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MINERALOGY OF MICACEOUS KIMBERLITE FROM THE JOS DYKE, SOMERSET ISLAND, N.W.T.

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ABSTRACT

The Jos micaceous kimberlite dyke consists essentially of an olivine–phlogopite–calcite (50–80%) rock. Olivine and phlogopite phenocrysts are set in a matrix of olivine, phlogopite, spinel, perovskite, serpentine, chlorite and calcite. Calcite exhibits a variety of habits, *e.g.*, anhedral groundmass crystals, microphenocrystic euhedral laths, euhedral rhombohedra in a matrix of anhedral grains. Xenocrysts (Cr–pyrope, Cr–diopside) derived from the breakdown of mantle-derived xenoliths are very rare, and megacrysts characteristic of kimberlite are scarce; only small amounts of magnesian ilmenite (MgO 13–19%) are present. Olivines range in composition from Fo$_{98}$ to Fo$_{86}$ with no correlation between crystal size and composition. Three distinct varieties of phlogopite exhibit complex mantling and zonation wih regard to Cr$_2$O$_3$ and TiO$_2$ contents. Spinels are Ti-rich members of the magnesian ulvöspinel–ulvöspinel–magnetite series. The Jos dyke is considered to be a highly evolved, carbonate-rich fraction of a micaceous kimberlite magma; compositional variations observed in olivine and phlogopite megacrysts are attributed to mixing of different batches of magma of very similar composition. Significant differences as to the composition and parageneses of mica are noted between this micaceous kimberlite and examples from southern Africa.

Keywords: Somerset Island, micaceous kimberlite, phlogopite, spinel, magma mixing.

SOMMAIRE

Le dyke de kimberlite à mica de Jos se compose, pour 50 à 80%, d'olivine, de phlogopite et de calcite. Les phénocristaux d'olivine et de phlogopite se trouvent dans une pâte d'olivine, phlogopite, spinelle, pérovskite, serpentine, chlorite et calcite. Le calcite présente plusieurs facies: cristaux allotriomorphes de la pâte, microphénocristaux idiomorphes en lattes, rhomboèdres idiomorphes dans une pâte de grains allotriomorphes. On observe, très rarement, des xénocristaux de pyrope et de diopside chromifères qui proviennent de la désagrégation de xénolithes mantelliques; les mégacristaux caractéristiques de kimberlite, rares aussi, consistent en ilménite magnésienne (MgO 13-19%). La composition de l'olivine varie entre Fo$_{98}$ et Fo$_{86}$, indépendamment de la taille du cristal. Trois types de phlogopite montrent un emmantèlement complexe de cristaux zonés en Cr et Ti. Les spinelles, riches en Ti, appartiennent à la série ulvospinelle magnésien–ulvospinelle–magnétite. Le dyke représenterait une fraction carbonatée très évoluée d'un magma kimberlitique à mica. La composition variable des mégacristaux d'olivine et de phlogopite résulterait du mélange de magmas de compositions voisines. Des différences importantes quant à la composition et paragenèse du mica distinguent cette kimberlite à mica des kimberlites sud-africaines.

(Traduit par la Rédaction)

Mots-clés: Ile Somerset, kimberlite micacée, phlogopite, spinelle, mélange de magmas.

OCCURRENCE AND PETROGRAPHY

The Jos micaceous kimberlite occurs as an exceptionally fresh isolated dyke that forms part of the Somerset Island kimberlite province in

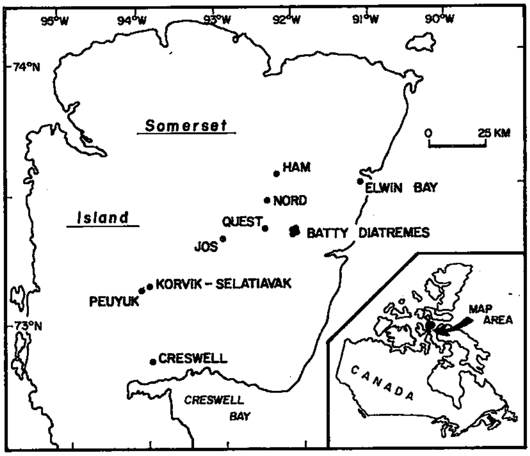

FIG. 1. The Somerset Island kimberlite province and the location of the Jos dyke.

the Canadian Arctic (Fig. 1). The dyke, 1–2 m wide, strikes approximately north–south and is about 1 km in length. No true outcrop is present, as the dyke exposure is confined to vertically transported frost-heaved regolith.

In hand specimen, phenocrysts of olivine and phlogopite are set in a fine-grained grey–green matrix which is mottled by white patches of carbonate. Few country-rock xenoliths are evident and ultramafic xenoliths are absent. The lack of xenoliths and of signs of brecciation indicates that intrusion has taken place under quiet, nonexplosive conditions, unlike the other Somerset Island occurrences which are breccia diatremes or the root zones of such diatremes.

In thin section, the kimberlite consists of large (1–5 mm) anhedral to euhedral olivines and phlogopites (1–3 mm) set in a groundmass of euhedral to subhedral olivine, phlogopite, spinel, perovskite and euhedral calcite within a mesostasis of serpentine, chlorite and anhedral calcite. Perovskite occurs as light brown, rounded crystals commonly with an opaque rutile rim. Olivines are typically fresh, with serpentinization confined to the crystal margins and to fractures. Pseudomorphic replacement by calcite, a common feature of other calcite-rich kimberlites, has not occurred.

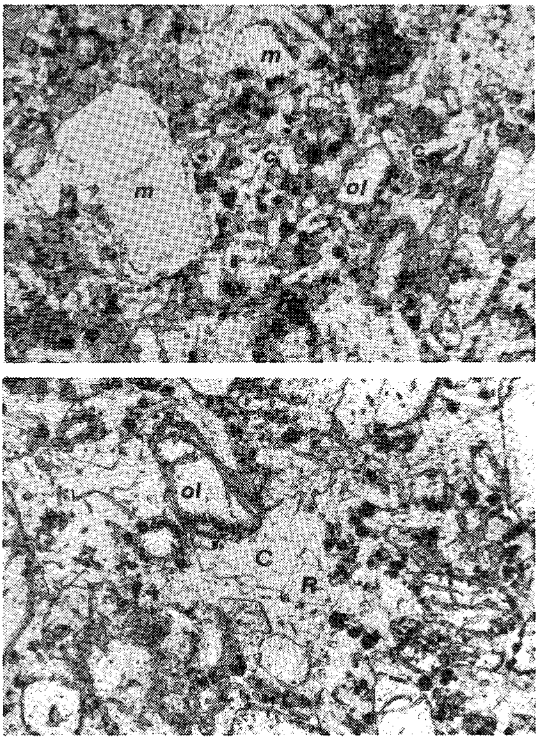

FIG. 2. (a) Jos kimberlite showing olivines (ol), type-B mica megacrysts (M) with type-C mica mantles and calcite laths (C) set in a groundmass of euhedral spinel and perovskite together with serpentine, chlorite and calcite. Magnification x 50. (b) Jos kimberlite showing calcite rhombs (R) within a matrix of anhedral calcite (C). Note the "necklaces" of opaque oxides around the olivines (ol). Magnification x 50.

Three habits of calcite (lath, rhombohedra and anhedral grains), determine the overall appearance of the groundmass, and two main textures are evident. In one case, calcite laths and euhedral colorless mica are set in a light green matrix consisting of an intimate mixture of serpentine, chlorite and anhedral calcite (Fig. 2a). The calcite laths might be termed microphenocrysts, and subparallel lath orientation, perhaps due to flowage, is evident in some specimens. The matrix is rich in oxide minerals, but the laths typically contain no inclusions of oxides and evidently have crystallized prior to the bulk of the groundmass. With increasing calcite content, this groundmass assemblage grades into irregular areas composed of interlocking anhedral calcite grains but lacking oxides and silicates.

In samples containing more than 70% calcite, a second type of groundmass texture is observed. In this case the silicate–oxide groundmass is of minor importance and is confined essentially to the margins of the olivine phenocrysts. Opaque minerals in these regions commonly form "necklaces" around the phenocrysts. Calcite laths are rare, and the bulk of the groundmass consists of euhedral rhombohedra of calcite set in a matrix of anhedral calcite, throughout which are scattered minor amounts of euhedral colorless mica (Fig. 2b). Pyrite is common in such samples. All gradations between these two extremes can be found, but calcite laths seem to occur only in the silicate–oxide fraction of the groundmass. Further details of the petrography are given with the descriptions of individual minerals.

All mineral analyses presented in this paper were obtained at Purdue University using an automated MAC 500 wavelength-dispersive microprobe. Raw X-ray-count data were processed by the Bence-Albee alpha-factor method.

MEGACRYSTS AND XENOCRYSTS

The Jos dyke is exceptionally poor in megacrysts and xenoliths. Separation of the heavy-mineral fraction from a one-kilogram sample gave only the following sparse assemblage.

Ilmenite

Seven magnesian ilmenites exhibit a wide range in composition (Cr_2O_3 0.39–4.56%, Al_2O_3 0.03–0.51%, MnO 0.26–0.64%, MgO 12.6–18.6%), and are similar to ilmenites found in other kimberlites. The very high MgO contents indicate that they belong to the high-MgO group of kimberlite ilmenites as found at Tunraq, Frank Smith, Wesselton and Premier (Mitchell 1979a).

Garnet

Four garnets are Cr-rich, Ti-poor pyropes (Cr_2O_3 3.6–6.6%, TiO_2 0.11–0.21%, Mg/Mg+Fe) 0.831–0.865) that can be classified as type-9 garnets in the statistical classification of Dawson & Stephens (1975). The garnets fall within the range of compositions found in Somerset Island garnet lherzolite xenoliths (Mitchell 1978a) and are undoubtedly xenocrysts derived from the fragmentation of such xenoliths. The type-1 and -2 garnets of Dawson & Stephens (1975), low-Cr pyropes, which seem to be the characteristic megacryst garnet of kimberlites on Somerset Island and elsewhere, seem to be absent in the Jos dyke.

Clinopyroxene

Ten clinopyroxenes were found; nine of these proved to be chrome diopsides similar to those found in garnet lherzolite xenoliths (TiO_2 0.07–0.61%, Al_2O_3 0.29–4.63%, Cr_2O_3 0.71–2.60%, Na_2O 1.13–2.69%, Mg/(Mg+Fe) 0.920–0.940). They undoubtedly are xenocrystic in origin. The wide range in Ca/(Ca+Mg) ratios (0.438–0.509), assuming that these pyroxenes were in equilibrium with orthopyroxene, indicates equilibration over a wide range of temperature (*ca.* 1000–850°C: Wells 1977), similar to that determined by Mitchell (1978a) for Somerset Island garnet lherzolites.

One other pyroxene, also considered to be a xenocryst, is an Al-rich, relatively Fe-rich specimen [Al_2O_3 8.2%, Mg/(Mg+Fe) 0.858], similar to aluminous pyroxene megacrysts found in alkali basalts.

Orthopyroxene

Four low-Al enstatites [Al_2O_3 1.00–1.39%, TiO_2 0.04–0.16%, Cr_2O_3 0.36–0.84%, CaO 0.34–0.85%, Mg/(Mg+Fe) 0.939–0.934] were found, similar in composition to the enstatites of garnet lherzolites. A xenocrystic origin is indicated.

MICA

Three distinct varieties of mica are recognizable. The least common, designated type A, exhibits a weak, light yellow-brown pleochroism and occurs entirely as megacrysts (phenocrysts?). Crystals are anhedral to subhedral and show no optical zonation. Type-A micas are commonly but not invariably mantled by a mica that exhibits a stronger pleochroism (type B) and by a further mantle of a colorless mica (type C). The mantles are not in optical continuity with each other and represent definite overgrowths.

Type-B megacrysts/phenocrysts exhibit a moderate, light yellow to light brown pleochroism and vary widely in size and habit. Isolated euhedral and subhedral grains are common, and several large (3 mm) grains with distorted cleavages showing undulose extinction were observed. Many of the type-B micas are mantled by type-C mica (Fig. 2a).

Type-C micas occur as mantles on all other micas and as discrete plates in the groundmass. They are very weakly pleochroic, from colorless to very light turquoise or very light brown, have moderate birefringence and show no optical zonation or undulose extinction. The margins of the euhedral type-C mica mantles are commonly subparallel to the subhedral type-B cores (Fig. 2a). The width of the mantles varies from a few microns to cases in which the mantle forms the bulk of the composite crystal, with the type-B core only a few tens of microns in cross-section. The core–mantle boundary is commonly marked by a chain of very small (< 5 μm) euhedral spinels. Type-C micas have crystallized contemporaneously with groundmass Ti-bearing spinels and perovskites, as evidenced by the common inclusion of these phases in the type-C micas but not in the type-A and -B micas.

Representative analyses of micas are given in Table 1. Major-element variations within and between grains are limited, and chemical variations are best illustrated in terms of the TiO_2 and Cr_2O_3 contents (Fig. 3).

Type-A micas are phlogopites [Mg/(Mg+Fe) 0.869–0.926] with low Cr_2O_3 ($< 0.25\%$) and low TiO_2 ($< 2.0\%$). Relatively little compositional variation is evident within and between crystals. Weakly zoned crystals have margins enriched in Fe relative to the core. Between grains there seems to be a negative correlation between Fe and Cr; those richest in Fe are poorest in Cr (Table 1, analyses 1–4).

Type-B micas are phlogopites [Mg/(Mg+Fe) = 0.839–0.927] showing a relatively wide range

TABLE 1. REPRESENTATIVE ANALYSES OF MICAS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	41.0	39.8	41.4	41.1	41.9	40.8	38.8	39.9	39.4	38.3	40.3	40.2	39.5	39.7	37.2	36.2	35.6	36.3
TiO_2	1.4	1.7	1.1	1.4	3.0	4.7	4.0	2.9	2.8	3.5	3.6	3.6	3.2	4.4	1.3	1.1	1.1	1.0
Al_2O_3	11.7	11.8	11.6	10.9	12.3	13.2	15.6	11.6	12.8	13.6	13.5	13.3	13.3	12.7	12.2	16.9	18.0	18.2
Cr_2O_3	0.1	0.0	0.2	0.0	0.1	0.1	0.5	0.1	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.0	0.0	0.0
FeO*	5.0	6.4	3.6	5.4	4.4	4.5	4.6	4.6	3.9	7.3	5.5	5.2	4.4	4.8	4.4	4.0	3.4	3.0
MgO	25.3	23.6	25.4	24.5	23.3	22.1	21.3	24.3	24.1	21.2	22.1	22.3	23.1	22.4	22.8	22.7	22.4	23.9
CaO	0.1	0.4	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.1	0.0	0.1	0.0	0.2	0.8	0.5	0.2	0.0
MnO	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
NiO	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Na_2O	0.3	0.1	0.1	0.3	0.2	0.1	0.1	0.3	0.2	0.2	0.2	0.1	0.3	0.3	0.0	0.0	0.0	0.2
K_2O	9.6	9.9	9.7	9.6	10.2	10.1	9.8	9.7	10.1	9.7	9.7	9.8	9.7	9.9	6.6	8.7	9.2	9.1
	94.5	93.9	93.2	93.4	95.5	95.8	95.0	93.4	93.5	94.1	95.0	94.9	93.7	94.6	85.6	90.2	90.0	91.8
Structural formula X 100 based on 22 oxygens																		
Si	589	581	598	598	593	577	554	580	571	561	577	575	571	571	580	539	533	531
Ti	15	19	12	15	32	50	43	91	30	39	38	39	34	47	15	10	12	10
Al	198	204	197	187	205	219	263	199	219	234	227	225	227	214	224	296	318	314
Cr	1	0	2	0	1	1	5	1	3	0	0	0	3	2	4	2	0	0
Fe	59	78	44	66	52	52	55	56	47	90	65	62	53	57	57	50	43	36
Mg	541	542	545	531	492	467	453	527	520	463	470	475	497	481	529	506	498	521
Ca	1	5	0	0	0	1	3	0	8	1	0	1	0	3	13	2	3	0
Mn	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
Ni	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Na	8	3	2	7	5	3	3	8	5	6	5	3	8	8	0	0	0	5
K	175	184	178	178	184	183	178	180	187	182	177	179	178	182	130	165	175	202

Analyses 1-4, Type-A phlogopites (1 and 2 core and margin); Analyses 5-14, Type-B phlogopites (5-7 zoning trends in a single crystal, 8-9, 11-12, 13-14, cores and margins, 10 iron-rich margin; Analyses 15-18, Type-C chloritized eastonitic phlogopites.
*Total Fe expressed as FeO.

in TiO_2 (2.5–5.6%) and Cr_2O_3 contents (Table 1, analyses 5–14). Most of the micas have Cr_2O_3 contents of less than 0.6% Cr_2O_3, and only three samples with distinctly higher chrome contents were found (1.1, 1.5, 1.6% Cr_2O_3). Increasing intensity of pleochroism is correlated with increasing TiO_2 content. Zonation within grains is only slight for major elements, but minor elements show very complex zonations (Fig. 3). Between grains, major- and minor-element variations are relatively large compared with type-A micas. No simple compositional trends are discernible, however. Figure 3 illustrates that there is a compositional gap in terms of the TiO_2 content between types A and B and that type-B micas always contain more TiO_2 than type-A micas. Type-B micas show no correlations between composition, size, habit or degree of distortion.

Type-C micas are poor in Ti, Cr, Fe, K and Si and rich in Al relative to type-A and -B phlogopites (Table 1, analyses 15–18). The overall lower FeO content, coupled with similar MgO contents, results in a slightly higher average Mg/(Mg+Fe) ratio of 0.917 (range 0.903–0.942), relative to types A and B [average Mg/(Mg+Fe) of 0.898 and 0.891, respectively]. Compositional variation is slight and the analyses are characterized by low totals. For reasons outlined below we consider that the type-C micas were originally eastonitic phlogopites that have now been partly altered to chlorite by deuteric processes.

Compared with other Somerset Island kimberlites, the Jos phlogopites are very similar in composition to phlogopite phenocrysts in the Tunraq micaceous kimberlite (Mitchell 1979a). Tunraq, however, lacks type-C groundmass micas even in the most evolved fractions, whereas these are common as a primary phase in the carbonate-rich portions of the Elwin Bay monticellite kimberlite (Mitchell 1978b), where they have formed later than brown, Ti-bearing phlogopite megacrysts.

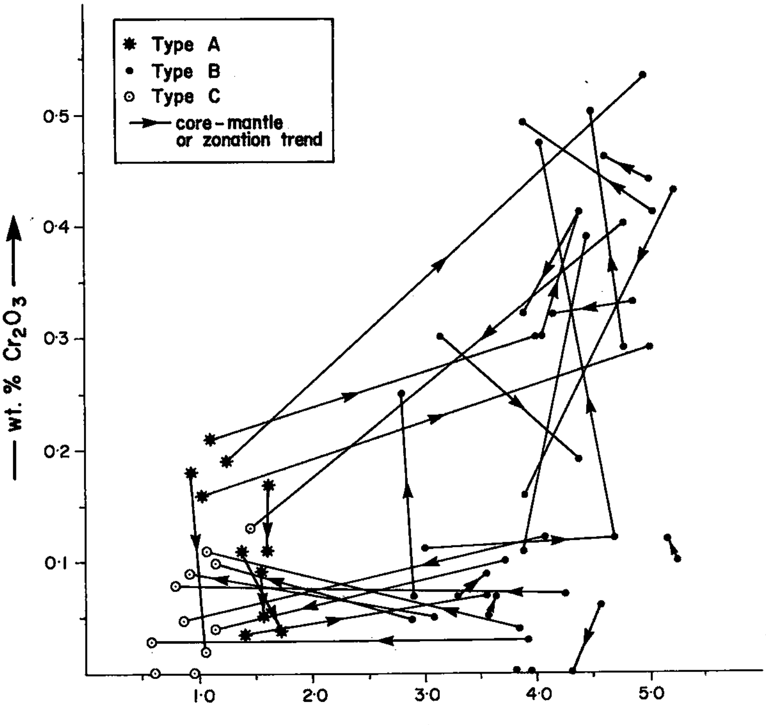

FIG. 3. Cr_2O_3 *versus* TiO_2 plot for micas of types A, B and C, illustrating mantling and zoning trends.

Smith *et al.* (1978) presented data showing that two types of groundmass mica exist in South African kimberlites: a very rare, relatively Fe-rich type [Mg/(Mg+Fe) 0.45–0.65, TiO_2 3–6%] designated type I and a common, relatively Mg-rich type [Mg/(Mg+Fe) 0.82–0.93, TiO_2 0.07–4.0%] designated type II. Jos type-A phlogopites are similar to the type-II micas of Smith *et al.* (1978). Type-B phlogopites overlap with the type-II micas of highest TiO_2 content (the bulk of the latter contain less than 3% TiO_2) and form a group that is significantly richer in TiO_2. No equivalents to the type-C micas were noted by Smith *et al.* (1978), and none of their type-I micas have been found at Jos or at Tunraq. A notable difference between the Jos type-A and -B micas and the South African type-II micas is that the former are all megacrysts/phenocrysts and the latter are all groundmass micas. In addition, none of the Jos micas have the optical characteristics of tetraferriphlogopite. Further, Jos type-B micas fall outside the range of compositions of South African mica megacrysts as defined by Dawson & Smith (1975). Significant differences exist, therefore, between the mica paragenesis of Somerset Island and that in South African kimberlites.

OLIVINES

Olivines show a wide range in size and habit. Large (1–5 mm) crystals tend to be rounded to anhedral; smaller crystals are commonly euhedral. Many of the largest crystals are more magnesian than the small crystals and may be considered to have formed prior to these. The relationship is not constant, however, and small Mg-rich euhedral crystals are common.

The olivines range in composition from Fo_{93} to Fo_{86} (Fig. 4). The absence of olivines richer in iron indicates that even in highly evolved kimberlites, olivines do not reflect the degree of differentiation. This absence supports the conclusions of Mitchell (1979a) and Boyd & Clement (1977) that kimberlite olivines are never richer in Fe than Fo_{85-86}.

NiO (0.16–0.38%) and CaO (0.02–0.16%) can be depleted or unchanged at the margins of crystals relative to the cores.

Figure 4 compares Jos olivine compositions

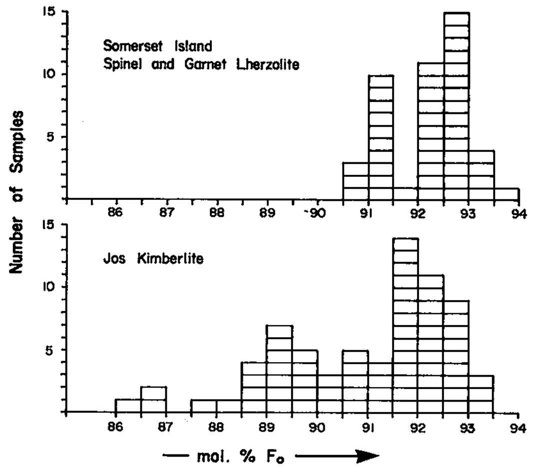

FIG. 4. Compositions of olivines in the Jos micaceous kimberlite compared with olivines from Somerset Island spinel and garnet lherzolites.

with those of olivines from Somerset Island spinel and garnet lherzolites. Overlap at the higher Fo contents possibly indicates that many of the large anhedral olivines could be xenocrysts, but no petrographic or chemical criteria are available to determine whether or not this is so. The paucity of xenocrysts demonstrably derived from fragmented lherzolites is an indication that the bulk of the olivine compositional range might be attributed to variations in phenocryst composition.

SPINEL

Representative analyses of spinel are given in Table 2. End-member spinel molecules are calculated as outlined by Mitchell & Clarke (1976), and the data are plotted in a reduced-iron spinel prism (Haggerty 1976) shown in Figures 5 and 6 to illustrate the compositional variation.

TABLE 2. REPRESENTATIVE ANALYSES OF SPINELS FROM THE JOS MICACEOUS KIMBERLITE DIKE

	1	2	3	4	5	6	7	8	9	10
TiO_2	0.5	0.6	12.8	21.6	23.8	14.1	17.1	20.4	18.0	11.1
Al_2O_3	10.5	16.9	12.7	9.7	4.9	6.0	6.4	5.2	2.1	11.0
Cr_2O_3	55.5	46.7	13.6	0.3	1.1	6.4	0.8	1.8	1.0	0.7
FeO*	20.5	21.5	43.7	48.6	48.5	56.7	55.5	52.7	61.0	61.0
MnO	0.3	0.3	0.5	0.5	0.9	0.6	0.7	0.8	0.7	0.7
MgO	13.0	12.6	15.8	17.3	17.6	14.1	16.0	17.2	13.6	12.1
	100.3	98.6	99.1	98.0	96.8	97.9	96.5	98.1	96.4	96.8
Recalculated Analyses$^+$										
Fe_2O_3	7.0	6.8	25.3	25.3	25.4	36.9	36.4	31.8	38.3	41.1
FeO	14.1	15.4	21.0	25.9	25.7	23.5	23.5	24.0	26.5	24.1
	100.9	99.3	101.7	100.6	99.4	101.6	100.9	101.2	100.2	100.9
$MgAl_2O_4$	19.0	30.3	18.1	12.9	6.7	8.0	8.6	6.9	2.8	15.2
Mg_2TiO_4	1.6	2.0	29.1	33.9	39.5	30.7	34.3	37.9	32.9	20.6
Mn_2TiO_4	-	-	0.8	0.7	1.3	0.9	1.0	1.1	1.0	1.1
Fe_2TiO_4	-	-	4.8	20.2	19.5	5.6	8.6	12.4	12.7	7.8
$MgCr_2O_4$	38.4	24.0	-	-	-	-	-	-	-	-
$MnCr_2O_4$	0.8	0.7	-	-	-	-	-	-	-	-
$FeCr_2O_4$	28.0	31.4	12.9	0.3	1.0	5.9	0.7	1.6	0.9	0.8
Fe_3O_4	12.2	11.6	34.4	32.1	32.2	48.7	46.8	40.2	49.7	54.7

Analyses 1-2, aluminous magnesian chromite; 3-10, magnesian ulvöspinel-ulvöspinel-magnetite; Total Fe calculated as FeO; + Fe_2O_3 and FeO calculated by Carmichael's (1967) method.

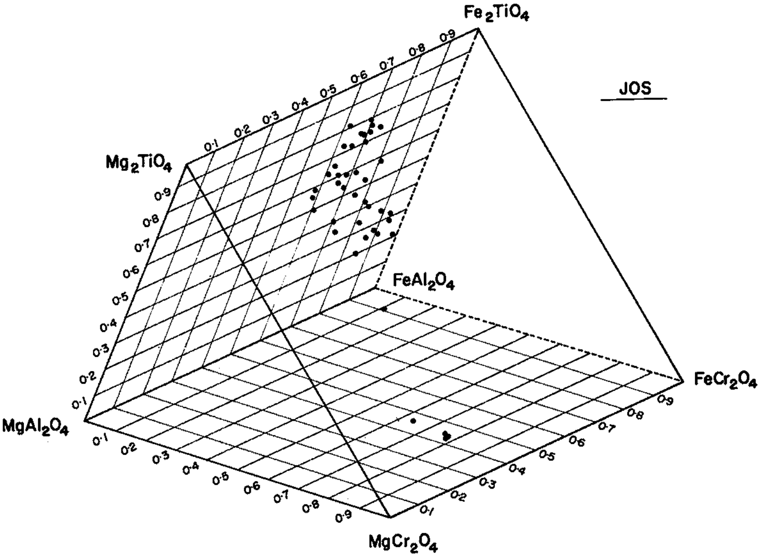

FIG. 5. Compositions of spinels from the Jos micaceous kimberlite plotted in a reduced-iron spinel prism.

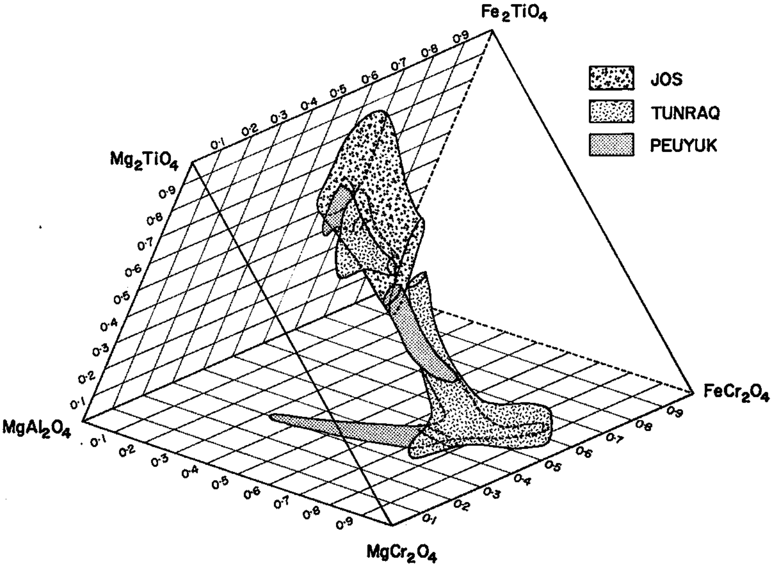

FIG. 6. Compositional fields of spinels from the Jos and Tunraq micaceous kimberlites (Mitchell 1979a) and the Peuyuk kimberlite (Mitchell & Clarke 1976).

The least evolved spinels are rare, rounded, transparent, red aluminous magnesian chromites. A thin (< 5 μm) opaque rim of titaniferous spinel is present on some examples. These spinels (Table 2, analyses 1–2) are similar in composition to spinels at the Cr-rich end of the aluminous magnesian chromite compositional trend found in the Peuyuk kimberlite (Mitchell & Clarke 1976).

Most of the spinels are members of the magnesian ulvöspinel–ulvöspinel–magnetite series (Table 2, analyses 3–10). The spinels range in size from a few microns up to 100 microns, with the majority being about 20–60 microns in cross-section and of euhedral to subhedral habit. The crystals are typically corroded and embayed, indicating that a euhedral spinel of octahedral habit has been extensively resorbed during crystallization of the later portions of the groundmass. Poorly developed "atoll spinels" (Mitchell & Clarke 1976) are common; the outer mantles are a spongy Ti-poor magnetite.

Individual spinels have widely varying compositions and are either uniform or weakly zoned towards margins depleted in Ti and enriched in Fe relative to the core. The magnesian ulvöspinel–ulvöspinel–magnetite assemblage is characterized by high Mg and Ti coupled with low Al and Cr. The evolutionary trend of spinel compositions (Figs. 5, 6) is across the spinel prism from relatively Al-rich types to types richer in Ti and Fe and poorer in Cr and Al at approximately constant Mg/(Mg+Fe) ratios. Some of the later and more Fe-rich spinels show an increase in Al relative to earlier spinels (Table 2, analysis 10). Spinels richest in Ti also have significant Mn enrichments, and the MnO contents of the Jos spinels (0.5–1.3%) are typically higher than those found in other similar spinels in Somerset Island kimberlites (< 0.5% MnO: Mitchell & Clarke 1976, Mitchell 1979a). The Ti-rich spinel assemblage is similar to that of the Tunraq fissile micaceous kimberlite (Mitchell 1979a), and both of these assemblages are poor in the $MgAl_2O_4$ component relative to Ti-rich spinels in the Peuyuk kimberlite (Fig. 7), providing further evidence in favor of the hypothesis of Mitchell (1979a) that spinels in micaceous kimberlites are in general poorer in Al than those in kimberlites.

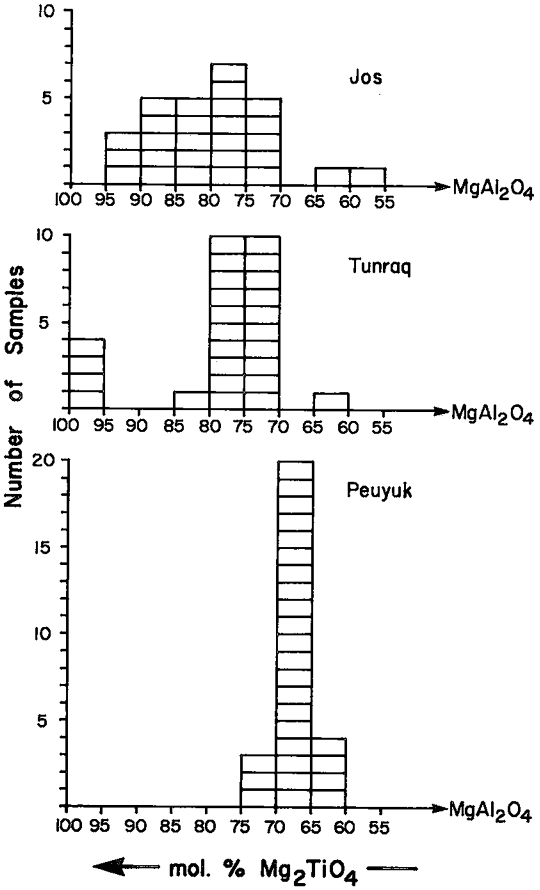

FIG. 7. Composition of Ti-rich spinels only in Somerset Island kimberlites, expressed in mol. % of Mg_2TiO_4 and $MgAl_2O_4$ to illustrate the aluminum-poor nature of spinels in micaceous kimberlites relative to those of kimberlite.

The lack of titaniferous magnesian aluminous chromites and titaniferous magnesian chromites, which are the characteristic earliest spinels in kimberlites (Mitchell & Clarke 1976, Haggerty 1976), together with the presence of a Mn- and Ti-enriched spinel assemblage, suggest that the Jos spinels have formed from a very evolved fraction of a micaceous kimberlite magma.

DISCUSSION

The Jos dyke has the attributes of a highly differentiated magmatic product, as it is characterized by a paucity of Cr-bearing spinels, an abundance of Ti-rich spinels, very high calcite contents and a paucity of megacrysts and mantle-derived xenoliths. The dyke is a rare example of how a kimberlite magma can differentiate under quiet intrusive conditions to a residual fraction that contains few of the characteristic "indicator minerals" of kimberlite. Cursory examination would not reveal the presence of magnesian ilmenite or Cr-pyrope, and on a petrographic basis the dyke might be classified as a lamprophyre or even a carbonatite. However, the rare kimberlite indicator-minerals and the presence of magnesian ulvöspinels reveal the true antecedents of the dyke. Even though the dyke contains major modal amounts (50–80%) of calcite it should not be termed a carbonatite, as Mitchell (1979b) has noted significant differences between the oxide and silicate mineralogy of carbonate-rich rocks associated with feldspathoidal-bearing alkaline rocks and those associated with kimberlites. To reflect this *petrogenetic* difference, the carbonate-rich residua of kimberlitic magmas are better termed *calcareous* or *calcite-rich kimberlites,* the classification being based upon the mineral assemblage present rather than solely upon the dominant modal phase.

The Jos intrusion is a micaceous kimberlite that falls within the spectrum of kimberlite types (kimberlite clan) described by Mitchell (1979b), between the Benfontein sill (Dawson & Hawthorne 1973) and the Premier carbonate dykes (Robinson 1975). Further differentiation of the Jos dyke would probably result in the formation of silicate-free carbonate dykes akin to the Premier dykes.

Petrographically, Jos resembles the calcite-rich phases of the Peuyuk, Korvik and Selatiavak kimberlites (Mitchell & Clarke 1976) but is, because of the higher calcite content and lack of Cr-rich spinels, considered to be much further evolved. The spinel compositions are similar to those of the later fractions of Tunraq micaceous kimberlite; Jos can be regarded as illustrating how this magma might have evolved if further differentiation had been able to occur.

Paragenetic and compositional variations exhibited by the olivine and mica megacrysts can best be explained by a crystal-fractionation magma-mixing model. Magma mixing, as used in this paper, does not imply the mixing of magmas of grossly different compositions but refers to the mixing of different batches of magma of similar composition. Boyd & Clement (1977) have advocated that complex relationships between size, habit and composition of the De Beers kimberlite olivines, similar to those found at Jos, are the result of the mixing of several generations of olivine crystals from different batches of magma of similar composition. This process can account for the coexistence of small, euhedral, relatively Mg-rich olivines and larger anhedral Fe-rich olivines in the same specimen.

Of the micas, only the type-C micas could have formed during the crystallization of the groundmass. Types A and B were not in equilibrium with the liquid that formed the groundmass, as is evidenced by their mantling by type-C mica and their absence as groundmass phases. The complex normal and reverse zoning with respect to TiO_2 and Cr_2O_3 (Fig. 3) and the mantling relationships between type-A and -B micas can best be explained by assuming that the micas are phenocrysts that crystallized from a magma that was either heterogeneous or variable in composition owing to the mixing of batches of magma with slightly different compositions. Smith *et al.* (1978) have ascribed similar intergrain chemical variations in magmas to the formation of local reservoirs of differing composition after the mechanical mixing of magma. Brooks & Printzlau (1978) have also proposed that reverse zoning in mafic minerals is the result of magma mixing.

Development of the Jos dyke may be envisioned as follows. A micaceous kimberlite magma, similar to that which formed the Tunraq micaceous kimberlite, pooled at depth and underwent differentiation which resulted in the loss of most of the heavy-mineral fraction and the mantle xenoliths. Liquidus phases were probably olivine, mica, Cr-spinel and perovskite, but only the lighter phases, olivine and mica, were kept in suspension by turbulence. The magma evolved towards a composition richer in Ti, Ca and CO_2. To this evolving magma were added at various times batches of similar kimberlite magmas. Each addition resulted in a slight change in the bulk composition of the magma pool, this being reflected in a change in the composition of the olivines and micas crystallizing. Repeated additions resulted in the complex mantling and zonation exhibited by the micas. Intrusion of the hybrid magma, bearing its suspension of megacrysts/phenocrysts resulted in a thorough mixing of these phases and accounts for the inter- and intragrain compositional heterogeneity seen in the Jos mica and olivine. At the time of final consolidation, the evolved liquid was crystallizing mica, olivine, Ti-rich spinels and perovskite. Since Ti was preferentially incorporated into the oxide phases, contemporaneous micas were Ti-poor but rich in Al. These aluminous (*ie.,* eastonitic) phlogopites nucleated epitactically about pre-existing phlogopites and formed discrete euhedral crystals of widely varying size throughout the groundmass. As crystallization progressed, mica, olivine and the oxides ceased to be liquidus phases. During the formation of the residual serpentine–chlorite–calcite mesostasis, the residual fluids partly chloritized the eastonitic phlogopites. It is thought unlikely that the type-C micas are pseudomorphs of types A and B, as chloritization of such micas would result in the formation of abundant secondary inclusions of rutile and ilmenite (or both), uneven alteration and preferential alteration along cleavages. None of these features are seen in the type-C micas.

In summary, the Jos dyke presents evidence concerning the ultimate differentiation products of micaceous kimberlite magmas and demonstrates the possibilities of magma mixing and crystal fractionation in the very fluid, carbonate-rich, highly evolved fractions.

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REFERENCES

BOYD, F.R. & CLEMENT, C.R. (1977): Compositional zoning of olivines in kimberlite from the De Beers mine, Kimberley, South Africa. *Carnegie Inst. Wash. Yearbook* **76**, 485-493.

BROOKS, C.K. & PRINTZLAU, I. (1978): Magma mixing in mafic alkaline volcanic rocks: the evidence from relict phenocryst phases and other inclusions. *J. Volc. Geothermal Res.* **4**, 315-331.

CARMICHAEL, I.S.E. (1967): The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contr. Mineral. Petrology* **14**, 36-64.

DAWSON, J.B. & HAWTHORNE, J.B. (1973): Magmatic sedimentation and carbonatitic differentiation in kimberlite sills at Benfontein, South Africa. *J. Geol. Soc. London* **129**, 61-85.

——— & SMITH, J.V. (1975): Chemistry and origin of phlogopite megacrysts in kimberlite. *Nature* **253**, 336-338.

——— & STEPHENS, W.E. (1975): Statistical classification of garnets from kimberlite and associated xenoliths. *J. Geol.* **83**, 589-607.

HAGGERTY, S.E. (1976): Opaque mineral oxides in terrestrial igneous rocks. *In* Oxide Minerals. (D. Rumble III, ed.), *Mineral. Soc. Amer. Short Course Notes* **3**, Hg101-300.

MITCHELL, R.H. (1978a): Garnet lherzolites from Somerset Island, Canada and aspects of the nature of perturbed geotherms. *Contr. Mineral. Petrology* **67**, 341-347.

——— (1978b): Mineralogy of the Elwin Bay kimberlite, Somerset Island, N.W.T., Canada. *Amer. Mineral.* **63**, 47-57.

——— (1979a): Mineralogy of the Tunraq kimberlite, Somerset Island, N.W.T. Canada. *In* Kimberlites, Diatremes and Diamonds: Their Geology, Petrology and Geochemistry (F.R. Boyd & H.O.A. Meyer, eds.), *Amer. Geophys. Union Spec. Pap.* **SP0024**, 161-171.

——— (1979b): The alleged kimberlite–carbonatite relationship: additional contrary mineralogical evidence. *Amer. J. Sci.* **279**, 570-589.

——— & CLARKE, D.B. (1976): Oxide and sulphide mineralogy of the Peuyuk kimberlite, Somerset Island, N.W.T., Canada. *Contr. Mineral. Petrology* **56**, 157-172.

ROBINSON, D.N. (1975): Magnetite–serpentine–calcite dykes at Premier Mine and aspects of their relationship to kimberlite and to carbonatite of alkalic carbonatite complexes. *Phys. Chem. Earth* **9**, 61-70.

SMITH, J.V., BRENNESHOLTZ, R. & DAWSON, J.B. (1978): Chemistry of micas from kimberlites and xenoliths. I. Micaceous kimberlites. *Geochim. Cosmochim. Acta* **42**, 959-971.

WELLS, P.R.A. (1977): Pyroxene thermometry in simple and complex systems. *Contr. Mineral. Petrology* **62**, 129-139.

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