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COMPOSITION OF SPINELS IN MICACEOUS KIMBERLITE FROM THE UPPER CANADA MINE, KIRKLAND LAKE, ONTARIO

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Abstract

The spinel assemblage in the Upper Canada mine micaceous kimberlite consists of discrete crystals of members of the magnesian ulvöspinel–magnetite series, together with discrete mantles of this composition upon cores of titaniferous magnesian chromite. Spinels have been extensively resorbed by the fluids that crystallized to form the groundmass. Crystals of titaniferous magnesian chromite are zoned from Ti-poor cores to Ti-rich margins with variable Fe/Fe+Mg ratio. Crystals of magnesian ulvöspinel–magnetites are continuously zoned from Ti-rich cores to Ti-free magnetite margins. Spinels in micaceous kimberlites are depleted in Al relative to spinels of similar Ti content in kimberlite. The unique spinel assemblage of individual kimberlitic intrusions is considered a function of the nature of coexisting minerals, local temperature–oxygen fugacity conditions and extent of resorption of preexisting spinels.

Sommaire

L'assemblage de spinelles qui caractérise la kimberlite micacée de la mine Upper Canada consiste en cristaux isolés de la série ulvite magnésienne–magnétite et en surcroissances de ces mêmes compositions sur des cristaux de chromite magnésienne titanifère. Ces spinelles ont été largement résorbés par les fluides qui ont formé la pâte. Les cristaux de chromite magnésienne titanifère sont zonés, pauvres en Ti au centre, riches en Ti à la périphérie, avec rapport Fe/(Fe+Mg) variable. Les cristaux de la série ulvite magnésienne–magnétite sont zonés de façon continue en Ti, dont la teneur décroît du centre à la périphérie, où elle tombe à zéro (magnétite). Les spinelles des kimberlites micacées sont appauvris en Al, en comparaison des spinelles de kimberlite de même teneur en Ti. L'assemblage de spinelles qui distingue chaque intrusion kimberlitique dépend de la nature des minéraux coexistants, des conditions locales de température et de fugacité d'oxygène et du degré de résorption des spinelles antérieurs.

(Traduit par la Rédaction)

Introduction

Recent studies have demonstrated that kimberlites are characterized by spinels that exhibit a wide range in composition, *i.e.*, from aluminous magnesian chromite to titaniferous magnesian chromite to members of the magnesian ulvöspinel–magnetite series (Haggerty 1975, Mitchell & Clarke 1976). The latter spinels, rich in Mg and Ti, are especially characteristic of kimberlites.

Few comparative data exist for micaceous kimberlite; it is important to characterize the spinel assemblage of these rocks to determine whether they are simply a variant of kimberlite enriched in phlogopite or a product of a distinct type of kimberlitic magmatism. It is also important from an economic viewpoint to determine the nature of the spinels in micaceous kimberlite, as this might permit discrimination between micaceous kimberlite, mica peridotite and lamprophyre.

The Micaceous Kimberlite at the Upper Canada Mine

A micaceous kimberlite dyke is exposed in the workings of the Upper Canada mine at Dobie, about 10 km east of Kirkland Lake, Gauthier Township. This kimberlite has the distinction of being the first true kimberlite to be discovered in Canada (Lee & Lawrence 1968). It occurs as thin dykes cutting Archean metavolcanic rocks and consists of round phenocrysts of pyrope, olivine and phlogopite set in a groundmass of olivine, phlogopite, serpentine, carbonate, perovskite, shortite, apatite and spinel (Lee & Lawrence 1968, Watkinson & Chao 1973). Preliminary examination of the spinel assemblage by Lee & Lawrence (1968) and Rimsaite (1971) has indicated that at least three types of spinel are present: chromite, titaniferous chromite and titaniferous magnetite. Conclusions presented in this paper are based upon analyses of spinels (100 analyses) found in three random samples of micaceous kimberlite exposed within the mine at the 838 m level.

Spinel Paragenesis

Spinels occur as large (0.04–0.25 mm) discrete crystals of magnesian ulvöspinel–magnetite or as discrete rims of this composition upon cores of subhedral to euhedral (0.004–0.04 mm) crystals of titaniferous magnesian chromite. The magnesian ulvöspinel–magnetite crystals are extensively corroded and embayed, consistent with corrosion and resorption of an original euhedral spinel by the fluid which remained after spinel crystallization and which eventually crystallized to form the bulk of the groundmass. Resorption of titaniferous spinels and magnetite appears to be characteristic of kimberlites (Mitchell & Clarke 1976) and mica peridotites. On the basis of their euhedral habit, both types of spinel are considered to have crystallized from the magma after the intrusive event which resulted in the rounding of preexisting phenocrysts, *i.e.*, they are post-fluidization spinels. No red transparent aluminous magnesian chromite was encountered in this study. The single example of this spinel in these rocks described by Rimsaite (1971) is similar to the rounded aluminous magnesian chromites in kimberlite, considered by Mitchell & Clarke (1976) to have formed prior to the fluidizing event. This type of spinel is common in kimberlite but seems relatively rare in this and other micaceous kimberlites (Mitchell 1977, 1978a).

TABLE 1. REPRESENTATIVE ANALYSES OF SPINELS FROM THE UPPER CANADA MINE MICACEOUS KIMBERLITE

	1	2	3	4	5	6	7	8	9
TiO_2	5.0	6.1	7.5	9.4	12.2	18.8	14.5	9.5	0.2
Al_2O_3	4.8	5.1	4.3	3.7	3.5	1.9	2.0	2.2	0.2
Cr_2O_3	50.1	46.8	34.6	25.9	23.9	1.5	0.0	0.1	0.0
FeO*	27.4	29.4	39.7	48.1	46.1	63.0	71.3	74.1	93.4
MnO	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.1
MgO	11.9	12.0	11.6	11.3	11.6	11.5	8.7	8.8	0.8
	99.6	99.9	98.2	98.9	97.9	97.3	97.1	95.3	94.7
Recalculated analyses+									
Fe_2O_3	9.8	10.8	20.6	27.4	23.5	35.7	44.5	53.1	69.2
FeO	18.7	19.7	21.1	23.4	24.9	30.8	31.3	26.2	31.1
	100.7	101.	100.2	101.6	100.2	100.8	101.6	100.5	101.6
$MgAl_2O_4$	8.4	8.8	7.0	5.6	5.3	2.7	2.7	3.1	0.3
Mg_2TiO_4	16.6	20.0	23.4	27.5	29.6	27.8	20.8	21.0	0.7
Mn_2TiO_4	-	-	-	-	1.1	0.9	0.9	1.0	-
Fe_2TiO_4	-	-	-	-	5.0	20.4	16.6	3.4	-
$MgCr_2O_4$	22.2	16.4	9.3	1.5	-	-	-	-	-
$MnCr_2O_4$	1.1	1.2	1.1	1.1	-	-	-	-	-
$FeCr_2O_4$	35.4	35.9	27.2	24.1	24.6	1.4	-	0.1	-
Fe_3O_4	16.3	17.7	32.1	40.2	34.5	46.8	58.9	72.4	99.0

Analyses 1-5: titaniferous magnesian chromites; analyses 6-9: magnesian ulvöspinel - ulvöspinel - magnetite.
* Total Fe calculated as FeO.
+ FeO and Fe_2O_3 calculated from total Fe by Carmichael's (1967) method.

Spinel Composition

Representative microprobe analyses of spinels are given in Table 1 and the field of compositions of the spinels is plotted in Figure 1 (trend UC) as end-member spinel molecules in a reduced-iron spinel prism as outlined by Mitchell

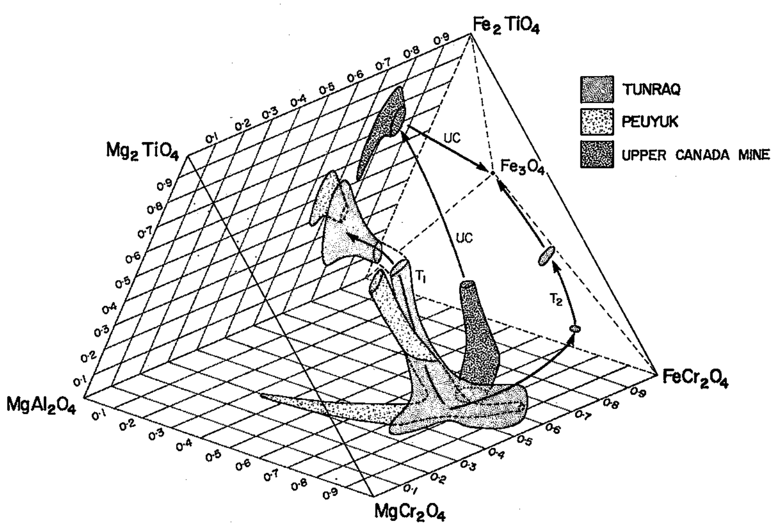

FIG. 1. Compositional trends for kimberlite (Peuyuk) and micaceous kimberlite spinels (Tunraq, Upper Canada) plotted in a reduced-iron spinel prism together with a second-order projection to illustrate trends towards Ti-free magnetite.

& Clarke (1976). This type of projection is useful for kimberlite spinels that have probably formed under relatively reducing conditions, *i.e.*, oxygen fugacities of less than 10^{-20} bars (Mitchell & Clarke 1976), in that it includes all the major elements determined. (Plotting the analyses in an oxidized-iron prism to illustrate variations in Fe_3O_4 and $MgFe_2O_4$ content does not change the conclusions of this paper and fails to illustrate the TiO_2 variations).

Crystals of titaniferous magnesian chromite are continuously zoned from Ti-poor cores to Ti-rich margins (Table 1, analyses 1-5). Increasing Ti is accompanied by increasing Fe and decreasing Cr at approximately constant Mg content. Titaniferous magnesian chromites richer in Ti than those shown in Figure 1 (ca. 12% TiO_2) may exist but the outer margins of the crystals cannot be analyzed because of excitation of the ulvöspinel overgrowths by the microprobe electron beam. None of the titaniferous magnesian chromites plotted on Figure 1 lies on possible mixing lines between this spinel and ulvöspinel; the variation in titanium is considered to represent true chemical zonation.

Members of the magnesian ulvöspinel–magnetite series are continuously zoned from 18–0% TiO_2 from cores to margins with the majority of crystals being zoned over the range 13–9% TiO_2. These spinels (Table 1, analyses 6-9) are characteristically poor in Cr and Al and rich in Ti and Fe relative to the earlier titaniferous magnesian chromites.

Spinel Crystallization

The development of the spinel assemblage, as evidenced by the textural and chemical data, is considered to be as follows: (1) Formation of aluminous magnesian chromite phenocrysts (Rimsaite 1971) prior to intrusion of the dyke. (2) Rounding of these chromites and other phenocrysts during fluidized intrusion. (3) Post-fluidization crystallization of discrete euhedral crystals of titaniferous magnesian chromite, accompanied by mantling of earlier aluminous magnesian chromite by titaniferous magnesian chromite. The latter become richer in Ti as crystallization progresses. (4) Termination of titaniferous magnesian chromite precipitation in response to changing physicochemical conditions in the magma. (5) Crystallization of magnesian ulvöspinel–magnetite as discrete euhedral crystals and as mantles on preexisting spinels. (6) Magnesian ulvöspinels evolve towards pure magnetite. (7) Spinel crystallization ceases in response to the changing composition of the magma. (8) Resorption of spinels in the residual fluids which crystallized to form the serpentine- and carbonate-rich groundmass.

Spinel Compositional Variations in Micaceous Kimberlites

Published compositional data for spinels from micaceous kimberlites exist only for the Tunraq micaceous kimberlite (Mitchell 1977, 1978a), a multiple intrusion within the Somerset Island kimberlite province of Arctic Canada. In this micaceous kimberlite two spinel crystallization trends are evident: (1) A trend from titaniferous magnesian chromite to magnesian ulvöspinel with no Ti-free magnetite formation, *i.e.*, a Ti enrichment trend (Trend T1, Fig. 1). (2) A trend from titaniferous magnesian chromite to titaniferous chromite to Ti-free magnetite with no magnesian ulvöspinel formation, *i.e.*, a magnesium depletion trend (Trend T2, Fig. 1). Both trends originate from the same titaniferous magnesian chromite composition, the initiation of trend T2 being considered to be due to the crystallization of abundant titaniferous phlogopite (Mitchell 1977, 1978a).

The Upper Canada mine micaceous kimberlite is not analogous to the Tunraq micaceous kimberlite as the spinels show features of both Tunraq trends, *i.e.*, the initial Mg depletion along the prism axis, the formation of magnesian ulvöspinel and pure Ti-free magnetite (Trend UC, Fig. 1). Ulvöspinels in the Upper Canada mine are richer in Fe and Ti than those at Tunraq; the majority of the titaniferous magnesian chromites are richer in Fe than their Tunraq counterparts. The two micaceous kimberlites are similar in the apparent rarity of pre-fluidization aluminous magnesian chromite.

Comparison with Kimberlite Spinels

Spinels from kimberlites resemble those from micaceous kimberlite in the wide compositional range and similar evolutionary trends of Ti and Fe enrichment coupled with high Mg contents (Fig. 1). The Upper Canada mine spinel assemblage is very similar to that of the Peuyuk, Korvik and Selatiavak kimberlites (Mitchell & Clarke 1976) in which titaniferous magnesian aluminous chromites are mantled by magnesian ulvöspinel–magnetites. The major difference is that spinels in the micaceous kimberlites are depleted in Al relative to spinels of similar Ti content in kimberlite: the earliest post-fluidization spinels in micaceous kimberlites contains

5–10 mol.% $MgAl_2O_4$ (Upper Canada, Tunraq), whereas those in kimberlite contain 13-17% mol.% $MgAl_2O_4$ (Peuyuk, Elwin Bay: Mitchell & Clarke 1976, Mitchell 1978b). The paucity of aluminous magnesian chromite typically containing 25–60% $MgAl_2O_4$ is a further indication of the overall Al depletion.

Conclusions

1. Micaceous kimberlites and kimberlites are characterized by the presence of spinels rich in Ti and Mg, *e.g.*, titaniferous magnesian chromites and spinels rich in magnesian ulvöspinel.
2. Spinels in micaceous kimberlites are deficient in Al relative to spinels in kimberlites.
3. Kimberlitic intrusions are characterized by an overall similarity of spinel compositional trends but each intrusion contains a unique spinel assemblage; where multiple intrusion occurs each phase of the intrusion contains a unique spinel assemblage. For example, at the Upper Canada mine, aluminous magnesian chromite→titaniferous magnesian chromite→ magnesian ulvöspinel→magnetite; at Elwin Bay, aluminous magnesian chromite→titaniferous magnesian aluminous chromite→magnetite (Mitchell 1978b); at Peuyuk A, aluminous magnesian chromite→titaniferous magnesian aluminous chromite; at Peuyuk C, aluminous magnesian chromite→titaniferous magnesian aluminous chromite → magnesian ulvöspinel → magnetite (Mitchell & Clarke 1976).

The above observations are as yet impossible to explain completely. The overall similarities must result from similarities in the process of magma genesis of each kimberlite within the mantle and it is upon these that the unique post-fluidization spinel assemblage is imposed by the vagaries of crystallization of individual batches of magma at high crustal levels. The initial trend to either kimberlite or micaceous kimberlite is probably induced in the mantle and this trend is merely emphasized by low-pressure differentiation, as the pre-fluidization aluminous liquidus phases differ greatly in relative abundance. Kimberlite crystallizes aluminous magnesian chromites with minor phlogopite whereas micaceous kimberlite crystallizes abundant phlogopite with rare aluminous magnesian chromite. This bulk compositional effect is undoubtedly due to different degrees of partial melting of the mantle source or to different amounts of high-pressure differentiation involving aluminous phases such as garnet and possible primary mantle phlogopite, or both. This conclusion implies that micaceous kimberlites and kimberlites might be distinct magma types and not petrographic varieties of a single magma type.

From the above discussion it is evident that the evolution of the post-fluidization spinel assemblage will be dependent upon whether the initial magma is kimberlite or micaceous kimberlite. Individual kimberlitic trends developed are dependent upon (1) whether phlogopite remains a liquidus phase (Upper Canada, Elwin) after fluidization or not (Tunraq, Peuyuk); (2) the amount and nature of other Ti-bearing phases that crystallize contemporaneously, *e.g.*, perovskite; (3) local fluid compositions and the temperature-oxygen fugacity path followed during crystallization, and (4) extent of resorption of pre-existing spinels.

Combinations of the above factors can lead to a myriad of possible crystallization paths and it is therefore not unexpected that individual kimberlites differ in their spinel assemblages. As yet insufficient data are available to determine whether any particular crystallization-resorption paths are followed in preference to others and which paths are due to the influence of particular combination of the above factors. Further studies of Canadian and South African kimberlites will help to clarify some of these problems.

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