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Mantle and crustal xenoliths from the Okenyenya lamprophyre diatreme: constraints on the upper mantle and lower crust beneath the Damara Belt, northwestern Namibia

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Mantle and crustal xenoliths and megacrysts hosted in an alnöite diatreme emplaced in the Mesozoic Okenyenya igneous complex in northwestern Namibia include ultramafic varieties – lherzolite, wehrlite and clinopyroxenite (all ± spinel ± amphibole), and mafic varieties – granulite, amphibolite, and eclogite. The megacryst suite includes amphibole, clinopyroxene, ilmenite, plagioclase and olivine. The peridotite xenoliths have textures ranging from coarse granular through porphyroclastic to granuloblastic and many show evidence of modal metasomatism by the presence of abundant amphibole. Olivine (Fo_{90} – Fo_{91}), orthopyroxene ($Wo_1En_{89}Fs_{10}$ – $Wo_1En_{90}Fs_9$) and clinopyroxene ($Wo_{46}En_{48}Fs_6$ – $Wo_{48}En_{52}Fs_8$) in the lherzolites are significantly more Mg-rich than those in the wehrlites (Fo_{89}-Fo_{69}; $Wo_1En_{77}Fs_{22}$). Calculated temperatures of equilibration of the lherzolites range from 950 to 1050°C, corresponding to a pressure range for the spinel lherzolites of 18 to 19 kbar. Pressure estimates of the wehrlites are constrained to between 7 and 20 kbar based on the amphibole stability field. Mafic xenoliths include two-pyroxene granulite (opx, cpx, plag, sp), amphibole-clinopyroxene granulite (cpx, amph, plag, sp, scapolite), amphibolite and amphibole eclogite with a mosaic granuloblastic texture. Clinopyroxenes show systematic differences in composition between the different mafic xenolith types, as does amphibole (titanian-magnesio-hastingsite in the eclogite; pargasite in the amphibolite and granulite). Pyroxene equilibration temperatures for the granulites range from 663 to 741°C, at pressures of less than 10 kbar on the basis of the equilibrium mineral assemblage. Equilibration temperatures of the eclogites are estimated at 1120°C (20 kbar) and 1160°C (30 kbar). On the basis of major and trace element compositions, the megacryst suite of minerals are interpreted as xenocrysts that crystallised from parental magmas more primitive (amphibole) and more evolved (clinopyroxene, ilmenite) than the host alnöite. A conceptual model for the mantle and lower crust beneath the Damara mobile belt is proposed in which a lower crust of two pyroxene and amphibole-pyroxene granulite overlies mantle comprising a heterogeneous mixture of spinel lherzolite, wehrlite, eclogite and clinopyroxenite down to a depth equivalent to at least 20 kbar, and which has experienced extensive invasive modal metasomatism and veining by incipient alkaline melts or fluids.

Introduction

Xenoliths hosted in alkali basalts, kimberlites and related alkaline rocks provide valuable information on the nature of the underlying crust and upper mantle that such xenoliths represent. Evaluation of their petrography and mineral chemistry, and the calculation of the temperatures and pressures of equilibration of such xenoliths, allows for the construction of stratigraphic sections through the underlying lithosphere.

Western and northwestern Namibia is host to numerous Mesozoic-aged anorogenic ring complexes that have intruded the Proterzoic-aged Damara belt, with Cape Cross, Messum, Brandburg, Okorusu and the Okenyenya complex being well known examples. Alkaline magmatism is commonly associated with these ring complexes and at Okenyenya manifests itself in the intrusion of several ultramafic lamprophyre dykes, plugs and two xenolith-rich volcanic diatremes. One of the latter, an ultramafic lamprophyre, contains xenoliths of the lower crust and upper mantle and provides a unique opportunity to look into the nature of a small portion of the lithosphere underlying the central Damara belt.

This paper is dedicated to Henno Martin whose contribution to the understanding of the geology of Namibia is unmatched, and who's interest in the alkaline ring complexes in northwestern Namibia formed an integral part of this understanding.

Geological Setting

The Okenyenya igneous complex situated in northwestern Namibia is one of a number of Mesozoic anorogenic ring complexes emplaced into the Swakop belt of the late-Proterozoic Damara Province in an area close to the southern margin of the Congo craton basement (Fig. 1). The focus of this study is a 100 m diameter diatreme of ultramafic lamprophyre (alnöite) that intrudes the Okenyenya igneous complex, located at 20°50'S, 15°2'E. The diatreme is one of a number of intrusive lamprophyre bodies (dykes, plugs) that cut the earlier rocks in the complex, but the only one that hosts an abundance of different mantle and crustal xenolith lithologies and megacryst phases. Table 1 contains a

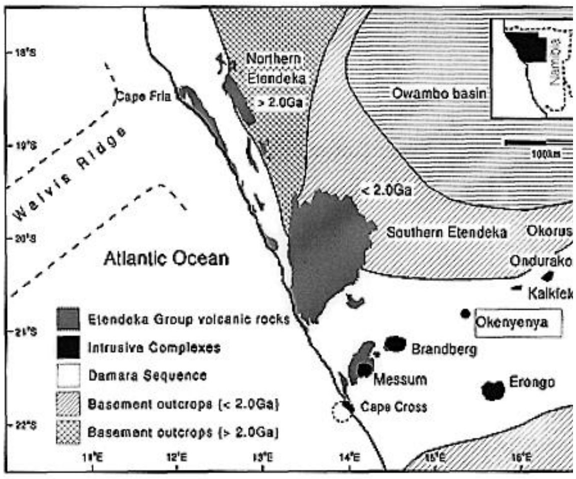

Figure 1: Location map showing the position of the Okenye
igneous complex in relation to the other Mesozoic ring c

Table 1: Summary of xenolith varieties in the Okenyenya alnöite diatreme

Group	Rock Type
Ultramafic xenoliths	Lherzolite, harzburgite, wehrlite and clinopyroxenite (± spinel, ± amphibole)
Mafic xenoliths	Granulite, amphibolite, eclogite
Megacrysts	Amphibole, clinopyroxene, ilmenite, phlogopite, apatite
Country rocks	Gabbro, syenite, lamprophyre

summary of the various xenolith types hosted by the intrusion.

Analytical Techniques

Mineral analyses were conducted using a Cameca Camebax electron microprobe in the Department of Geological Sciences, University of Cape Town. Operating conditions were 15KV and 40nA, except for NiO in olivine which was determined at 25KV. Standardisation was against natural and synthetic mineral standards. Rare earth element abundances in amphibole megacrysts were determined by gradient ion chromatography following the procedures, and with similar accuracy and precision, to those outlined in le Roex and Watkins (1990).

Petrography

Ultramafic xenoliths

Two groups of ultramafic xenoliths are recognised within the Okenyenya diatreme; Type I peridotites from the Cr-diopside lherzolite group, and Type II wehrlites belonging to the Al-augite wehrlite-pyroxenite group, as defined by Harte and Hawkesworth (1989). The Type I peridotite xenoliths are dominantly lherzolite with less abundant harzburgite. Accessory phases include spinel and amphibole, and where the abundance of these exceed 1 wt.%,they will be used as qualifiers, e.g. spinel lherzolite. The modal mineralogy of selected xenoliths is reported in Table 2. The peridotite xenoliths show a range in textures from coarse granular through porphyroclastic to granuloblastic (Harte, 1977) and although the predominant texture is coarse granular (Fig. 2a), all three textures may be exhibited in a single sample. These latter samples are termed intermediate (Fig. 2b) following the nomenclature of Moore (1986). Deformation in the coarse and porphyroclastic olivine and orthopyroxene is evident in the undulose extinction, deformation bands, and well-developed sub-grain boundaries. Deformation is absent in the granuloblastic mineral phases. Spinel mainly occurs as an interstitial phase and typically mantles both clinopyroxene and orthopyroxene in a necklace texture (Fig. 2c). Small rounded or euhedral spinels can occur as inclusions in the olivine, orthopyroxene and clinopyroxene granuloblasts, and numerous tiny euhedral spinels have exsolved from the coarse clinopyroxene and orthopyroxene. These textural features suggest that the Okenyenya peridotites have undergone sub-solidus re-equilibration.

The Type II wehrlites are composed predominantly of olivine and clinopyroxene, although significant amphibole may also occur in these rocks. The wehrlites contain on average 50% olivine and 30% clinopyroxene, with the balance of phases comprising amphibole and spinel in varied proportions. Like the Type I peridotites, the wehrlites have textures ranging from coarse granular to granuloblastic. Amphiboles in two of the wehrlites are concentrated in distinct bands and the texture and morphology of these bands indicate that they are vein features (Fig. 2d). The exsolution of minute spinels in the clinopyroxene in the wehrlites suggest that these rocks have also undergone sub-solidus re-equilibration.

Mafic xenoliths

Mafic xenoliths found in the Okenyenya diatreme include mafic granulites, amphibolites and amphibole eclogites. The granulite xenoliths comprise two varieties: single pyroxene granulite composed of clinopyroxene, plagioclase, amphibole, spinel and scapolite, and two-pyroxene granulite comprising the same assemblage plus orthopyroxene but minus scapolite. Representative modal analyses of the mafic xenoliths are reported in Table 2. The granulites all display metamorphic textures ranging from coarse granular through porphyro-

Table 2: Modal proportions of selected ultramafic and mafic xenoliths from the Okenyenya alnöite diatreme; oliv = olivine; opx = orthopyroxene; cpx = clinopyroxene; spn = spinel; gar = garnet; amph = amphibole; plag = plagioclase; scap = scapolite.

Xenolith Type	Sample Number	Lithology	Oliv	Opx	Cpx	Spn	Gar	Amph	Plag	Scap
Ultramafic	JJG 3095b	Spinel lherzolite	40	45	10	5	-	-	-	-
	SRN 9	Spinel lherzolite	46	22	29	3	-	-	-	-
	SRN 24	Lherzolite	50	20	25	1	-	-	-	-
	SRN 26	Lherzolite	55	25	30	tr.	-	-	-	-
	SRN 31	Amphibole wehrlite	50	-	35	8	-	7	-	-
	SRN 134	Amphibole lherzolite	43	15	22	13	-	7	-	-
Mafic	SRN 118	Amphibolite	-	-	38	-	-	60	-	-
	SRN 130	Amphibole clinopyroxene granulite	-	-	40	5	-	20	20	15
	SRN 115	Amphibole eclogite	-	-	46		26	28	-	-
	SRN 116	Two-pyroxene granulite	-	10	40	20	-	-	25	-
	SRN 130	Amphibole two-pyroxene granulite	-	18	45	7	-	15	15	-

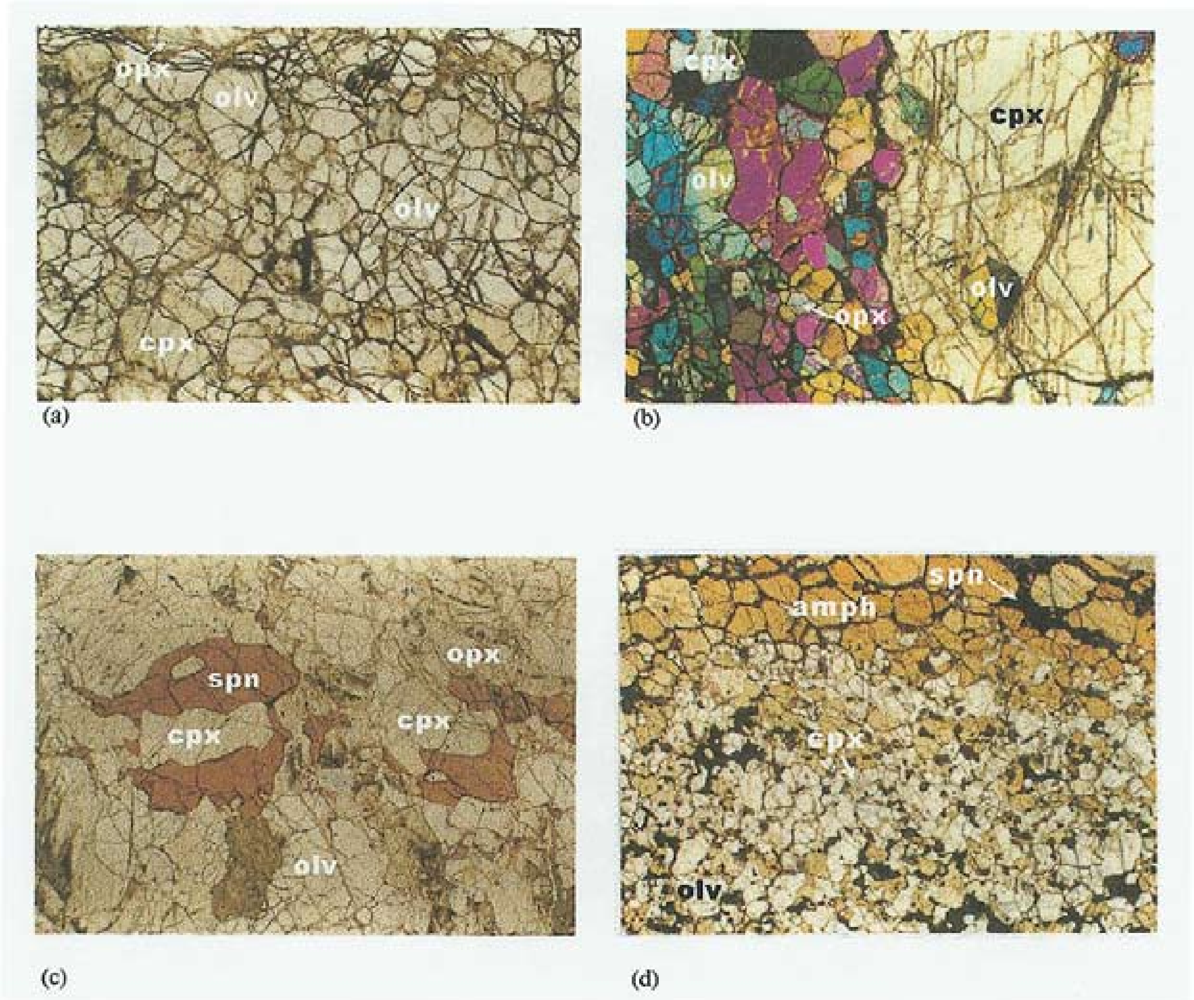

Figure 2: (a) Typical coarse textured lherzolite containing abundant olivine and orthopyroxene, and lessor clinopyroxene. PPL. 2x magnification. – (b) Intermediate textured lherzolite showing coarse clinopyroxene and olivine surrounded by finer-grained neoblastic olivine, orthopyroxene, and clinopyroxene. XPL. 2x magnification. – (c) Spinel lherzolite depicting the typical necklace texture of aluminous brown spinels surrounding coarse clinopyroxene. PPL. 5x magnification. – (d) Typical amphibole wehrlite showing a broad band of amphibole at the top of the photo. These bands are believed to be vein features in the wehrlites due to the cross-cutting relationships. PPL. 5x magnification.

clastic to granuloblastic. Rare layering of clinopyroxene-rich and plagioclase-rich bands is interpreted to reflect metamorphic banding (Fig. 3a). Typically, large porphyroclasts of clinopyroxene are surrounded by a granuloblastic matrix of the other major mineral varieties. Granular scapolite occurs with plagioclase, whereas spinel commonly occurs as an anhedral interstitial phase or as numerous tiny inclusions in coarse plagioclase. Rare symplectic textured intergrowths of spinel and clinopyroxene also occur. The amphibole in the granulites is commonly granular and replaces clinopyroxene but, in some samples, occurs as exsolution laths along prominent clinopyroxene cleavages. The mafic amphibolite xenoliths range from amphibole-dominated varieties to lithologies containing roughly equal proportions of clinopyroxene and amphibole (Fig. 3b). Spinel and other oxides form minor components and mica and plagioclase occasionally occur as a secondary interstitial phase. Textures in the amphibolites range from coarse granular to intergranular with the latter recognised as a relict igneous texture. The two eclogite samples examined in this study have a classic mosaic granuloblastic texture in which fresh, euhedral garnet, clinopyroxene and amphibole exhibit 120° triple grain junctions (Fig. 3c) indicative of complete re-crystallisation (Harte, 1977). Other mafic xenoliths include single examples of a composite xenolith comprising granulite with a cross-cutting amphibolite vein, and a phlogopite-clinopyroxene glimmerite.

Megacrysts

Megacryst phases include titaniferous amphibole and significantly lessor clinopyroxene, ilmenite and phlogopite. Apatite and magnetite occur as inclusions in amphibole and ilmenite megacrysts and are grouped into the megacryst suite. The amphibole megacrysts range in size from 2 to 10 cm and two petrographic

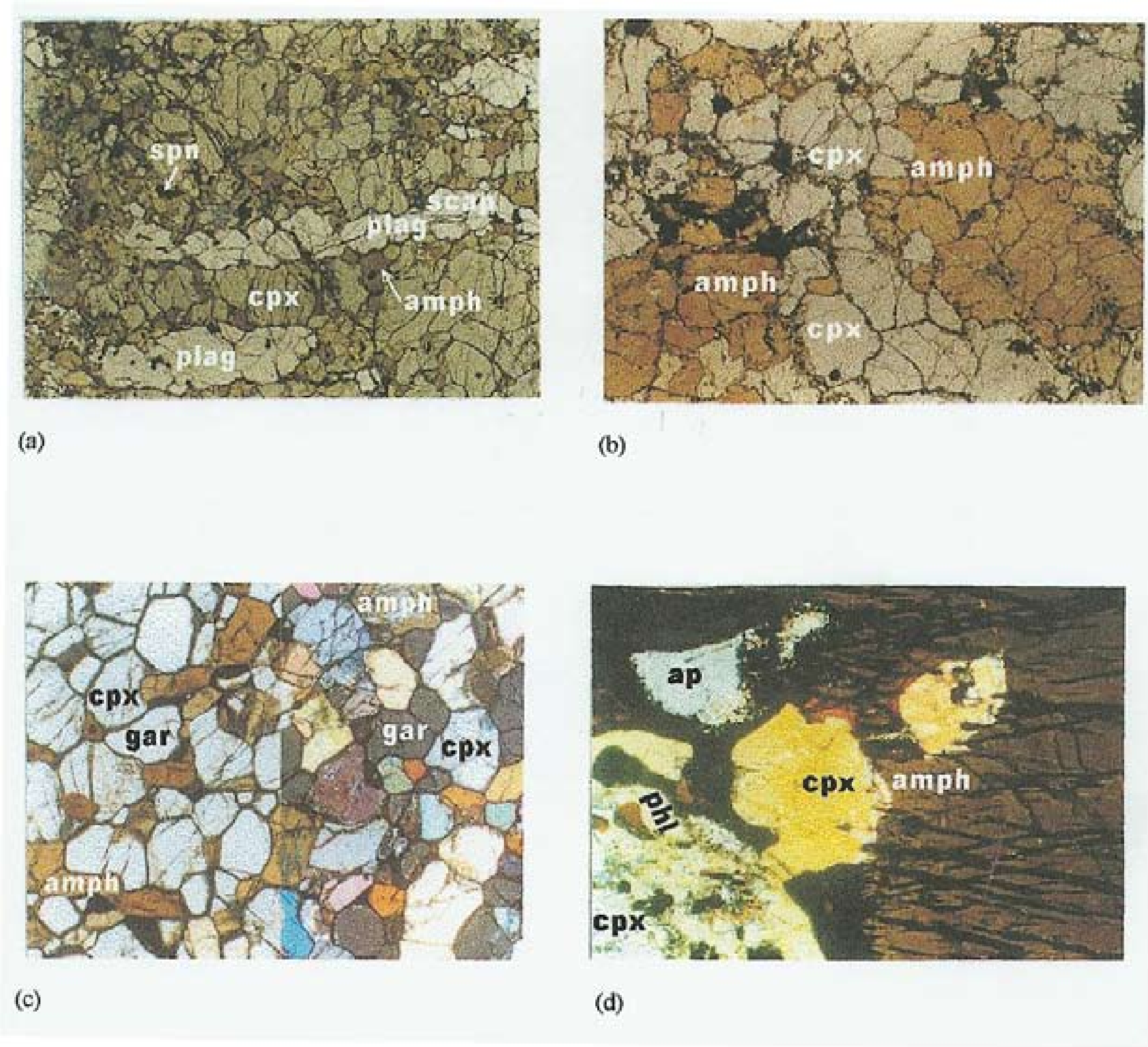

Figure 3: (a) Metamorphic banding in the granulites as reflected in the band of plagioclase and clinopyroxene-dominated crystallisation respectively. PPL. 10x magnification. – (b) Typical amphibolite xenolith containing equal proportions of amphibole and clinopyroxene. PPL. 10x magnification. – (c) Amphibole-bearing eclogite showing 120° triple junction grain boundaries indicative of complete xenolith recrystallisation. PPL and XPL. 2x magnification. – (d) Amphibole megacryst poikilitically enclosing clinopyroxene, phlogopite, and apatite. XPL. 12x magnification.

Table 3: Selected olivine analyses from Okenyenya ultramafic xenoliths; sp lherz = spinel lherzolite; amph lherz = amphibole lherzolite; am wehr = amphibole wehrlite.

	SRN26 oliv	SRN25 oliv	SRN24 oliv	SRN24 oliv	SRN134 oliv	SRN12 oliv	SRN129 oliv
	sp lherz	*sp lherz*	*sp lherz*	*sp lherz*	*am lherz*	*am wehr*	*am wehr*
SiO_2	40.70	40.46	40.38	39.92	38.69	37.77	39.89
TiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Al_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
FeO	9.11	10.82	11.67	13.30	23.19	27.65	15.94
MnO	n.d.	0.15	0.13	0.18	0.30	0.43	0.25
MgO	50.15	48.45	46.78	45.26	38.35	34.90	43.85
CaO	n.d.	0.07	0.04	0.14	0.04	0.04	0.06
NiO	0.37	0.38	0.35	0.30	0.11	0.06	0.31
Total	99.90	100.33	99.35	99.10	100.68	100.80	100.30
Fo	90.9	88.9	87.7	85.8	74.7	69.2	83.1
Fa	9.1	11.1	12.3	14.2	25.3	30.8	16.9

n.d. = not detected

types occur. The first and most common variety is fresh, with a subtle light-dark brown pleochroism and a well-developed cleavage. These amphiboles contain poikilitically enclosed phlogopite, clinopyroxene, ilmenite, magnetite and apatite (Fig. 3d). Some of the amphiboles of this type have thin, dark, alteration rims that appear to have resulted from interaction with the host magma. The second population of amphibole megacrysts are recrystallised, with a distinct porphyroclastic texture. The cleavage and inclusions present in the first population are only preserved in the porphyroclasts of the recrystallised amphibole megacrysts. The ilmenite megacrysts range in size from 1 to 5 cm and occur as subhedral to euhedral crystals commonly fractured and altered to perovskite along their grain margins. Polygranular and mosaic textures, common in ilmenite megacrysts from kimberlites (Shulze, 1987), are occasionally observed. Inclusions of apatite are rare and amphibole inclusions absent. One large ilmenite megacryst contains as an inclusion an elongate pod (2 x 8mm) of recrystallised clinopyroxene.

Mineral Chemistry

Ultramafic xenoliths

The olivine in the lherzolite xenoliths ranges in composition from Fo_{89} to Fo_{91}, whereas the olivine in the wehrlites shows distinct inter-sample variation (Fo_{69} to Fo_{89}; Table 3, Fig. 4). The lherzolite olivines have high and relatively restricted NiO (0.34 to 0.45 wt.%) and low CaO (0.04 to 0.06 wt.%) contents, consistent with olivine in lherzolite xenoliths from localities worldwide (Kohler and Brey, 1990). In contrast, the wehrlites have lower NiO (0.06 to 0.30 wt.%) which decreases with decreasing Mg#, and generally higher and more variable CaO contents (0.04 to 0.25 wt. %).

The orthopyroxenes in the spinel lherzolites are Mg-rich enstatites (Mg# = 89 to 91; Fig. 4) with elevated aluminium contents (4 to 5 wt.% Al_2O_3; Table 4), whereas those in the amphibole lherzolites are more Fe-rich (Mg# ~78; Fig. 4) and have higher Al_2O_3 contents (6 to 8 wt.%). The clinopyroxenes in the ultramafic xenoliths span a wide compositional range. Those in the spinel lherzolites are predominantly Cr-rich (Cr_2O_3 = 0.53 to 1.09 wt.%) endiopside (Mg# = 0.88 to 0.92), whereas those in the amphibole lherzolites are augites (Mg# = 77-80; Fig. 4) and have lower Cr_2O_3 contents (<0.2 wt.%). The wehrlitic clinopyroxenes have variable Cr content (Cr_2O_3 = detection limit to 0.76 wt.%) and compositions ranging from endiopside to augite (Mg# = 0.86 to 0.70; Table 4; Fig. 4). The majority of clinopyroxene in both the lherzolites and wehrlites have Al_2O_3 contents of 6 to 7 wt.%. In both orthopyroxene and clinopyroxene there is a systematic decrease in Al_2O_3 and increase Cr_2O_3 content as the Cr# (Cr/(Cr+Al)) values of the co-existing spinel increases. Similarly elevated aluminium contents in clinopyroxenes have been

Table 4: Selected pyroxene analyses from Okenyenya ultramafic and mafic xenoliths and megacrysts. sp lherz = spinel lherzolite; am lherz = amphibole lherzolite; wehr = wehrlite; am wehr = amphibole wehrlite; gran = granulite; am eclog = amphibole eclogite; 2 px gran = two pyroxene granulite.

	SRN24	SRN24	SRN25	SRN25	SRN26	SRN26	OKJ59b	SRN131	SRN134	SRN134	JJG3097b
	sp lherz	*sp lherz*	*sp lherz*	*sp lherz*	*sp lherz*	*sp lherz*	*sp lherz*	*sp lherz*	*am lherz*	*am lherz*	*wehr*
SiO_2	51.89	52.16	51.39	54.62	55.55	52.62	54.20	55.72	52.70	50.27	48.01
TiO_2	0.51	0.76	0.41	0.13	n.d.	0.11	0.13	n.d.	0.09	0.7	1.18
Al_2O_3	6.64	3.78	6.44	5.01	4.01	5.19	4.58	4.16	4.99	7.75	8.20
Cr_2O_3	0.74	0.79	0.82	0.41	0.50	0.90	0.32	0.48	n.d.	n.d.	n.d.
FeO	3.23	5.27	2.95	6.92	5.83	2.69	6.73	6.00	14.21	6.61	7.32
MnO	n.d.	0.21	n.d.	n.d.	0.13	n.d.	0.13	n.d.	0.31	0.14	0.18
MgO	15.56	17.00	15.50	32.55	33.71	16.20	33.55	33.34	27.65	13.24	11.91
CaO	20.83	18.11	19.75	0.73	0.61	21.44	0.69	0.62	0.68	20.68	22.08
Na_2O	1.55	1.52	1.48	0.12	0.09	1.34	0.10	0.14	n.d.	1.48	1.01
K_2O	n.d.	0.06	n.d.	n.d.	n.d.	0.08	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.95	99.60	99.28	100.49	100.40	100.50	100.43	100.46	100.63	100.87	99.89
Wo	46.3	39.5	45.3	1.4	1.2	46.5	1.31	1.20	1.3	46.7	49.78
En	48.1	51.5	49.4	88.1	90.1	48.9	88.70	89.74	76.6	41.6	37.34
Fs	5.6	9.0	5.3	10.5	8.7	4.6	9.99	9.06	22.1	11.7	12.88

n.d. = not detected

Table 4 continued…

	SRN129	SRN12	SRN115	SRN115	SRN116	SRN116	SRN 130	SRN130	SRN7	SRN128	SRN120	SRN118
	am wehr	*am wehr*	*am eclog*	*am eclog*	*2 px gran*	*2 px gran*	2 px gran	*2 px gran*	*gran*	*gran*	*amphibolite*	*amphibolite*
SiO_2	53.57	50.36	50.43	51.00	51.14	52.56	51.32	49.17	47.69	48.22	49.23	46.29
TiO_2	0.50	0.37	0.88	0.80	0.30	n.d.	n.d.	0.83	1.00	1.23	1.63	1.92
Al_2O_3	2.71	6.93	8.20	7.91	7.08	5.38	6.69	8.20	10.40	9.67	5.22	9.92
Cr_2O_3	0.45	n.d.	n.d.	0.12	n.d.	n.d.	n.d.	0.10	n.d.	0	0	n.d.
FeO	5.70	7.13	8.35	8.81	6.11	14.59	16.00	6.54	8.03	6.64	9.31	8.42
MnO	0.17	0.23	0.17	0.01	n.d.	0.29	0.29	0	0.20	0	0.14	0.17
MgO	15.24	13.31	12.18	12.51	13.51	26.99	25.59	12.89	10.48	11.45	11.36	10.06
CaO	20.13	20.38	15.76	16.07	21.05	0.56	0.59	21.50	20.98	21.41	21.09	21.85
Na_2O	1.79	1.21	3.88	3.06	1.40	0.07	n.d.	1.01	1.68	1.93	1.97	1.54
K_2O	n.d.	n.d.	0.15	0.01	n.d.	n.d.	n.d.	n.d	n.d.	n.d.	n.d.	n.d.
Total	100.20	99.90	100.01	100.30	100.59	100.44	100.59	100.24	100.46	100.55	99.95	100.10
Wo	44.0	45.8	40.2	39.8	47.2	1.1	1.2	48.3	50.2	50.3	47.8	51.5
En	46.3	41.7	43.2	43.1	42.1	75.9	73.1	40.3	34.8	37.5	35.8	33.0
Fs	9.7	12.5	16.6	17.1	10.7	23.0	25.7	11.5	15.0	12.2	16.4	15.5

n.d. = not detected

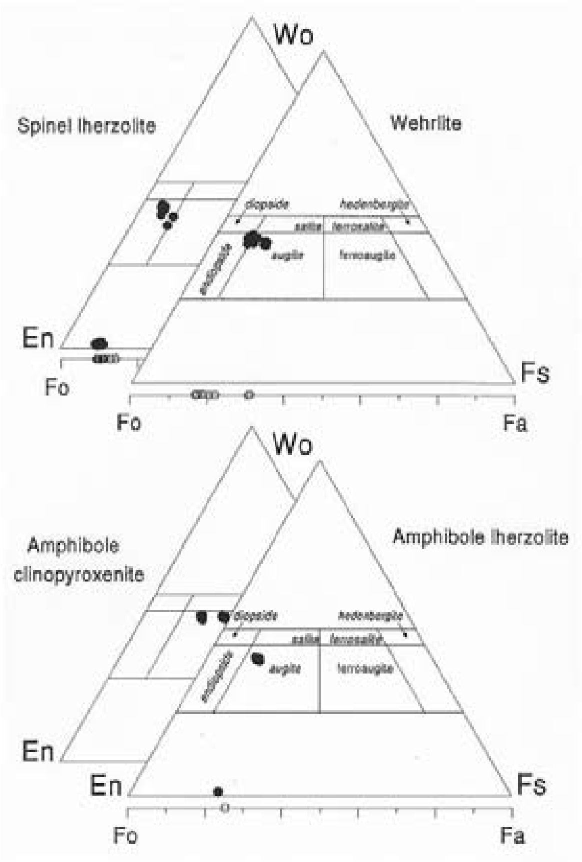

Figure 4: Pyroxene and olivine compositions in ultramafic xenoliths found in the Okenyenya alnöite diatreme.

observed at localities elsewhere and are typically accompanied by the presence of highly aluminous spinel (Morris, 1986).

The spinels in the lherzolites are aluminous, with Cr# less than 0.25. They lie in a restricted area in the spinel-hercynite-chromite-picotite plane of the spinel prism and have chemical variation best described by substitutions of Cr ↔ Al and Fe^{2+} ↔ Mg. The wehrlitic spinels contain minor or no Cr and fall within the spinel-hercynite-magnetite-magnesioferrite plane of the prism. Chemical variations in these spinels involve substitutions of Al ↔ Fe^{3+} and Fe^{2+} ↔ Mg. The Cr# and Mg# of the lherzolitic spinels at Okenyenya are similar to spinels in lherzolite from the San Luis Potisi in Central Mexico (Heinrich and Besch, 1992) and are indicative of the relatively undepleted nature of this spinel lherzolite suite.

The amphiboles in the ultramafic xenoliths are magnesio-hastingsites and pargasites (Leake, 1978). The amphibole in each of the five amphibole-bearing ultramafic xenoliths analysed is chemically distinguishable (Table 5), with two having amphiboles which show a lack of equilibration (variable TiO_2, FeO, MgO, Al_2O_3 and K_2O). Amphiboles in a xenolith with a crosscutting amphibole vein show systematic compositional change away from the vein. This is well illustrated by a TiO_2 profile across the xenolith (Fig. 6).

Mafic xenoliths

The clinopyroxenes in the granulites range from salite to augite in composition, whereas the clinopyroxene in the amphibolites are augites (Table 4; Fig. 5). Al_2O_3 contents of clinopyroxene in both the granulite and amphibolite is high (5.22 to 13.6 wt.%; Table 4). The clinopyroxenes in the amphibole eclogites are Na-rich augites, distinctly different to the clinopyroxene in the rest of the mafic xenolith suite (Table 4; Fig. 5), having lower TiO_2 (<1 wt.%) and higher Na_2O (>3 wt.%) and K_2O (up to 0.26 wt.%) contents.

The amphiboles in the mafic xenoliths are ferroan pargasite and pargasite (Leake, 1978) and are broadly similar across the various mafic xenoliths (Table 5). However, a feature of the amphiboles from the granulites is their relatively high concentration of calculated Fe^{3+}. The amphibole of the two-pyroxene granulite has Na_2O > 3 wt%, and one of the amphibolite xenoliths has a true kaersutitic amphibole with Ti of greater than 0.5 atomic mass units. The amphibole in the amphibole eclogite is best classified as a titanian magnesio-hastingsite, with CaO contents lower, and Na_2O contents and Mg# higher than in amphiboles in the other mafic xenoliths (Table 5). Mg#'s in clinopyroxene and amphibole in the granulites correlate well, suggesting that the two phases are in equilibrium (Fig. 7). The orthopy-

Table 5: Representative analyses of amphiboles from mafic and ultramafic xenoliths from the Okenyenya diatreme; am lherz = amphibole lherzolite; am eclog = amphibole ecglogite; pyrox = pyroxenite; 2 px gran = two pyroxene granulite; gran = granulite.

	SRN134	SRN134	SRN12	SRN12	SRN31	SRN129	SRN115	JJG3097a	SRN130	SRN128	SRN7	SRN7	SRN6
	am lherz	*am lherz*	*am wehr*	*am wehr*	*am wehr*	*am wehr*	*am eclog*	*pyrox*	*2 px gran*	*2 px gran*	*gran*	*amph-ibolite*	*amph-ibolite*
SiO_2	41.66	41.63	39.96	41.20	39.70	44.66	41.70	39.72	40.83	40.34	38.90	38.82	40.20
TiO_2	2.39	2.74	2.99	1.19	4.88	2.74	3.93	3.25	2.64	1.57	1.47	3.20	4.24
Al_2O_3	16.09	16.12	15.60	16.10	15.89	11.05	14.46	16.25	16.14	17.47	17.60	16.53	14.52
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	0.49	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
FeO	9.37	9.32	10.91	10.48	7.69	7.90	11.58	11.23	9.96	10.56	11.75	12.65	10.43
MnO	n.d.	0.13	n.d.	0.14	0.14	n.d.	0.01	0.16	0.13	n.d.	0.16	0.15	n.d.
MgO	14.29	14.72	12.78	14.23	14.57	17.01	13.11	12.56	13.44	13.04	11.87	11.26	12.86
CaO	11.32	11.24	11.54	11.01	12.06	10.23	8.75	12.05	11.40	11.66	11.51	11.42	11.44
Na_2O	3.43	3.53	2.78	3.15	2.43	3.22	3.95	3.05	3.07	3.89	2.75	3.07	2.45
K_2O	0.48	0.44	1.12	0.65	2.12	1.21	0.65	0.58	0.62	0.58	1.42	0.95	2.03
Total	99.03	99.87	99.90	98.15	99.48	98.51	98.14	98.85	98.23	99.11	97.43	98.05	98.23

n.d. = not detected

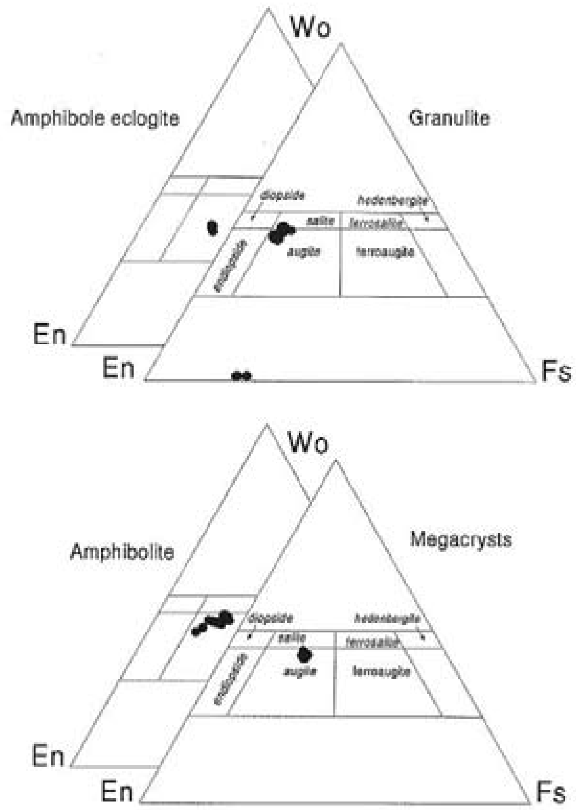

Figure 5: Pyroxene compositions in mafic xenoliths and megacrysts found in the Okenyenya alnöite diatreme.

roxene in the two-pyroxene granulite is an Al-rich ferrohypersthene (Table 4; Fig. 5).

Spinel in the mafic granulites are aluminous, plot within a restricted area on the spinel-hercynite-magnetite-magnesioferrite side of the spinel prism, and are broadly similar to those observed in the wehrlite and amphibole-bearing lherzolite of the ultramafic suite. The garnets in the amphibole eclogite are a mixture of pyrope, almandine and grossular (Table 6) and are broadly similar to those found in eclogite xenoliths in Northern Cape kimberlites (Robey, 1981).

Plagioclase in the granulites and the one amphibolite xenolith shows a restricted range in composition (An_{50} to An_{60}), as does the scapolite (Meionite 64 to 77; Cl - 0.11 to 0.65 wt.%; Table 7). Mica in the amphibolite (Table 7) and the glimmerite xenoliths is phlogopite, and overlaps with the compositional range defined by the phenocrystic phlogopite in the host magma (le Roex and Lanyon, 1998).

Megacrysts

The amphibole megacrysts range in composition between titanian-magnesian hastingsite and titanian-magnesio hastingsite (Leake, 1978), and in the literature would commonly be called kaersutites. Individual grains are chemically homogeneous but, as a group, they span a moderate range in major element composition (Table 8). Mg# ranges from 0.51 to 0.80, Al_2O_3 from 12.1 to 14.6 wt%, Na_2O from 2.48 to 3.39 wt% and K_2O from 1.67 to 2.24 wt%. The ilmenite megacrysts and ilmenite inclusions in the amphibole meg-

Table 6: Selected analyses of spinels and garnets from ultramafic and mafic xenoliths in the Okenyenya diatreme. Fe_2O_3 calculated following Droop (1987). sp lherz = spinel lherzolite; am lherz = amphibole lherzolite; am wehr = amphibole wehrlite; gran = granulite; eclog = eclogite.

	OKJ 59B sp	SRN 25 sp	SRN 134 sp	SRN 12 sp	JJG 3097b sp	SRN 116 sp	SRN 128 sp	SRN 7 sp	SRN 115 gar	SRN 115 gar
	sp lherz	*sp lherz*	*am lherz*	*am wehr*	*wehr*	*gran*	*gran*	*gran*	*eclog*	*eclog*
SiO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	40.00	39.97
TiO_2	0.16	0.17	0.08	0.07	0.42	n.d.	n.d.	n.d.	0.17	0.13
Al_2O_3	54.82	52.84	57.87	58.49	55.01	59.92	58.81	56.63	22.96	22.73
Cr_2O_3	9.76	11.80	0.58	0.18	0.17	n.d.	0.34	0.31	0.01	0.14
Fe_2O_3	5.47	5.66	8.46	7.55	10.66	6.47	6.91	9.36	0	0
FeO	7.19	7.94	15.53	18.36	21.55	16.19	18.19	20.05	18.65	18.63
MnO	0.12	0.12	0.15	.22	0.32	0.13	0.43	0.35	0.38	0.43
MgO	21.49	20.94	16.33	14.64	12.64	16.05	14.64	13.39	13.64	13.61
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	0.17	n.d.	n.d.	4.26	4.39
NiO	0.40	0.30	0.23	0.16	-	0.10	n.d.	0.10	-	-
Na_2O	-	-	-	-	-	-	-	-	0.01	0.01
Total	99.42	99.7	99.23	99.67	100.77	98.93	99.32	100.09	100.08	100.04

n.d. = not detected

Table 7: Representative analyses of scapolite and mica in the Okenyenya crusted and amphibolite xenoliths. CO_2 calculated; gran = granulite; amph = amphibolite; glim = glimmerite; scap = scapolite.

	SRN 128	SRN 128	SRN 7	SRN 7	SRN 6	SRN 6	SRN 13
	gran	*gran*	*gran*	*gran*	*amph*	*amph*	*glim*
	scap	*scap*	*scap*	*scap*	*mica*	*mica*	*mica*
SiO_2	45.46	46.41	44.19	44.55	36.21	36.46	37.71
TiO_2	n.d.	n.d.	n.d	n.d.	5.58	5.73	4.86
Al_2O_3	27.38	26.99	26.16	26.71	15.77	15.11	17.19
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
FeO	n.d.	0.24	0.33	n.d.	11.6	12.87	8.71
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	0.14	n.d.
MgO	n.d.	0.07	0.10	n.d.	15.57	15.35	18.18
CaO	17.96	16.17	18.45	18.45	n.d.	n.d.	0.18
Na_2O	3.44	4.32	3.01	3.03	0.72	0.67	0.54
K_2O	0.04	0.13	0.16	0.17	8.68	8.5	8.62
Cl	0.10	0.51	0.16	0.18	-	-	-
CO_2	3.50	3.40	3.54	3.60	-	-	-
Total	97.88	98.24	96.10	96.87	94.13	94.83	95.99

n.d. = not detected

Table 8: Average megacryst compositions in Okenyenya alnöite diatreme

	Amph	1σ	Cpx	1σ	Oliv	1σ	Ilm	1σ
SiO_2	40.87	0.39	50.55	0.35	40.21	0.58	0.01	0.00
TiO_2	3.99	0.34	1.10	0.10	-	-	41.07	1.98
Al_2O_3	12.75	0.81	4.57	0.32	0.03	0.03	0.47	0.11
Cr_2O_3	0.01	0.00	0.01	0.01	-	-	0.01	0.00
FeO	14.19	1.63	10.80	0.29	13.14	3.05	51.92	2.24
MnO	0.11	0.08	0.18	0.05	0.16	0.11	0.41	0.11
MgO	11.63	0.83	10.87	0.27	45.64	2.28	3.08	1.03
CaO	10.43	0.35	19.41	0.32	0.14	0.10	0.01	0.00
Na_2O	2.98	0.24	2.53	0.16	-	-	-	-
K_2O	1.95	0.12	0.01	0.02	-	-	-	-
NiO	-		-		0.24	0.13	-	-
Total	98.91		100.03		99.56		96.98	
		Wo	45.2	Fo	86.1			
		En	35.2	Fa	13.9			
		Fs	19.6					

acrysts have a restricted compositional range. MgO contents are generally less than 6 wt%, and Cr_2O_3 is <0.1%. TiO_2 contents range from approximately 40 to 46 wt% (Table 8).

The clinopyroxene megacrysts are Na-rich augites (Table 8; Fig. 5), and are similar to clinopyroxene megacrysts typically found in alkaline lavas (Shulze, 1987; Wilkinson, 1975; Liotard *et al.*, 1988). The mica that occurs as inclusions in amphibole megacrysts is phlogopite, with compositions that are very similar to phlogopite megacrysts from alkali basalts world-wide (Shulze, 1987). They are distinguished from the groundmass phlogopite in the host magma (Lanyon and le Roex, 1995) in that they have distinctly lower TiO_2 contents and correspondingly higher Al_2O_3 contents. Chondrite normalised patterns of REE in selected amphibole megacrysts (Table 9) are enriched in the middle-REE and depleted in the heavy-REE (Fig. 8), a pattern that is typical of amphibole megacrysts in alkali basalts world-wide (Irvine and Frey, 1984).

Geothermobarometry

Ultramafic xenoliths

A wide variety of geothermometers over a range of possible mantle pressures were applied to the spinel lherzolite xenoliths of the Okenyenya volcanic breccia. The methods of Kohler and Brey (1990) gave the most internally consistent results and are reported here. Kohler and Brey's (1990) methods use the application of three different barometers that take into effect the influence of Na in pyroxene on two-pyroxene thermometers. The three thermometers applied are based on: (1) enstatite exchange between clinopyroxene and orthopyroxene; (2) Ca content of orthopyroxene; (3) partitioning of Na between clinopyroxene and orthopyroxene. All three thermometers gave consistent results with the average calculated temperatures for the spinel lherzolite in the range of 988 to 1113°C, at a pressure of 20 kbar. The most suitable geobarometer for garnet-free assemblages is based on the Ca content of olivine and requires ultra-high precision analysis (Jurewicz and Watson, 1988). Geobarometers based on the Al_2O_3 solubility in orthopyroxene are not well established for this phase when occurring in equilibrium with spinel. However,

Table 9: Rare earth element analyses of selected amphibole megacrysts

Element	SRN 57	JJG 3098	JJG 3099
La	6.35	5.64	5.32
Ce	18.8	20.6	17.3
Pr	3.33	3.38	3.35
Nd	16.2	14.7	15.9
Sm	4.05	3.83	4.05
Eu	1.31	1.26	1.32
Gd	3.71	3.34	3.81
Tb	0.50	0.46	0.51
Dy	2.55	2.22	2.66
Er	1.04	0.86	1.07
Yb	0.71	0.59	0.76

Webb and Wood (1986) calculated the composition of spinel and garnet co-existing with two pyroxenes and olivine in the system $CaO-MgO-Al_2O_3-Cr_2O_3-SiO_2$ and demonstrated that the depth of spinel stability and the depth of the spinel to garnet transition increase with an increase in overall Cr content in the system. One may thus obtain a maximum pressure of stability for the spinels in the Okenyenya lherzolites by correlating the Cr/Cr+Al content of spinel with pressure within the spinel lherzolite stability field; this gives a maximum pressure of equilibration of 17 to 19 kbar. This maximum pressure also agrees with the maximum pressure derived by extrapolating the temperature range obtained from the spinel lherzolites at Okenyenya onto the "oceanic geotherm" of Mercier (1980).

Temperature estimates for the garnet-free wehrlites are complicated in that the absence of orthopyroxene from the system negates the use of two-pyroxene thermometry. The presence of amphibole in the wehrlites, however, means that the stability field of amphibole co-existing with a peridotite mineral assemblage may be used to derive a pressure and temperature range for the assemblage (Wallace and Green, 1991). The stability limit for pargasitic amphibole in spinel peridotite under water-saturated conditions is 900°C (at 7 kbar) to 980°C (at 20 kbar). Under water-undersaturated conditions, pargasite is stable from 900°C (at 7kbar)) to 1030°C (at 18 kbar). The maximum pressures defined by this approach are consistent with those derived for the spinel lherzolite assemblages.

Mafic xenoliths

The two-pyroxene geothermometers of Bertrand and Mercier (1985), and Brey and Nickel (1987) were applied to the two-pyroxene granulites. Calculated temperatures show a relatively narrow range of 663 to 741°C. Pressure estimates for garnet-free assemblages are not feasible, although Stoltz (1987) has proposed that garnet-free, pyroxene-bearing granulites equilibrate at pressures of less than 10 kbar. The commonly used Ellis and Green (1979) clinopyroxene-garnet geothermometer was applied to the amphibole eclogite xenoliths to yield equilibration temperatures of 1119°C and 1161°C at 20 and 30 kbar, respectively (amphibole is stable to a maximum pressure of 30 kbar; Wallace and Green, 1991).

Discussion

Integration of the modal mineralogy, mineral chemistry and textural variations found in the mantle xenolith suite sampled by the Okenyenya lamprophyre allows comment to be made on the nature and evolution of the underlying mantle beneath the Damara Belt in north-western Namibia. The majority of xenoliths found are spinel lherzolites of the Type I Cr-diopside suite (Harte and Hawkesworth, 1989) with major element mineral chemistry indicative of geochemically depleted upper mantle. These xenoliths are believed to represent the ambient, sub-continental lithospheric mantle beneath the Damara Belt. The presence of spinel-pyroxene clusters in the spinel lherzolite xenoliths and exsolution of euhedral spinels from both orthopyroxene and clinopyroxene provides evidence of local re-equilibration of the upper mantle beneath this region. Porphyroclastic textures in mantle derived xenoliths have been interpreted by Harte (1977) to result from the deformation and recrystallisation of previously coarse-grained rocks, an interpretation consistent with the similar mineral compositions (including porphyroclasts and neoblasts) and calculated temperatures (950 to 1050°C) for both the coarse-grained and porphyroclastic lherzolites at Okenyenya. The presence of spinel exsolution in pyroxenes from both the undeformed coarse-grained xenoliths and the deformed porphyroclastic xenoliths suggests further that the deformation event was not related to the change in conditions which led to the subsolidus re-equilibration of these rocks. Thus, the deformation and recrystallisation of the lherzolites is interpreted to reflect a response to localised stress at depths of 18 to 19 kbar and temperatures of 950 to 1050°C

The wehrlite xenoliths at Okenyenya are internally homogeneous, have similar mineral modes and textures, yet show a significant variation in mineral composition between samples. The textures and mineral compositions of these rocks and the clinopyroxenite classify them into the Type II Al-augite wehrlite-pyroxenite group of xenoliths (Harte and Hawkesworth, 1989). Wehrlites are commonly believed to represent the products of metasomatism of lherzolitic mantle either by incipient carbonatitic melts (Yaxley *et al.*, 1991) or by hydrous alkaline fluids, with amphibole being an important metasomatic product (Wilshire and Shervais, 1975). The occurrence of composite xenoliths in which Type II pyroxenites intrude Type I lherzolites led Wilshire and Shervais (1975) to suggest that Type II rocks represent intrusive dykes and net vein systems resulting from intrusive processes such as filter pressing and wall rock interaction (Wilshire *et al.*, 1980). The composite xenoliths from the Okenyenya diatreme are consistent with this interpretation and show that metasomatism of Type I lherzolites has accompanied the intrusion of the Type II rocks. For example, the majority of the Okenyenya wehrlites contain interstitial amphibole replacing clinopyroxene, with one specific sample containing two distinct amphibole-dominated veins on the margins of the xenolith. The distinct chemical gradients in amphibole composition (TiO_2, Al_2O_3, MgO) away from the vein (Fig. 6) are consistent with an origin through metasomatic processes (Wilshire and Shervais, 1975; Griffin

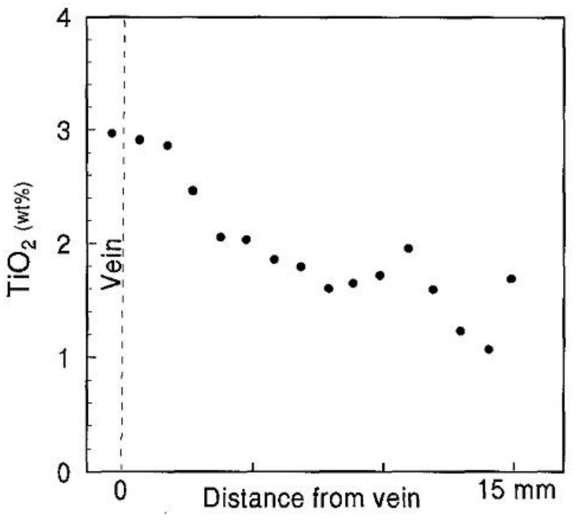

Figure 6: Variation in TiO_2 content in amphiboles with distance from the cross-cutting vein in the composite xenolith.

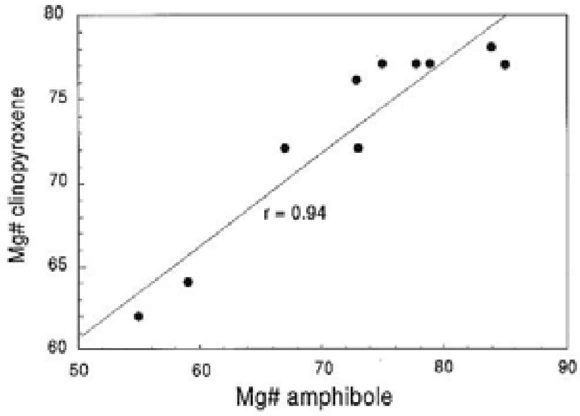

Figure 7: Plot of *mg#* (atomic Mg*100/(Mg+Fe^{2+})) of clinopyroxene versus *mg#* of coexisting amphibole for the granulite xenoliths in the Okenyenya alnöite diatreme.

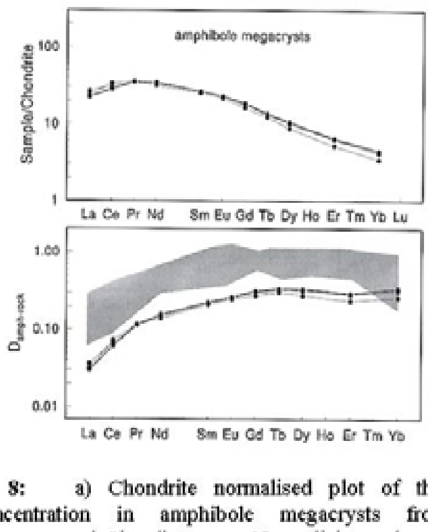

Figure 8: a) Chondrite normalised plot of the REE concentration in amphibole megacrysts from the Okenyenya alnöite diatreme. Normalising values of Sun and McDonough (1989). (b) 1 Calculated partition coefficients for the REE between the alnöite matrix and the amphibole megacrysts. Shaded area represents the range in partition coefficients for amphibole megacrysts in alkali basalts hosts from the experimental work of Irvine and Frey (1984).

et al., 1984). The elevated CaO contents of olivines in the wehrlites (0.06 to 0.26 wt.%) compared to the spinel lherzolites (0.04 to 0.06 wt.%) are similarly consistent with modal and cryptic metasomatic processes (e.g. Jurewicz and Watson, 1988). The abundance of amphibole in the Okenyenya wehrlites and absence of carbonates suggest that metasomatism below this region of the Damara Belt was dominated by hydrous alkaline fluids, rather than incipient carbonatitic melts, with the amphibole-dominated bands resulting from crystallisation of a residual hydrous fluid along the margins of conduits. The similar deformational and recrystallisation features to those exhibited by the lherzolites are interpreted to indicate similar localised stress conditions.

The mineralogy, composition and metamorphic banding (alternating plagioclase-scapolite-rich layers and amphibole-clinopyroxene-rich layers) of the granulite xenoliths found in the Okenyenya diatreme are interpreted to reflect an origin through metamorphism of a mafic igneous protolith at lower crustal depths, with subsequent hydration of the anhydrous assemblage by sub-solidus reaction with an alkaline, hydrous, mantle-derived fluid (e.g. Menzies *et al.*, 1985; Stoltz 1987; Wass and Hollis, 1983; Stosch and Langmuir, 1984). Evidence for a CO_2 component in the fluid is found in the presence of scapolite which is generally considered to result from metamorphic or metasomatic reactions involving a CO_2-rich fluid phase, calcic plagioclase and sulphides (Jones *et al.*, 1983). That these reactions have not proceeded to equilibrium is indicated by the unrealistic temperature (~950°C) calculated for the granulites using the amphibole-plagioclase geothermometer of Blundy and Holland (1990).

Bergman *et al.* (1981) note that CIPW normative compositions of Ti-rich amphibolite veins have nephelinitic to basanitic affinities, whereas Menzies *et al.* (1982) have interpreted amphibolite veins as frozen conduits of undersaturated alkaline melts. The amphiboles in the amphibolites from Okenyenya are rich in Ti, Fe, and K, outlining the alkaline nature of the magma or fluid from which they were derived. The amphibolite veins are likely to have formed either by crystallisation of alkaline magmas or through reaction between a highly alkaline hydrous fluid and anhydrous phases of the wallrock (e.g. Menzies *et al.*, 1982). The presence of intergranular igneous textures and the absence of evidence for amphibole replacing an anhydrous phase suggests that the former alternative may be more appropriate. The variety of textures in the amphibolite xenoliths indicate that they have experienced variable degrees of recrystallisation.

Whole rock, major element composition of the Okenyenya amphibole eclogite xenoliths, calculated using the compositions and estimated modal proportions of the constituent minerals, indicate that they are basaltic with approximately 3 wt% Na_2O+K_2O and 45 wt% SiO_2. The presence of Fe-, K-, and Ti-rich amphibole in the eclogites suggests that the magma from which these rocks crystallised was enriched in alkaline components and, following White *et al.* (1972) who recorded similar amphibole-xenoliths from Kakanui, New Zealand, the Okenyenya eclogite xenoliths are interpreted to have formed by deep-seated crystallisation of a nephelinitic magma. Complete recrystallisation of the eclogite has resulted in its mosaic granuloblastic texture (Harte, 1977). Equilibration temperatures for the eclogitic xenolith range from approximately 1120°C at 20 kbar to 1160°C at 30 kbar. High temperature and pressure eclogites are considered to have formed as direct products of mantle magmatic events or through metamorphism of basaltic rocks crystallised in the lower crust (Harte and Hawkesworth, 1989). The alkaline magmatism resulting in the formation of the amphibolite and amphibole eclogite xenoliths may thus be related to magmatism associated with the formation of the Okenyenya igneous complex. The Okenyenya complex was emplaced at surface over a period of ± 5 Ma (Milner *et al.*, 1993) with alkaline magmatism (alkaline and ultramafic lamprophyres) dominating the final stages of evolution of the complex (le Roex *et al.*, 1996). Crystallisation of similar magmas at depths within the shallower upper mantle and lower crust as amphibolite veins or, at greater depths, as amphibole eclogite assemblages is thus possible. Alternatively, the amphibole-bearing ultramafic rocks, amphibolites and eclogites could represent products of earlier alkaline metasomatism unrelated to the Okenyenya igneous complex. For example, Miller (1983) has argued that the central zone of the Damara Belt may represent the site of an early Pan-African subduction zone. Hydration of the lithospheric mantle and overlying crust could have resulted from upward percolating fluids derived from the subducting slab (Ernst, 1999). Aspects of the mineral chemistry (Na-rich nature of the pyroxenes and amphiboles) are consistent with such an interpretation but in the absence of age information further speculation is not justified.

In order to evaluate megacryst - host magma relationships at Okenyenya, major and trace element partition coefficients have been calculated for clinopyroxene and amphibole megacrysts. An estimate of the coexisting magma composition was obtained by cold leaching hand-picked matrix material in 6M HCl (to remove alteration). This leaching might have caused a loss in primary carbonate phases which in turn would result in the absolute abundances being over-estimated but the likely error in this regard is estimated to be less than 10%. Fe^{2+}/Mg partition coefficients have been calculated for the clinopyroxene megacrysts and the host matrix. Using Fe_2O_3/FeO ratios of 0.2 and 0.3 for the host magma, the calculated Fe^{2+}/Mg partition coefficients (KD's) are 1.06 and 0.93, respectively. These values are significantly higher than the experimentally determined average of 0.29 (Green *et al.*, 1974; Stolper and Walker, 1980; Irvine and Frey, 1984). The Mg# of the magma in equilibrium with the average clinopyroxene megacryst would be 0.35 which is significantly lower than that of the matrix (0.63 with $Fe_2O_3/FeO = 0.3$). The data for the clinopyroxene megacrysts at Okenyenya support the conclusions of various workers (e.g. Schulze, 1987 and references therein) that Na-rich salite clinopyroxenes are generally not related to their host magmas but are crystallisation products of more evolved magmas at depth.

Irvine and Frey (1984) have shown that REE abundances in amphibole megacrysts are generally consistent with crystallisation from the host magmas at high pressures. Calculated partition coefficients for amphibole megacryst – matrix pairs from the Okenyenya diatreme are slightly lower than, but mimic, the shape of the experimental field (Fig. 8) suggesting that the liquid from which the amphibole megacrysts crystallised had a similar REE pattern, but lower absolute concentrations, than that measured for the matrix, i.e. the parental magma was less evolved than the alnöite host. The major and trace element data for the clinopyroxene and amphibole megacrysts suggest therefore that the clinopyroxene and amphibole megacrysts represent two distinct populations, the former having crystallised from a more evolved magma, the latter from a more primitive magma than the host.

Schulze (1987) has proposed the classification of megacrysts in alkaline magmas into Type A (cogenetic) and Type B (exotic). In contrast to the suggestions of Irvine and Frey (1984) and Schulze (1987), i.e. that most Ti-rich amphibole megacrysts are high-pressure crystallisation products of their host magmas, the amphibole megacrysts in the Okenyenya diatreme appear to be of Type B but may have formed from an earlier magmatic or metasomatic event in the lithospheric mantle (Menzies and Wass, 1983). This earlier event was a precursor to the main eruptive event which transported the megacrysts to the surface (Menzies, 1983). The clinopyroxene megacrysts are similarly classified as Type B megacrysts and their intergrowth with other megacryst phases such as ilmenite, phlogopite and apatite suggests that these are also Type B megacrysts. This interpretation is consistent with that of Schulze (1987), viz. that both Na-salite megacrysts and Ti-rich mica megacrysts are generally unrelated to their host magma and are derived from more evolved magmas at shallow depths within the mantle

In summary, the overall diversity of upper mantle and lower crustal xenoliths found in the Okenyenya diatreme indicates a complex and dynamic subcontinental lithosphere beneath the Okenyenya complex which has experienced a protracted history of partial melting, metasomatism and metamorphism. Combining the mineralogical, textural and geothermobarometric information from these samples allows the construction of a hypothetical cross-section of the lower-crust and upper mantle beneath the Okenyenya igneous complex, as illustrated in Figure 9. Following this model, the lower crust beneath the Damara Belt comprises mafic granulite to a depth of approximately 30 km. The definition

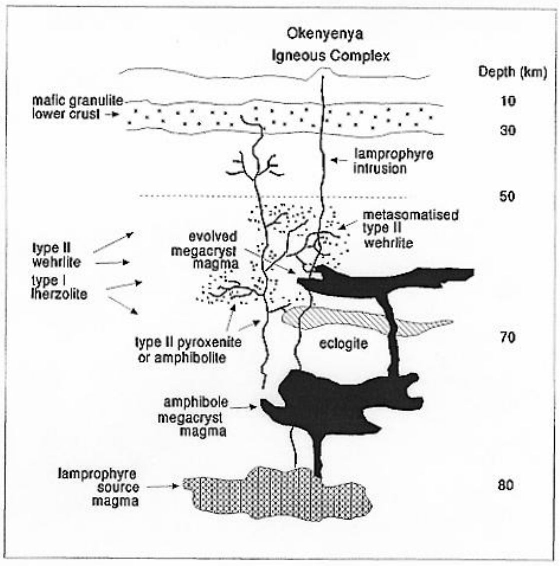

Figure 9: Schematic cross section of the lower crust and upper mantle beneath the Okenyenya igneous complex, northwestern Namibia

of the crust-mantle transition based on basalt xenolith studies has been severely hampered by the lack of pressure estimates on spinel lherzolite assemblages. Based on the pressure estimates from garnet pyroxenites included in alkali basalts, O'Reilly *et al.* (1986) suggest that the crust-mantle transition occurs at approximately 30 km depth and that the boundary is defined by the transition from dominantly mafic granulite wallrock to spinel lherzolite wallrock. The transition from spinel lherzolite to garnet lherzolite is then determined by the depth of the phase change of spinel to garnet (Harte and Hawkesworth, 1989).

The different mantle lithologies (spinel lherzolite, wehrlite and eclogite) and their range in textures provide evidence for a complex upper mantle which, on the basis of recrystallisation textures, appears to have been subjected to local stress conditions. The near ubiquitous presence of amphibole in many of the lithologies provides strong evidence for upwelling alkaline fluids having permeated the upper mantle (giving rise to amphibole lherzolite and amphibole wehrlite assemblages through metasomatism, and amphibole eclogite through deep-seated crystallisation of nephelinitic or lamprophyric magma) and lower reaches of the continental crust (giving rise to amphibolite and amphibole-bearing granulites). The fluid composition is likely to have had a significant CO_2 component leading to the formation of scapolite through reaction with plagioclase. The origin of these fluids is unknown but could be related to the widespread Mesozoic magmatism that occurred in this region between ~135 and 123 Ma (Milner *et al.*, 1995) and was associated with the early phase of upwelling of the Tristan mantle plume (Milner and le Roex, 1996), or they could record earlier, more regional hydration of the lithospheric mantle and lower crust. One source of such regional fluids could be the possible subduction zone environment postulated to be associated with the central zone of the Damara Belt (Miller, 1983).

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References

Bergman, S.C., Foland, K.A. and Spera, F.J. 1981. On the origin of an amphibole-rich vein in a peridotite inclusion from the Lunar Crater Volcanic Field, Nevada, U.S.A. *Earth Planet. Sci. Lett.*, **56**, 343-361.

Bertrand, P. and Mercier, J.-C.C. 1985. The mutual solubility of coexisting ortho- and clinopyroxene: Toward an absolute geothermometer for the natural system? *Earth Planet. Sci. Lett.*, **76**, 109-122.

Blundy, J.D. and Holland, T.J.B. 1990. Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contrib. Mineral. Petrol.*, **104**, 208-224.

Brey, G.P. and Nickel, K.G. 1987. An equation for a DI-EN thermometer calibrated from experiments on natural compositions. *Abstr. 4th Int. Kimb. Conf., Geol. Soc. Austr. Abstr. Series*, **16**, 228.

Droop, G.T.R. 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxides from microprobe analysis using stoichiometric criteria. *Mineral. Mag.*, **51**, 431-436.

Ellis, D.J. and Green, D.H. 1979. An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contrib. Mineral. Petrol.*, **72**, 13-22.

Ernst, W.G. 1999. Hornblende, the continent maker – Evolution of H2O during circum-Pacific subduction versus continental collision. *Geology,* **27**, 675-678.

Green, D.H., Edgar, A.D., Beasley, P., Kiss, E. and Ware, N.G. 1974. Upper mantle source for some hawaiites, murgearites and benmoreites. *Contrib. Mineral. Petrol.*, **48**, 33-43.

Griffin, W.L., Wass, S.Y. and Hollis, J.D. 1984. Ultramafic xenoliths from Bullenmerri and Gnotuk maars, Victoria, Australia: petrology of a subcontinental crust-mantle transition. *J. Petrol.*, **25**, 53-87.

Harte, B. 1977. Rock nomenclature with particular relation to deformation and recrystallisation textures in olivine-bearing xenoliths. *J. Geol.*, **85**, 279-288.

Harte, B. and Hawkesworth, C.J. 1989. Mantle domains and mantle xenoliths. *Abstr. 4th Int. Kimb. Conf. Geol. Soc. Aus. Abstr. Series*, **14**, 649-686.

Heinrich, W. and Besch, T. 1992. Thermal history of the upper mantle beneath a young back-arc extensional zone: ultramafic xenoliths from San Luis Potosi, Central Mexico. *Contrib. Mineral. Petrol.*, **111**, 126-142.

Irvine, A.J. and Frey, F.A. 1984. Trace element abundances in megacrysts and their host basalts: constraints on partition coefficients and megacryst genesis. *Geochem. Cosmochim. Acta*, **48**, 1201-1221.

Jones, A.P., Smith, J.V. and Dawson, J.B. 1983. Glasses in mantle xenoliths from Olmani, Tanzania. *J. Geol.*, **91**, 167-178.

Jurewicz, A.J.G. and Watson.E.B. 1988. Calcium partitioning and calcium-magnesium distribution between olivines and coexisting melts, with petrological applications. *Contrib. Mineral. Petrol.*, **99**, 176-185.

Kohler, T.P. and Brey, G.P. 1990. Calcium exchange between olivine and clinopyroxene calibrated as a geobarometer for natural peridotites from 2 to 60 kb with applications. *Geochem. Cosmochim. Acta*, **55**, 2375-2388.

Lanyon, R. and le Roex, A. P. 1995. Petrology of the alkaline and ultramafic lamprophyres associated with the Okenyenya igneous complex, northwestern Namibia. *S.A. J. Geol.*, **98**, 140-156.

le Roex, A. P. and Lanyon, R. 1998. Isotope and trace element geochemistry of Cretaceous Damaraland lamprophyres and carbonatites, northwestern Namibia: Evidence for plume-lithosphere interactions. *J. Petrol.*, **39**, 1117-1146.

le Roex, A.P. and Watkins, R.T. 1990. Analysis of rare-earth elements in geological samples by gradient ion chromatography: An alternative to ICP and INAA. *Chem. Geol.*, **88**, 151-162.

le Roex, A.P., Watkins, R.T. and Reid, A.M. 1996. Geochemical evolution of the Okenyenya sub-volcanic ring complex, northwestern Nambia. *Geol. Mag.*, **133**, 645-670.

Leake, B.E. 1978. Nomenclature of amphiboles. *Amer. Mineral.*, **63**, 1023-1052.

Liotard, J.M., Briot, D. and Biovin, P. 1988. Petrological and geochemical relationships between pyroxene megacrysts and associated alkali-basalts from Massif Central, France. *Contrib. Mineral. Petrol.*, **98**, 81-90.

Menzies, M.A. 1983. Mantle ultramafic xenoliths in alkaline magmas: evidence for mantle heterogeneity modified by magmatic activity, 111-138. *In*: Hawkesworth and Norry (eds) *Continental basalts and mantle xenoliths*. Shiva, UK, 272pp.

Menzies, M.A. and Wass, S.Y. 1983. CO_2-rich mantle below southeastern Australia: rare earth element, Sr and Nd isotopic study of Cenozoic alkaline magmas and apatite-rich xenoliths, Southern Highland Province, New South Wales, Australia. *Earth Planet. Sci. Lett.*, **65**, 287-302.

Menzies, M.A., Kempton, P. and Duggan, M. 1982. Nature of the continental mantle below the Geronimo volcanic field, Arizona, U.S.A. *Terra Cognita*, **2**, 230-231.

Menzies, M.A., Kyle, P. and Gamble, J. 1985. Fragments of aged enriched sub-continental lithosphere entrained in asthenospheric alkaline magmas erupted at Foster Crater, Antarctica (Abstr.). *EOS*, **66**, 409.

Mercier, J-C.C. 1980. Single pyroxene geothermobarometry. *Tectonophysics,* **70**, 1-37.

Miller, R. McG. 1983. The Pan-African Damara Orogen of Southwest Africa/Namibia, 431-515. *In*: Miller, R. McG. (ed.) *Evolution of the Damara Orogen*. Spec. Publ. geol. Soc. S. Afr., 515 pp.

Milner, S.C. and le Roex. A.P. 1996. Isotope characteristics of the Okenyenya igneous complex, northwestern Namibia: constraints on the composition of the early Tristan plume and the origin of the EM 1 mantle component. *Earth Planet. Sci. Lett.*, **141**, 277-291.

Milner, S.C., Le Roex, A.P. and Watkins, R.T. 1993. Rb-Sr determinations of rocks from the Okenyenya igneous complex, northwestern Namibia. *Geol. Mag.*, **130**, 335-343.

Milner, S.C., Le Roex, A.P. and O'Connor, J.M. 1995. Age of Mesozoic igneous rocks in northwestern Namibia, and their relationship to continental breakup. *J. geol. Soc. London*, **152**, 97-104.

Moore, R.O. 1986. *A study of kimberlites, diamonds and associated rocks and minerals from the Monastery Mine, South Africa*. Unpubl. PhD thesis, Univ. Cape Town, 251 pp.

Morris, P.A. 1986. Constraints on the origin of mafic alkaline volcanics and included xenoliths from Oberon, New South Wales, Australia. *Contrib. Mineral. Petrol.*, **93**, 207-214.

O'Reilly, S.Y., Griffin, W.L. and Johnson, B.D. 1986. Petrologic constraints on geophysical models for the lower crust, Moho and mantle: thermal and seismic interpretations. *Abstr. 4th Int. Kimb. Conf., Geol. Soc. Aust. Abstr. Series*, **16**, 303-315.

Robey, J. van A. 1981. *Kimberlites of the Central Cape Province, R.S.A*. Unpubl. PhD. thesis. Univ. Cape Town.

Schulze, D.J. 1987. Megacrysts in alkalic volcanic rocks, 433-451. *In*: Nixon, P. (ed.) *Mantle Xenoliths*, John Wiley & Sons. New York, 844 pp.

Stolper, E. and Walker, D. 1980. Melt density and the average composition of basalt. *Contrib. Mineral. Petrol.*, **74**, 7-12.

Stolz, A.J. 1987. Fluid activity in the lower crust and upper mantle: mineralogical evidence bearing on the origin of amphibole and scapolite in ultramafic and mafic granulite xenoliths. *Mineralog. Mag.*, **51**, 719-732.

Stosch, H.-G. and Langmuir, G.W. 1984. Evolution of the lower continental crust: granulite facies xenoliths from the Eifel, West German. *Nature,* **311**, 368-370.

Sun, S.-s. and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *In*: Sanders, A.D. and Norry, M.J. (eds) *Magmatism in Ocean Basins*. Geol. Soc. Lond., 313-345.

Wallace, M.E. and Green, D.H. 1991. The effect of bulk composition on the stability of amphibole in the upper mantle: Implications for solidus position and mantle metasomatism. *Mineralog. Petrol.*, **44**, 1-19.

Wass, S.Y. and Hollis, J.D. 1983. Crustal growth in southeastern Australia - evidence from lower crustal eclogitic and granulitic xenoliths. *J. Metamorph. Petrol*., **1**, 25-45.

Webb, S.A.C. and Wood, B.J. 1986. Spinel-pyroxene-garnet relationships and their dependence on Cr/Al ratio. *Contrib. Mineral. Petrol.*, **92**, 471-480.

White, A.J.R., Chappel, B.W. and Jakes, P. 1972. Coexisting clinopyroxene, garnet and amphibole from an `eclogite', Kakanui, New Zealand. *Contrib. Mineral. Petrol.*, **34**, 185-191.

Wilkinson, J.F.G. 1975. Al-spinel Ultramafic-Mafic Inclusion Suite and High Pressure Megacrysts in an Analcimite and Their Bearing on Basaltic Magma Fractionation at Elevated Pressures. *Contrib. Mineral. Petrol.*, **53**, 71-104.

Wilshire, H.G. and Shervais, J.W. 1975. Al-augite and Cr-diopside ultramafic xenoliths in basaltic rocks from western United States. *Phys. Chem. Earth*, **9**, 257-272.

Wishire, H.G., Pike, J.E.N., Meyer, C.E. and Schwarzmann, E.C. 1980. Amphibole-rich veins in lherzolite xenoliths, Dish Hill and Deadman Lake, California. *Am. J. Sci.*, **280A**, 576-593.

Yaxley, G.M., Crawford, A.J. and Green, D.H. 1991. Evidence for carbonatite metasomatism in spinel peridotite xenoliths from western Victoria, Australia. *Earth Planet. Sci. Lett.*, **107**, 305-317.