

## **A pyrope-spinel (alkremite) xenolith from Moses Rock Dike: first known North American occurrence**

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### **Abstract**

Pink pyrope garnet (Py 80 Gr 8 Alm 12) and black Cr-poor spinel ( $Mg/[Mg + Fe] = 0.84$ ;  $Cr_2O_3 = 10$  wt.%) occur in subequal amounts in a 3.5 cm alkremite xenolith from Moses Rock Dike, San Juan County, Utah, a kimberlite pipe. Primary garnet and spinel are more magnesian than these phases in similar xenoliths from kimberlite pipes in South Africa and the U.S.S.R. Subsequent alteration and hydration along cracks and grain boundaries produced secondary minerals that account for less than 5 percent of the rock. The presence of iron-bearing kornepupine in the secondary mineral assemblage suggests that alteration occurred at elevated temperatures and crustal pressures.

### **Introduction**

An unusual xenolith from Moses Rock Dike, a kimberlite pipe on the southeastern edge of Monument Valley, Utah (McGetchin, 1968; McGetchin and Silver, 1972), contains pink, gem quality pyrope-rich garnet and black spinel as primary phases. Unlike other deep-seated inclusions (such as peridotite and eclogite) which are typically extensively altered to greenschist facies minerals at this locality, the garnet-spinel "alkremite" (a mnemonic name of Russian origin for a rock enriched in Al, Si, and Mg (Ponomarenko, 1975)), contains less than five percent of secondary minerals. The secondary minerals include kornepupine (Seifert, 1975), Mg-rich chlorite, zoned, pink Cr-bearing corundum, garnet with more calcium and less magnesium, Cr-enriched spinel and Fe-Ni sulfide.

### **Occurrence and associations**

The primary garnet (G 1) is anhedral, equant and colorless in thin-section. It has an average grain size of 5 mm. The primary spinel (Sp 1) is anhedral,

brown in thin-section, and averages 10 mm in grain size (Fig. 1). A striking feature of the spinel is the presence of finely exsolved rutile plates on (111) planes (Fig. 2). Extremely small euhedral inclusions, possibly of corundum, occur in spinel as well. The garnet, in contrast, is inclusion-free.

The formation of secondary minerals has occurred along cracks and recrystallized spinel margins. Tan to colorless Mg-rich chlorite is the most abundant secondary phase. It is effectively isolated from primary spinel either by a rim of secondary dark brown, Cr-spinel (Sp 2), or by bladed, colorless kornepupine which grows perpendicular to Sp 1 edges (Fig. 3). Spinel 2 varies in bulk composition particularly with respect to titanium and chromium. These variations simply may reflect the composition of adjacent phases. In this paper, spinel 2a is the more chromium-rich variety, while spinel 2b is the more titanium-rich variety. Pale to deep pink subhedral corundum, zoned with respect to Cr, occurs less frequently as rims and crack fillings in Sp 1 (Fig. 3). Corundum is always found to be intergrown with grains of Sp 2a and thus separates Sp 1 from chlorite along grain

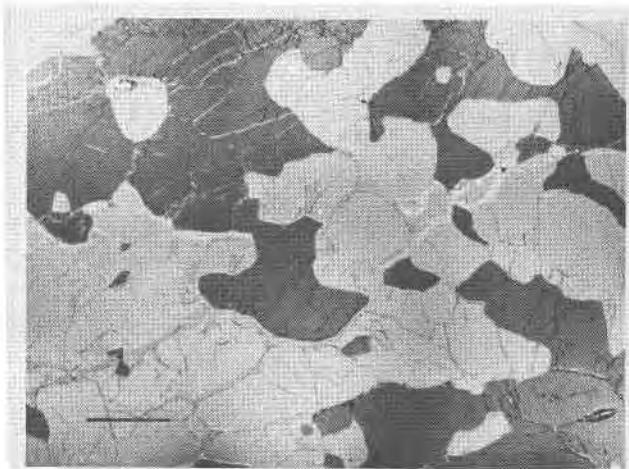


Fig. 1. Textural relations in alkremite. Light material (arrows) along grain boundaries is the alteration assemblage that includes chlorite, kornepupine, secondary garnet, corundum and secondary spinel. Rutile exsolution lamellae can be seen in several spinel grains in the field of view. The texture seen in this photomicrograph is similar to that illustrated by Nixon *et al.*, (1978). Scale bar is 2 mm. 1 = primary spinel; 2 = primary garnet.

boundaries (see analysis Sp 2a, Table 1). A Ti-rich type of secondary spinel (Sp 2b) is less abundant and may represent some involvement of rutile-bearing Sp 1 in the secondary reaction. Subhedral to euhedral grossularitic garnet (G 2) occurs in association with chlorite and has been observed growing on Cr-spinel (Sp 2b) rims. Fe-Ni sulfides occur as blebs along cracks and grain boundaries in association with chlorite. Representative electron microprobe analyses of primary and secondary phases are given in Table 1.



Fig. 2. Rutile exsolution (light, parallel bands) in primary spinel, which is rimmed by kornepupine, chlorite and secondary spinel. Note sealed cracks which cut exsolution lamellae (arrows). These cracks contain secondary spinel, chlorite, corundum and/or iron nickel sulfides. Crossed polars. Scale bar is 0.20 mm. 1 = primary spinel; 2 = primary garnet.

## Discussion

Other alkremite occurrences have been reported from kimberlites in South Africa and the U.S.S.R. (Nixon *et al.*, 1978). These samples range in size from mm-size chips to nodules of tens of centimeters in maximum dimension (Ponomarenko, 1975; Nixon *et al.*, 1978). The Moses Rock alkremite is about 3.5 cm in maximum dimension. The other alkremites differ from the Moses Rock sample by having late stage amphibole, diopside, phlogopite, serpentine, and carbonate and by occasionally exhibiting inclusions of olivine and spinel in garnet (Nixon *et al.*, 1978; Ponomarenko, 1975). Cumulus textures have been observed in some samples (Nixon *et al.*, 1978), however, the texture of the Moses Rock alkremite is interlobate granoblastic and definitely metamorphic in nature (Moore, 1970). The Mg content in pyrope from the Moses Rock alkremite is one of the highest reported from this rock type. In addition, it is one of the most pyrope-rich garnets analyzed from Moses Rock (McGetchin, 1968).

Since the alkremite xenolith in question exhibits a metamorphic texture, its origin could be other than cumulate. Zoned and unzoned stringers of pyroxenite in the ultramafic complex at Ariège, France (Conquéré, 1977) contain spinel with composition identical to that of the spinel in the alkremite from

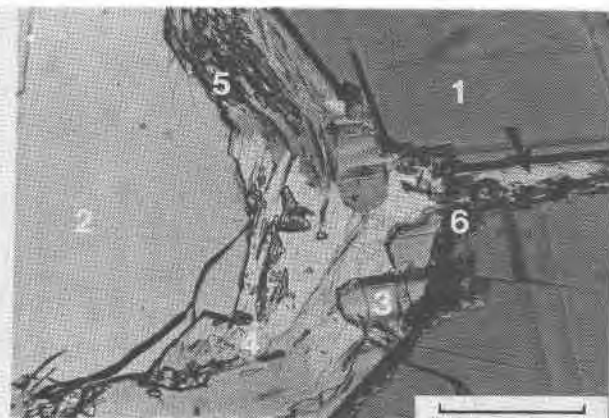


Fig. 3. Detail of bladed kornepupine growing perpendicularly to margin of primary spinel. Note that kornepupine or secondary spinel effectively isolates primary spinel from chlorite. Dark mottled grains of spinel 2b are seen along contact between kornepupine and primary spinel and between chlorite and primary spinel in the right-hand portion of this photomicrograph. Secondary grossularitic garnet is always associated with chlorite but occasionally is observed growing adjacent to kornepupine or to primary garnet. Transmitted light photomicrograph. Plane polarized light. Scale bar is 0.20 mm. 1 = primary spinel; 2 = primary garnet; 3 = kornepupine; 4 = chlorite; 5 = secondary garnet; 6 = secondary Cr-rich spinel; corundum (arrow).

Table 1. Compositions of primary and secondary minerals in the Moses Rock alkremite\*

	G 1	Sp 1	G 2	Sp 2a	Sp 2b	Korn	Chl	Cor
SiO <sub>2</sub>	41.93	0.0	41.46	0.0	0.0	27.38	29.86	0.0
TiO <sub>2</sub>	0.0	0.0	0.07	0.0	7.0	0.03	0.0	0.0
Al <sub>2</sub> O <sub>3</sub>	24.29	61.06	22.73	49.30	58.17	44.33	22.66	96.18
Cr <sub>2</sub> O <sub>3</sub>	0.53	8.93	0.75	20.45	9.13	1.71	0.82	3.24
FeO	6.50	7.63	7.30	9.91	8.20	4.07	1.62	0.64
MnO	0.20	0.13	0.51	0.34	0.0	0.04	0.0	0.0
MgO	23.38	22.15	13.75	19.54	16.98	16.25	32.73	0.19
CaO	3.13	0.0	14.43	0.0	0.0	0.0	0.0	0.0
NiO	0.0	0.0	0.02	0.23	0.34	0.06	0.34	0.0
Total	99.96	99.90	101.02	99.77	99.82	93.83	88.03	100.25
Oxygen Basis	12	4	12	4	4	†	14	3
Si	2.937	0.0	2.984	0.0	0.0	1.008	2.760	0.0
Al	2.003	1.813	1.928	1.553	1.752	1.924	2.470	1.943
Ti	0.0	0.0	0.002	0.0	0.125	0.001	0.0	0.0
Cr	0.028	0.177	0.042	0.431	0.184	0.050	0.060	0.044
Fe	0.380	0.160	0.439	0.221	0.175	0.124	0.125	0.009
Mn	0.01	0.002	0.029	0.007	0.0	0.004	0.0	0.0
Mg	2.439	0.832	1.474	0.778	0.646	0.892	4.514	0.0
Ca	0.234	0.0	1.111	0.0	0.0	0.0	0.0	0.0
Ni	0.0	0.008	0.0	0.004	0.006	0.001	0.024	0.0
Total	8.031	2.992	8.009	2.994	2.888	4.004	9.953	1.996

\*Electron microprobe analyses of major and minor phases in alkremite in terms of oxide weight percent; structural formula calculations for each phase are included. G 1 = primary garnet; Sp 1 = primary spinel; G 2 = secondary grossularitic garnet; Sp 2a = secondary Cr-rich spinel; Sp 2b = secondary Ti-rich spinel; Korn = kornierupine; Chl = secondary chlorite; Cor = corundum. Analyses represent average compositions of major and minor phases.

†Formula normalized to 4 cations.

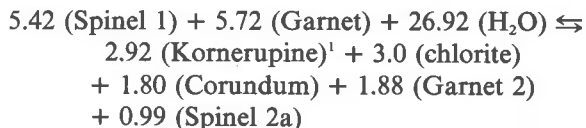
Moses Rock. In addition, the pyroxenites at Ariège contain abundant pyrope garnet associated with spinel and variable amounts of recrystallized pyroxenite along the intrusive contacts. Although the garnet composition in the alkremite xenolith is more pyrope than that of garnet in the pyroxenites, it is entirely possible that the alkremite could have been produced by a similar reaction between pyroxenite melt and peridotite in the upper mantle beneath Moses Rock Dike.

Of particular interest in the alkremite from Moses Rock is the presence of kornierupine, a hydrated magnesium-aluminum silicate, among the secondary minerals (see Table 1 for analyses). Experimental results on the stability of kornierupine (Seifert, 1975) suggest that the lower stability limit of Mg-kornier-

upine in the system MgO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O (MAS-H<sub>2</sub>O) is 4.5 kbar and 735°C. However, reactions involving the formation of kornierupine in equilibrium with chlorite, corundum and spinel, the observed secondary mineral assemblage in the alkremite, are bracketed at pressures at or above 5.5 kbar and at temperatures at or above 760°C in the system MAS-H<sub>2</sub>O. The stable assemblages bracketed by these *P-T* conditions include the mineral pairs corundum-kornierupine, chlorite-kornierupine and chlorite-spinel. Natural occurrences of kornierupine are found primarily in granulite facies metapelites. Seifert (1975) has estimated conditions necessary for the formation of these naturally occurring kornierupine-bearing granulites to be at least 9 kbar. However, because the effects of adding FeO, Na<sub>2</sub>O and B to the MAS-H<sub>2</sub>O

system are unknown, the equilibrium pressure of formation of kornepine in the xenolithic assemblage could be less than 9 kbar and possibly as low as 3–4 kbar.

The secondary mineral assemblage can be explained by the breakdown of the primary mineral assemblage in the presence of a limited amount of H<sub>2</sub>O-rich fluid. An approximate chemical balance, determined by least squares methods using the mineral formulae given in Table 1, is given by:



The reaction was apparently isochemical for major elements although minor elements such as nickel, chrome, and copper appear to have been introduced (Fig. 4). The presence of these additional elements is manifested by the occurrence of pentlandite and chalcopyrite as accessory phases found only in chlorite-rich reaction zones in grain boundary cracks. The reaction balanced well using the simple system (MgO)–(SiO<sub>2</sub>)–(Al<sub>2</sub>O<sub>3</sub>) or by using a combination of major and minor elements such as (MgO + FeO)–(Al<sub>2</sub>O<sub>3</sub> + Cr<sub>2</sub>O<sub>3</sub>).

It should be noted that the proportions of the primary phases that result from this calculation approximates the volumetric proportions of primary garnet and spinel in the xenolith; the proportions of secondary phases with respect to one another differ only slightly from those observed in the thin section.

### Conclusions

In summary, the occurrence of an alkremite xenolith at Moses Rock Dike is a further indication of a complex petrogenetic evolution for the mantle beneath this locality. The primary phases in the alkremite formed at mantle depths, possibly as cumulates, but more likely as a result of metasomatic reactions at intrusive contacts between pyroxenite melt and peridotite. Later alteration along cracks within minerals and cracks associated with grain boundaries occurred through reaction with hydrous kimberlitic fluids ostensibly at elevated temperatures at deep crustal pressures.

<sup>1</sup> Water assumed to be 2 (OH) per formula unit following Seifert (1975, p. 59).

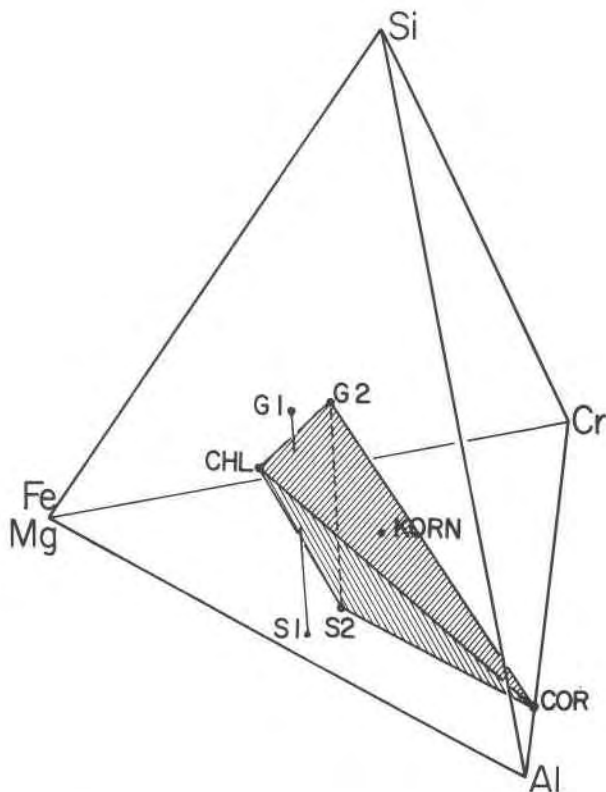


Fig. 4. Graphical representation of the mass balance equation given in the text. Plot is in atomic weight percent showing the relationship of the chemistry of the primary phases to secondary phases growing along cracks and grain boundaries. Note that the bulk composition of the rock lies halfway between primary spinel (S 1) and primary garnet (G 1) close to the chlorite corner of the four phase volume represented by chlorite (Chl), secondary spinel (S 2), secondary garnet (G 2), and corundum (Cor). In this plot, the reaction is modelled as a simple grain boundary reaction. The formation of alteration products requires the introduction of H<sub>2</sub>O to the primary assemblage.

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