Megacrysts and ultramafic xenoliths from Kundelungu kimberlites (Shaba, Zaire)

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Abstract

Some twenty kimberlite pipes outcrop along the eastern and western borders of the Kundelungu plateau, Shaba Province, Zaire. They are arranged roughly along two north–south trending alignments. The pipes probably intruded the Bangweulu Block, which stabilized around 1800 Ma. The exceptionally fresh kimberlites contain mantle-derived nodules (peridotites and eclogites), as well as megacrysts which may reach up to several cm in diameter. The most important megacrysts are garnets, ilmenites, clinopyroxenes, orthopyroxenes and olivines. Micas and diamonds are rarely observed. The clinopyroxenes can be subdivided in two groups: (1) a Ca-rich, low-T type, similar to the Cr-rich diopsides found in 'depleted' (granular) peridotites; and (2) subcalcic clinopyroxene comparable to the megacrysts and to the clinopyroxenes of 'fertile' (sheared) peridotites. The orthopyroxenes are less frequent and are Ca-poor enstatites (0.07–0.42 wt.% CaO) and Ti-bronzites (CaO <1.3 wt.%). All the analysed garnets are Ca-rich (>4.5 wt.% CaO) and all fall in the lherzolite field defined by Sobolev *et al.*, 1973. The low-Ca garnets which appear in many diamond-bearing kimberlites have never been observed in Zaire, neither in the diamond-poor Kundelungu pipes nor in the diamond-rich Mbuji-Mayi pipes. The ilmenites define a trend close to the 'magmatic Mg-enrichment trend'. The olivine macrocrysts have Fo contents comparable to those of peridotites (Fo90–93). The ultramafic nodules comprise lherzolites, harzburgites, pyroxenites, wehrlites and dunites. The granular textures and P–T equilibrium conditions (770–1380°C and 28–61 kbar) deduced from their mineral compositions, show clearly that they were derived from a mantle zone on the continental geotherm (90–190 km depth). The eclogite nodules, which are less frequent, contain only two mineral phases (pyrope–almandine–grossular and omphacite), and the texture and the mineral compositions are similar to those of Roberts Victor eclogites. Our findings support the conclusion of Nixon and Condliffe (1989) that low-T peridotites, eclogites and pyroxenites derived from 'depleted' lithosphere, while Cr-poor garnet, subcalcic diopside and bronzite megacrysts cristallized from fertile asthenosphere.

KEYWORDS: megacryst, lherzolite, harzburgite, kimberlite, Kundelungu, Zaire.

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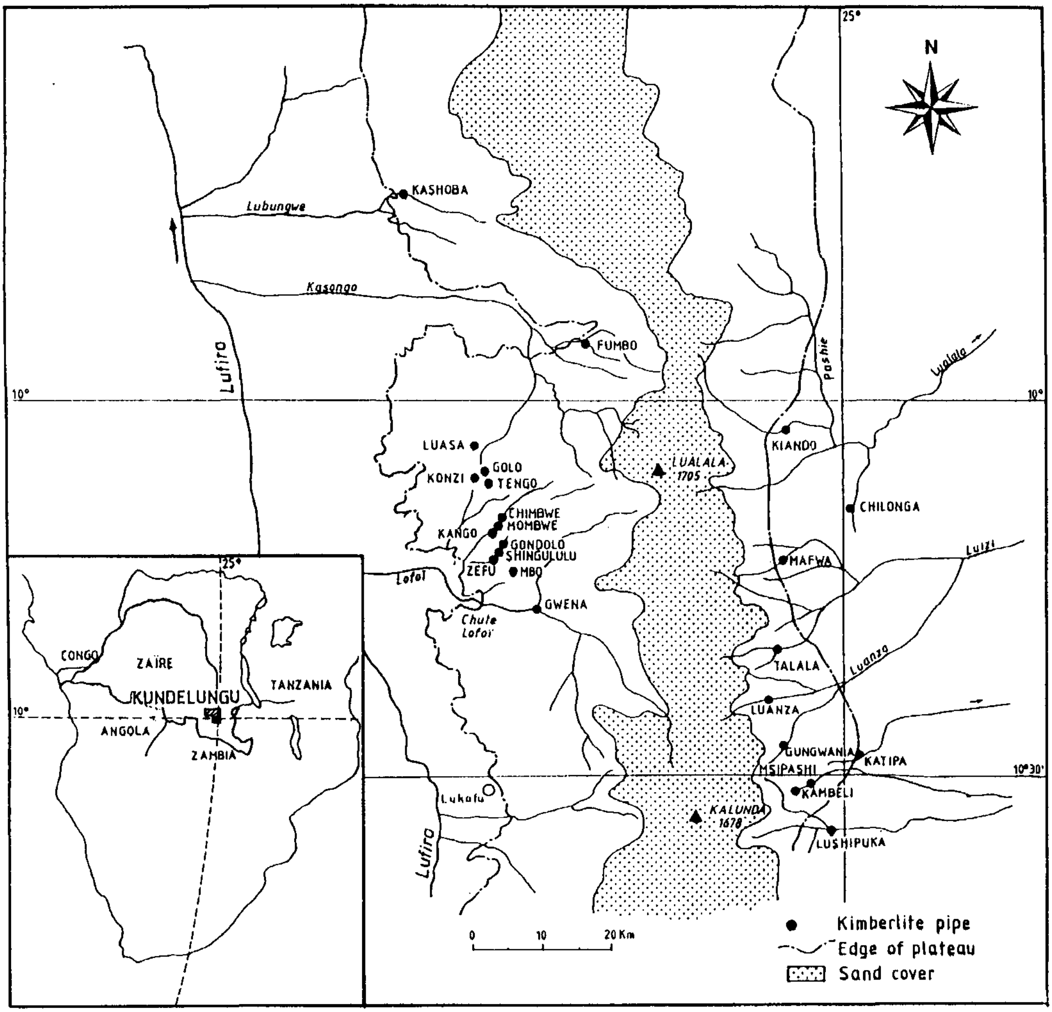

FIG. 1. Distribution of kimberlite pipes in the Kundelungu region, Shaba Province, Zaire (modified from Verhoogen, 1936).

Introduction

Two kimberlite provinces are at present recognized in Zaire: the diamond-rich kimberlites from Mbuji Mayi in the East Kasai region and the diamond-poor kimberlites from the Kundelungu High Plateau in the Shaba region (Demaiffe *et al.*, 1991). In the Kundelungu area some twenty kimberlite pipes outcrop along two north-south trending alignments on the eastern and western borders of the Plateau (Fig. 1). The kimberlites most likely intruded into the western border of the Bangweulu Block, which was cratonized about 1800 Ma ago (Ngoyi et *al.*, 1991). The pipes have not yet been radiometrically dated, but they are most likely of Cretaceous age as is the case for the majority of the kimberlite occurrences from Central and Southern Africa.

Kimberlites characteristically contain large isolated crystals and ultramafic inclusions, whose abundance and granulometry vary from pipe to pipe (Nixon and Boyd, 1973*b*; Boyd and Clement, 1977; Eggler *et al.*, 1979; Dawson, 1980; Garrison and Taylor, 1980; Gurney *et al.*, 1979; Mitchell, 1986; Hunter and Taylor, 1984). Following Clement *et al.* (1984) we will use the term 'macrocryst' in a descriptive, non-genetic sense. The term 'megacryst' is reserved for members of the 'discrete nodule suite'.

Very few data on inclusions from the Kundelungu kimberlites have been published thus for (Verhoogen, 1938). The results for Zairian kimberlites summarized in Nixon (1987) only pertain to the Mbuji-Mayi region. The most frequently observed macrocrysts in the Kundelungu kimberlites are garnet, pyroxene, ilmenite and olivine. Mica and diamond rarely occur. Lherzolites and garnet-bearing harzburgites are the most frequent ultramafic xenoliths. Dunites and eclogites are less common, and only one pyroxenite has been found. The grain-size ranges from 0.5 cm up to 8 cm for the megacrysts and from 0.4 cm up to 5 cm for the xenoliths. The megacrysts and ultramafic xenoliths give an apparent porphyritic texture to the kimberlitic rock. The groundmass consists of olivine, monticellite, spinel, perovskite, ilmenite, calcite and serpentine. The abundances of the megacrysts and inclusions vary from pipe to pipe. Garnet and ilmenite are most abundant, which partly reflects their higher resistance to weathering. Less resistant olivine and orthopyroxene are less abundant in the most weathered kimberlite pipes (e.g. Luanza and Talala). The ultramafic nodules are most prominent in the Gwena and Msipashi pipes. Diamond rarely occurs in the Kundelungu rocks.

After optical studies of thin sections and polished mounts, the composition of the mineral grains was determined by Electron Microprobe Microanalysis at the Université Catholique de Louvain-la-Neuve (analyst: J. Wautier) and at the University of Leeds (garnet and ilmenite only; analyst: E. Condliffe). Measurement conditions were the same at both laboratories: 15 kV acceleration voltage, 10 s counting time, ZAF absorption correction procedure.

The megacrysts

Olivine. The large olivine crystals are either products of the disaggregation of peridotite nodules or are crystals formed at depth and entrained by the ascending kimberlitic magmas. Most of the macrocrysts are pale brown, fractured and rounded. Serpentine often fills grain fractures and forms rims. Many macrocrysts show signs of strain, such as undulatory extinction and mosaic recrystallisation

TABLE 1. Representative composition of olivine from Kundelungu kimberlites

	Ko8	Ko9	Te12	Te67	Te86	Kl74	Kl78	Ms14
SiO_2	40.38	40.58	40.84	40.26	40.75	40.75	40.89	40.85
TiO_2	0.01	0.03	0.06	n.d.	n.d.	0.06	0.03	0.01
Al_2O_3	0.06	0.01	0.03	n.d.	0.01	0.02	0.06	0.03
Cr_2O_3	0.06	n.d.	0.06	n.d.	n.d.	n.d.	0.09	0.08
FeO*	8.87	11.12	10.00	7.21	8.82	8.38	8.41	8.82
MnO	0.07	0.14	0.05	0.11	0.09	0.16	0.07	0.15
MgO	50.18	47.99	48.74	50.87	50.08	50.29	50.11	49.62
NiO	0.09	0.21	0.31	0.08	0.27	0.23	0.26	0.08
CaO	0.10	0.08	0.02	0.02	0.02	0.02	0.07	0.06
Total	99.82	100.16	100.11	98.55	100.04	99.91	99.99	99.70
Numbers of ions on basis of 4(O)								
Si	1.001	0.999	1.002	1.000	0.996	0.995	0.998	1.000
Ti	0.010	0.030	0.001	0.000	0.000	0.001	0.001	0.000
Al	0.002	0.000	0.001	0.000	0.000	0.000	0.002	0.001
Cr	0.001	0.002	0.001	0.000	0.000	0.000	0.002	0.002
Fe	0.179	0.187	0.205	0.147	0.180	0.171	0.172	0.180
Mn	0.001	0.002	0.001	0.002	0.002	0.003	0.002	0.003
Mg	1.809	1.805	1.783	1.849	1.823	1.831	1.822	1.810
Ni	0.001	0.005	0.005	0.001	0.004	0.004	0.004	0.001
Ca	0.003	0.005	0.001	0.001	0.001	0.001	0.002	0.002
Mole %								
Fo	90.9	90.5	89.4	92.5	90.9	91.3	91.3	90.8
Fa	9.1	9.5	10.4	7.5	9.1	8.7	8.7	9.2

* Total iron as FeO; Fo = forsterite; Fa = Fayalite

textures. Rare olivine crystals contain enstatite and garnet inclusions.

The chemical composition of representative olivine grains is shown in Table 1. The forsterite content ranges from 89.4 to 92.5 mol.%, the NiO content from 0.03 to 0.38 wt.%. The CaO content never exceeds 0.11 wt.%. Chemical composition by itself does not suffice to distinguish the various olivine types. Nonetheless, one can distinguish phenocrysts from megacrysts and fragments of mantle nodules on the basis of morphological features, optical properties and mosaic texture.

Orthopyroxene. Orthopyroxene is present as monocrystalline, rounded grains that may attain sizes of 8 cm (sample MsO2). The colour varies from greyish-brown to brownish-green. It also occurs as inclusions in garnet.

Representative analyses are shown in Table 2. The megacrysts can be subdivided in an enstatite and bronzite group on the basis of CaO , Al_2O_3, TiO_2 and FeO contents. The chromium content is high in both groups. A similar grouping of orthopyroxene composition has been observed in the Monastery (Gurney *et al.*, 1979) and Hamilton Branch (Schulze, 1984) kimberlites. Bronzite MsO2 resembles orthopyroxene from Tanzanian kimberlites (Nixon and Condliffe, 1989). Chromium-rich orthopyroxene has been found in the kimberlites from Colorado-Wyoming (Eggler *et al.*, 1979) and from Fayette County (Hunter and Taylor, 1984). The large size of the minerals indicates that these orthopyroxene grains did not originate from disaggregation of peridotite inclusions.

Clinopyroxene. Megacrystal clinopyroxene occurs exclusively as monomineralic grains. Clinopyroxene is more abundant than orthopyroxene. The colour varies from emerald green to dark green. The rounded shape and grain fractures attest to the wear

TABLE 2. Representative composition of orthopyroxene from Kundelungu kimberlites

	Bronzites				Enstatites			
	Ms27	MsO2	Lu17	Kl62	Kl45	Ze33	Gw70	Gu82
SiO_2	57.65	55.78	56.91	56.43	58.68	57.75	56.99	57.10
TiO_2	0.15	0.13	0.07	0.16	0.09	0.09	0.03	0.05
Al_2O_3	1.21	1.23	1.04	0.96	0.47	0.57	0.56	0.49
Cr_2O_3	0.17	0.22	0.24	0.48	0.35	0.32	0.31	0.44
Fe_2O_3*	0.24	0.11	0.00	0.91	0.00	0.79	1.73	2.08
FeO	6.14	5.45	6.16	4.62	4.32	4.96	2.78	2.87
MnO	0.12	0.12	0.15	0.06	0.12	0.17	0.11	0.07
MgO	33.52	32.84	33.33	34.08	35.82	35.10	36.20	36.25
CaO	1.52	1.30	1.06	1.16	0.26	0.51	0.33	0.07
Na_2O	0.24	0.21	0.17	0.15	0.11	0.09	0.07	0.09
K_2O	n.d.	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.96	97.41	99.13	99.01	100.22	100.35	99.11	99.51
Number of ions on basis of 6 (O)								
Si	1.974	1.974	1.983	1.963	2.003	1.971	1.964	1.959
Al^{iv}	0.026	0.026	0.017	0.037	0.000	0.029	0.023	0.020
Ti	0.004	0.003	0.002	0.004	0.002	0.002	0.001	0.001
Al^{vi}	0.023	0.025	0.025	0.002	0.019	0.002	0.000	0.000
Cr	0.005	0.006	0.007	0.013	0.009	0.009	0.008	0.012
Fe^{3+}	0.006	0.003	0.000	0.024	0.000	0.020	0.045	0.054
Fe^{2+}	0.176	0.161	0.179	0.135	0.123	0.142	0.080	0.082
Mn	0.003	0.004	0.004	0.002	0.003	0.005	0.003	0.002
Mg	1.711	1.733	1.731	1.767	1.823	1.786	1.859	1.854
Ca	0.056	0.049	0.040	0.043	0.010	0.029	0.012	0.003
Na	0.016	0.014	0.011	0.010	0.007	0.006	0.005	0.006
K	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Mg/Mg+Fe	0.91	0.91	0.91	0.93	0.94	0.93	0.96	0.96

* calculated by charge balance

suffered during ascent to the surface. Interlamellar pyroxene–ilmenite composite grains that are often observed in kimberlites are absent from the Kundelungu rocks.

The chemical composition of representative grains is summarized in Table 3. The Ca/(Ca+Fe) ratio allows us to distinguish a subcalcic (0.36–0.39) and calcic (0.41–0.45) group; this subdivision corresponds to the high and low temperature groups of peridotites defined by Boyd (1987). The calcic pyroxenes are richer in chromium (1.56–2.73 wt.%) and sodium (1.47–2.76 wt.%) and have distinctly higher Mg/(Mg+Fe) ratios (0.91–0.93) than the subcalcic pyroxenes. These Cr-rich clinopyroxenes show similarities with pyroxenes from lherzolite inclusions but are classified as megacrysts because the grain size can exceed 1 cm. Eggler and McCallum (1976) previously recognized a similar dichotomy of clinopyroxene composition in the kimberlites from Colorado-Wyoming on the basis of chromium content. The subcalcic clinopyroxenes resemble the 'discrete nodules' of Nixon and Boyd (1973*b*). Omphacite, a major component of eclogites, has not been observed as individual grains in mineral concentrates. This accords with the rarity of eclogitic inclusions in the Kundelungu kimberlites. In this respect the Kundelungu and Mbuji Mayi kimberlites (Mvuemba, 1980) differ considerably.

Application of the 20 kbar pyroxene solvus (Lindsley and Dixon, 1976) shows that the Kundelungu clinopyroxenes crystallized over a temperature interval ranging from 1000 to 1450°C. This range is typical for clinopyroxene megacrysts occurring in kimberlites from other regions (Fig. 2).

Garnet. Garnet is the second most abundant mineral grain after ilmenite. The colour varies from deep-red to orange-red; the shape is generally spherical. Some grains show fractured surfaces, or

TABLE 3. Representative compositions of clinopyroxene megacrysts from Kundelungu kimberlites

	Subcalcic				Calcic			
	ZeCPX3	MsCPX2	Ms51	Ze109	Lu23	Ko140	Te57	Gw54
SiO_2	54.30	53.58	54.30	53.97	55.13	54.09	53.57	54.87
TiO_2	0.28	0.23	0.28	0.27	0.17	0.02	0.08	0.21
Al_2O_3	2.46	2.60	2.46	2.30	2.85	2.57	0.59	3.00
Cr_2O_3	0.78	0.79	0.78	0.63	1.56	2.73	1.72	1.90
Fe_2O_3*	2.44	2.78	1.98	3.73	0.36	0.37	0.05	n.d.
FeO	2.10	1.74	2.58	0.96	2.36	1.86	2.10	2.63
MnO	0.08	0.10	0.08	0.07	0.07	0.05	0.03	0.12
MgO	19.77	19.23	19.77	19.85	15.36	15.57	16.57	15.36
CaO	15.71	15.50	15.71	16.23	18.70	17.77	22.13	18.02
Na_2O	1.62	1.77	1.62	1.57	2.64	2.64	1.47	2.69
K_2O	0.04	0.06	0.04	0.05	0.02	n.d	0.01	0.01
Total	99.58	98.38	99.60	99.63	99.22	97.67	98.32	98.81
Number of ions on basis of 6 (O)								
Si	1.954	1.952	1.967	1.939	2.000	1.993	1.988	1.999
Al^{iv}	0.046	0.048	0.043	0.061	0.000	0.007	0.002	0.001
Al^{vi}	0.058	0.063	0.061	0.039	0.122	0.105	0.022	0.128
Ti	0.008	0.006	0.007	0.008	0.005	0.001	0.002	0.006
Cr	0.022	0.023	0.022	0.018	0.045	0.080	0.050	0.055
Fe^{3+}	0.066	0.076	0.049	0.101	0.010	0.010	0.001	0.000
Fe^{2+}	0.063	0.053	0.073	0.029	0.072	0.057	0.062	0.080
Mn	0.002	0.003	0.002	0.002	0.002	0.002	0.001	0.004
Mg	1.060	1.044	1.063	1.063	0.831	0.855	0.915	0.834
Ca	0.606	0.605	0.606	0.625	0.727	0.702	0.842	0.703
Na	0.103	0.125	0.115	0.109	0.186	0.189	0.105	0.190
K	0.002	0.001	0.002	0.002	0.001	0.000	0.000	0.000
Ca/Ca+Mg	0.36	0.37	0.36	0.37	0.47	0.45	0.48	0.46
Mg/Mg+Fe	0.94	0.95	0.94	0.97	0.92	0.94	0.94	0.91

* Calculated by charge balance

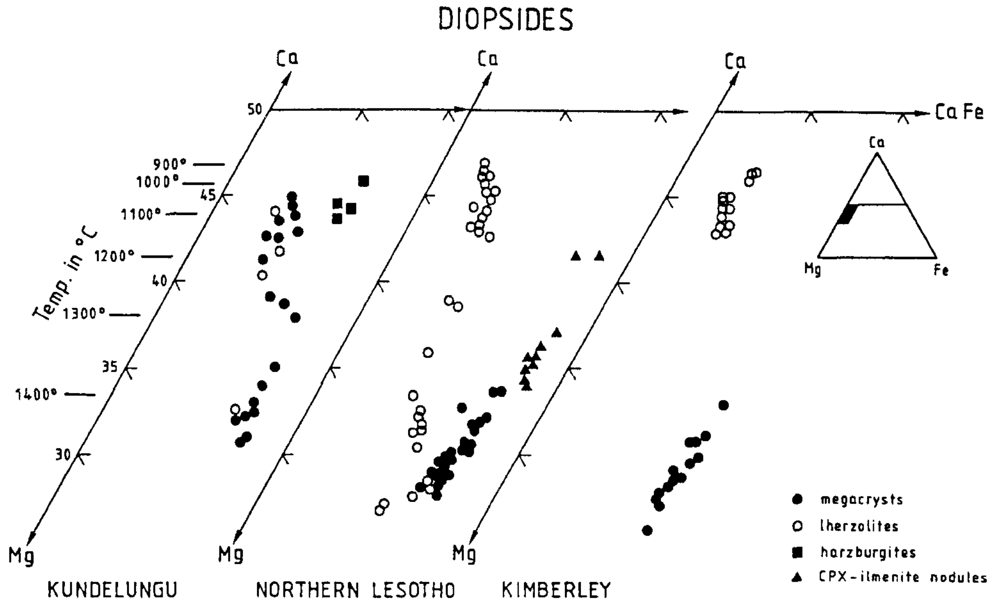

FIG. 2. Composition of diopside megacrysts from kimberlites. Kundelungu: this work; Lesotho: Nixon and Boyd (1973*a*); Kimberley: Boyd and Nixon (1978).

fractures filled with secondary alteration products. The dimension of the grains may exceed 5 cm.

Representative analyses are shown in Table 4. The garnet is pyrope-rich (63–73 mol.%). There is Cr-rich variety (2.55 to 7.44 wt.% Cr_2O_3) which also has slightly higher Ca/(Ca+Mg) ratios (0.14–0.21), a Cr-poor variety (0.36–2.43% Cr_2O_3) with lower Ca/(Ca+Mg) ratios (0.10 to 0.16). Garnets of similar composition are present in North American kimberlites (Eggler *et al.*, 1979). Cr-rich garnets are similar composition to garnets occuring in garnet harzburgite xenoliths. This suggest that certain Cr-rich megacrysts (diopside and garnet) may be derived from peridotite xenoliths.

Chromium and calcium abundances are linearly correlated (Fig. 3). The Kundelungu garnets plot within the lherzolite field defined by Sobolev *et al.* (1973) Subcalcic garnet has not been observed in Zaire kimberlites, neither at Kundelungu nor at Mbuji Mayi (Mvuemba, 1980). Because subcalcic garnet often occurs included in diamond, several authors have postulated that subcalcic garnet is an indicator for the presence of diamond. It has never been observed in Zaïre kimberlites, not even in the diamond-bearing rocks from Mbuji Mayi. Our findings support the conclusion of Nixon and Condliffe (1989) that the presence of subcalcic garnet and diamond are not directly related.

Ilmenite. Ilmenite is the predominant mineral phase in almost all the pipes. The grains are generally rounded and often covered by a white, leucoxene rim. They are either monocrystalline or polycrystalline, are often fractured and show undulose extinction. The replacement is mostly to rutile, perovskite and spinel.

There is considerable compositional variation, which is also expressed in the magnetic susceptibility (Table 5 and Fig. 4). The non-magnetic ilmenites are enriched in the geikielite end-member (up to 60 mol.% $MgTiO_3$), but are poor in hematite (less than 20 mol.% Fe_2O_3). The reverse holds for the magnetic ilmenites. The variable Fe^{2+}/Fe^{3+} ratios reflect significant changes in oxygen fugacity. In the $MgTiO_3$–$FeTiO_3$–Fe_2O_3 diagram (Fig. 4), the Kundelungu ilmenites plot along the 'magmatic magnesium enrichment trend' defined by Haggerty *et al.* (1979). A similar behaviour was noted for ilmenites from Tanzania (Nixon and Condliffe, 1989).

The ilmenite macrocrysts (mono- or polycrystalline) are generally homogeneous. Nonetheless, some crystals exhibit compositional zoning (Table 5: Kl1c(ore) and Kl1r(im)). The rim is enriched in Mg and Mn, but depleted in Fe^{2+} and Fe^{3+}. Zoned ilmenites are known from several kimberlite provinces (Haggerty *et al.*, 1979; Pasteris, 1980; Shee, 1984; Agee *et al.*, 1982). The Mg-enrichment

TABLE 4. Representative compositions of garnet from Kundelungu kimberlites

	Cr-poor garnets				Cr-rich garnets			
	Gu10	Ms11	Gw12	Kl10	Ms6	Ko142	Gw76	Gw78
SiO_2	41.39	41.96	41.62	41.36	41.33	40.24	40.99	41.01
TiO_2	0.28	0.66	0.25	0.81	0.80	0.06	0.08	0.13
Al_2O_3	22.39	21.01	22.58	21.73	17.55	18.14	19.07	19.32
Cr_2O_3	1.90	2.15	2.26	0.36	6.53	7.44	6.29	6.29
Fe_2O_3*	0.00	1.43	0.00	1.70	1.63	0.00	0.18	0.00
FeO	8.56	6.57	8.12	9.38	5.89	7.88	7.67	7.89
MnO	0.43	0.26	0.44	0.38	0.28	0.44	0.36	0.33
MgO	20.11	21.15	19.74	18.94	20.58	18.58	19.83	19.38
CaO	4.26	4.42	4.62	5.04	5.36	6.10	5.23	5.29
Total	99.32	99.61	99.63	99.70	99.95	98.88	99.70	99.64
Numbers of ions on basis of 24(O)								
Si	5.943	5.983	5.952	5.958	5.969	5.937	5.949	0.953
Ti	0.030	0.071	0.027	0.028	0.087	0.007	0.008	0.015
Al	3.789	3.513	3.805	3.690	2.987	3.154	3.261	3.305
Cr	0.216	0.242	0.256	0.041	0.746	0.867	0.722	0.722
Fe^{+3}	0.000	0.154	0.000	0.184	0.177	0.000	0.020	0.000
Fe^{+2}	1.027	0.784	0.977	1.013	0.712	0.972	0.931	0.958
Mn	0.053	0.032	0.053	0.047	0.035	0.055	0.044	0.000
Mg	4.305	4.494	4.208	4.066	4.430	4.085	4.289	4.194
Ca	0.655	0.675	0.708	0.778	0.830	0.964	0.813	0.823
Mg/Mg+Fe	0.81	0.85	0.81	0.82	0.86	0.81	0.82	0.81
Ca/Ca+Mg	0.13	0.13	0.14	0.14	0.16	0.19	0.16	0.16

* Calculated by charge balance

of the rims is often ascribed to reaction with the kimberlitic host magma. Haggerty *et al.* (1979) invoke a crystal–liquid reaction as a result of a decrease in pressure. The decrease in oxygen fugacity is manifested by the lower ferric iron content of the rim. Parfenoff (1982) proposed that Fe^{3+}- and Cr-rich ilmenites could be indicators of the presence of diamond. However, it turns out that these ilmenites frequently occur in diamond-poor Kundelungu kimberlites and are rare or absent from the diamond-bearing Mbuji Mayi kimberlites.

Mica. Phlogopite is typical of kimberlites, but its abundance varies from pipe to pipe (Table 6). In some pipes (Luanza and Zefu) phlogopite is completely chloritized, in others it is completely absent as reported previously for kimberlites that are rich in calcite and/or serpentine (Mitchell, 1986). Spinel reaction rims are common, and the flakes are usually contorted and broken. Calcite is often present in fractures and cleavage planes. The phlogopite minerals are Mg-rich; the Mg/(Mg+Fe) ratio ranges between 0.86 and 0.90. The TiO_2 content ranges from 0.58 to 3.77 wt.% and the Al_2O_3 content from 11.5 to 14.01 wt.%. They belong to the Type II defined by Smith *et al.*, 1978.

The ultramafic xenoliths

Petrography and chemical composition

The ultramafic inclusions consist of peridotites (lherzolites, harzburgites, wehrlites and dunites), clinopyroxenites and eclogites. The harzburgites are devoid of clinopyroxene. The inclusions have rounded or disc-shaped form and the size varies from 0.2 to 10 cm. The peridotites belong to two different textural types: a granular or granoblastic texture (cf. Nixon and Boyd, 1973*a*), and a neoblastic texture characterized by deformation features and recrystallization of olivine. Only one single clinopyroxenite inclusion with fasculate texture was observed in the Kundelungu samples. Eclogites only occur in the Gwena pipe; they are composed of omphacite and garnet (pyrope-almandine-grossular) and are similar

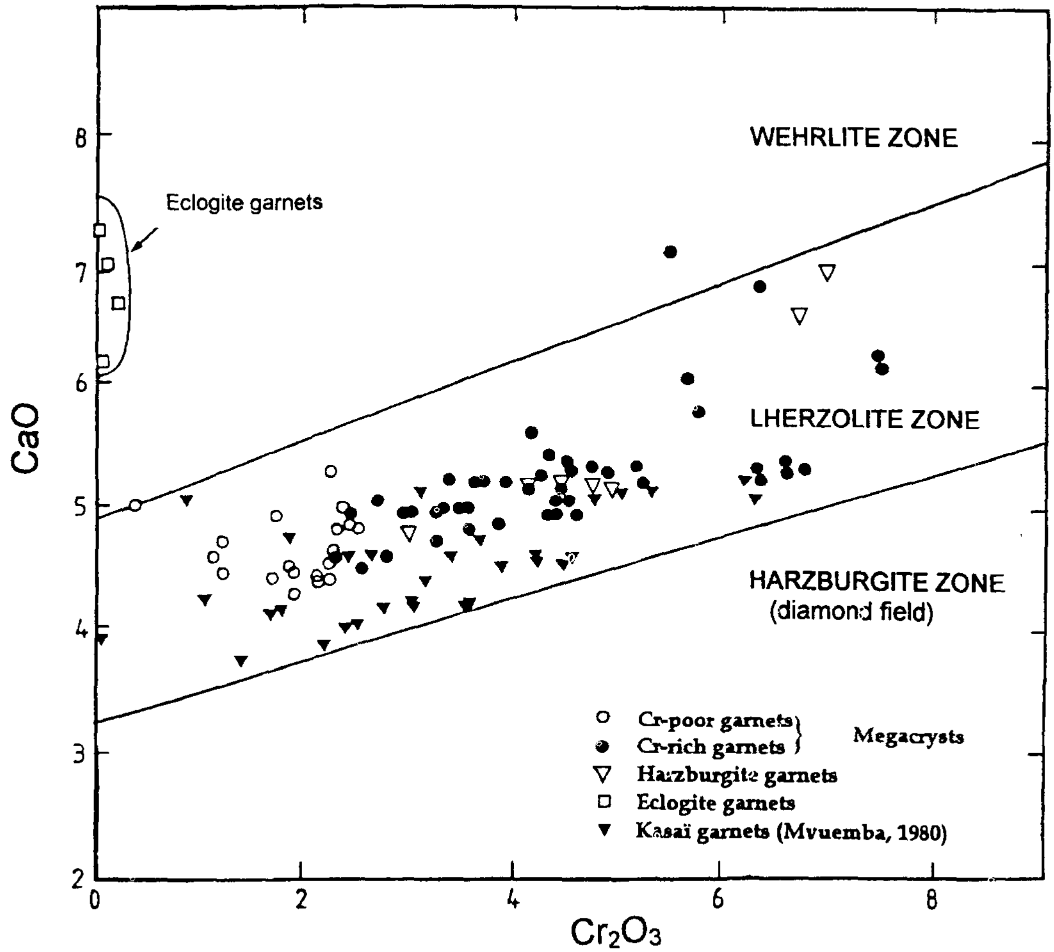

FIG. 3. Composition of garnet megacrysts. Kundelungu: this work; Kasai: Mvuemba (1980); lherzolite field as defined by Sobolev *et al.* (1973).

to the eclogites from the Roberts Victor Mine. The inclusions were subjected to stress and corrosion, as witnessed by fracture of mineral grains and the disc shape of the inclusions. The chemical analyses of mineral grains are listed in tables 7 and 8, and summarized in Table 9.

Olivine. The olivines are fractured or are present as polycrystalline aggregates (in dunites); stress induced undulose extinction is common. There are no compositional differences between olivines from lherzolites and harzburgites. The Mg/(Mg+Fe) ratio is comprised between 0.92 and 0.93. The only exception is the lower value of 0.88 for olivine from sheared peridotite LH-Ms1. Nixon and Boyd (1973*a*) likewise did not detect a significant difference between the two peridotite types from Lesotho. The lowest Mg/(Mg+Fe) ratio measured in olivines from kimberlites is 0.86. The nickel content ranges from 0.02 to 0.41 wt.%.

Orthopyroxene. The Mg/(Mg+Fe) ratios of orthopyroxene from ultramafic nodules generally fall between 0.91 and 0.94. A slightly larger range (0.91–0.96) is observed in orthopyroxene grains from Kundelungu peridotites. Orthopyroxenes from harzburgites have a lower CaO content than those from lherzolites (0.17–0.29 wt.% versus 0.26–1.46 wt.%).

Clinopyroxene. Clinopyroxenes from wehrlites and lherzolites with granular texture have similar Ca/(Ca+Mg) ratios (0.45–0.49). The high values

TABLE 5. Representative compositions of ilmenite from Kundelungu kimberlites

	non-magnetic ilmenites			magnetic ilmenites			zoned ilmenites	
	Kl02a	Gw12a	Ms21a	Kl17b	Ms06b	Mb41b	Kl01c	Kl01r
TiO_2	51.28	47.12	52.08	35.86	40.88	36.37	46.41	55.01
Al_2O_3	0.55	0.42	0.49	0.44	0.15	0.32	0.27	0.28
Cr_2O_3	0.15	0.14	0.51	0.05	0.75	1.23	0.20	0.14
Fe_2O_3*	9.26	15.12	8.33	34.61	25.08	31.19	15.58	5.36
FeO	27.74	28.86	26.79	23.42	28.14	26.31	29.94	23.55
MnO	0.25	0.27	0.19	0.01	0.09	0.12	0.22	0.42
MgO	10.71	7.63	11.37	5.13	5.04	3.97	6.65	14.45
Total	99.47	99.56	99.76	99.52	100.15	99.51	99.29	99.30
Numbers of ions on basis of 3(O)								
Ti	0.904	0.852	0.911	0.667	0.754	0.682	0.848	0.945
Al	0.015	0.012	0.013	0.013	0.004	0.009	0.008	0.008
Cr	0.003	0.003	0.009	0.001	0.015	0.024	0.004	0.003
Fe^{3+}	0.172	0.282	0.153	0.683	0.472	0.602	0.290	0.099
Fe^{2+}	0.525	0.577	0.514	0.478	0.568	0.532	0.603	0.443
Mn	0.005	0.005	0.004	0.003	0.002	0.003	0.005	0.008
Mg	0.374	0.273	0.394	0.189	0.184	0.148	0.241	0.492
Mole %								
$FeTiO_3$	53.91	58.44	52.66	49.24	58.08	55.42	61.46	45.45
$MgTiO_3$	37.78	27.71	40.00	19.10	18.69	15.11	24.18	50.00
Fe_2O_3	8.31	13.85	7.34	32.16	23.23	29.47	14.63	4.55

* Calculated by charge balance

underscore the affiliation with the low-T xenoliths (Boyd, 1987; Nixon and Condliffe, 1989). In contrast, clinopyroxenes from deformed lherzolites have the lower Ca/(Ca+Mg) ratios typical of subcalcic diopsides from high-*T* peridotites (Tables 7 and 8). The Na_2O content of clinopyroxenes from low-*T* peridotites varies between 0.95 and 2.78 wt.%; in clinopyroxenes from high-*T* peridotites it is less than 0.18 wt.%. The Na-rich (5.18–5.48 wt.% Na_2O) omphacites from eclogite inclusions have low Cr_2O_3 (<0.09 wt.%) and TiO_2 (0.27 wt.%) concentrations, but have higher Ca/(Ca+Mg) ratios (0.51–0.52) than the diopsides from lherzolites. The eclogite inclusions from Kundelungu show a strong resemblance to those from the Roberts Victor Mine (Boyd and Nixon 1975). Clinopyroxenes from pyroxenite contain higher amounts of TiO_2 (0.49–1.56%) and FeO (4.6–5.3%) and have higher Ca/(Ca+Mg) ratios (0.51–0.52) than the lherzolites (Table 8).

Garnet. Garnets from harzburgites generally have a kelyphitic rim or a corona of Cr-rich phlogopite. Olivine inclusions are common, but only in harzburgites and eclogites. The composition of garnets from harzburgites fall in the lherzolite field defined by Sobolev *et al.* (1973). These garnets are calcic and Cr-rich (4.08–6.66 wt.% Cr_2O_3); the Mg/(Mg+Fe) ratios vary between 0.79 and 0.83. In contrast, the garnets from eclogites are pyrope-almandine-grossular solid solutions, having Ca/(Ca+Mg) ratios between 0.32 and 0.34, and Mg/(Mg+Fe) ratios between 0.46 and 0.48 (Table 8 and Fig. 3).

Spinel. This accessory mineral is scarce in the peridotites from Kundelungu, but is an abundant late solidification product within the kimberlite matrix. Spinel also often forms coronas around garnet. The composition of these Cr-spinels is similar to that reported for harzburgites from India by Ganguly and Bhattacharya (1987); the Cr_2O_3 content is somewhat higher (48.3–58.2 wt.%), the TiO_2 content lower (0.15–2.1 wt.%). The MgO varies from 11.8 to 12.7 wt.%.

P-T conditions recorded by ultramafic xenoliths

Ultramafic xenoliths are primarily studied to determine the pressure and temperature at which the mineral components were in thermodynamic equilibrium. For this purpose we have applied the computer program TEMPEST of Finnerty and Boyd (1984), in which several combinations of geotherm-

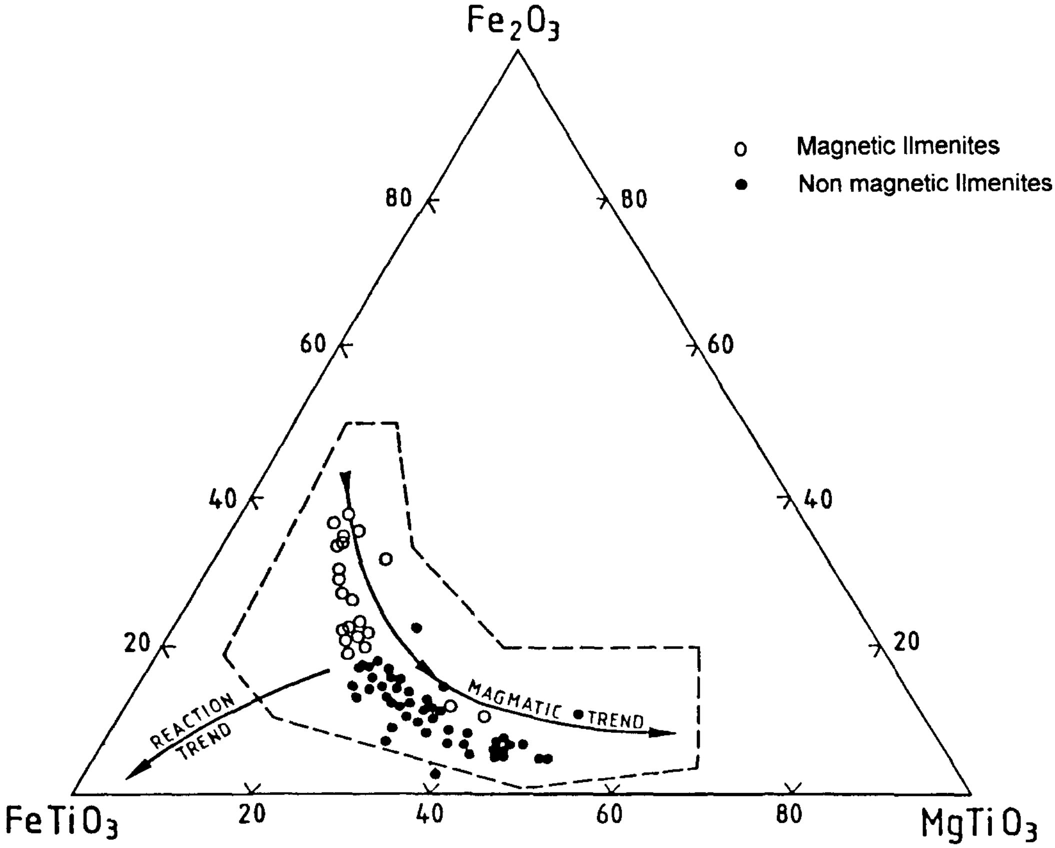

FIG. 4. Composition of ilmenite megacrysts. Open symbols = magnetic; filled symbols = non-magnetic. Magmatic Mg-enrichment trend from Haggerty *et al.* (1979).

ometers and geobarometers are used. We have chosen the more commonly used thermobarometers to facilitate comparison with published estimates for peridotites from kimberlites. The combination FB86-MC74 (see Table 10) was applied to calculate *P–T* conditions for lherzolites, the combination OW79-MC74 for harzburgites. The equilibrium temperature of eclogites was estimated with the aid of the thermometer designed by Ganguly (1979).

The peridotite assemblages from Kundelungu cover a fairly large *P–T* domain (Fig. 5; Table 10): from 700 to 1390°C and from 26 to 61 kbar. The *P–T* diagram indicates two groups of peridotites, such as previously observed for mantle xenoliths from below the Kaapvaal Craton (Boyd 1987): (*a*) peridotites exhibiting equilibration temperatures < 1100°C (garnet harzburgites and granular textured lherzolites). These xenoliths are comparable to the 'depleted peridotites' from lithospheric mantle. (*b*) high-temperature ($T > 1100$°C) sheared or mylonitic lherzolites, represented in our collection by sample LH-Ms1.

The depleted low-*T* peridotites plot along the continental geotherm derived by Pollack and Chapman (1977). By comparison, the Tanzanian peridotites plot slightly off this reference geotherm (Fig. 5). However, given the small number of data points, it is as yet not possible to propose a specific 'Kundelungu geotherm'. Figure 5 shows that the xenoliths entrained by the Kundelungu kimberlites derive from minimum mantle depths ranging between 90 and 190 km using the methods outlined. Equilibration depths for the high-*T* xenoliths from the Kaapvaal Craton vary from 130 to 220 km using many methods (Finnerty and Boyd, 1987). The kimberlitic magma, considered as host to inclusions and megacrysts, originated from even greater mantle depths (> 220 km).

TABLE 6. Representative compositions of phlogopites from Kundelungu kimberlites

	Te90	Te91	Te108	Kl40
SiO_2	38.88	38.95	40.03	36.51
TiO_2	3.52	3.38	0.58	3.77
Al_2O_3	13.74	13.70	11.57	14.01
Cr_2O_3	0.40	0.23	0.11	0.66
FeO*	4.94	4.73	6.16	5.96
MnO	0.02	n.d.	n.d.	0.08
MgO	22.67	22.97	25.09	20.94
NiO	0.05	0.13	0.07	0.01
CaO	n.d.	0.13	n.d.	0.04
Na_2O	0.16	0.21	0.20	0.08
K_2O	9.81	9.82	10.67	8.92
H_2O	3.73	3.75	3.74	3.60
Total	97.65	98.00	98.22	94.58
Numbers of ions on basis of 24(O,OH)				
Si	5.634	5.616	5.827	5.488
Ti	0.354	0.367	0.064	0.426
Al	2.347	2.333	1.985	2.482
Cr	0.046	0.026	0.012	0.079
Fe	0.599	0.570	0.750	0.750
Mn	0.003	n.d.	n.d.	0.011
Mg	4.897	4.946	5.444	4.693
Ni	0.002	0.016	0.009	0.005
Ca	n.d.	0.016	n.d.	0.007
Na	0.044	0.058	0.056	0.022
K	1.813	1.809	1.982	1.710
OH	4.000	4.000	4.000	4.000
Mg/Mg+Fe	0.891	0.897	0.879	0.862

Total Fe calculated as FeO

Petrologic significance of megacrysts and ultramafic inclusions

The association of kimberlites and megacrysts is a worldwide one that can hardly be considered as fortuitous. But in spite of numerous detailed studies, the genetic relationships between megacryst mineral phases and kimberlite host magma are not yet clearly understood. The central question pertains to whether the megacrysts are phenocrysts or xenocrysts, and has been addressed by several authors.

Eggler *et al.* (1979) distinguished two megacryst populations: a Cr-rich and a Cr-poor one. This criterion cannot be applied to the Kundelungu megacrysts except for garnets, which consist of two distinct groups (separated at 2.5 wt.% Cr_2O_3). Only the Cr-poor variety appears to be present in the Gibeon kimberlite, Namibia (Sprigg, 1988). Nixon and Boyd (1973*b*) argued that grain dimension, chemical homogeneity, mylonitic or fractured nature imply that the megacrysts have crystallized over a long span of time in a liquid different from the kimberlite magma. Studies of $P-T$ equilibration conditions rather appear to indicate that megacrysts formed over a large temperature interval (1000–1400°C) and at pressures around 50 kbar (Gurney *et al.*, 1979). The Ca/(Ca+Mg) ratio of diopside is related to equilibrium temperature. The ratio is low in high-T megacrysts and increases with fractionation and with decreasing temperature; whence its use as a geothermometer (Schulze, 1987).

On the basis of Cr content two types of garnet can be recognized in the Kundelungu kimberlites, although this is not the case for olivines and ilmenites. The Cr-rich garnet is derived from disaggregated peridotite whereas the Cr-poor garnets are widely considered to represent the crystallization products of deep-seated magmas of probable asthenospheric origin (Nixon and Boyd, 1973*b*; Boyd and Nixon, 1975; Gurney *et al.*, 1979; Harte, 1983).

Ilmenite within Kundelungu kimberlites presents an interesting case, because two types can be distinguished on the basis of magnetic susceptibility, and hence on Fe^{3+} and Mg content. The ilmenites plot along the magmatic Mg-enrichment trend defined by Haggerty *et al.* (1979). Some ilmenite crystals are zoned, with rims being enriched in Mg and Mn and depleted in Fe. The abrupt Mg-enrichment of the outer zone is attributed by several authors to reaction with the kimberlite host attending a sudden decrease in pressure. This is taken as evidence for a xenocrystal origin of the ilmenite megacrysts.

According to Wyllie (1987) the megacrysts could be produced by interaction of a peridotitic liquid derived from the fertile asthenosphere with harzburgite within the lithosphere. Such a liquid can be trapped at the base of the lithosphere and can survive there for a long time as a liquid because the initial temperature is well above the solidus.

The peridotitic ultramafic inclusions can be grouped into two populations on the basis of texture and calculated $P-T$ equilibrium conditions. The first group consists of low-T peridotites that are depleted in 'basaltic elements', notably Ti and Fe. The second, high-T group comprises undepleted (fertile) peridotites that generally show deformation textures.

The thermobarometric calculations appear to indicate that the lithosphere below the 1800 Ma old Bangweulu Block extended at the time of eruption to a depth of approximately 200 km. Indeed, the eclogites, low-T peridotites and pyroxenites are considered to be derived from the 'depleted' lithospheric mantle, while the Cr-poor garnet, subcalcic diopside and bronzite megacrysts crystallized from

TABLE 7. Analyses of minerals from Kundelungu lherzolites

	Granular lherzolite, low-T LH-Ko4				Sheared lherzolite, high-T LH-Ms1		
	ol	opx	cpx	sp	ol	opx	cpx
SiO_2	40.93	57.17	54.15	0.05	40.12	56.21	54.09
TiO_2	0.02	0.06	0.11	2.05	n.d.	0.12	0.31
Al_2O_3	0.01	0.63	1.84	11.42	n.d.	1.31	0.31
Cr_2O_3	n.d.	0.25	1.32	48.32	0.04	0.28	0.45
Fe_2O_3*	0.80	2.41	1.01	7.73	0.94	n.d.	n.d.
FeO	6.82	3.14	1.62	16.90	10.73	5.78	4.75
MnO	0.08	0.12	0.09	0.32	0.14	0.09	0.09
MgO	51.04	36.07	17.11	12.68	47.87	32.88	21.31
NiO	0.02	n.d.	0.05	0.02	n.d.	n.d.	n.d.
CaO	0.21	0.34	19.32	0.13	0.09	1.48	16.32
Na_2O	0.01	0.07	1.09	n.d.	0.01	0.18	0.51
K_2O	0.01	0.03	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.95	100.29	97.71	99.62	99.94	98.33	98.14
Mg/Mg+Fe	0.930	0.953	0.950	0.572	0.888	0.910	0.889
Ca/Ca+Mg	0.003	0.007	0.448	0.007	0.001	0.031	0.355

* calculated by charge balance

TABLE 8. Analyses of minerals from Kundelungu garnet harzburgite, wehrlite and eclogite

	Garnet harzburgite Hz-Ms6				Wherlite Wh-Gw1		Eclogite Ecl-Gwe2	
	ol	opx	gt	sp	ol	cpx	cpx	gt
SiO_2	40.92	56.99	41.13	0.03	39.93	53.65	54.28	39.18
TiO_2	n.d.	0.01	n.d.	0.15	0.02	0.15	0.27	0.20
Al_2O_3	0.05	0.51	19.17	9.45	0.02	2.75	7.46	22.31
Cr_2O_3	n.d.	0.24	6.66	58.18	n.d.	2.24	n.d.	n.d.
Fe_2O_3*	0.55	1.77	0.68	5.76	3.06	1.76	5.38	0.23
FeO	7.10	3.17	6.90	15.74	5.81	0.83	1.02	20.16
MnO	0.06	0.10	0.48	0.28	0.08	0.02	0.01	0.52
MgO	50.72	36.00	19.11	11.78	50.92	16.54	15.87	7.21
NiO	n.d.	n.d.	n.d.	0.03	0.02	n.d.	n.d.	n.d.
CaO	0.03	0.29	6.57	n.d.	n.d.	21.26	10.72	10.42
Na_2O	0.09	n.d.	0.06	n.d.	0.01	1.53	5.29	n.d.
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	0.03	0.01	n.d.
Total	99.52	99.08	100.76	101.40	99.87	100.76	100.31	100.23
Mg/Mg+Fe	0.93	0.95	0.83	0.57	0.94	0.97	0.95	0.48
Ca/Ca+Mg	0.00	0.01	0.19	0.00	0.00	0.49	0.52	0.33

* calculated by charge balance

TABLE 9. Ranges of composition of megacrysts and of minerals in ultramafic xenoliths

		Ca/(Ca+Mg) mol. ratios	Mg/(Mg+Fe)	Cr_2O_3	TiO_2 wt. percent	Na_2O
Megacrysts						
Cr-poor garnets		0.10–0.16	0.80–0.85	2.55–7.44	0.01–0.80	–
Cr-rich garnets		0.14–0.21	0.78–0.85	0.36–2.43	0.17–.81	–
Calcic diopside		0.42-0.49	0.90–0.93	1.56–2.73	0.02–0.21	1.4–2.76
Subcalcic diopside		0.32–0.39	0.88–0.91	0.41–1.56	0.18–0.40	1.5–3.42
Bronzite		0.0012–0.031	0.91–0.93	0.17–0.48	0.07–0.16	0.15–0.24
Enstatite		0.0011–0.029	0.91–0.96	0.14–0.44	0.03–0.17	0.06–0.18
Magnetic ilmenite		–	0.18–0.28	0.02–2.64	30.9–41.7	–
Non-magnetic ilmenite		–	0.32–0.58	0.02–0.70	53.1–46.0	–
Lherzolite	ol	0.01–0.03	0.88–0.93	0.00–0.04	0.00–0.05	–
	cpx	0.35–0.45	0.89–0.95	0.45–2.05	0.06–0.39	0.51–2.78
	opx	0.005–0.031	0.91–0.93	0.25–0.34	0.06–0.12	0.07–0.18
Harzburgite	ol	–	0.92–0.93	0.00–0.05	0.00–0.06	–
	opx	0.003–0.005	0.94–0.95	0.2–0.4	0.01–0.08	0.00–0.17
	grt	0.14–0.19	0.79–0.83	4.08–6.66	0.11–0.22	0.00–0.06
Wehrlite	ol	–	0.87–0.93	–	–	–
	cpx	0.47–0.49	0.92–0.95	1.05–2.24	0.15–0.20	1.53–2.27
Eclogite	cpx	0.51–0.52	0.78–0.90	–	0.22–0.27	5.18–5.40
	grt	0.32–0.34	0.46–0.48	–	0.13–0.20	–
Pyroxenite	cpx	0.52	0.85	–	1.57	0.54

ol = olivine; cpx = clinopyroxene; opx = orthopyroxene; grt = garnet

TABLE 10. Temperature and pressure of equilibrium of Kundelungu peridotites and eclogites

Specimen	Pipe	Textural type	Mineralogy ol	opx	cpx	gt	sp	Temp. in °C	Pressure in kbar
HZ-Gw1	Gwena	granular	x	x	n	x	n	948	43
HZ-Gw2	Gwena	granular	x	x	n	x	n	1011	49
HZ-Ms3	Msipashi	granular	x	x	n	x	n	834	33
HZ-Ms4	Msipashi	granular	x	x	n	x	n	768	28
HZ-Ms6	Msipashi	granular	x	x	n	x	x	957	36
LH-Kl1	Kambeli	granular	x	x	x	n	n	947	36
LH-Te2	Tengo	granular	x	x	x	n	n	970	46
LH-Ms1	Msipashi	sheared	x	x	x	n	n	1387	61
LH-Ko4	Konzi	granular	x	x	x	n	x	1061	51
ECL-GW1	Gwena	granoblastic	n	n	x	x	n	894	37
ECL-Gw2	Gwena	granoblastic	n	n	x	x	n	874	39

LH = lherzolite   ECL = eclogite   x = present
Hz = harzburgite   n = non observed
Temperature and pressure of lherzolites are calculated by FB86-MC74 couple and *T* and *P* of harzburgites by OW79-MC74 combination.
Temperature of eclogites are calculated by GA79 thermometer.
FB86: Finnerty & Boyd, 1986.
OW79: O'Neil & Wood, 1979.
MC74: MacGregor, 1974.
GA79: Ganguly, 1979.

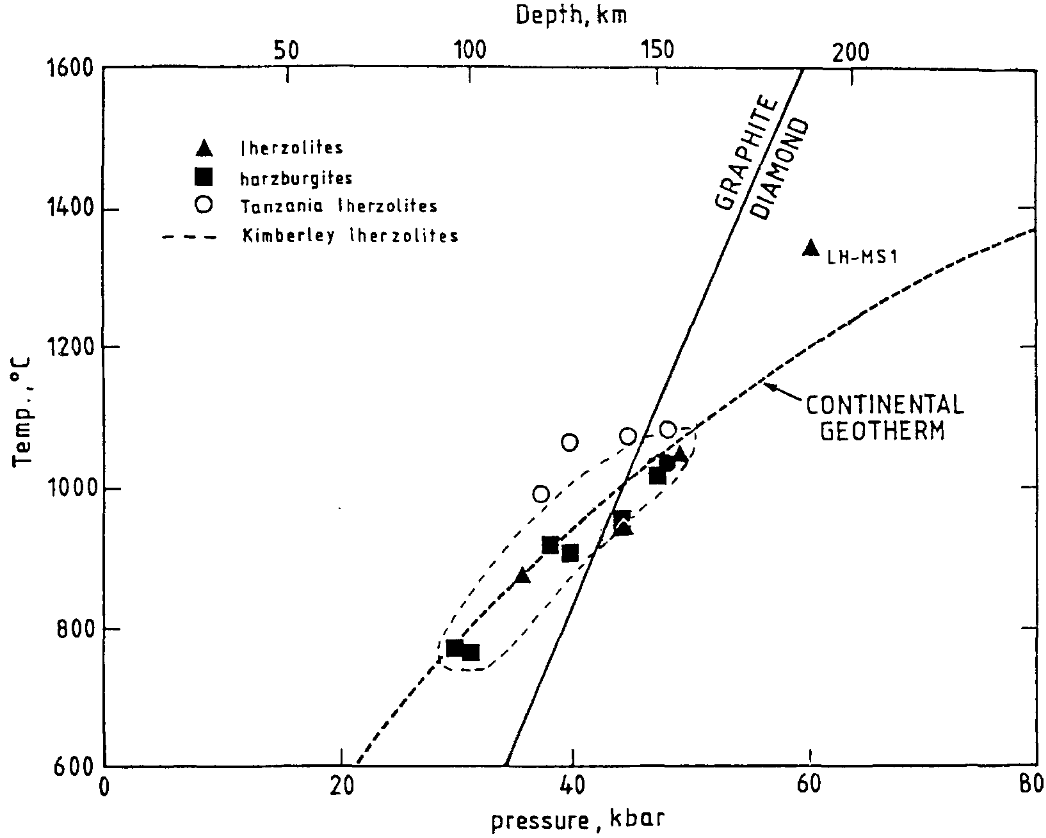

FIG. 5. Calculated $P-T$ equilibration conditions for inclusions from Kundelungu kimberlites. Kimberley lherzolite data from Boyd and Nixon (1978); Tanzania lherzolites (Lashaine alkali basalt) data from Reid *et al.* (1975); graphite–diamond boundary from Kennedy and Kennedy (1976); continental geotherm from Pollack and Chapman (1977).

'fertile' asthenospheric mantle material (Nixon and Condliffe, 1989).

The absence of very depleted xenoliths (harzburgites with subcalcic garnet) and of subcalcic garnet grains in the Kundelungu kimberlites may be seen as an indication of very low diamond content. But we question the reliability of this 'indicator' in view of the fact that subcalcic garnet has never been observed in fluvial concentrates in the Kasai kimberlite region, which is nonetheless famous for its high diamond content (Mvuemba, 1980).

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