivine peridotite unit of cycle 1. The stratigraphic column is drawn for the geology along the section line ABC. Field relations by D. Hawke.

cycle indicates that the intrusive complex is south-facing, as are the enclosing metavolcanic flows (Bennett 1978). These data suggest that rocks of the layered series in this complex originally formed in a horizontal attitude and probably at a very shallow crustal level. Several pulses of magmatic intrusion, each of which may have had a surface (volcanic) expression, are required to explain the cyclic nature of these igneous rocks. Further, a magnetic anomaly slightly elliptical in a NE-SW direction and caused largely by the alteration of olivine and pyroxene(s) to a serpentine-magnetite assemblage, indicates that the ultramafic rocks of all five cycles do not have unexposed extensions much beyond the presently observed outcroppings. From the above information, we conclude that the complex is cigar-shaped, its long axis plunging to the southeast at a rather steep angle, caused by one or more periods of deformation that similarly folded and deformed the enclosing volcanic rocks.

GEOLOGY OF THE ORE ZONE

The ore zone, identified as cycle 1 in Figure 2, is

confined to a salient of ultramafic rock at the northern margin of the complex. A geological plan and stratigraphic section of its geology are presented in Figure 4. Three N-S oriented sampling profiles (AB, BC and DE in Fig. 4) indicate that this zone is layered. Rather thin members of clinopyroxenite and peridotite overlie a thick unit of olivine peridotite to form the cycle-1 sequence of magmatic cumulates. A poorly exposed wedge of olivine peridotite along the southwestern margin of the ore zone represents the lowermost portion of a second cycle. Diamond drilling carried out over a period of 20 years beginning in the 1930s indicates that the base of the ore zone plunges S35°E at approximately 40° (Bennett 1978, Fig. 9). The magmatic layering was not recognized at that time; hence no estimate of its attitude was reported.

Pyrrhotite, chalcopyrite and pentlandite occur not only as disseminated phases within the olivine peridotite but also in carbonate-quartz veins that occur throughout cycle-1 rocks and at the contacts of the complex with the metavolcanic country-rock. The distribution of these veins is shown in Figure 4. Combined values of Cu and Ni in the veins run as high

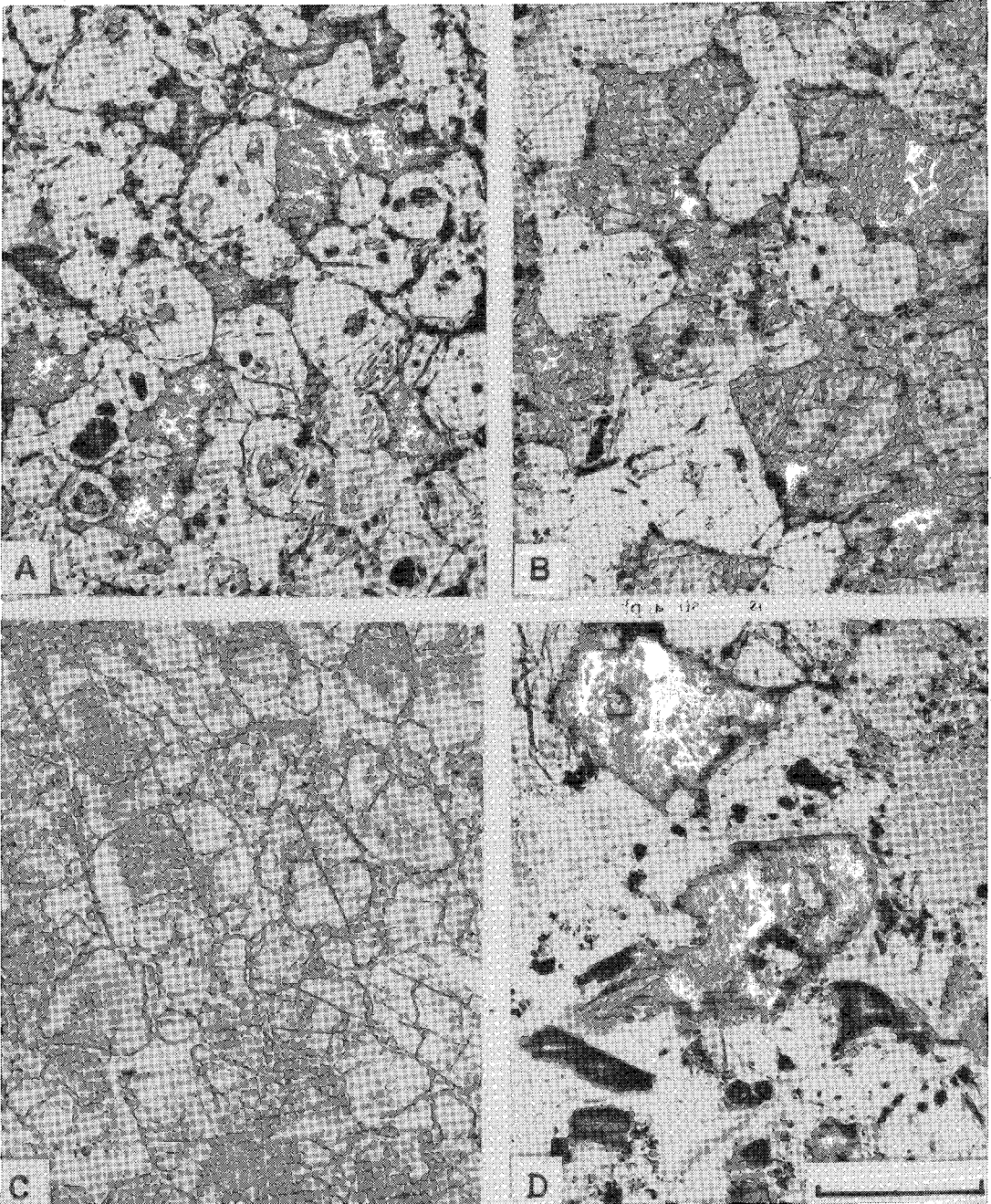


FIG. 5. Microphotographs (transmitted light) of cumulate ultramafic rocks from the Kanichee intrusive complex. 5A. Serpentinized olivine grains enclosed by postcumulus augite, cycle 3, olivine peridotite. 5B. Cumulus serpentinized olivine and fresh clinopyroxene in peridotite from cycle 4. 5C. Unaltered cumulus clinopyroxene from clinopyroxenite member of cycle 5. 5D. cumulus hornblende crystals partly replaced by tremolite (colorless) in clinopyroxenite member of cycle 1. Scale bar is 1.0 mm.

as 12 wt. %; precious-metal values for Pt, Pd and Au average close to 2110, 9015 and 2117 ppb, respectively (Naldrett & Cabri 1976).

PETROGRAPHY

Olivine-chromite cumulates

Dunite (> 90 modal % olivine) or olivine peridotite (or both) form the basal member of each magmatic cycle. These rocks consist of equant to oval-shaped grains of serpentinized olivine 0.1–1 mm in diameter, with variable amounts of intercumulus clinopyroxene, amphibole and their alteration products (Fig. 5A). Nowhere is the olivine fresh; typically, it is represented by a serpentine mesh and, less commonly, by hourglass cells (Wicks *et al.* 1977); secondary magnetite is abundant within the mesh rims. Grains of cumulus chromite rimmed by secondary magnetite are typically wholly enclosed within olivine. Fresh postcumulus clinopyroxene is present in these rocks from all five magmatic cycles.

Normally, however, it was replaced by a mixture of serpentine, talc and tremolite (Fig. 5A). Brown pleochroic igneous hornblende occurs in very small amounts as a postcumulus interstitial phase in most samples of dunite and peridotite of all five cycles. It is replaced, in many cases completely, by actinolite.

Olivine-clinopyroxene-chromite cumulates

The presence of both olivine and clinopyroxene as cumulate minerals serves to distinguish the olivine

cumulates from the peridotites and pyroxenites of each magmatic cycle. In the latter rock-type, clinopyroxene forms 90 modal % or more of the cumulus silicate phases. Chromite remains as a cumulus mineral in the lowermost part of the peridotite member of each cycle, but rapidly disappears upward in the section, as indicated by the geochemical data presented in a subsequent section. Small-scale (cm to mm size) phase layering has been observed in thin section from two samples of peridotite. In both, thin layers rich in clinopyroxene are sandwiched between much thicker layers rich in olivine.

Olivine and clinopyroxene in these rock types are equant to tabular in shape and 0.5 to 2.0 mm in maximum dimensions. Whereas olivine is invariably replaced by serpentine, the clinopyroxene is generally quite fresh or variably altered to tremolite (Fig. 5 B,C). Representative compositions of cumulus clinopyroxene from the peridotites in cycles 3 and 5, derived by electron-microprobe analysis, are reported in Table 1.

As in the olivine peridotites, brown pleochroic hornblende occurs as a minor postcumulus phase in most samples of the peridotite, occasionally being so abundant as to poikilolithically enclose small crystals of olivine and clinopyroxene. It is more abundant in the upper portions of the peridotite and certainly more so in pyroxenite than in olivine peridotite. In cycle-1 pyroxenites, the hornblende sporadically occurs as a cumulus phase exhibiting excellent basal sections often partially replaced by actinolite (Fig. 5D). Results of the partial analysis of both amphiboles are presented in Table 1. The igneous amphibole is classified as titaniferous magnesiohornblende (Leake 1978). The actinolite that replaces it contains only 0.1 wt. % TiO₂. These data suggest that the tabular, near-opaque zones intergrown with actinolite consist of cryptocrystalline rutile.

Plagioclase cumulates

Within the pyroxenites that immediately underlie the gabbro layer of cycle 5, modal olivine is very scarce; interstitial, postcumulus(?) leucocratic minerals (plagioclase ± quartz) occur in small amounts between interlocking, equant clinopyroxene crystals; igneous hornblende is nearly absent, and cumulus magnetite-ulvöspinel solid solution now replaced by a titanite-leucoxene (rutile + hornblende) assemblage makes its first appearance. Titanium oxide, which occurs in the igneous amphibole in the ultramafic rocks, is concentrated in the oxide mineral(s) of the gabbro member of this cycle. The gabbro consists of saussuritized plagioclase, unaltered clinopyroxene, rare chlorite-serpentine mixtures pseudomorphous after olivine, and leucoxene. Feldspar and clinopyroxene each con-

TABLE 1. COMPOSITION OF CLINOPYROXENE AND AMPHIBOLE, KANICHEE COMPLEX

	1	2	3	4	5	6	
SiO ₂	53.03	52.94	51.72	53.13	43.22	58.04	
TiO ₂	0.33	0.47	0.32	0.38	4.74	0.11	
Al ₂ O ₃	1.29	1.62	1.15	1.22	10.92	0.08	
FeO	6.80	6.98	6.29	6.70	11.41	6.94	
MgO	18.15	17.74	17.20	15.18	14.46	21.15	
CaO	21.63	21.36	21.14	21.81	11.30	11.73	
	101.23	101.11	97.82	98.42	96.05	98.05	
Number of ions on basis of							
	6 oxygens			24 O, (OH)			
Si	1.994	1.992	2.009	2.052	Si	6.482	8.167
Al	0.006	0.008	—	—	Al	1.518	—
	2.00	2.00	2.009	2.052		8.00	8.167
Al	0.051	0.064	0.053	0.056	Al	0.412	0.014
Ti	0.010	0.014	0.009	0.011	Ti	0.533	0.013
Fe ²⁺	0.213	0.219	0.204	0.216	Mg	3.288	4.430
Mg	1.016	0.994	0.995	0.873	Fe ²⁺	0.827	0.543
Ca	0.677	0.669	0.685	0.702	Fe ³⁺	5.00	5.00
	1.967	1.961	1.946	1.858	Ca	0.605	0.272
						1.434	1.372
						2.019	1.644
Wo	35.5	35.7	36.4	39.2			
En	53.3	49.4	52.8	48.7			
Fs	11.2	14.9	10.8	12.1			
100 $\frac{Mg}{Mg+Fe}$	82.7	82.0	82.9	80.2		69.3	84.5

Compositions are based on results of partial electron-microprobe analysis by O. Malik of the following: 1. clinopyroxene, DH-75, cycle 3; 2. clinopyroxene, DH-101, cycle 5; 3. clinopyroxene, DH-98, cycle 5; 4. clinopyroxene, DH-95, cycle 5; 5. igneous hornblende, DH-34-1, cycle 1; 6. tremolite, DH-34-2, cycle 1.

stituted 45–50 modal % of the primary rock. The transition from pyroxenite to these plagioclase-rich rocks occurs over a stratigraphic distance of less than 15 metres.

The quartz gabbro unit that occurs at the top of the stratigraphic section is poorly exposed, so our knowledge of its mineralogy is limited. The absence of altered olivine, the presence of interstitial quartz and the distinctly higher modal concentration of leucoxene serve to distinguish this rock type from the olivine gabbro. A single specimen from the central portion of the quartz gabbro zone is rich in leucoxene, pyrite, carbonate and chlorite; it may represent the sheared remnants of an oxide horizon in this layered sill (cycle 5).

Mineralized olivine cumulates of the ore zone

Unlike their equivalents higher in the stratigraphic section, the mineralized rocks show extensive alteration. This is expressed in the pervasive development of not only serpentine and tremolite but also talc, carbonate minerals and chlorite. These phases completely replace, commonly as pseudomorphs, the primary silicate minerals and also occur in vein systems that permeate these rocks on all scales. In addition, pronounced recrystallization and apparent remobilization of original magmatic Fe–Ni–Cu sulfides into microscopic to macroscopic vein systems has occurred in these rocks.

Disseminated Ni–Cu–Fe sulfides occur within the olivine-rich cumulates of all five cycles in this layered complex. Samples not from the ore zone have metal values in the range 0.2–0.5 wt. % combined Ni + Cu. Those from the open-pit area of cycle 1 normally fall in the 0.5–1.0 wt. % range. Those samples from the ore zone that show the least talc–chlorite–carbonate alteration consist of small domains (2–4 cm in diameter) of net texture (Naldrett 1973) in which loosely packed serpentinized olivine grains are poikilitically enclosed by a pyrrhotite–chalcopyrite–pentlandite–magnetite assemblage (Fig. 6A, B); these occur within much larger silicate domains of serpentinized olivine, postcumulus clinopyroxene and brown igneous hornblende (variously altered to tremolite). The distribution of the sulfide minerals that forms the net texture is considered to be magmatic in origin, but it is questionable whether the mineralogy of the sulfide–oxide assemblage reflects the original bulk-chemistry of the immiscible sulfide liquid from which the assemblage formed (*cf.* Groves & Keays 1979). Nowhere have we observed massive sulfide zones, which suggests to us that the quantity of sulfide liquid that formed at the magmatic stage was insufficient to segregate and form major concentrations of sulfide minerals.

An intermediate stage in the alteration of the olivine peridotite of the ore zone is characterized by

the extensive development of talc and smaller amounts of carbonate (probably magnesite) apparently at the expense of previously formed serpentine and tremolite. Net-textured mineralization remains clearly recognizable in these rocks. The interstitial sulfide–oxide assemblage is coarse grained; commonly, feathery blades of serpentine, with a strong preferred orientation, grow outward from elongate grains of serpentinized olivine into the opaque minerals of the net-texture assemblage (Fig. 6B, C).

The most altered rocks in the ore zone, and those with the highest Ni + Cu values for “disseminated ore”, consist of the talc–carbonate assemblage that has been fractured on a very fine scale to produce chaotic networks of irregular zones and veins consisting of chlorite (anomalous brown to near-isotropic interference colors), coarse-grained dolomitic(?) carbonate and, rarely, talc. The vein systems commonly show a preferred orientation as do associated sulfide veins and stringers, which are increasingly common in specimens of this type. These sulfide veins may be similar in mineralogy or very much richer in chalcopyrite compared to the interstitial sulfide assemblage, and are considered to be clear evidence of remobilization of the opaque minerals. In such rocks, the interstitial sulfides are now commonly intergrown with coarse-grained carbonate, which often forms the core area of these interstitial intergrowths. Also, olivine, previously transformed to a pseudomorph of serpentine–tremolite–talc–carbonate intergrowths, is replaced by one or more of the Ni–Cu–Fe sulfides (Fig. 6D).

Cu-rich veins within the ore zone

In Figure 4, the distribution of the mineralized carbonate–quartz veins is shown to be largely restricted to olivine peridotite. They are up to 1 m in width, clearly cut the olivine peridotite, and contain pockets and lenses of massive chalcopyrite, pyrrhotite and pentlandite. In some cases, these show crude bands of sulfide each 2–5 cm thick and parallel to the vein walls. Narrow alteration zones, enriched in tremolite, chlorite or talc, commonly border the vein assemblage. Unlike the disseminated mineralization in olivine peridotite, in which pyrrhotite is normally the most abundant sulfide phase, chalcopyrite is by far the most abundant sulfide in the vein system. Factors suggesting that the vein mineralization represents remobilized magmatic sulfides previously resident in the olivine peridotite include (a) restriction of veins to olivine peridotite, and possibly to a relict fracture-pattern in the peridotite, (b) clear similarity of major sulfide–oxide minerals in both environments, although abundances differ, and (c) association of carbonate – ore minerals in the vein

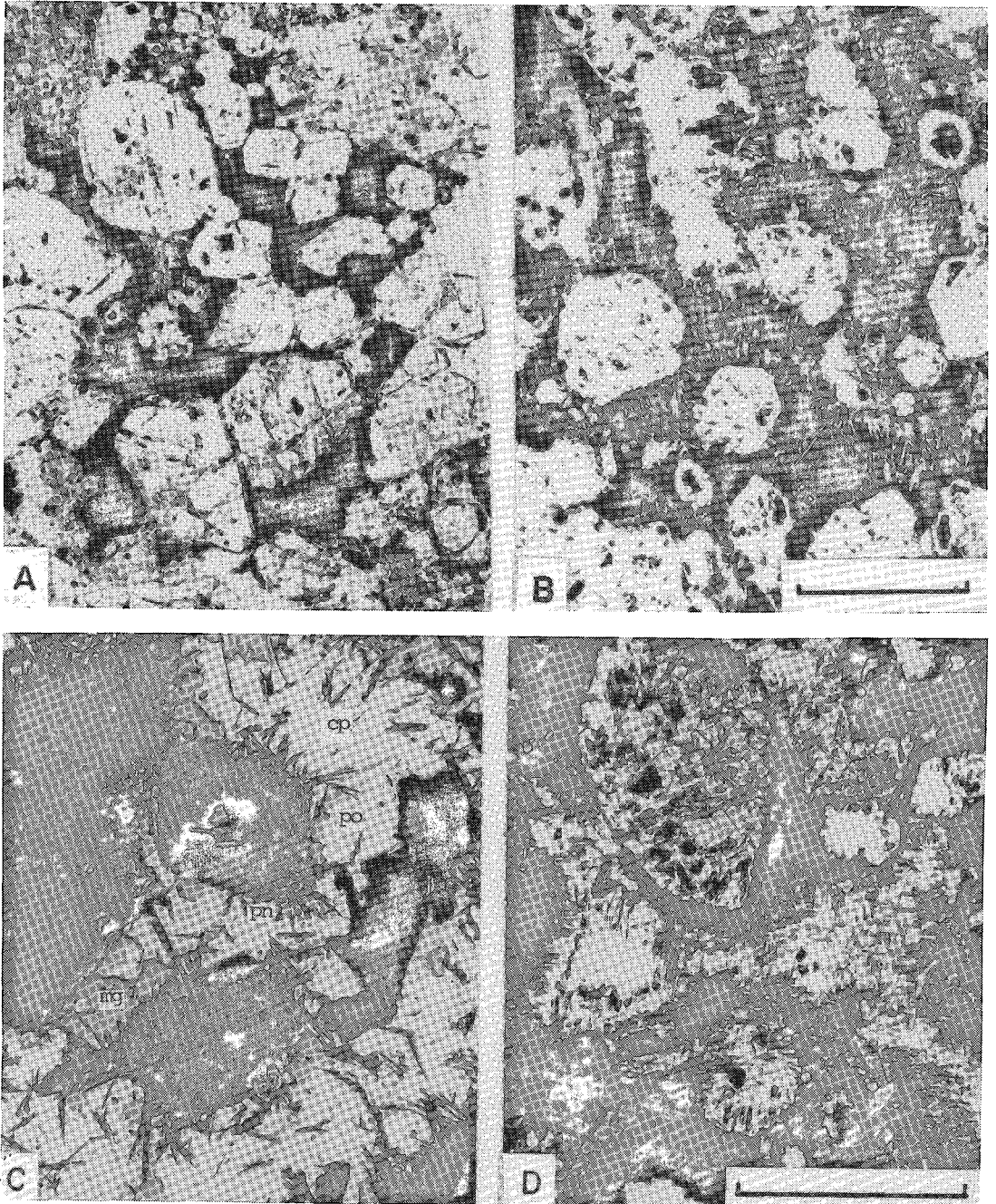


FIG. 6. Microphotographs of sulfide-oxide-silicate assemblages from the olivine peridotite member, cycle 1, Kanichee intrusive complex. A and B transmitted light, C and D reflected light. Scale bars 1.0 mm. 6A. Opaque interstitial sulfide-oxide assemblage enclosing serpentinized olivine grains. 6B. Similar to A but including oriented feathery serpentine intergrown with recrystallized postcumulus sulfide minerals. 6C. Interstitial pyrrhotite-chalcopyrite-magnetite-pentlandite assemblage enclosing serpentinized olivine as in A and B. 6D. Cumulus olivine grains now totally replaced by intergrown pyrrhotite, pentlandite and minor serpentine; also, postcumulus recrystallized sulfide-oxide assemblage as in C.

system and that same association in the last recognized stage of alteration, in the disseminated ores within olivine peridotite.

PETROLOGY

In Figure 7, a summary picture of the stratigraphy of the intrusive complex is presented. The distribution of the cumulus and postcumulus phases, together with visual estimates of the modal abundance of the former, allows for a clear distinction of the five magmatic cycles. Cycle 5 is the thickest unit; in addition to plagioclase, it contains all of the phases and rock types present in the underlying units. The olivine peridotite cumulates in cycle 1 contain, on average, a higher proportion of disseminated Ni-Cu sulfides than similar rock-types higher in the complex.

The stratigraphy illustrated for cycles 1 - 4 and the ultramafic portion of cycle 5 is almost entirely defined by the variation in the proportions of cumulus olivine and clinopyroxene. In Figure 8, the systematic variation in wt.% SiO_2 , CaO and $(\text{MgO} + \text{FeO}^T)$ for specimens from cycles 2-5 reflects the variation in the proportion of these two mafic minerals. Representative whole-rock compositions of the major rock-types are listed in Table 2. The chemistry of the dunites and olivine peridotites in each cycle is very similar and is quite different from that of associated peridotites. The clinopyroxenites in cycle 5 can be distinguished from the more olivine-rich cumulates using these same oxides. However, the boundary with the peridotites is perfectly gradational, in contrast to the abrupt differences in chemistry (and modal mineralogy) between the olivine and olivine - clinopyroxene cumulates.

Opaque, steel-grey cumulus grains of chromite occur in small amounts throughout the ultramafic cumulates in each cycle, as indicated in Figure 7. The distribution of Cr illustrated in Figure 8 indicates that chromite is most abundant in the olivine-rich cumulates of each cycle. The rapid decrease in Cr from the peridotites to the pyroxenite and gabbro members of cycle 5 is due to the early crystallization of chromite and indicates that these latter rock-types crystallized from a fractionated silicate liquid that had been strongly depleted in this element.

The distribution of Ni is very similar to the trends exhibited by $\text{MgO} + \text{FeO}^T$, which suggests that cumulate olivine in the dunites and peridotites played a major rôle in controlling its distribution in the ultramafic rocks of the complex. Cu exhibits a similar pattern, but at certain horizons within the pyroxene-rich cumulates of cycles 4 and 5, it is enriched to a considerable extent above background levels, probably owing to the same postmagmatic hydrothermal processes that formed the chalcopyrite-rich carbonate veins in the ore zone.

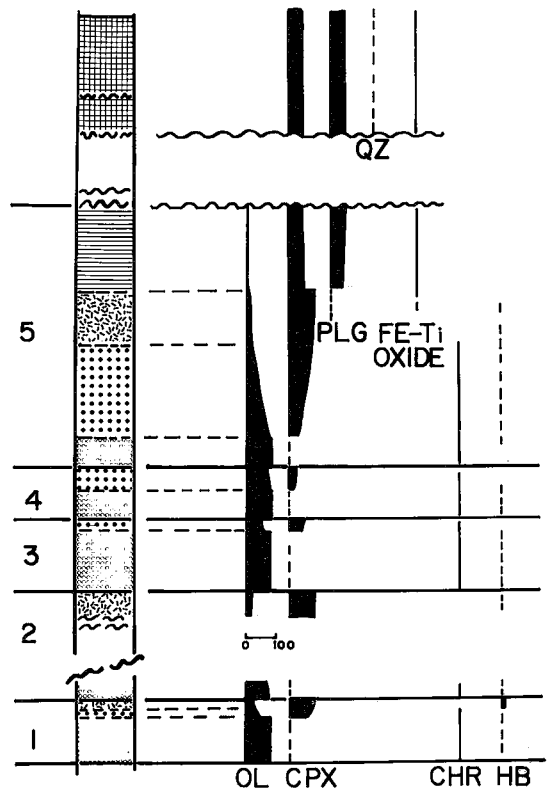


FIG. 7. Stratigraphy and modal variation in the Kanichee intrusive complex. Solid shading and bars, cumulus phases; dashed bars, postcumulus phases. Proportions of cumulus phases were determined by visual estimates; scale bar is for cumulus phases only.

Abrupt changes in CaO, $(\text{MgO} + \text{FeO}^T)$, Al_2O_3 and Cr and gradational changes in SiO_2 and TiO_2 in Figure 8 mark the transition from clinopyroxenite to olivine gabbro in cycle 5. The changes in the first three oxides are caused by the sharply delimited first appearance of cumulus plagioclase as a major phase and the corresponding decrease in cumulus clinopyroxene.

Throughout the ultramafic members of all five cycles, brown igneous hornblende occurs as a postcumulus phase. Its distribution largely determines the wt.% TiO_2 values reported in Figure 8 for these rock types. In cycle 5, TiO_2 progressively increases upward in the cycle. In the olivine and quartz gabbros, it is found in leucoxene (after intergrowths of ilmenite and magnetite). The leucoxene appears in place of the pleochroic amphibole in plagioclase-rich cumulates and is significantly more abundant in the quartz-bearing gabbros, as the chemical data in Figure 8 indicate. The differences in mineralogy

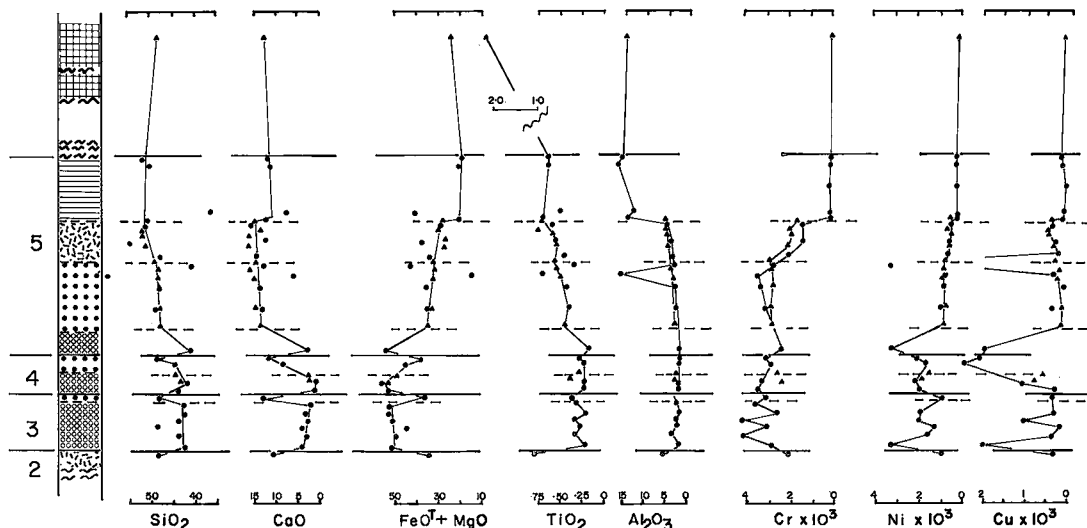


FIG. 8. Element-variation diagram for cycles 2-5, Kanichee intrusive complex. Solid dots are for data from A-A¹ section; x for B-B¹ traverse.

and chemistry between these two types of gabbro and the variation of these properties with stratigraphic height suggest that the quartz gabbro unit is a differentiate of the same magma that formed the olivine gabbro and ultramafic rocks of cycle 5.

Projections in the Ol-Cpx-Pl-Qz tetrahedron

The order in which the major cumulus minerals appear in the rocks of this intrusive complex can be understood by examining the phase relations in the pseudoquaternary system Ol-Cpx-Pl-Qz as it has been drawn by Irvine (1979, 1970) and illustrated in Figure 9. Of particular interest are the composition volumes for olivine, plagioclase, clinopyroxene and orthopyroxene, the position of the cotectic surface a-d-c-f, which represents the locus of liquids in equilibrium with olivine and clinopyroxene, and particularly the isobaric univariant curves such as a-d that define a range of liquid compositions from which olivine, clinopyroxene and plagioclase can crystallize. Also presented in Figure 9 are the pseudoquaternary phase-relations projected from the Pl, Cpx and Ol apices of the tetrahedron. On these projections are plotted the cation-normative compositions (Irvine & Baragar 1971) of a suite of rocks from all five cycles in the layered intrusive complex.

In the plagioclase projection, the olivine-rich cumulates (dunites and olivine peridotites) are tightly clustered about the olivine apex of the projection, indicating that the chemistry of these cumulate rocks is in agreement with petrographic data, which indicate that they originally consisted of 75-100 modal

% olivine. The presence of postcumulus clinopyroxene is responsible for their skewed distribution toward the Cpx apex of the figure. They do not lie on the Ol-Cpx composition line, most probably owing to serpentine and talc alteration of the primary olivine, during which a loss of MgO or relative gain of SiO₂ (or both) shifts the compositions toward the Qz apex of the projection. This is most noticeable in samples from cycle 1 (ore zone), where talc alteration is particularly pronounced and pervasive. By far the largest proportion of the peridotites plotted in this figure consist of nearly equal to somewhat greater proportions of normative clinopyroxene relative to olivine. This is consistent with the modal data on the cumulate phases summarized in Figure 5. The clinopyroxenites all lie on the quartz-rich side of the Cpx-Opx tie-line. This may be accounted for by the presence of small amounts of postcumulus feldspar and secondary quartz, both of which are common in the pyroxene-rich cumulates located immediately beneath the olivine gabbro of cycle 5.

These ultramafic cumulates have bulk compositions that lie very close to the Ol-Cpx-Qz plane of the composition tetrahedron; hence the plagioclase projection quite accurately illustrates the proportions of cumulus olivine and clinopyroxene. The olivine cumulates in each cycle of the complex have crystallized from a silicate magma that plots within the olivine volume of the tetrahedron in Figure 9. The peridotites and pyroxenites crystallized from a derivative of this same magma. It has precipitated both olivine and clinopyroxene with falling temperature as its composition migrated across the

TABLE 2. REPRESENTATIVE WHOLE-ROCK COMPOSITIONS⁽¹⁾, KANICHEE INTRUSIVE COMPLEX, ONTARIO

Specimen	DH 74 Dunite base of cycle 4 A-A ¹	DH 77 OL Peridotite Cycle 3 A-A ¹	DH 50 Peridotite Cycle 4 A-A ¹	DH 47 Pyroxenite Cycle 5 A-A ¹	DH 93 OL Gabbro Cycle 5 A-A ¹	DH 37 QZ Gabbro Cycle 5(?) B-B ¹	*KC-5 ¹ Calculated parent magma composition	*KC-5 ¹¹ Calculated parent magma composition
SiO ₂ (wt.%)	44.11	42.91	48.68	51.49	49.67	48.45	48.60	48.51
TiO ₂	0.20	0.18	0.48	0.52	0.67	2.17	0.48	0.98
Al ₂ O ₃	1.97	1.68	3.28	4.56	15.84	14.11	7.46	9.50
Fe ₂ O ₃ (2)	1.90	1.90	2.05	2.09	2.23	3.81	2.18	2.60
FeO (2)	13.51	14.93	10.14	7.32	7.55	12.04	9.20	10.03
MnO	0.25	0.27	0.22	0.01	0.18	0.26	0.17	0.21
MgO	36.87	35.06	20.17	17.39	9.80	6.95	18.78	15.27
CaO	0.96	2.97	14.72	15.68	11.49	11.93	11.93	11.89
Na ₂ O	0.05	0.06	0.15	0.75	2.05	0.08	0.95	0.72
K ₂ O	0.01	0.01	0.03	0.10	0.47	0.05	0.19	0.16
P ₂ O ₅	0.02	0.02	0.04	0.02	0.03	0.07	0.01	0.04
S	0.15	0.01	0.04	0.07	0.02	0.08	0.05	0.09
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Cr (ppm)	3515	2597	2804	2143	103	18	1922	1337
Ni	1700	1840	820	545	185	48	814	692
Co	144	139	93	74	55	62	87	223
Cu	269	282	255	341	134	114	358	298
Zn	118	146	78	77	81	143	81	101

(1) The results of each analysis have been recalculated to 100 wt. % on a volatile-free basis. (2) Fe₂O₃ and FeO have been recalculated from total iron using the relationship Fe₂O₃ = TiO₂ + 1.5 (after Irvine & Baragar 1971). † Section is shown in Figure 2. * KC-5¹ includes all rock types in cycle 5 except the quartz gabbro, weighted according to their abundance in the stratigraphic section (Fig. 3). KC-5¹¹ includes the quartz gabbro horizon.

cotectic surface *adcf* toward the plagioclase-saturated curve *a-d*.

The gabbros that lie at the top of cycle 5 are the only rocks in the complex believed to contain cumulus plagioclase. Hence, only these rocks can be expected to have compositions near the isobaric univariant curve *a-d-e* in the various projections of Figure 9. In these three projections, liquids on the curve *a-d* will crystallize olivine; those beyond *d* and toward *e* will precipitate orthopyroxene (in addition to plagioclase and clinopyroxene in all cases). In each projection, the olivine gabbros plot adjacent to the projected curve *a-d* and, depending upon the projection, within the liquidus region for olivine, clinopyroxene or plagioclase but never orthopyroxene. In these diagrams, one sample is consistently richer in the calcium-bearing phases (plagioclase or clinopyroxene) probably owing to epidote-carbonate veins in the specimen. All three gabbros are olivine-normative, and their chemistry, interpreted in terms of these projections, supports our conclusion that they and the underlying ultramafic rocks of cycle 5 form a comagmatic suite.

For the quartz gabbro unit that lies at the top of the stratigraphic section in Figure 7, we have a single composition, and it is quartz normative. In the three projections of Figure 9, it plots in the orthopyroxene field and in the general vicinity of the projected position of the liquidus curve *d-e*. To the extent that conclusions may be drawn from a single data-point,

it is probable that the quartz gabbro member is a differentiate of the same parent-magma that formed the previously described comagmatic suite of rocks in this cycle (5).

COMPOSITION OF THE PARENT MAGMA(S)

The five cycles of magmatic cumulates that constitute the exposed portion of the Kanichee intrusive complex have each crystallized from a separate pulse of magma. An accurate estimate of the composition of each pulse is unknown, since clear examples of chilled margins have not been observed. One way to explain how each cycle of cumulates formed requires the partial crystallization of silicate melt while the magma was at rest at the site of intrusion. The cumulates and residual fractionated liquid could then have been separated (and not at the same stage for each pulse), the latter to form volcanic flows and near-surface hypabyssal intrusive bodies. Irvine & Smith (1967) used this concept and a variant of it to explain the formation of the cycles of ultramafic rocks in the Muskox complex from a magma of tholeiitic basalt composition. More recently, Campbell (1977) argued that the macrorhythmic units in the Jimberlana complex most probably formed by the same process. In the present case, using this mechanism, crystallization of an olivine-rich mafic magma can, in general terms, explain the formation of the cumulate ultramafic rocks in cycles 1-4, as

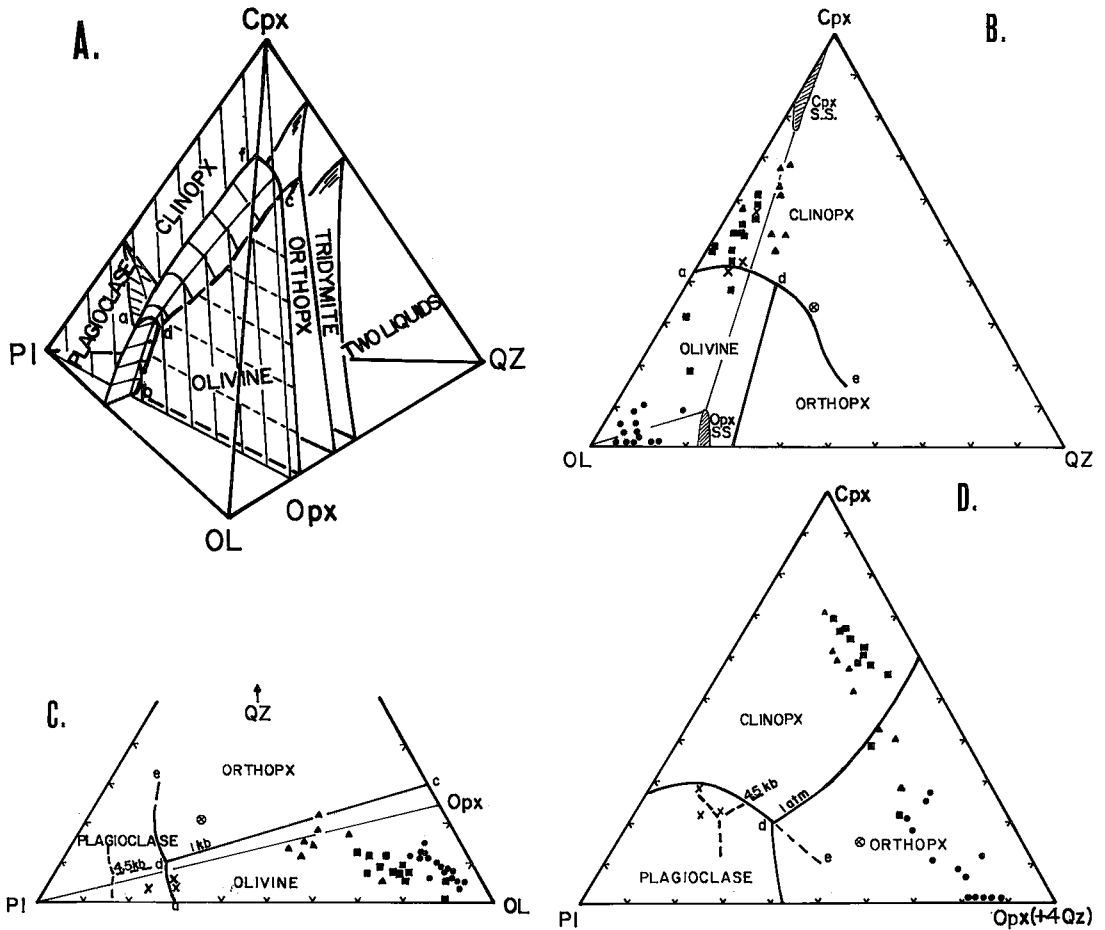


FIG. 9. Mafic and ultramafic rock composition from the Kanichee intrusive complex plotted on projections of the Ol-Cpx-Pl-Qz tetrahedron. 9A. Phase relations in the pseudoquaternary system Ol-Cpx-Pl-Qz as visualized by Irvine (1970, 1979) for volcanic and hypabyssal conditions of crystallization. 9B. Composition of mafic and ultramafic rocks from cycles 2-5 plotted on the plagioclase projection of Figure 9A. Ortho- and clinopyroxene compositions are taken from Irvine's (1970) data on the Muskox complex. Curve *d-e* is the extension of *a-d* into the silica-saturated portion of the Ol-Cpx-Pl-Qz system. • olivine cumulates (dunites and olivine peridotites); ■ olivine + clinopyroxene cumulates (wehrlite or peridotite); ▲ clinopyroxene-rich cumulates (clinopyroxenites); x and ⊕ clinopyroxene + plagioclase cumulates with minor cumulus olivine (olivine gabbro) or interstitial Qz (quartz gabbro), respectively. 9C. Clinopyroxene projection, with some data plotted as in B. Dashed curves are for estimate of position of phase boundaries at 4.5 kbar (Green & Ringwood 1967). 9D. Olivine projection of Figure 9A. Phase boundaries at 4.5 kbar from Green & Ringwood (1967).

well as the more complete sequence represented in cycle 5.

The fact that the ultramafic rocks that form cycles 1-4 are igneous cumulates precludes the possibility that they crystallized from an olivine-rich ultramafic magma. This is further substantiated by 1) the similarity in mineralogy, textures and chemistry of these cumulates to those that form the lower portion of cycle 5 and 2) the presence of cumulate chromite with olivine in the olivine peridotites of all

five cycles. Unlike cycles 1-4, cycle 5 probably represents a nearly complete sequence of cumulates and related derivative lithologies. If so, it is the only cycle from which the composition of the initial magma for all cycles might be estimated.

The proportions of gabbro and ultramafic rock-types in cycle 5 indicate that the magma from which it crystallized is intermediate between basalt and an olivine-rich ultramafic composition. Clearly then, the Kanichee intrusive complex is not a member of the

peridotitic class of intrusions of komatiitic affinity that Naldrett (1981) and Ross & Travis (1981) described. It may be a member of Naldrett's class of layered intrusive complexes (type 2a) that are thought to crystallize from picritic (tholeiitic) magmas or it may represent the product of crystallization of a magma of komatiitic basalt composition. The authors mentioned did not include in their classification scheme a category for layered complexes of the latter type. That such liquids do form layered intrusions is suggested by published material on the sills in the Cape Smith Fold Belt reported by Francis & Hynes (1979). Certainly, some of the layered flows and sills in Munro Township, Ontario have crystallized from similar magma-compositions, given that volcanic rocks in this range are recognized from that area. A mineralized example of this type is the Mt. Sholl mafic-ultramafic complex described by Mathison & Marshall (1981). They suggested that the gabbro-peridotite suite, host to the disseminated and massive Ni-Cu sulfides at the base of this complex, crystallized from a magma of basaltic komatiite composition.

In Table 2, we list two estimates of the magma composition from which cycle-5 rocks in the Kanichee complex crystallized. They were calculated from compositions of representative rock-types weighted according to their abundance in this cycle. Both estimates have MgO values in the high-magnesium-basalt range (12–20 wt. % MgO) and less than 10 wt. % Al_2O_3 . These features are consistent with the observation that olivine and clinopyroxene are the early cumulus silicate phases in each of the cycles of the Kanichee complex. This feature indicates that they are members of Jolly's (1980) magnesian or magnesian tholeiite suite and distinguishes them from layered complexes of his tholeiite suite, in which olivine and plagioclase are the two earliest magmatic phases. The absence of olivine or pyroxene spinifex in the border phases of the Kanichee complex and of rocks of known komatiitic affinity in the host volcanic sequence indicates that the complex crystallized from a magma belonging to the magnesian tholeiite suite. The values (wt. % basis) of the ratios $\text{Al}_2\text{O}_3/\text{TiO}_2$ and $\text{CaO}/\text{Al}_2\text{O}_3$ (≈ 10 and > 1.1 , respectively) for the

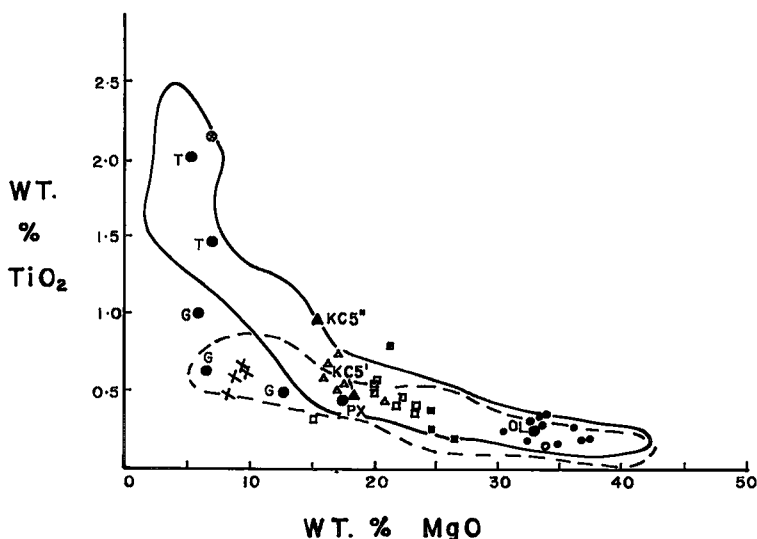


FIG. 10. Chemical composition of the Kanichee mafic and ultramafic rocks from cycles 2–5 plotted on a wt. % TiO_2 versus MgO diagram. Solid curve outlines gabbros, basalts and a few pyroxenitic rocks of tholeiitic affinity. The area encompassed by the dashed curve encloses data-points for komatiite-suite volcanic and plutonic rocks of mafic and ultramafic composition as well as tholeiitic ultramafic cumulates. Data base for these curves include Arndt (1977), Arndt *et al.* (1977), Naldrett & Cabri (1976) and MacRae (1969). Symbols for Kanichee data as in previous diagrams; open symbols are for cycle 5 and solid symbols for cycles 2, 3 and 4. Large solid circles are for olivine (OL) and pyroxene (PX) ultramafic cumulates and komatiitic (G) and tholeiitic (T) gabbros, all from layered sills, Cape Smith Fold Belt, Quebec (Francis & Hynes 1979). Large solid triangles KC5' and KC5'' represent two estimates of magma composition from which cycle-5 cumulates (Kanichee) crystallized.

two estimates of the magma composition from which cycle-5 rocks crystallized (Table 2) support this conclusion and indicate that these compositions are not members of a typical komatiitic (AUK) suite (see Nesbitt *et al.* 1979).

By far the most widely used chemical variation-diagrams in the recent geological literature to distinguish rocks of komatiitic affinity from those of tholeiitic suites [or of komatiitic and magnesian affinity from those of the magnesian tholeiite suite, using Jolly's (1980) terminology] are those in which MgO is plotted versus TiO₂ and Al₂O₃ versus FeO*/(FeO* + MgO). In themselves, these diagrams are not infallible, as Nesbitt *et al.* (1979) and Naldrett (1981) pointed out. The boundary separating the two suites in the latter plot should be used with caution when extended to regions other than the Abitibi belt, a point emphasized by Nesbitt *et al.* (1979). In Figures 10 and 11, we present on these two diagrams data for the various cycles of the Kanichee complex and for layered sills, most of which are from the Abitibi belt.

In the MgO versus TiO₂ diagram, compositions of most of the ultramafic rocks fall in the area in which both tholeiitic and komatiitic fields overlap.

The few remaining data-points for ultramafic compositions and the single data-point for quartz gabbro lie in the tholeiitic field, whereas the compositions of the olivine gabbros lie wholly within the field for rocks of the komatiitic suite. One estimate of the magma composition for cycle 5 lies within the tholeiitic field, whereas the other is in an area in which the tholeiitic and komatiitic fields overlap. The trend exhibited by the Kanichee data is similar to that illustrated by gabbros and ultramafic cumulates from layered sills described by Francis & Hynes (1979). These rocks occur within a volcanic sequence containing spinifex-bearing komatiitic basalts.

In the Al₂O₃ versus FeO*/(FeO* + MgO) diagram (Fig. 11), the ultramafic rocks of all cycles from the Kanichee complex plot wholly within the tholeiitic field of the diagram, whereas the two estimates of the parent magma for cycle 5 and the olivine gabbros from this cycle plot on the komatiitic side of the figure; the olivine gabbro compositions plot in a region in which volcanic rocks of komatiitic, tholeiitic, or Al-rich basaltic affiliation may plot, as recognized by Naldrett & Goodwin (1977). The single quartz gabbro composition lies in the tholeiitic field, as it does in Figure 10. In this diagram, the Kanichee

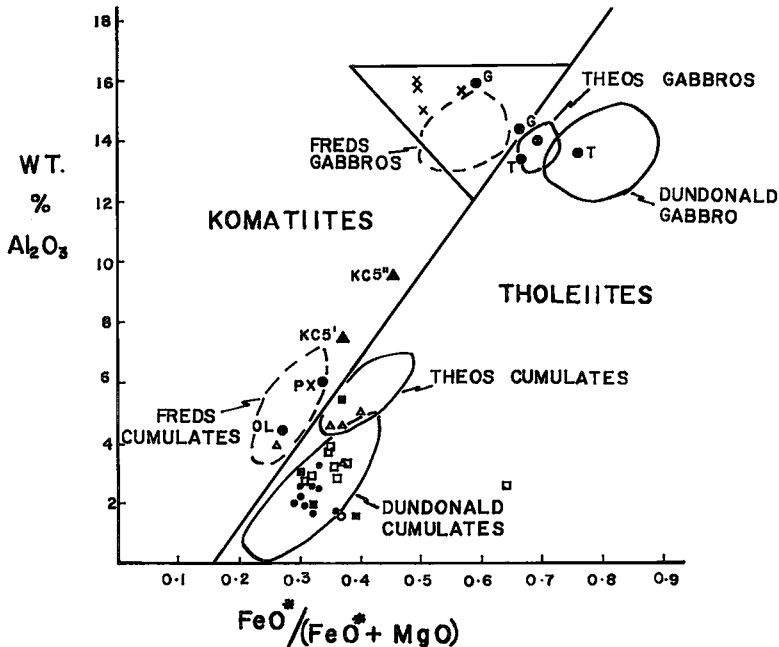


FIG. 11. Distinction between rock types in layered mafic-ultramafic sills of tholeiitic and komatiitic affinities on a wt. % Al₂O₃ versus FeO*/(FeO* + MgO) diagram (FeO* represents total Fe expressed as FeO). Boundary for fields of komatiites and tholeiites is from Naldrett & Cabri (1976); triangular area outlined in vicinity of gabbros of komatiitic affinity is from Naldrett & Goodwin (1977). Solid curves outline mafic and ultramafic plutonic rocks of tholeiitic affinity; dashed curves for similar rock-types of komatiitic affinity. Source of data base and character of symbols as in Figure 10.

data are compared to trends exhibited by layered bodies of both tholeiitic (Dundonald sill and Theo's flow) and komatiitic (Fred's flow) affinity. The trend of the Kanichee data differs from both these groups and from the komatiitic trend exhibited by the cumulates and differentiates of the layered sills from the Cape Smith Fold Belt (Francis & Hynes 1979), also plotted in Figure 10.

A majority of the analytical data from the Kanichee complex plotted in Figure 10 lies within the overlapping regions of the tholeiitic and komatiitic fields. For this reason, the diagram offers no definitive information concerning the chemical affinity of the parent magma of this complex. In terms of Figure 11, the chemistry of the ultramafic cumulate rocks suggest that they formed from a tholeiite magma-source, whereas the gabbroic differentiates (olivine-bearing types) are as magnesian or more so than the gabbros from the layered komatiitic sills shown in Figure 11. The weak Fe-enrichment trend shown by the olivine gabbros in cycle 5 of the Kanichee complex is also exhibited by the plagioclase-rich differentiates (anorthositic gabbros) in the layered komatiitic sills (Ship Hill and Koede bodies) from the Kaapmuiden area, Barberton Mountain Land, South Africa (Viljoen & Viljoen 1970). Such differentiation trends clearly contrast with the more regular Fe-enrichment patterns exhibited by both the komatiitic and magnesian tholeiite sills illustrated in Figure 11. Factors such as (1) the Fe/Mg ratio of the silicate phases that form the ultramafic cumulates, (2) the presence and proportions of Fe-rich cumulate phases other than olivine and pyroxenes, *e.g.*, spinel-group minerals, and (3) the proportion and composition of the interstitial postcumulus liquid to these cumulate phases in the ultramafic rocks, all will determine where both the ultramafic cumulates and gabbroic differentiates plot in the Al_2O_3 versus $FeO^*/(FeO^* + MgO)$ diagram. It is beyond the scope of this paper to pursue the topic further, but it is clear at this point that the interpretation of these variation diagrams should be viewed with caution when individual whole-rock compositions from layered sills and flows are used to estimate the chemical affinity of the parent magmas.

Taken in its entirety, the available information suggests to us that all five cycles of the Kanichee intrusive complex crystallized from repeated pulses of a high-magnesium basaltic magma. It is a member of Jolly's (1980) magnesian tholeiite suite, as is the composition of the magmas from which the Dundonald sill and Theo's flow crystallized; both have a similar proportion of clinopyroxene cumulates to that observed in cycle 5 of the Kanichee complex. We suspect that the layered sills reported by Francis & Hynes (1979) may also be members of this suite, based upon their analytical data (Al_2O_3/TiO_2 and

CaO/Al_2O_3) for chilled marginal rocks and the absence of spinifex in these rocks. These features contrast with those reported for layered mafic sills of similar mineralogy in Minnesota (Schultz 1982); there, pyroxene spinifex is observed in the chilled margin of the intrusion, and estimates of the composition of the parent magma [in terms of Al_2O_3/TiO_2 and CaO/Al_2O_3 ratios and Al_2O_3 versus $FeO^*/(FeO^* + MgO)$] are consistent with a komatiitic basalt composition.

SUMMARY

The relevant points to be emphasized concerning the geology and origin of the Kanichee layered intrusive complex include the following: 1) The complex consists of five magmatic cycles, each of which originated from very similar magma-sources to form four cycles of ultramafic cumulates and a final cycle that also has gabbroic differentiates. In each, olivine, chromite and clinopyroxene are the major cumulus phases; plagioclase is a significant cumulus phase in the final cycle. 2) Each cycle of cumulates has crystallized from a high-magnesium basaltic magma. The order of appearance of the cumulus phases in each cycle, the value of the ratios Al_2O_3/TiO_2 and CaO/Al_2O_3 for two estimates of the composition of the parent magma, and the absence of olivine or clinopyroxene spinifex in rocks at the margin of the intrusive body, all indicate that this magma is a member of Jolly's (1980) magnesian tholeiite suite. 3) The remobilization of disseminated postcumulus Ni-Cu sulfides and associated Au and platinum-group metals by hydrothermal processes into vein systems in the olivine peridotite of the earliest cycle of the complex is responsible for significant concentrations of these elements. Owing to the abnormally high concentrations of precious metals, these rocks have been mined periodically over the past 60 years.

ACKNOWLEDGEMENTS

This research has been supported by grants from the Natural Sciences and Engineering Research Council and the Department of Energy, Mines and Resources. This study was made possible by the cooperation of R. Stavely and J. Koza of Kanichee Mines Inc. In periodic visits to the mine site during the period 1976-1977, much generous technical assistance was provided by Mr. L. Belamy and his associates on the mine staff, for which the authors are particularly grateful. Constructive criticism of the various versions of this manuscript by colleagues in the Department of Geology, Laurentian University and by two external referees have measurably improved the quality of the paper.

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Received July 1, 1982, revised manuscript accepted February 1, 1983.