

Alkremite, garnetite and eclogite xenoliths from Bellsbank and Jagersfontein, South Africa

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Abstract

Alkremites (garnet–spinel–corundum), garnetites, and eclogites (garnet–clinopyroxene) from Bellsbank and Jagersfontein kimberlites show textural and mineralogical evidence of crystal fractionation from evolving aluminous magma: *e.g.*, Ca and P increase in garnet as Cr and Ti decrease in most spinels. Detailed variations of Cr and Ti in garnet and spinel require several parental magmas. Corundum in alkremites contains 0.1–0.2 wt.% TiO₂, 0.2–0.5 Cr₂O₃, and 0.5–1.2 Fe₂O₃. Mica (0.7–3.4 TiO₂) in grain boundaries is secondary. Foundering or subduction of Al-rich sediments (perhaps chloritized ocean crust) may have generated local Al enrichment in the upper mantle to provide diverse source regions for alkremite magmas.

Introduction

Alkremite xenoliths composed of flesh-colored pyrope-rich garnet and spinel occur rarely in kimberlites (S. Africa, Mathias *et al.*, 1970; Nixon *et al.*, 1978; U.S.S.R., Ponomarenko, 1975; U.S.A., Padovani and Tracy, 1981). Two models for their origin are: early accumulation from an aluminous melt at about 75 km depth prior to clinopyroxene crystallization characteristic of abundant eclogites (Nixon *et al.*, 1978), and reaction between peridotite and clinopyroxenitic magma (Padovani and Tracy, 1981). We present chemical data for alkremite and garnet xenoliths from Bellsbank and Jagersfontein, South Africa, and make comparisons with Bellsbank eclogites (Bishop *et al.*, 1978; Carswell *et al.*, 1981).

Samples and petrography

Bellsbank

Specimen BD1830 (thin sections A and B) is a rounded alkremite xenolith 4 cm across with 10% dark-green spinel (3 mm) interstitial to a mosaic of flesh-colored garnets (5 mm). Marginal inclusions of corundum (0.5 mm) in spinel are adjacent to grain-boundary alteration. Specimens BD2033A (1 cm) and BD2033B (2 cm) are monomineralic garnet rocks (5 mm grain size) with grain boundaries picked out by secondary mica; BD2033B is

sheared with pyrite and calcite in veins, and it contains a single opaque grain (2 mm) of altered sulfide. Eclogite BD2033C (1.5 cm) has similar amounts of coarse garnet and interstitial clinopyroxene, which are altered next to grain-boundary phlogopite. Flaky alteration of garnet next to phlogopite in BD2033A, B and C is apparently responsible for the unusual pink color; this is distinctive compared to the flesh and honey colors respectively of garnets from alkremites and common Bellsbank eclogites.

Jagersfontein

Three rounded xenoliths (3–4 cm across) of alkremite (BD3737, A1, A2, E) are composed of coarse flesh-colored garnet (5 mm, 70%), interstitial dark-green spinel (5 mm, 25%) and violet prismatic corundum (3 mm, 5–10%, lamellar twinning). The corundum forms a lineated fabric, and occurs interstitial to, or more commonly enclosed by, garnet and spinel. Spinel rims some corundum grains. Alkremites F and G lack corundum, and are texturally similar to 1830A,B. Alkremite C (3 cm) contains spinel (1 cm, 70%), garnet (25%) and patches of mica (5%). Xenolith B is essentially a garnetite, with euhedral garnets (5 mm) and rare spinel outlined by grain boundary alteration; however, most spinel occurs as euhedra (<1 mm) associated with grain-boundary mica and calcite. Secondary veins of calcite pervade all the Jagersfontein samples.

Table 1. Electron microprobe analyses of Bellsbank samples

	BD2033A		BD2033B		BD2033C			BD1830A				BD1830B		
	gt	mica ¹	gt	gt	cpx	mica ²	gt	sp	cor	mica ³	gt	sp	cor	
P ₂ O ₅	0.016	-	0.019	0.032	-	-	0.086	nd	nd	-	0.078	nd	nd	
SiO ₂	42.2	39.3	42.3	42.6	56.2	38.2	41.4	0.07	0.09	36.5	41.7	0.05	0.04	
TiO ₂	0.05	1.02	0.01	0.04	0.06	0.98	0.10	0.12	0.19	0.7	0.11	0.08	0.08	
Al ₂ O ₃	22.8	16.3	22.4	22.3	7.6	18.3	23.4	65.4	99.0	21.2	23.5	65.3	98.2	
Cr ₂ O ₃	0.36	0.48	0.34	0.22	0.23	0.17	0.06	0.46	0.44	-	0.05	0.49	0.17	
FeO _T	11.3	6.6	9.9	10.0	1.1	7.3	10.0	13.5	1.08	7.4	9.9	13.3	0.94	
MnO	0.28	0.06	0.28	0.22	0.01	0.10	0.20	0.04	nd	-	0.21	0.06	nd	
MgO	20.3	20.2	19.4	17.2	13.3	20.2	13.2	20.5	0.12	19.2	13.0	20.4	0.08	
NiO	nd	0.06	nd	nd	0.14	0.05	nd	0.65	nd	-	nd	0.67	0.04	
ZnO	nd	na	nd	nd	na	na	nd	0.10	nd	na	nd	0.07	nd	
CaO	3.5	0.03	5.6	8.7	17.9	0.03	12.1	nd	nd	-	12.1	nd	nd	
Na ₂ O	0.04	0.18	0.03	0.03	3.92	0.40	0.03	nd	nd	-	0.04	nd	nd	
K ₂ O	nd	9.9	nd	nd	nd	10.3	nd	nd	nd	10.1	nd	nd	nd	
Sum	100.857	94.38	100.291	100.542	100.46	96.44	100.576	100.19	100.92	95.1	100.688	100.35	99.55	

One, two, and three decimal places represent energy-dispersive, routine wavelength-dispersive and special wavelength-dispersive analyses, respectively. na not analyzed. nd not detected. Micras: analysis #1 includes BaO 0.12, Rb₂O 0.05, F nd, Cl 0.08; analysis #2 0.33, 0.03, nd, 0.05; analysis #3 by R.L. Hervig. Iron in corundum is probably ferric: multiply FeO by 1.11.

All samples show varying degrees of annealing, with a development of polygonal mosaic texture for garnets. However, the frequent occurrence of euhedral or subhedral spinel, and of euhedral prismatic corundum, suggests an igneous origin. The spinel rims around some corundum crystals suggest a possible reaction with liquid, and could not have formed by subsolidus reaction between corundum and the adjacent garnet. Although somewhat ambiguous, the textures suggest an origin as cumulates dominated by garnet, but with subsequent metamorphism.

Chemical data

Electron microprobe analyses (Tables 1 and 2) used a combination of energy- and wavelength-dispersive meth-

ods (Dawson and Smith, 1977). A ZnO standard was used for Zn in spinel, and a Ca₂P₂O₇ standard for P. The interference on PK α by second-order CaK β ₁ was checked by careful scanning at 0.005 \AA intervals. All minerals are essentially homogeneous based on analyses at the center and margin of grains. High totals for garnet and spinel merely result from inadequacy of the correction procedures, and atomic ratios should be satisfactory.

Figure 1 shows the Ca-Fe-Mg ratios of the present and related garnets. All garnets from alkremites fall in a band with generally low Fe (6-21 atomic %) and a considerable range of Ca from 3 to 37 atomic %. The Bellsbank garnets from Nixon *et al.* (1978) and Table 1 form a tight trend from Ca₉Mg₇₀Fe₂₁ (2033A) to Ca₃₁Mg₅₀Fe₁₉ (1830A,B),

Table 2. Electron microprobe analyses of Jagersfontein samples

	BD 3737C			BD3737G			BD3737A2				BD3737E			BD3737F		BD3737A1			BD3737B	
	gt	sp	mica	gt	sp	serp	gt	sp	co	mica	gt	sp	co	gt	sp	gt	sp	co	gt	sp
P ₂ O ₅	0.051	nd	nd	0.037	nd		0.055	nd	nd	nd	0.048	nd	nd	0.052	nd	0.058	nd	nd	0.062	nd
SiO ₂	41.3	0.24	37.4	41.5	0.4	32.8	41.2	0.168	0.01	35.9	41.4	0.07	0.06	40.9	0.11	40.4	0.05	0.06	40.7	0.08
TiO ₂	0.149	0.278	0.96	0.198	0.196		0.222	0.144	0.210	3.40	0.222	0.100	0.198	0.189	0.122	0.201	0.131	0.163	0.272	0.116
Al ₂ O ₃	24.2	65.8	18.1	24.3	66.0	16.0	24.5	66.7	97.8	20.8	24.6	67.8	97.8	24.2	66.9	24.1	66.6	97.7	23.6	63.0
Cr ₂ O ₃	0.133	1.748	0.101	0.054	0.82		0.127	0.972	0.458	0.113	0.137	1.00	0.417	0.061	0.552	0.061	0.454	0.178	0.078	0.577
FeO _T	8.3	10.6	3.7	9.8	12.7	13.0	8.0	10.0	0.67	5.8	7.8	9.7	0.54	8.8	11.0	10.6	13.7	0.83	8.9	16.5
MnO	0.613	0.121	0.02	0.326	0.06		0.316	0.074	nd	0.02	0.300	0.06	nd	0.258	0.05	0.226	0.053	nd	0.157	0.081
MgO	19.0	22.4	23.0	17.2	21.6	24.3	17.0	21.9	0.13	18.8	17.1	22.9	0.19	15.9	22.1	14.5	20.2	0.12	14.6	20.2
NiO	nd	0.19	0.08	nd	0.32		nd	0.17	nd	nd	nd	0.21	nd	nd	0.44	nd	0.38	nd	nd	nd
ZnO	na	0.228	na	na	0.201		na	0.253	na	na	na	0.268	na	na	0.280	na	0.281	na	na	0.124
CaO	6.5	nd	nd	7.9	nd	0.3	9.4	nd	0.06	0.10	9.4	nd	0.03	10.3	nd	10.2	nd	0.03	12.0	nd
Na ₂ O	0.070	nd	0.062	0.03	nd		0.051	nd	nd	0.461	0.04	nd	nd	0.02	nd	0.10	nd	nd	0.04	nd
K ₂ O	nd	nd	10.7	nd	nd		nd	nd	nd	9.8	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sum	100.316	101.603	94.123	101.345	102.295	86.4	100.871	100.379	99.538	95.194	101.007	102.108	99.235	100.680	101.273	100.446	101.852	99.081	100.369	100.678

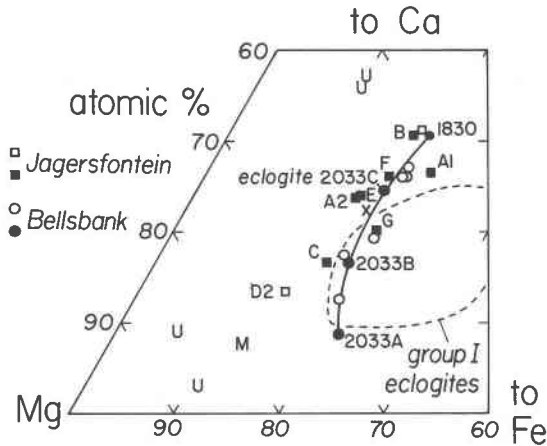


Fig. 1. Ca-Mg-Fe plot of garnets from alkremites, garnetites and eclogites. Open and filled symbols for Bellsbank and Jagersfontein xenoliths are from Nixon *et al.* (1978) and Tables 1 and 2, respectively. The cross is for a Roberts Victor specimen (Nixon *et al.*), U is for Udachnaya, U.S.S.R. (Ponomarenko, 1975), and M for Moses Rock, Utah (Padovani and Tracy, 1981). The field of Group I eclogites from Roberts Victor (MacGregor and Carter, 1970) is outlined. Specimen 1988 (Nixon *et al.*) is omitted because it contains olivine.

and the garnets from other S. African alkremites scatter considerably about the Bellsbank trend, but not as far as the specimens from U.S.A. and U.S.S.R. Note that two of the Bellsbank garnets (2033A,B) are from garnetites, and one 2033C is from an eclogite.

Figure 2 shows selected minor elements in garnet and spinel plotted versus CaO in garnet in order to test the model of crystal-liquid fractionation (Nixon *et al.*, 1978). This model is supported by the textural evidence, but chemical evidence might be complicated by sub-solidus annealing. The overall increase of P_2O_5 in garnet for the specimens in Tables 1 and 2 is consistent with crystal fractionation from early garnets low in Ca and P to late ones rich in these elements. This sequence is confirmed in general by the decrease of Cr in coexisting spinel, but spinels of alkremites 295, 524 and 526 have anomalously high Cr with respect to the spinels from the other S. African alkremites. Associated garnets of these three Bellsbank alkremites also tend to be rich in Cr with respect to the poorly defined trend for the other alkremites; in addition, the garnet from alkremite D2 (Jagersfontein) has higher Cr than garnets from an alkremite and a garnetite from Bellsbank with similar Ca, although the Ti contents in the D2 garnet and spinel fall close to general trends for alkremites. Furthermore, the garnets from two garnetites (2033A,B) and an eclogite (C) from Bellsbank have lower Ti than garnets from alkremites. Sub-solidus annealing cannot account for deviations from the main trend, shown very tentatively by dashed lines, and further specimens should be collected and studied to check whether the anomalous specimens are members of distinct chemical series.

The spinel analyses in Tables 1 and 2 are similar to earlier analyses for alkremitic spinels. Nickel is higher (NiO 0.66 wt.%) in the Bellsbank spinels (1830A,B) than in the Jagersfontein ones (0.17–0.44), but analyses of Nixon *et al.* (1978) show an opposite relation (Bellsbank 0.25, 0.23; Jagersfontein 0.68). Analyses for zinc show a similar confusing relation, and neither element can be correlated with any major element in either spinel or garnet.

The corundums from the alkremites carry significant TiO_2 (0.08–0.21 wt.%), Cr_2O_3 (0.17–0.46), Fe_2O_3 (0.5–1.2) and MgO (0.08–0.19), and there is no obvious correlation with any other chemical parameter, even for the unambiguously primary corundums of the Jagersfontein alkremites. These ranges of Fe_2O_3 and Cr_2O_3 match those of secondary corundums in Bellsbank eclogites more closely than those of primary texture (Carswell *et al.*, 1981).

Clinopyroxene of eclogite 2033C is lower in TiO_2 and higher in Cr_2O_3 than the more omphacitic pyroxenes of Bellsbank kyanite eclogites (Carswell *et al.*, 1981). In general, the garnet of these kyanite eclogites is less pyropic than the garnets of 2033A, B and C. The major elements of garnets and clinopyroxenes from Roberts Victor and Bellsbank eclogites (Bishop *et al.*, 1978) are similar to those for 2033C, and although there is a broad similarity between major elements in garnets of these eclogites with those of alkremites (Dawson, 1980, p. 188), eclogitic garnets tend to be richer in Cr and Ti. There are close matches for Ti and Cr in garnets from alkremites

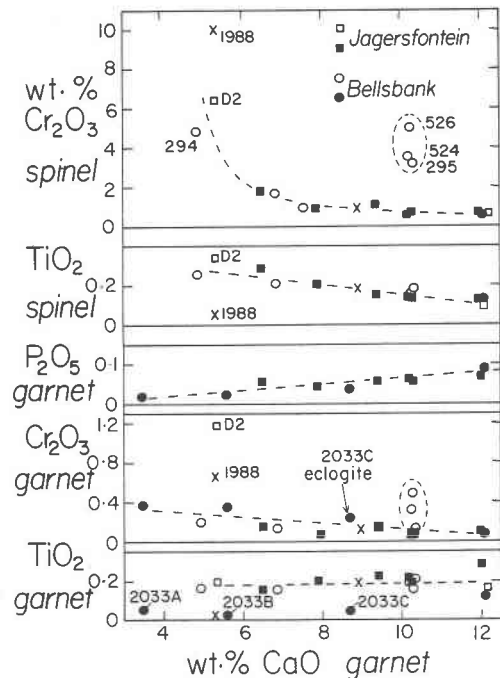


Fig. 2. Minor-element trends for spinel and garnet. Symbols as in Fig. 1.

with garnets from Roberts Victor amphibole eclogite 1188 and Bellsbank eclogites 1829/2 and 2031/2,3 (Bishop *et al.*, 1978). Eclogite 2029/1 is also comparable with alkremites because of presence of rare pleonaste grains with 0.06 and 0.26% ZnO; furthermore the pleonastes occur in the grain boundaries very similarly to spinels in the Jagersfontein alkremite 3737B.

Grain-boundary micas have FeO, TiO₂, Cr₂O₃ and BaO similar to those for Fe-rich micas of type II in kimberlite groundmass (Smith *et al.*, 1978, 1979), and penetration of kimberlite into grain-boundary expansion cracks is indicated. Unusually high Al₂O₃ in mica (up to 21 wt.% in 1830A) suggests reaction with the aluminous primary phases, particularly corundum.

Discussion

The cumulate textures and chemical trends of the present samples are consistent with fractional crystallization. Although alkremite xenoliths (Ponomarenko, 1975) are unusual for low Si and high Mg and Al, Nixon *et al.* (1978) showed that only slight enrichment of Mg and Al in the source of the parent liquid is needed for cotectic precipitation of garnet and spinel in the CMAS system at 26 kbar. The textural evidence that corundum crystallized first in the Jagersfontein alkremites indicates the highly-aluminous bulk composition. Rare spinel rims around corundum might suggest a reaction with intercumulus liquid; absence of chemical gradients might result from solid-state annealing.

Alkremites may be closely related to some but not all eclogites. The group I eclogites at Roberts Victor (MacGregor and Carter, 1970) were attributed to crystallization from a liquid, and their garnets overlap slightly in major-element composition with alkremitic garnets (Fig. 1); furthermore, garnet from eclogite 2033C lies in the alkremite trend for Ca-Mg-Fe. Despite this overlap, alkremite xenoliths are rare, and an unusual combination of moderate pressure, high Al and moderate Ca may be required. As crystal-liquid fractionation proceeds in the *pure* CMAS system, spinel reacts with liquid and should not persist into a stage analogous to that in which garnet and clinopyroxene coprecipitate to form most cumulate eclogites (Nixon *et al.*, 1978). Alkremites are too low in CaO and too high in Al₂O₃ to be capable of generating aluminous eclogites (*e.g.*, kyanite eclogites; Green, 1967, Table 1) by sub-solidus reaction, and the aluminous eclogites may represent higher-pressure products of an Al-rich melt which might form alkremites at lower pressure. Further experiments are needed to map out the stability fields in the CMAS system over a range of pressure, and the effects of Fe/Mg and Cr/Al substitutions should be evaluated. In the meantime, the close chemical relationships between garnets of alkremites and eclogites (*e.g.*, Fig. 1) suggests that the factors controlling the crystallization of spinel and clinopyroxene are rather subtle.

Thermobarometry of 2033C from Fe/Mg partition between garnet and clinopyroxene (Ellis and Green, 1979) gives some condition between 1140°C, 26 kbar and 1200°C, 47 kbar, which corresponds to the estimate for kyanite eclogites at Bellsbank (Carswell *et al.*, 1981); also similar is the partitioning of Ti and Cr. Comparison of mineral compositions from Table 1 with those of Bishop *et al.* (1978) and Nixon *et al.* (1978) suggests that: (1) 2033A and B are garnet cumulates from an early magma that had not become enriched in Ti, (2) eclogite 2033C precipitated from a low-Ti magma similar to those for 2029/1 and 2031/1 (Bishop *et al.*, 1978) and (3) alkremite 1830 is more fractionated than the other Bellsbank alkremites, as demonstrated by highest grossular content in its garnet, and lowest Cr in both garnet and spinel.

Finally, the cause of the presumed local Al enrichment of the source regions of alkremitic magmas deserves discussion. Direct survival from the accretion stage of Earth history is unlikely because no meteorite has an appropriate composition; even the refractory inclusions from Type 3 carbonaceous chondrites (Grossman, 1980) are too rich in Ca. Sinking of a dense phase during early melting (Smith, 1982) and subsequent return to the upper mantle by solid-state convection is a second possibility, so long as mixing with peridotitic material does not occur; spinel and corundum are possible dense phases. Perhaps more plausible is foundering or subduction of crust in which alteration and sedimentary processes had produced Al-enrichment. In particular, chlorite in altered oceanic crust (Humphris and Thompson, 1978) may be involved via subduction as a means of generating Mg, Al-rich regions of the upper mantle; relatively unaltered crust would provide source regions for eclogite. However, chlorite could not be involved directly in the source regions of alkremites because its thermal stability is too low (Staudigel and Schreyer, 1977). Incidentally, chlorite is an alteration product of Moses Rock alkremite (Padovani and Tracy, 1981).

It is obvious that systematic study of alkremites from many localities is needed to further test the model of crystal fractionation in various alkremitic magmas. Isotopic studies to determine the crystallization and metamorphic history must take into account the grain-boundary infiltration of kimberlitic material.

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