Lower crustal granulite xenoliths in carbonatite volcanoes of the Western Rift of East Africa

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Abstract

Sporadic small garnet granulite and two-pyroxene granulite xenoliths found in the carbonatite tuffs and lavas near Fort Portal, South West Uganda, are chiefly silica-saturated and rich in Al_2O_3 (> 20 wt. %) and Na_2O (c. 2 to 4 wt. %). Three *REE* patterns are distinguished: *LREE* enriched—*HREE* depleted with a positive Eu anomaly; *LREE* depleted—*HREE* relatively enriched and flat; and *LREE* slightly enriched with a very weak Eu anomaly and high overall *REE*. The xenoliths are considered to represent original basaltic melts and fractional crystallisation products, varying with the dominance of the clinopyroxene, plagioclase or olivine crystallising phase. It is thought that *REE* abundances were established before metamorphism.

The clinopyroxenes are low-jadeitic augites, the orthopyroxenes, aluminous hypersthenes and the garnets, pyrope–almandine with constant grossularite. Plagioclase varies with increasing metamorphic grade from labradorite to andesine-oligoclase. Scapolite (meionite), alkali-feldspar, quartz, mica, amphibole, rutile and apatite are minor phases and some appear to be metasomatic.

Calculated temperatures of metamorphic equilibration range from 580 to 800 °C at pressures > 4 kbar for the two-pyroxene granulites and > 6 kbar for the garnet granulites. A known geophysical discontinuity marking a density change at 16 km in the Western Rift may be due to the presence of two-pyroxene granulite, calculated to become garnet-bearing at depths greater than 23 km. The absence of proven omphacite-bearing eclogite xenoliths (with no plagioclase) indicates that the greatest depth of crustal sampling by the carbonatite in the Fort Portal field is about 25 km which could be the depth of the Moho in this area.

KEYWORDS: lower crustal granulite xenoliths, carbonatite, western rift, East Africa.

Introduction

THE Fort Portal volcanic field, including Kesekere, is one of four areas of Quaternary-Recent maars and tuff cones flanking Mount Ruwenzori in the western branch of the East African rift system. Unlike the other three volcanic fields (Fig. 1) which are dominated by highly potassic, silica-under-saturated tuffs and lavas (Lloyd, 1981) the Fort Portal rocks are carbonatite-rich. The field is dominated by tuffs but there are occasional car-

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bonatite flows and dykes (Fig. 2, Nixon and Hornung, 1973).

The xenolith content of the volcanoes also differs. At Katwe-Kikorongo and Bunyaruguru there are highly metasomatised mantle varieties—mica clinopyroxenites of similar chemistry to the feldspathoidal lavas (Lloyd, 1981) but no recorded lower crustal xenoliths. Within the Fort Portal field there are few deep-seated xenoliths of any kind. However, there are small (1–5 cm) feldspar-bearing garnet granulites mentioned by von Knorring and Du Bois (1961) and which are the subject of this study.
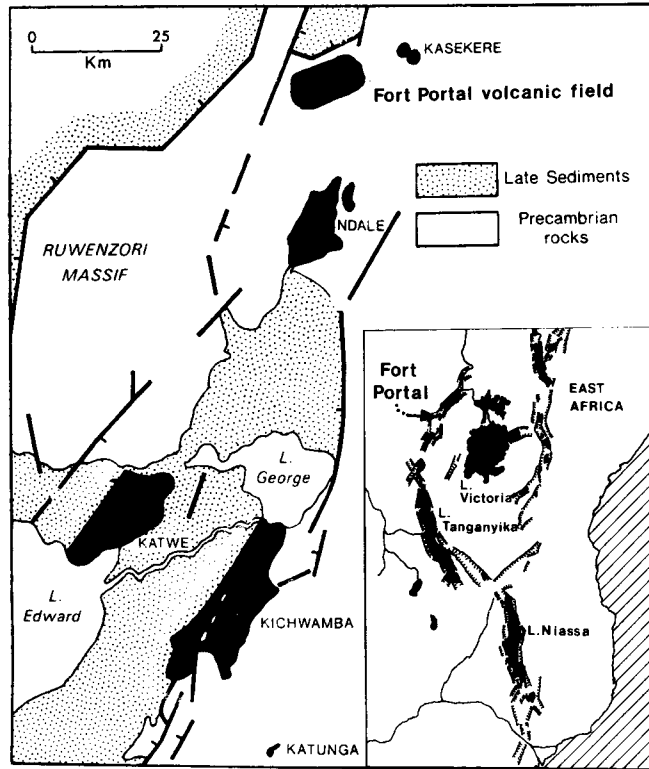
FIG. 1. Part of the Western Rift of the East African rift system showing the volcanic areas (black) near Ruwenzori, in particular the Fort Portal volcanic field. The inset shows the East African rift system.

Similar xenoliths have been described from kimberlites in a high heat-flow environment around the edge of the Kaapvaal Craton in southern Africa (Griffin et al., 1979). Their occurrence here within a rift zone floored by Kibaran (c. 1300 Ma) rocks away from the craton is compatible with previous observations. The high heat flow associated with lithospheric stretching and asthenospheric uprise in African rifts has been well documented (e.g. Fairhead, 1986). Furthermore, a lower crustal granulite layer could be a significant factor in not only modelling the isotopic signatures of the volcanic rocks occurring within the rift, for example to the south at Virunga (Vollmer and Norry, 1983a) but in confirming the existence of the postulated 500 Ma metasomatic event affecting the lithosphere beneath the rift (Vollmer and Norry, 1983b).

Petrography

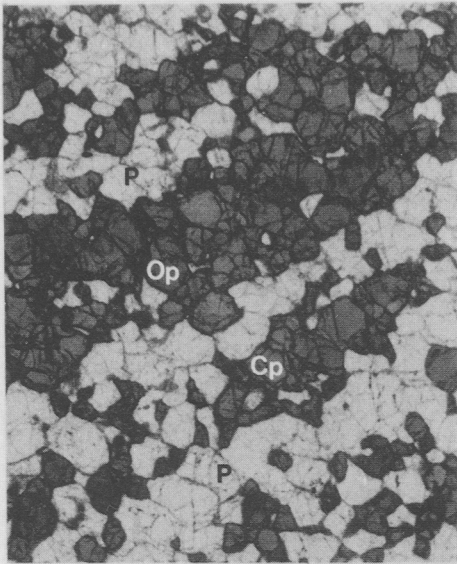Two main petrographic types of granulite can be distinguished: those with garnet (garnet granulites) and those with orthopyroxene (two-pyroxene granulites). In all but two xenoliths, garnet and orthopyroxene are mutually exclusive. Plagioclase and clinopyroxene are the other major minerals and are common to both types of xenolith.

Textures are granoblastic, and major minerals are present in approximately equal proportions (Fig. 3). Grain sizes range from about 0.5 to 2 mm, but PHN 869e is somewhat finer grained (0.2 to 0.5 mm). Pyroxene grains are slightly larger than average in PHN 909a and garnets tend to be slightly larger than other minerals in some garnet granulites.

In general the garnet granulites have an even distribution of phases, though the garnets tend to group in small clusters. However, the two-pyroxene granulites exhibit distinct segregation into pyroxene- and plagioclase-rich layers. This may reflect an original igneous texture.

PHN 909a is unusual in that it contains garnet as two unequally sized porphyroblasts in one part of the xenolith. Both grains are enclosed by clinopyroxene. These garnets are considered to be anomalous on thermometric grounds (see below).

FIG. 2. The Fort Portal carbonatite field modified after Nixon and Hornung (1973), showing the major tuff cones, limits of the tuffs, and granulite xenolith sample locations. Inset: the smaller Kesekere field to the east (see Fig. 1).

Otherwise, the mineral and textural character of this xenolith is the same as the two-pyroxene granulites (Fig. 2). It may be that these garnets, which are much larger than those in the garnet granulites, are relict xenocrysts incorporated from the mantle rocks invaded by the magmatic proto-lith of this xenolith.

There is evidence that some of the xenoliths have suffered shear. Multiple twins in plagioclase are often curved and grains display undulose extinction. Plagioclase and pyroxene can be seen to be recrystallising to a finer grained polycrystalline aggregate within which individual grains show crisp extinction.

Garnets are pale pink to colourless and though usually anhedral, may occasionally develop planar crystal faces. Kelyphitic rims, characteristic of garnets in similar xenolith suites (e.g. Griffin et al., 1979; Rogers, 1977) are ubiquitous. In two xeno-liths the garnets contain small (< 0.05 mm) inclu-sions of clinopyroxene, plagioclase and quartz. The presence of these inclusions may be related to the growth of garnet at the expense of orthopyroxene and plagioclase due to reaction (1), discussed below. The garnets are generally criss-crossed by fractures.

Clinopyroxenes are pale green to colourless and non-pleochroic, with poor crystal form and cleav-age.

Plagioclase is generally fresh. Rod-like inclusions of kyanite or sillimanite occur commonly in the grain margins (cf. Jones et al., 1983). P,T estimates (see below) are compatible with the occurrence of either of these polymorphs. Scapolite also occurs as rare inclusions in the plagioclase.

Orthopyroxene is olive-green with characteristic red-green pleochroism. Trails of inclusions are common and impart a schiller structure.

One of the two xenoliths containing both garnet and orthopyroxene (PHN 869e) also contains minor phases not found in the other xenoliths. They are quartz, alkali feldspar, primary biotite and rare apatite and rutile. Associated micro-textures, ob-served during investigation by electron micro-probe, are suggestive of a metasomatic origin.

Secondary alteration to mica and amphibole is usually present at grain boundaries. Only PHN 869d shows extensive alteration and much of the pyroxene has broken down to mica. Sometimes, as in PHN 869c the alteration can be seen extending across the xenolith section, apparently following some line of weakness or inhomogeneity (see Fig. 3d).

Xenolith composition

Whole-rock major, trace (except Rb) and Rare Earth Element (REE) chemistry of the xenoliths was investigated by Inductively Coupled Plasma Source Spectrometry (I.C.P.) at Kings College, London. Rb was determined on the Atomic Ab-sorption Spectrometer in the Earth Sciences Department at Leeds University, used in emission mode. Major, trace and REE analyses are given in Tables 1 to 3.

Major elements. Like a number of other suites of basic granulite xenoliths (Ehrenberg and Griffin, 1979; Rogers, 1977) the xenoliths in this study have a restricted, basaltic major element chemistry. On

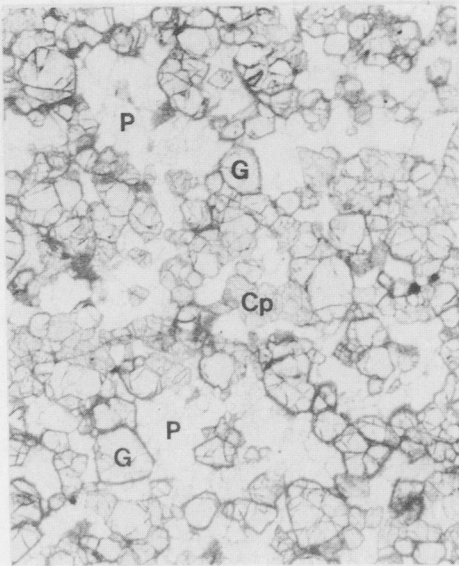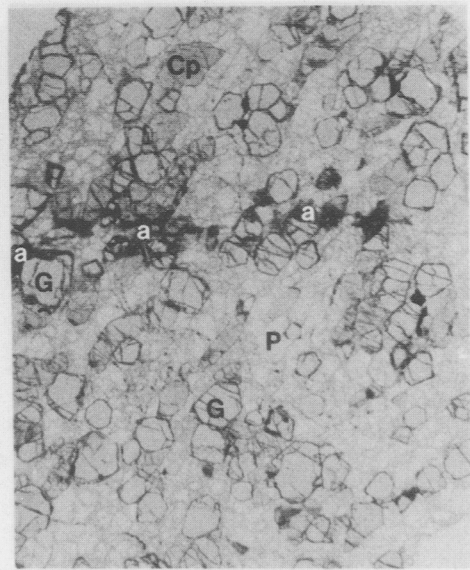## 2-PYROXENE-GRANULITE XENOLITHS

A. PHN 822

B. PHN 909a

GARNET-GRANULITE XENOLITHS

C. PHN 869b

D. PHN 869c

FIG. 3. Textures in two-pyroxene granulites and garnet granulites from the Fort Portal carbonatite field, western Uganda. G, garnet; P, plagioclase; Cp, clinopyroxene; Op, orthopyroxene; a, alteration products including secondary amphibole and mica. All views are 15 mm across.

TABLE 1. Major analyses of granulite xenoliths from
carbonatites, Fort Portal, W. Uganda

PHN	822	869a	869b	869c	869d	869e	881a	909a	916a
SiO_2	51.20	50.10	47.30	50.60	50.30	52.60	50.70	53.00	48.20
TiO_2	0.24	0.36	0.21	0.30	0.62	1.33	0.77	0.25	1.79
Al_2O_3	17.10	16.00	22.10	21.60	16.30	14.10	15.00	17.10	15.20
Fe_2O_3	1.22	1.52	1.13	1.11	1.50	2.24	1.71	1.24	2.27
FeO	6.89	8.58	6.42	6.29	8.50	12.66	9.69	6.99	12.83
MnO	0.10	0.18	0.07	0.11	0.13	0.22	0.19	0.13	0.26
MgO	9.18	9.11	10.10	6.28	8.50	7.23	8.45	8.33	6.21
CaO	11.60	12.00	10.70	10.70	9.79	8.45	11.60	11.80	11.30
Na_2O	2.20	1.99	1.89	3.38	3.89	2.16	2.38	2.61	2.54
K_2O	0.33	0.36	0.20	0.23	0.49	0.67	0.43	0.17	0.63
P_2O_5	n.f.	0.15	0.14	0.17	0.13	0.19	0.15	0.15	0.21
Total	100.06	100.35	100.26	100.77	100.15	101.85	101.07	101.77	101.44

Fe_2O_3 is estimated from the ratio of $Fe^{2+}:Fe^{3+}$ for basaltic rocks as given by
Brooks (1976).

n.f. - not found; H_2O not determined

Two-pyroxene granulites: PHN 822, PHN 909a

Garnet granulites: PHN 869a, 869b, 869c, 869d, 869e, 881a, 916a

TABLE 2. Selected whole rock trace element analyses (ppm);
granulite xenoliths, Fort Portal.

PHN	822	869a	869b	869c	869d	869e	881a	909a	916a
Ba	214	134	142	240	661	554	132	338	215
Co	37	40	42	33	37	40	40	33	37
Rb	10	5	9	8	11	14	15	6	16
Sc	29	40	5	17	25	37	34	38	40
Sr	268	227	297	307	334	255	214	258	334
V	179	260	43	88	221	255	241	264	348
Zr	179	59	8	329	417	89	138	396	129
K/Rb	137	299	92	119	185	199	119	118	163
Ba/Sr	0.80	0.59	0.48	0.78	1.98	2.17	0.62	1.31	0.64
Rb/Sr	0.04	0.02	0.03	0.03	0.03	0.05	0.07	0.02	0.09

Two-pyroxene granulites: PHN 822, 909a
Garnet granulites: PHN 869a, 869b, 869c, 869d, 869e, 881a, 916a

the basis of major elements, they compare most closely with continental tholeiite basalts (Carmichael et al., 1974, p. 432). CIPW norms support this comparison; all but PHN 916a are hypersthene-normative, with silica-saturated, tholeiitic character. Xenoliths PHN 869b, c are slight exceptions. Though still tholeiitic, they have a chemistry very similar to cumulate gabbros from the Stillwater Complex, U.S.A. (Carmichael et al., 1974, p. 477) and are characterised by Al_2O_3 over 20 wt. %. PHN 916a, like PHN 1646 from Lesotho (Rogers, 1977), has an alkali-basalt chemistry.

Na_2O is the dominant alkali, ranging from 1.99 to 3.89 wt. %. K_2O ranges from 0.17 to 0.67 wt. % and shows no marked depletion when compared to analyses of basaltic rocks. As noted by Rogers

(1977) for lower crustal xenoliths from Lesotho, this is in contrast to the alkali-depleted nature often reported for granulites from exposed ancient metamorphic terrain (e.g. Pride and Muecke, 1980; Newton et al., 1980).

SiO_2 analyses are higher than those reported for most other suites of basic xenoliths, with the exception of those reported by Ehrenberg and Griffin (1979) from the Colorado Plateau (see Kay and Kay, 1981). Suites with lower SiO_2 tend to have a character more akin to alkali basalts.

On a TiO_2-K_2O-P_2O_5 diagram (Pearce et al., 1975) all but one of the xenoliths plot within the 'non-oceanic' basalt field, providing further evidence for their continental character (Fig. 4).

Trace elements. Several of the trace elements

TABLE 3.

Whole rock rare earth element analyses for granulites,

Fort Portal, in ppm.

PHN	822	869b	869d	916a
La	0.34	2.87	3.47	16.67
Ce	0.47	6.02	5.54	36.50
Pr	0.08	0.69	0.58	4.69
Nd	0.72	2.91	2.13	20.57
Sm	0.41	0.50	0.35	4.95
Eu	0.38	0.37	0.47	1.62
Gd	0.77	0.39	0.57	5.81
Dy	1.14	0.32	0.76	6.47
Ho	0.27	0.07	0.17	1.40
Er	0.80	0.20	0.52	3.96
Yb	0.81	0.17	0.51	3.72
Lu	0.12	0.03	0.08	0.56
Y	6.66	1.62	4.24	34.79

PHN 822 is a two-pyroxene granulite, the remainder are

garnet-granulites.

(Ba, Rb, Sc, V, Zr) show wide variation (Table 2) which does not reflect the more even distribution of the major elements. Ba/Sr ratios, ranging from 0.5 to 0.8, are similar to those of continental tholeiites except for three xenoliths, PHN 869d, e and PHN 909a. Values for these are two to three times higher.

Rb/Sr ratios are low for all the xenoliths compared to tholeites, but are consistently higher than those calculated from data given by Rogers (1977) for Lesotho xenoliths. This is due chiefly to the very much lower Sr concentrations in the Fort Portal xenoliths.

K/Rb ratios fall within, or slightly above the Main Igneous Trend of Shaw (1968), though the value of 299 for PHN 869a is rather high. These

values indicate that very little if any fractionation of Rb has occurred with respect to K.

Rare Earth Elements (REE). The *REE* data are given in Table 3 and Fig. 5. PHN 1646 is a granulite xenolith from the Lesotho suite that has been analysed twice by Instrumental Neutron Activation (Rogers, 1977, 1980; dotted lines in Fig. 5) and by I.C.P. in this study to give a comparison between the two techniques.

As with the trace elements, the *REE* data for the Fort Portal xenoliths show wide variation. Three *REE* patterns can be recognised from Fig. 5: *LREE* enriched—*HREE* depleted with a positive Eu anomaly (nos. 2 and 3); *LREE* depleted—relatively *HREE* enriched and relatively flat (no. 1); and slightly *LREE* enriched with a very weak negative Eu anomaly (nos. 4 and 5). This last pattern also has *REE* concentrations at least an order of magnitude greater than the other xenoliths and is notable for its similarity to the pattern for PHN 1646 from Lesotho (Rogers, 1977, 1980). The pattern for PHN 869d (no. 3) is somewhat intermediate. The *LREE* pattern is very smooth and similar to that for PHN 869b, whilst the *HREE* pattern is very similar to that for PHN 822.

Discussion of the REE patterns. Rogers (1980) attempted to model the *REE* patterns for the Lesotho xenoliths by considering processes of partial melting and fractional crystallisation. The

FIG. 4. Granulite xenoliths plotted on the TiO_2-K_2O-P_2O_5 basalt discrimination diagram of Pearce et al. (1975), showing their 'non-oceanic' (continental tholeiitic) affinities (below the line).
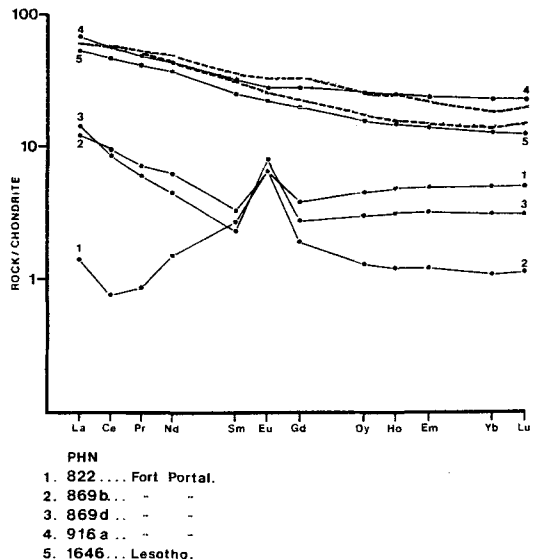

FIG. 5. Rare earth elements for Fort Portal xenoliths compared with chondrite. Broken lines are instrumental neutron activation analyses of PHN 1646 (Rogers, 1977, 1980), included for comparison with the I.C.P. analysis in this study. Chondrite values from Evensen et al. (1978).

latter was qualitatively successful in reproducing the REE patterns. Of the xenoliths in this study, the REE patterns for PHN 916a and PHN 869b (garnet granulites) are very similar to the modelled patterns in Rogers' work. On this analogy the pattern for PHN 916a is thought to represent a parental liquid composition (cf. PHN 1646, Rogers, 1980, p. 204 and this study); this view is supported by the alkali-basalt character of the major elements. Collectively these data suggest that PHN 916a represents the liquid from which some of the other xenoliths were derived by fractional crystallisation; as has been noted, the major element chemistry is consistent with a cumulate origin for some xenoliths.

REE patterns for PHN 822 and PHN 869d do not match the modelled patterns produced in Rogers' work. However, their patterns could also result from processes of fractional crystallisation. Rogers suggested that clinopyroxene, plagioclase and olivine were important crystallising phases. Crystallisation of these phases in different proportions to those used in Rogers' model may result in patterns similar to those for PHN 822 and 869d (though see below with regard to LREE to Sm for this xenolith). Rogers proposed that plagioclase formed 55 to 76% of the crystallising phases, based on the normative mineralogy. It is considered that clinopyroxene was the dominant crystallising phase in the magmatic protolith of these particular

samples. K_d values for REE in clinopyroxenes are given in Cox et al. (1979). These show that REE become increasingly incompatible towards the LREE end. Crystallisation of clinopyroxene would thus produce a cumulus phase enriched in HREE as seen in PHN 822 and PHN 869d (Fig. 5). Simultaneous crystallisation of plagioclase would produce a positive Eu anomaly.

The pronounced LREE enrichment in PHN 869d is attributed to contamination by the host carbonatite (see Discussion).

The chondrite-normalised whole rock patterns do not correspond closely with the existing granulite mineralogy. For example, the REE pattern for PHN 869b does not show the HREE enrichment that would be expected if garnet had been an original crystallising phase. In contrast, the two-pyroxene granulite, PHN 822, shows greatest HREE enrichment. From similar evidence in the Lesotho xenoliths, Rogers (1980) was able to demonstrate that it was probable that the REE abundances were established before metamorphism. This conclusion is supported by the REE data of Ehrenberg and Griffin (1979) and the REE data presented here.

Mineral composition

Pyroxenes. Clinopyroxene analyses are close to augite compositions (Table 4, Fig. 6). They are
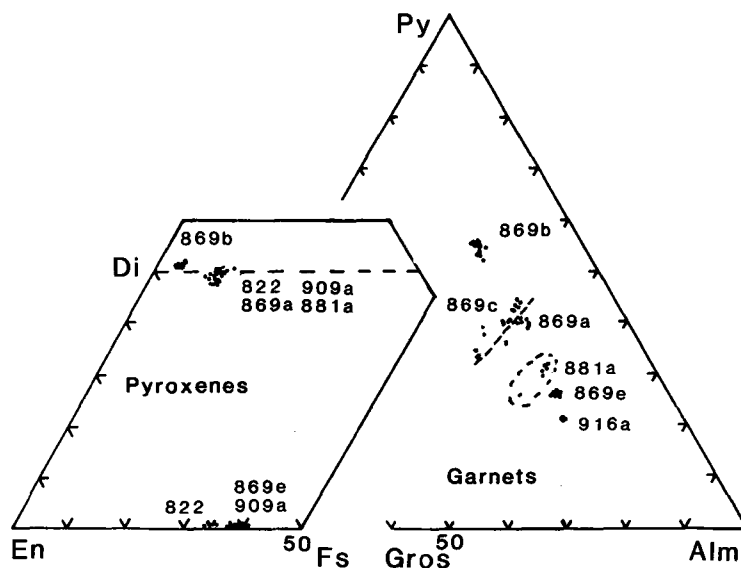

FIG. 6. Plots of garnet and pyroxene compositions in terms of the Ca, Fe and Mg end members. Each dot represents an analysis. The more variable rim compositions for garnets are also included, showing the trend towards grossularite (see text).

similar to those reported for clinopyroxenes in some other xenolith suites, notably Ehrenberg and Griffin (1979). Jadeite contents are low ($< 1\%$ of $Wo + En + Fs + Ca + Ts + Jd$) and acmite is a negligible component. The clinopyroxene in PHN 869b shows an excess of Ca above that required to fill the $M2$ site. It is unclear why this should be so, but it is possible, for thermodynamic reasons, that the small excess of Ca is accommodated in the $M1$ site (Lindsley *et al.*, 1981). Orthopyroxenes are aluminous hypersthenes (*c.* En_{65}) with low minor constituents.

The main variation in pyroxene compositions within the suite occurs in the Fe/Mg ratios. There is little or no zoning.

Garnets. The garnet cores have remarkably constant grossular contents; variation between xenoliths occurs parallel to the almandine–pyrope join (Table 5, Fig. 6). This is reflected in a general correlation between the almandine contents of the garnets and the whole-rock FeO content.

There is usually a tight grouping of analyses from each xenolith. However, in xenoliths PHN 869a, c and 881a, the garnets show variation in grossular

TABLE 4.   Electron microprobe (EDS) analyses (wt%) and cations per 6 oxygens

for clinopyroxenes (cpx) and orthopyroxenes (opx) from granulite xenoliths,

Fort Portal.

PHN	822		869b	881a	909a	
	cpx (16)	opx (8)	cpx (11)	cpx (8)	cpx (2)	opx (3)
SiO_2	50.00	51.30	51.05	52.77	50.22	50.77
TiO_2	0.74	0.03	0.88	0.25	0.62	0.08
Al_2O_3	6.68	4.06	7.88	4.01	5.65	4.28
Cr_2O_3	0.17	0.09	0.06	0.09	0.17	0.08
FeO^*	6.97	21.83	2.54	6.12	6.84	23.68
MnO	0.14	0.43	0.03	0.05	0.11	0.50
MgO	11.99	21.74	13.89	13.10	11.83	20.04
CaO	22.34	0.23	22.46	21.88	22.30	0.25
Na_2O	0.88	0.18	1.23	1.67	1.52	0.02
Total	99.91	99.89	100.02	99.94	99.26	99.70
Si	1.853	1.907	1.850	1.944	1.879	1.904
Ti	0.021	-	0.024	0.007	0.018	0.002
Al	0.292	0.178	0.337	0.174	0.250	0.190
Cr	0.005	0.003	0.002	0.003	0.005	0.003
Fe^*	0.216	0.679	0.077	0.189	0.215	0.744
Mn	0.005	0.014	-	-	-	0.016
Mg	0.663	1.205	0.750	0.719	0.660	1.123
Ca	0.886	0.019	0.872	0.864	0.894	0.010
Na	0.063	0.013	0.086	0.119	0.111	-
Total	4.004	4.018	3.998	4.019	4.032	3.992

(16) - number of spot analyses in average.   *Total Fe as Fe^{2+}

PHN 822 and 909a are two-pyroxene granulites;   the others are garnet granulites.

TABLE 5.   Electron microprobe (EDS) analyses (wt%) and cations per 12 oxygens

for garnets from garnet granulite xenoliths, Fort Portal.

PHN	869a (4)	869b (12)	869c (8)	881a (4)
SiO_2	39.03	41.14	40.03	39.38
TiO_2	0.09<	0.02<	0.05<	0.05<
Al_2O_3	22.02	23.26	22.04	21.34
FeO^*	21.07	14.09	19.20	23.99
MnO	0.54	0.19	0.36	0.56
MgO	10.90	15.48	12.24	8.49
CaO	6.20	6.69	6.06	6.04
Na_2O	n.f.	0.23	n.d.	n.d.
Total	99.85	101.10	99.98	99.85
Si	2.967	2.979	2.996	3.017
Al	1.965	1.983	1.944	1.940
Fe^*	1.335	0.852	1.202	1.538
Mn	0.035	0.012	0.023	0.038
Mg	1.230	1.669	1.366	0.970
Ca	0.503	0.518	0.486	0.496
Total	8.035	8.013	8.017	7.999

(12) - number of spot analyses in average

*Total Fe as Fe^{2+}; n.f. not found, n.d. not determined

< - concentration less than 2 standard deviations

TABLE 6. Electron microprobe (EDS) analyses (wt%) and
cations for 5 oxygens for plagioclases.

	PHN 822	PHN 909a	PHN 869a	PHN 869e	PHN 881a
SiO_2	52.09	55.11	58.12	61.20	61.81
Al_2O_3	29.48	27.90	24.24	24.21	23.95
CaO	12.25	10.52	7.54	6.00	5.61
Na_2O	4.53	5.50	7.12	7.86	8.27
K_2O	0.25	0.28	0.41	0.86	0.57
Total[*]	98.79	99.43	98.53	100.28	100.34
Si	2.392	2.497	2.638	2.718	2.739
Al	1.596	1.490	1.350	1.269	1.251
Ca	0.603	0.511	0.367	0.286	0.266
Na	0.403	0.483	0.627	0.678	0.711
K	0.015	0.016	0.023	0.049	0.032
Total	5.009	4.997	5.005	5.000	4.999
End member compositions:	$An_{60}Ab_{40}$	$An_{50}Ab_{50}$	$An_{37}Ab_{63}$	$An_{28}Ab_{72}$	$An_{26}Ab_{74}$

[*]The oxide totals include minor amounts of TiO_2, FeO and MnO not given here
PHN 822 and 909a are two-pyroxene granulites, the remainder are garnet granulites.

content from rim to core; this variation is also matched by equally large variation along the rim over a few tens of microns.

Plagioclase. The chemistry of the plagioclases can be linked in a general way to the xenolith type (Table 6). In the two-pyroxene granulites, the plagioclase is labradorite or calcium-rich andesine, whilst the garnet granulites are characterised by calcium-poor andesine or oligoclase. The two types of xenolith can be linked by reaction (1), below. It is apparent that 20 to 25% An has been lost from the plagioclase during the progression across the reaction from left to right.

Potassium contents are very low, but are two to three times higher in the garnet granulites than in the two-pyroxene granulites.

Scapolite. This phase occurs as very small inclusions in plagioclase in PHN 869e and PHN 881a. It is close to the calcium-rich end-member meionite; sulphur and chlorine were detected by microprobe analysis. The presence of meionite in plagioclase can be due to the following reaction (Deer *et al.,* 1966):

$$3CaAl_2Si_2O_8 + CaCO_3 =$$
$$\text{An} \qquad\qquad \text{Cc}$$
$$Ca_4Al_6SiO_{24}CO_3(+SO_4,Cl).$$
$$\text{Me}$$
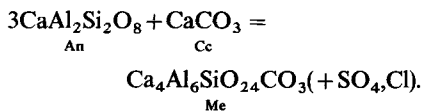
Equilibration temperatures and depth of origin

Temperatures of equilibration were estimated using several geothermometers. Calibrations of the Fe–Mg exchange reaction between garnet and clinopyroxene by Råheim and Green (1974), Ganguly (1979), Saxena (1979) and Ellis and Green

(1980) were used for the garnet granulites. Powell's (1978) calibration of the Ca–Mg exchange reaction between coexisting clino- and orthopyroxene was used for the two-pyroxene granulites.

Of the calibrations employed for the garnet granulites, the results given by those of Ganguly (1979) and Ellis and Green (1980) are the most consistent (see also Essene, 1982). For pressures between 4 and 12 kbar, estimated temperatures fall in the range 600 to 800 °C. The quoted range of temperatures also allows for the presence of Fe^{3+} in garnet and clinopyroxene. Råheim and Green (1974) noted that the presence of Fe^{3+} in these phases would have a significant effect on the calculated temperatures. Irving (1974) gives an estimate of the likely maximum amount of Fe^{3+} in such phases. Using his estimates, 'adjustments' were made to the temperatures in order to allow for this effect, resulting in a reduction of between 80 and 100 °C for the calculated temperatures (Fig. 7).

Temperatures calculated by the geothermometer of Råheim and Green (1974) were comparatively low, a phenomenon noted by other workers (e.g. Dahl, 1980). Temperatures calculated by Saxena's (1979) geothermometer gave results ranging from 600 to nearly 1000 °C. These were considered too inconsistent and there was evidence to suggest that they were sensitive to the concentrations of other elements besides Fe and Mg, notably Al and Na.

Temperatures calculated for the two-pyroxene granulites ranged from 583 ± 22 °C to 628 ± 27 °C for pressures from 4 to 12 kbar. The error values are derived from a formulation given by Powell (1978). These temperatures are consistent with the two-pyroxene granulites being of lower grade than the garnet granulites.
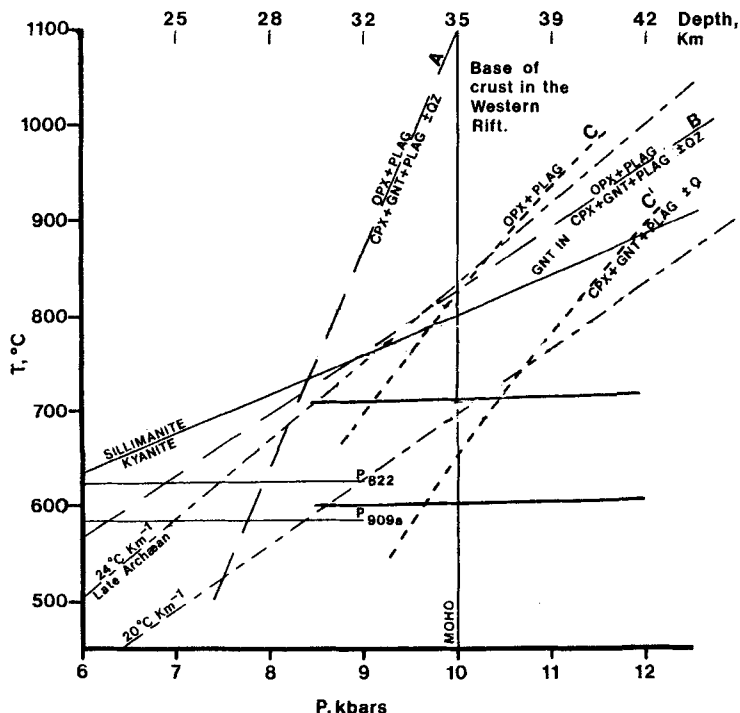
FIG. 7. Position in P,T space of granulite xenoliths from Fort Portal, Uganda. The range of equilibrium temperatures (between the two thicker horizontal lines) for garnet granulites (PHN 869a, b, c and PHN 881a) incorporate an adjustment for Fe^{3+} (see text). Temperatures for two-pyroxene granulites (PHN 822, 909a) calculated from the geothermometer of Powell (1978). Sources of data: A, Irving (1974); B, Green and Ringwood (1967); (straight line extrapolations of these data) C-C' O'Hara (1977); extrapolation from O'Hara et al. (1971). Depth to Moho of 35 km is regarded as a maximum value. 24 °C km^{-1} geotherm after O'Hara from Tarney and Windley (1977).

It has been noted that the two-pyroxene granulite, PHN 909a, contains two garnets considered to be xenocrysts. Evidence for disequilibrium is yielded by the application of garnet–clinopyroxene geothermometers. These give temperatures 200 °C above those estimated by the two-pyroxene model of Powell (1978).

Pressure estimates are not so easily arrived at, since no suitably formulated geobarometers exist for rocks with these phases, but lacking quartz.

The position in P,T space of the reaction

opx + Ca rich plag =
         gnt + cpx + Na rich plag ± quartz   (1)
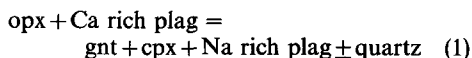
has been investigated by several authors (Green and Ringwood, 1967; Ito and Kennedy, 1971; Irving, 1974; O'Hara et al., 1971). O'Hara (1977) considers that this reaction defines low- and high-pressure assemblages in rocks of basic composition; thus the above reaction should provide a means of estimating equilibration pressures. Unfortunately, the experimentally-derived positions of this re-action are subject to wide variation, making precise pressure estimation impossible. However, it is considered that the likely minimum pressure experienced by the garnet granulites is about 6.5 kbar (c. 23 km), although the work of Ito and Kennedy (1971) indicates that the assemblage garnet + clino-pyroxene + plagioclase could be stable at pressures as low as 3 kbar at 600 °C. The crust in the Western Rift is 32 to 35 km thick according to Bram and Schmeling (1976) and Wohlenberg (1976). If these xenoliths do indeed come from the lower crust, then the maximum pressure at which they could have equilibrated is constrained to about 10 kbar. Bram and Schmeling (1976) also found a marked geophysical discontinuity at 16 km in this region (a continental discontinuity is known to occur at this level in other parts of the world). This discontinuity indicates a marked density change and the above authors consider that it divides the upper and lower crust. We conclude that the two-pyroxene granulite xenoliths from Fort Portal came from depths in excess of 16 km, but less than 23 km.

Discussion

Our data indicate that the xenoliths represent metamorphosed rocks of basaltic chemistry with hypersthene-normative character. The nature of the major, trace and *REE* data suggests that at least some of the xenoliths were cumulates; high CaO, Al_2O_3, low MgO and positive Eu anomalies support this view. It was during the original crystallisation of the parent magma that the *REE* patterns were established.

The basaltic pile is considered to have been metamorphosed at temperatures estimated at between 580 and 800 °C and pressures in excess of 4 kbar (6 kbar in the case of the garnet granulites). However, Ehrenberg and Griffin (1979) noted that the low jadeite contents of the pyroxenes in garnet granulite xenoliths from the Colorado Plateau conflicted with other evidence for a deep crustal origin. Low jadeite contents are also a feature of the garnet granulites in this study and may mitigate against a lower crustal origin. Relating *P,T* estimates for xenoliths in this study to those from work on the garnet granulite–eclogite transition by O'Hara *et al.* (1971), Irving (1974) and Green and Ringwood (1967) indicates that eclogite is only likely to be stable in the deepest levels of the continental crust. In the Western Rift, lithospheric thinning has occurred in conjunction with increased geothermal gradients due to asthenospheric uplift (Fairhead and Reeves, 1977). Consequently, it may be that garnet granulites have been sampled by the carbonatite only from the low-pressure regions of their stability field, say from 23 to 25 km (see Fig. 7), where plagioclase is not breaking down to form jadeite.

There is some evidence to suggest that the granulite has, in places, reacted with the carbonatite magma. The pronounced *LREE* enrichment in PHN 869d is attributed to this phenomenon. Further evidence in this xenolith is the alteration of much of the clinopyroxene to secondary mica (minor alteration of pyroxene rims to secondary mica also occurs in other xenoliths in this suite). Rogers and Hawkesworth (1982) reported that certain of the Lesotho xenoliths also showed an unusual enrichment in *LREE*. They also noted that in these xenoliths the isotope systematics appeared to have been disturbed. They attributed these features to contamination by the host kimberlite. It is thought that similar processes have occurred beneath Fort Portal, acting upon the crust from which the xenoliths were derived.

The presence of scapolite in the plagioclase could also be due to the host carbonatite magma. However, scapolite is known from many granulite terrains and is recorded as a common phase in other xenolith suites (e.g. Lovering and White, 1969; Griffin *et al.*, 1979; Okrusch *et al.*, 1979); its presence may simply be a manifestation of a CO_2-rich volatile phase in the lower crust (e.g. Collerson and Fryer, 1978; Collerson and Bridgwater, 1979; Newton *et al.*, 1980).

Many authors have considered the implications of mafic granulite xenoliths for the nature of the lower crust (e.g. Edwards *et al.*, 1979; Ehrenberg and Griffin, 1979; Irving, 1974; Lovering and White, 1969; Meyer and Brookins, 1976; McGetchin and Silver, 1972; Okrusch *et al.*, 1979; Rogers, 1977, 1980; Rogers and Hawkesworth, 1982; Wass and Hollis, 1983). Xenolith suites are known from a number of continental areas, including Africa, Australia, North America and Europe (see Kay and Kay, 1981). All these suites display a general consistency of composition and mineralogy.

From *P,T* estimates, frequent association with ultramafic (mantle-derived) xenoliths, and their occurrence in mantle-derived volcanic rocks (kimberlites, carbonatites, minettes, serpentinite diatremes and alkali-basalts), it is apparent that these xenoliths come from the lower structural levels in the crust. More direct evidence for the occurrence of these sorts of rocks in the lower crust is found in the Ivrea Zone of the Western Alps (Mehnart, 1975). Here, there is a continuous section from mantle lherzolites, through basic granulites similar to the xenoliths in this study, to gneisses characteristic of many exposed granulite terrains.

Geophysical studies of rocks with basaltic chemistry and high-grade mineralogy have shown that their seismic velocities are consistent with those known to characterise the lower crust (Christensen and Fountain, 1975).

From the above evidence it is now held widely that xenoliths of basaltic chemistry with low- to medium-pressure assemblages equivalent to granulite facies are representative of at least part of the lower crust; such rocks may have played a significant role in the development of the crust (Rogers and Hawkesworth, 1982; Wass and Hollis, 1983; O'Reilly and Griffin, 1985).

Data presented here are consistent with those reported for other xenolith suites, particularly with those from Lesotho, bordering the Natal–Namaqua mobile belt (Rogers, 1977, 1980). It is apparent that the lower crust beneath Fort Portal, Uganda, has mafic granulite as a major component.

The emplacement of the magmatic protolith together with subsequent granulite facies metamorphism has played a significant role in the early development of the lower crust in the Western Rift of East Africa. However the timing of these events is unknown. The observed metasomatic features in the granulite xenoliths could be related to the

generation of the Quaternary alkaline volcanicity, including carbonatites of the region.

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