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Petrology and geochemistry of peridotite xenoliths from the Letlhakane kimberlites, Botswana

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Abstract The diamondiferous Letlhakane kimberlites are intruded into the Proterozoic Magondi Belt of Botswana. Given the general correlation of diamondiferous kimberlites with Archaean cratons, the apparent tectonic setting of these kimberlites is somewhat anomalous. Xenoliths in kimberlite diatremes provide a window into the underlying crust and upper mantle and, with the aid of detailed petrological and geochemical study, can help unravel problems of tectonic setting. To provide relevant data on the deep mantle under eastern Botswana we have studied peridotite xenoliths from the Letlhakane kimberlites. The mantle-derived xenolith suite at Letlhakane includes peridotites, pyroxenites, eclogites, megacrysts, MARID and glimmerite xenoliths. Peridotite xenoliths are represented by garnet-bearing harzburgites and lherzolites as well as spinel-bearing lherzolite xenoliths. Most peridotites are coarse, but some are intensely deformed. Both garnet harzburgites and garnet lherzolites are in many cases variably metasomatised and show the introduction of metasomatic phlogopite, clinopyroxene and ilmenite. The petrography and mineral chemistry of these xenoliths are comparable to that of peridotite xenoliths from the Kaapvaal craton. Calculated temperature-depth relations show a well-developed correlation between the textures of xenoliths and *P-T* conditions, with the highest temperatures and pressures calculated for the deformed xenoliths. This is comparable to xenoliths from the Kaapvaal craton. However, the *P-T* gap evident between low-*T* coarse peridotites and high-*T* deformed peridotites from the Kaapvaal craton is not seen in the Letlhakane xenoliths. The *P-T* data indicate the presence of lithospheric mantle beneath Letlhakane, which is at least 150 km thick and which had a 40mW/m^2 continental geotherm at the time of pipe emplacement. The peridotite xenoliths were in internal Nd isotopic equilibrium at the time of pipe emplacement but a lherzolite xenolith with a relatively low calculated temperature of equilibration shows evidence for remnant isotopic disequilibrium. Both harzburgite and lherzolite xenoliths bear trace element and isotopic signatures of variously enriched mantle (low Sm/Nd, high Rb/Sr), stabilised in subcontinental lithosphere since the Archaean. It is therefore apparent that the Letlhakane kimberlites are underlain by old, cold and very thick lithosphere, probably related to the Zimbabwe craton. The eastern extremity of the Proterozoic Magondi Belt into which the kimberlites intrude is interpreted as a superficial feature not rooted in the mantle.

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Introduction

Although small in size, ultramafic xenoliths in kimberlite diatremes provide the best direct information on the nature of the underlying upper mantle. During the last two decades, considerable effort has been undertaken to disclose the nature and evolution of the upper mantle beneath the Kaapvaal craton in South Africa using petrological, geochemical and isotope data on mantle xenoliths. However, information on the upper mantle below Botswana is not available in the international literature, partly due to a lack of suitable peridotite xenoliths available for study. Mantle derived xenoliths have previously been recovered from the Orapa kimberlite in Botswana, but these are almost exclusively of the megacryst and eclogite variety (Shee 1978; Robinson et al. 1984; Shee and Gurney 1979; Deines et al. 1991). The presence of ultramafic xenoliths in the neighbouring

Letlhakane kimberlites is therefore of particular interest as it provides the first detailed information on the nature of the peridotitic mantle below Botswana.

Baldock et al. (1976) divided the geology of Botswana into cratonic regions, mobile belts and platform regions. The cratonic regions, represented by the Kaapvaal and Zimbabwe cratons (Fig. 1), comprise Archaean gneisses and tonalites varying in age from 3.6 to 2.5 Ga (Barton and Key 1983; Hawkesworth et al. 1979). The Zoetfontein fault or lineament (Fig. 1) is considered by Stowe et al. (1984) to represent the northern boundary of the Kaapvaal craton. The Kaapvaal and Zimbabwe cratons are separated by the 3800 to 2600 Ma old Archaean Limpopo Mobile Belt, until they become obscured by younger deposits in the west. Other Mobile belts in Botswana include the early Proterozoic Magondi (2200 to 2050 Ma) and Kheis (1800 to 1740 Ma) Belts. The diamondiferous Orapa and Letlhakane kimberlites are intruded into the Magondi Mobile Belt, a SE-vergent fold and thrust belt (Hartnady et al. 1985) composed of volcanics, orthoquartzites and carbonate sequences. Stowe et al. (1984) interpreted the Magondi Belt as belonging to the Eburnian Orogenic Cycle and classified it as part of the Kgalagadi tectonic province. Whereas Stowe et al. (1984) interpreted the Magondi Belt as curving southeastwards into the Mahalapaye area of Botswana, Carney and Dowsett (1991) as well as Aldiss and Carney (1992) are of the opinion that it continues southwestward into the Okwa area, since the overall structure and metamorphism in the Mahalapye area appear to be similar to those of the Southern Marginal Zone of the Limpopo Mobile belt. Given the general correlation of diamond-bearing kimberlites with old stable cratons, the Magondi Belt setting of the Orapa and Letlhakane kimberlites is somewhat anomalous. In view of the tectonic setting of the kimberlites it is desirable to characterise the underlying peridotitic mantle. The specific aims of this study are therefore:

(1) to investigate the nature of the peridotitic upper mantle below the Letlhakane kimberlites,

(2) to determine the thermal state of the lithosphere at the time of eruption,

(3) to establish its geochemical and isotopic character,

(4) to contrast the data assembled with existing data for xenoliths of deep lithosphere from beneath recognised cratonic areas of southern Africa.

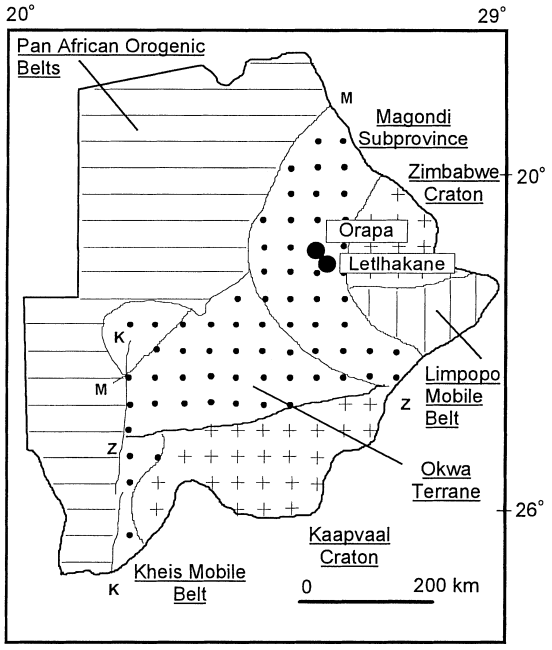

Fig. 1 The distribution of major Archaean, Eburnian and Kibaran crustal units in Botswana as interpreted by Stowe et al. (1984). *M-M* Makgadikgadi Lineament, *K-K* Kalahari Lineament, *Z-Z* Zoetfontein fault

The Letlhakane kimberlites

The Letlhakane Diamond Mine is located approximately 190 km west of Francistown and approximately 40 km south-east of the Orapa Diamond Mine (Fig. 1). Two kimberlite diatremes, locally known as DK1 and DK2, were discovered in 1968. The two bodies have surface areas of 11.6 and 3.6 hectares respectively. DK1 is currently an open cast diamond mine, while DK2 was mined for a short period between 1985 and 1986. Both diatremes consist predominantly of weathered, diatreme facies tuffisitic kimberlite breccia of the Group 1 kimberlite type. They contain xenoliths of Karoo age rocks and are overlain by a 4 to 10 m thick cover of Kalahari sand and calcrete. The kimberlites are therefore considered to be clearly post-Karoo and pre-Kalahari in age. They are probably of the same age as the Orapa kimberlite, which has been dated at 93 Ma (Davis 1977). The presence of a small amount of sedimentary crater facies material in DK1 indicates that very little erosion occurred subsequent to pipe emplacement.

Methods

Minerals were analysed for major and minor elements with the JEOL Superprobe electron microprobe at Rhodes University. A beam current of 25 nA and EHT of 15 kV was used. Peak and background counting times were set at 20 and 10 s respectively. A beam diameter of 10 μm was used for all analyses, and the ZAF correction procedure was used in data reduction. Detection limits were on the order of 0.02 wt% for most elements, while the detection limit for FeO and NiO was approximately 0.04 wt%.

Radiogenic isotope analyses were performed in the Hugh Allsopp Laboratory at the University of the Witwatersrand. The xenoliths were crushed in a steel mortar and pestle, and sieved into a size fraction ranging from 250 to 500 μm diameter. Garnet and clinopyroxene were then separated on a magnetic separator, leached in warm 6N HCl overnight and etched in 4% HF for 30 min. Final hand cleaning of all separates was done under a microscope and only clear, pristine grains with no surface or internal blemishes were selected for analysis. Subsequently, the separates were examined at high magnification in alcohol on a dark-field stage as a final check for purity. This aided in the detection of minute mineral inclusions and these grains were removed from the separates prior to analysis. It is stressed that all grains finally dissolved were optically pure and of a uniform colour. The pure mineral separates were dissolved in Savillex beakers in pure HF with a few drops of added HNO_3 to retard the formation of insoluble fluorides. After drying down the dissolved samples were taken up in 6N HCl and split into spiked and unspiked aliquots. Rb, Sr and the Rare Earth Elements (REE) were separated first using standard cation

exchange resin; further separation of Sm and Nd was performed using HDEHP coated teflon powder contained in thin glass columns (Richard et al. 1976). Total method blanks for these procedure never exceeded 140 picograms, and were generally < 100 pg. Blank contributions (with the exception of Rb), are insignificant for these samples, and blank corrections have not been applied. Concentration measurements were carried out on a single-collector Micromass 30 mass spectrometer (Rb, Sm and Nd) and multicollector VG354 (Sr). All isotopic compositions were determined on the VG354. Uncertainty estimates are ±0.5 relative percent for all element concentrations. $^{87}Sr/^{86}Sr$ in the Eimer and Amend standard is 0.708008 ± 32 (one standard deviation for 49 analyses). $^{143}Nd/^{144}Nd$ in BCR-1 basalt standard is 0.51264 ± 17 (one standard deviation for 10 analyses). Long-term duplicate analyses suggest an estimated uncertainty on $^{147}Sm/^{144}Nd$ of 0.28% and on $^{143}Nd/^{144}Nd$ of 0.004%.

Petrography

The xenolith suite at Letlhakane (Stiefenhofer 1993) includes peridotites, pyroxenites, eclogites, megacrysts, MARID and glimmerite xenoliths (Dawson 1980, 1987). Samples were collected from coarse concentrate oversize at the mine and range in size from 1.5 to 5 cm in diameter.

Peridotite xenoliths are represented by garnet-bearing harzburgites and lherzolites as well as an unusual suite of spinel-bearing lherzolite xenoliths. Most peridotites are coarse, but some are intensely deformed. Both garnet harzburgites and garnet lherzolites are in many cases variably metasomatised and show the introduction of metasomatic phlogopite and ilmenite. The full range of unmetasomatised garnet peridotite (GP) through garnet phlogopite peridotite (GPP) to garnet-free, phlogopite-bearing peridotite (PP) as recognised by Erlank et al. (1987) and Waters (1987) in peridotite xenoliths from the Kaapvaal craton, is represented. However, amphibole-bearing phlogopite-potassic richterite peridotites (PKP) were not found.

Some of the garnet harzburgites that contain no visible diopside, have garnets and enstatites whose compositions suggest saturation with Ca (Fig. 2). Hence it is likely that some of the "harzburgites" are probably related to the garnet lherzolites, with the absence of clinopyroxene being a function of the small sample size. The nature of garnet peridotite xenoliths with no visible evidence for metasomatism (the GP rocks of Erlank et al. 1987) is described first.

Garnet harzburgites

These rock types are dominated by coarse equant textures and contain the assemblage olivine + orthopyroxene + garnet. Discrete grains of Cr-spinel are present in some samples.

Garnets vary from rounded to anhedral and elongate shapes. They range in size from 2.5 to 6 mm with an average of approximately 3.5 mm. Kelyphitic rims are well developed in most cases with secondary metsomatic phlogopite and brown, euhedral Al-spinel as the major alteration products.

Olivines are colourless and anhedral with straight to gently curving grain boundaries. Grain sizes vary from 1 to 10 mm with an average of 4 mm. Undulose extinction in the olivines is common, as are serpentine-filled cracks and veinlets.

Orthopyroxenes exhibit a similar texture and appearance to olivine, with the exception of smaller grain size (average 3 mm). Localised areas of possible disequilibrium in the grains are indicated by more undulating grain boundaries relative to the olivines.

Garnet lherzolite xenoliths

Major minerals include olivine, orthopyroxene, clinopyroxene and garnet. Secondary metasomatic phlogopite forms the most common accessory mineral and is associated with kelyphite resulting from garnet breakdown. Textures, based on the classification of Harte (1977) vary from coarse to mosaic porphyroclastic. None of the deformed peridotites recovered exhibits fluidal textures.

The size, shape and colour of the garnets vary with textural type. The deformed lherzolites display smaller (< 0.5-2 mm) rounded or disc-shaped garnets than the coarse textured varieties. Garnets in the coarse textured xenoliths vary from dark orange to reddish purple in colour. Kelyphite rims are well developed and in extreme cases kelyphite pseudomorphs are present after garnet. Coarse textured peridotites contain larger (up to 5 mm), more rounded, purple garnets. Kelyphite rims in these xenoliths are generally not as well developed as in the porphyroclastic peridotites.

Clinopyroxenes occur as anhedral, bright green to very pale green grains with curving grain boundaries which vary from 1 to 8 mm in size. Undulose extinction may be present, particularly in clinopyroxenes from deformed peridotites. Primary clinopyroxene grains often exhibit rims of finely crystallised "spongy" material. This is best observed in the deformed, porphyroclastic-textured lherzolites.

Olivine neoblasts vary from 0.1 to 0.2 mm in size while porphyroclasts may be up to 8 mm long. The shape of the olivine varies from anhedral, with smoothly curving grain boundaries to irregular in the case of deformed peridotites. Olivines in the deformed xenoliths also exhibit undulose extinction and deformation lamellae.

Orthopyroxenes are colourless, anhedral and range in size from 1 to 6 mm. Undulose extinction and irregular grain boundaries are common in orthopyroxene from deformed lherzolites.

Metasomatised peridotite xenoliths

A number of the coarse textured peridotite xenoliths are metasomatised and show the introduction of modal phlogopite. In these rocks garnet textures vary considerably between samples and range from round, pristine grains to highly irregular, partly kelyphitised fragments set in rounded intergrowths of bright-green clinopyroxene, phlogopite and spinel. Clinopyroxenes in the metasomatised lherzolites show textural features not observed in the non-metasomatised garnet peridotites. They are typically finergrained than associated olivine and orthopyroxene. Clinopyroxenes in the

metasomatised xenoliths exhibit a close spatial association with garnet in that they occur as patchy, irregular grains around garnet or as rounded grains intergrown with coarse phlogopite. Kinked, deformed primary metasomatic phlogopite < 2mm in size is present in all samples. The abundance of phlogopite is negatively correlated with that of garnet. Ilmenite is present in some samples in metasomatic veins which vary in width from 1 to 9 mm.

Spinel lherzolites

An unusual suite of garnet-free, spinel-bearing lherzolite xenoliths occurs in the Letlhakane kimberlite.

The spinels display an irregular, anhedral shape and grain size varies from < 0.6 mm to 3.5 mm. Spinel colour ranges from a deep reddish-brown to nut brown in thin section. Primary metasomatic hydrous minerals are absent and the minerals in these xenoliths are generally finer-grained than the garnet-bearing lherzolites and harzburgites.

Textures vary from coarse to granuloblastic and most samples contain a few porphyroclasts. These porphyroclasts are < 8mm in size (on average about 3 mm) and comprise olivine, orthopyroxene and clinopyroxene. Most exhibit uneven grain boundaries and all show undulose extinction. Orthopyroxene porphyroclasts may contain exsolution lamellae of clinopyroxene.

The textures of the Letlhakane spinel lherzolite xenoliths differ considerably from those described from the Kaapvaal Craton (Boyd 1989). The Letlhakane examples are much finer-grained and the spinel occurs as discrete, anhedral grains and not as symplectites with orthopyroxene. Spinel is also more abundant in the Letlhakane xenoliths.

Mineral chemistry

Garnet

Garnet in the peridotite xenoliths ranges from low-Ca harzburgitic varieties to Ca-saturated lherzolitic types. Cr contents are variable and range up to 11 wt%, with highest Cr contents in garnets from low-Ca harzburgite xenoliths (Fig. 2). TiO_2 contents range up to 1.3 wt%, with highest TiO_2 occurring in garnets from the metasomatised xenoliths, which contain primary metasomatic phlogopite (the GPP xenoliths of Erlank et al. 1987).

Olivine

Olivine compositions in the Letlhakane peridotites (Fig. 3) range between 88% and 94% Fo. Average Fo contents are highest in the spinel-bearing lherzolites and the low-Ca harzburgite xenoliths.

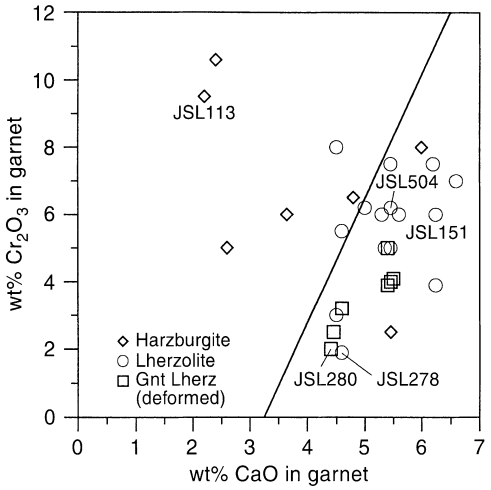

Fig. 2 Plot of CaO and Cr_2O_3 contents for garnets from peridotite xenoliths at Letlhakane. The *solid line* is the Ca saturation of Gurney (1984), and separates garnets from low- Ca harzburgite xenoliths from garnets derived from Ca-saturated lherzolite xenoliths. Sample numbers of xenoliths selected for isotopic study indicated

Orthopyroxene

Orthopyroxenes are all enstatites and have compositions in a narrow range (En_{90} to En_{95}), generally slightly more magnesian than those of coexisting olivines. The highest mg-numbers are from low-Ca harzburgite xenoliths. Al_2O_3 contents are in the range 0.5 to 2.6 wt%. Orthopyroxene in the spinel-bearing lherzolite xenoliths contain the highest Al_2O_3.

Clinopyroxene

Clinopyroxenes in the Letlhakane xenoliths are diopsides with a range in 100(Ca/Ca+Mg) of 34 to 52. Cr_2O_3 contents vary up to 5 wt%. Na_2O contents of the clinopyroxenes are variable, ranging up to 4 wt%. The

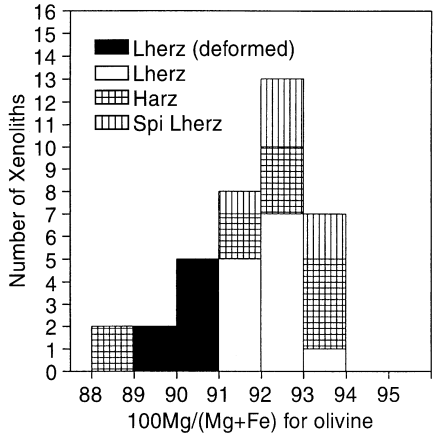

Fig. 3 Histogram of forsterite content of olivine in lherzolite and harzburgite xenoliths from the Letlhakane kimberlite

highest Cr_2O_3 and Na_2O contents are found in clinopyroxenes from xenoliths with accessory primary metasomatic phlogopite (Fig. 4).

Spinel

Primary spinel in the xenoliths has Cr_2O_3 between 10 and 63 wt%, Al_2O_3 between 7 and 50 wt% and TiO_2 between 0 and 2 wt%. The highest Cr_2O_3 contents are encountered in the metasomatised lherzolite xenoliths and the low-Ca garnet harzburgite xenoliths. The highest Al_2O_3 values are associated with spinels from the spinel-bearing peridotites. Maximum TiO_2 contents occur in spinels from metasomatised xenoliths.

Phlogopite

Carswell (1975) as well as Dawson and Smith (1975) have provided data showing that coarse, primary metasomatic phlogopite and finer-grained, kimberlite-derived secondary mica in xenoliths can be distinguished on the basis of mineral chemistry. Secondary micas are enriched in TiO_2, Cr_2O_3, Na_2O and FeO relative to the coarse, primary metasomatic micas. This is also the case at Letlhakane. Coarse, primary metasomatic micas typically have less than 1 wt% TiO_2 and Cr_2O_3 while finer-grained late secondary micas have TiO_2 and Cr_2O_3 contents of up to 4 wt% and 2.5 wt% respectively. Na_2O concentrations are generally lower than 0.5 wt%, with the higher values reporting in the finer-grained late stage secondary mica. FeO contents in coarse, primary metasomatic mica are typically lower than 3 wt%. This contrasts with an average value of 4 wt% FeO for late stage, secondary mica in the Letlhakane peridotite xenoliths.

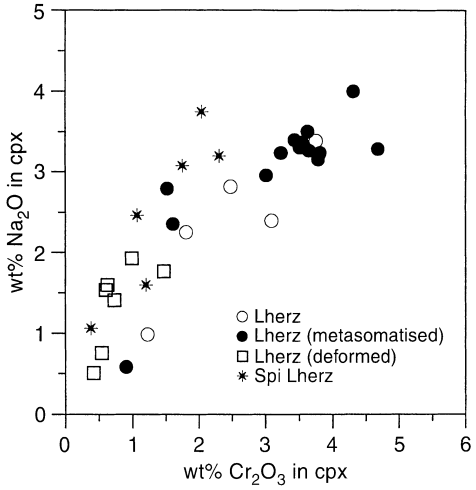

Fig. 4 Plot of Na_2O vs Cr_2O_3 for clinopyroxenes from Letlhakane xenoliths

Ilmenite

Ilmenite in three metasomatised, garnet-free, phlogopite-bearing peridotite xenoliths is a magnesian, metasomatic variety with MgO and Cr_2O_3 contents in the ranges 13 to 18 wt% and 2.4 to 4.4 wt% respectively.

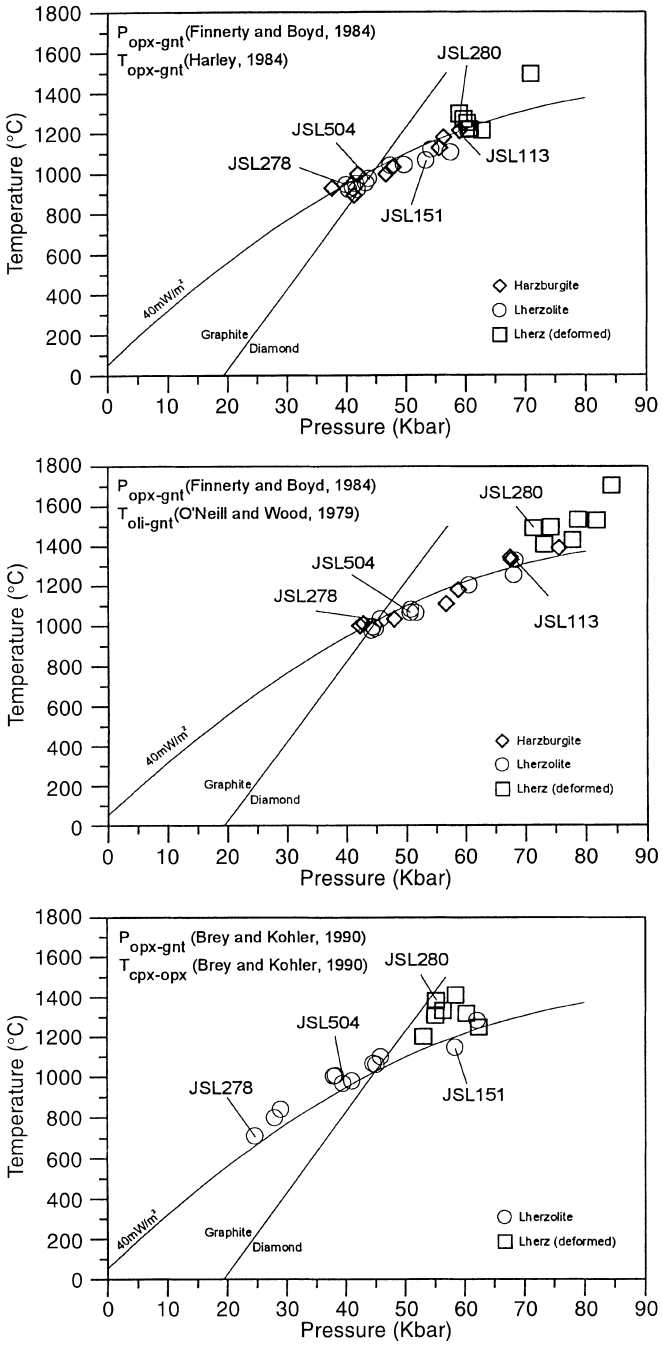

Fig. 5 Geotherm plots for xenoliths from Letlhakane utilising the thermobarometer combinations of Finnerty and Boyd (1984) vs Harley (1984), Finnerty and Boyd (1984) vs O'Neill and Wood (1979) and Brey and Kohler (1990). The diamond-graphite univariant reaction curve (Kennedy and Kennedy 1976) as well as the 40 mW/m^2 continental geotherm (Pollack and Chapman 1977) indicated by the *solid lines*. Sample numbers of xenoliths selected for isotopic study indicated

Table 1 Mineral chemistry of Letlhakane peridotite xenoliths selected for isotopic study (*N/A* not analysed, *N/D* not detected, *LHERZ* lherzolite, *HARZ* harzburgite, *DEF* deformed, *GNT* garnet, *OLI* olivine, *OPX* orthopyroxene, *PHL* phlogopite, *SPI* spinel)

Sample	JSL113	JSL113	JSL113	JSL113	JSL151	JSL151	JSL151	JSL151	JSL278	JSL278	JSL278	JSL278	JSL504	JSL504
Mineral	GNT	OLI	OPX	CHR	GNT	CPX	OPX	PHL	GNT	OLI	CPX	OPX	OLI	GNT
Rock Type	harz Low-Ca	harz Low-Ca	harz Low-Ca	harz Low-Ca	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse	Lherz Coarse
Number	6	6	6	1	3	1	3	2	5	5	5	5	3	3
SiO_2	41.55	40.85	57.81	N/A	41.18	55.27	57.51	41.65	41.82	40.99	53.67	57.55	40.18	40.48
TiO_2	0.02	N/A	N/D	0.68	0.19	0.09	0.04	0.63	0.08	N/A	0.17	0.06	N/A	0.25
Al_2O_3	17.05	N/A	0.72	6.92	19.15	0.85	0.58	12.51	22.17	N/A	3.11	0.82	N/A	19.30
Cr_2O_3	9.19	N/A	0.49	59.89	6.14	0.91	0.31	0.94	1.82	N/A	1.61	0.20	N/A	6.15
FeO	5.86	7.03	4.04	17.45	6.11	2.02	4.27	3.07	7.91	8.50	2.07	5.07	8.42	7.70
MnO	0.32	0.08	0.10	0.25	0.30	0.05	0.09	0.02	0.48	0.07	0.06	0.11	0.10	0.42
NiO	0.03	0.35	0.10	0.14	0.04	0.06	0.20	N/A	0.03	0.40	0.05	0.11	0.40	N/D
MgO	23.88	51.34	35.48	13.46	20.41	19.24	36.60	25.16	20.58	49.78	15.75	35.97	50.85	20.17
CaO	2.18	N/D	0.39	N/A	6.20	21.70	0.70	0.06	4.62	N/D	20.54	0.26	0.02	5.56
Na_2O	0.04	N/A	0.24	N/A	N/D	0.58	0.06	0.10	0.02	N/A	2.35	0.07	N/A	0.04
K_2O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.41	N/A	N/A	N/A	N/A	N/A	N/A
TOTAL	100.11	99.66	99.38	98.78	99.72	100.77	100.36	94.79	99.53	99.74	99.38	100.23	99.98	100.08
Mg/Mg + Fe		0.929								0.913			0.915	

Mineral zoning

Nixon and Boyd (1973 a,b) were among the first to report zoned minerals (particularly garnet) in deformed lherzolite xenoliths from northern Lesotho. Several subsequent studies (Smith and Ehrenberg 1984; Smith and Boyd 1987, 1989) illustrated that mineral zoning is a common feature in deformed peridotites, but that it is less common in coarse peridotites.

Zoning is present in a few samples from Letlhakane, but is not confined to any particular rock type. Olivines and orthopyroxenes are not zoned. Zoned garnets exhibit increasing TiO_2, Na_2O and Al_2O_3 and decreasing Cr_2O_3 from core to rim. The concentrations of TiO_2, Al_2O_3 and Na_2O in some of the clinopyroxenes are variable throughout grains but do not show a consistent pattern from core to rim. CaO contents in zoned clinopyroxene typically increase from core to rim while MgO contents decrease.

Xenolith thermobarometry

Pressure-temperature conditions were calculated according to the orthopyroxene-garnet thermometer of Harley (1984), the orthopyroxene-garnet barometer of Finnerty and Boyd (1984), the olivine-garnet thermometer of O'Neill and Wood (1979) and the thermobarometer combinations of Brey and Kohler (1990). Mineral chemistry data used in the calculations are averages of core analyses from several grains of each required mineral species.

The temperature-depth relations (Fig. 5) show a well-developed correlation between the textures of xenoliths and calculated P-T conditions of equilibration. Calculated equilibration temperatures and pressures plot close to the 40 mW/m^2 continental geotherm of Pollack and Chapman (1977). The Letlhakane kimberlites appear to have sampled xenoliths over a considerable depth range in the lithosphere. Deformed peridotites are restricted to the high pressure-high temperature end of the data array with coarse textured peridotites and harzburgites producing lower calculated conditions of equilibration.

Isotope chemistry

Samples selected for isotopic study consist of low-Ca depleted garnet harzburgite sample JSL113, deformed, high temperature lherzolite xenolith JSL280, cold, coarse granular lherzolite xenoliths JSL151, JSL278 and JSL505, and spinel-bearing lherzolite xenoliths JSL124 and JSL154. Electron microprobe analyses of minerals in these samples are presented in Table 1.

Garnet harzburgite

Garnet from the subcalcic harzburgite xenolith is characterised by elevated Nd and Sr concentrations, and Sm/Nd lower than the chondritic ratio, consistent with light rare earth element enrichment (Table 2; Fig. 6). This is accompanied by an extremely radiogenic $^{87}Sr/^{86}Sr$ isotopic composition ($^{87}Sr/^{86}Sr = 0.709121$) and unradiogenic $^{143}Nd/^{144}Nd$ (0.511877). These characteristics are similar to those for harzburgitic garnets in concentrate from Cretaceous kimberlites at Kimberley and Finsch in South Africa (Fig. 7), and is a signature associated with equilibration in an aged, metasomatically enriched environment (Richardson et al. 1984). These garnets are essentially Rb-free and must have incorporated radiogenic Sr by diffusive exchange with their Rb enriched host rocks (Richardson et al. 1984, 1993).

A Nd depleted mantle model age of 3240 Ma is calculated for the garnet in this xenolith, possibly demonstrating the ancient origin of the lithospheric root

JSL504	JSL504	JSL504	JSL280	JSL280	JSL280	JSL280	JSL124	JSL124	JSL124	JSL124	JSL154	JSL154	JSL154	JSL154
CPX Lherz Coarse 6	OPX Lherz Coarse 6	PHL Lherz Coarse 2	OLI Lherz Def 6	GNT Lherz Def 6	CPX Lherz Def 6	OPX Lherz Def 6	OLI Spi lherz Coarse 7	CPX Spi lherz Coarse 7	OPX Spi lherz Coarse 7	SPI Spi lherz Coarse 5	OLI Spi lherz Coarse 7	CPX Spi lherz Coarse 1	OPX Spi lherz Coarse 5	SPI Spi lherz Coarse 3
54.29	57.21	41.29	40.8	42.44	54.82	57.35	40.88	53.26	56.45	N/A	41.13	54.66	56.85	N/A
0.28	0.07	0.79	N/A	0.91	0.28	0.15	N/A	0.35	0.04	0.06	N/A	0.39	0.06	0.12
2.72	0.66	12.55	N/A	20.49	2.18	1.03	N/A	6.00	2.49	43.02	N/A	6.42	1.93	39.02
3.02	0.36	0.80	N/A	2.08	0.63	0.20	N/A	1.75	0.39	25.24	N/A	2.04	0.31	30.14
2.14	4.85	3.22	9.91	7.63	4.29	5.78	7.61	1.38	4.98	11.92	6.29	1.36	4.13	11.5
0.08	0.12	0.02	0.11	0.27	0.15	0.13	0.08	0.06	0.14	0.14	0.08	0.04	0.10	0.16
0.06	0.10	24.79	0.37	N/D	0.16	0.12	0.37	N/D	0.08	0.21	0.36	0.07	0.03	0.10
15.71	35.69	N/D	48.75	22.03	20.77	33.48	51.12	13.71	35.26	19.08	51.90	13.62	35.81	18.43
18.43	0.38	0.37	0.03	4.45	14.88	1.44	0.22	20.37	0.16	N/A	N/D	17.46	0.19	N/A
2.95	0.12	10.40	N/A	0.08	1.59	0.32	N/A	3.07	0.05	N/A	N/A	3.74	0.05	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
99.70	99.56	94.23	99.98	100.39	99.75	100.02	100.09	99.96	100.05	99.68	99.76	99.80	99.45	99.48
			0.898				0.923				0.936			

underneath the Letlhakane kimberlite. However, given the likelihood of open system behaviour, the typical model age approach is probably not valid. Indeed, recent evidence for zoning in diamond inclusion garnets (Shimizu and Sobolev 1995) suggests that these garnets are perhaps younger than 3 Ga. It is possible that extreme $^{143}Nd/^{144}Nd$ isotopic compositions in low Ca garnets from harzburgite xenoliths were inherited from their ancient precursors but that their present Sm/Nd values were imposed recently and hence do not relate to the neodymium isotopic composition (Pearson et al. 1995b).

Deformed garnet lherzolite

On a Sm-Nd isochron diagram the deformed garnet lherzolite xenolith yields a garnet-diopside age of 81 ± 17 Ma which is within error of the inferred age of the host kimberlite (Fig. 8). Garnet in this xenolith is inferred to be light rare earth element depleted while clinopyroxene shows an Sm/Nd ratio lower than the chondritic ratio, consistent with light rare earth element enrichment (Fig. 6). Garnet and clinopyroxene isotopic compositions are characterised by radiogenic $^{143}Nd/^{144}Nd$ and unradiogenic $^{87}Sr/^{86}Sr$, and plot in the

Table 2 Trace element abundances and isotopic ratios for Letlhakane peridotite xenoliths[a]

Sample	Rb ppm	Sr ppm	$^{87}Sr/^{86}Sr$[b]	±	Sm ppm	Nd ppm	$^{143}Nd/^{144}Nd$	±
Low-Ca harzburgite								
JSL113 Gnt	0.009	3.38	0.709121	38	0.481	1.878	0.511877	32
Coarse lherzolites								
JSL151 Gnt	0.003	0.751	0.710509	88	0.402	1.62	0.511834	90
JSL151 Cpx	–	350.8	0.708458	38	0.299	4.84	0.511694	20
			0.708463	22				
JSL278 Gar	0.009	–	–	–	1.33	1.33	0.512877	36
JSL278 Cpx	0.02	345.8	0.705548	26	5.42	31.58	0.512290	20
			0.705527	30				
JSL504 Gnt	0.12	–	–	–	1.694	2.15	0.512964	38
JSL504 Cpx	–	333	0.704761	24	4.08	19.49	0.512691	20
			0.704806	24				
Deformed lherzolite								
JSL280 Gnt	0.004	0.702	0.704465	36	1.16	1.46	0.513071	18
JSL280 Cpx	0.05	101.7	0.702645	24	1.639	5.98	0.512904	16
			0.702712	34				
			0.702671[c]	30				
Spinel lherzolites								
JSL124 Cpx	0.04	127.1	0.702302	26	4.59	18.82	0.511551	18
			0.702297	28			0.511556	22
JSL154 Cpx	–	–	0.711390	28	–	–	0.511699	24
			0.711162	36				

[a] Uncertainties in isotopic ratios are 2 sigma in-run statistics for last significant digits.
[b] Sr isotopic compositions given for both spiked and unspiked aliquots.
[c] Separate dissolution.

isotopically depleted segment (relative to bulk earth) of the Nd-Sr diagram (Fig. 7). These isotopic characteristics are similar to high temperature deformed lherzolites from the Kaapvaal lithosphere (Richardson et al. 1985; Walker et al. 1989; Hops 1989; Pearson et al. 1995a)

Coarse garnet lherzolites

Coarse garnet lherzolite xenoliths JSL504, JSL278 and JSL151 contain mineralogical and textural evidence for trace element enrichment and for modal metasomatism. They are characterised by radiogenic $^{87}Sr/^{86}Sr$ and unradiogenic $^{143}Nd/^{144}Nd$ isotopic compositions, consistent with time averaged trace element and light rare earth element enrichment (Fig. 7). Sample JSL151 with the most radiogenic $^{87}Sr/^{86}Sr$ and least radiogenic $^{143}Nd/^{144}Nd$ isotopic composition relative to the rest of the coarse peridotite xenoliths, is characterised by the lowest Sm and Nd contents in garnet and clinopyroxene (Table 2; Fig. 6). However, both garnet and clinopyroxene have Sm/Nd lower than chondrite (implying light rare earth element enrichment; Fig. 6) and this is consistent with the isotopically enriched character of this xenolith.

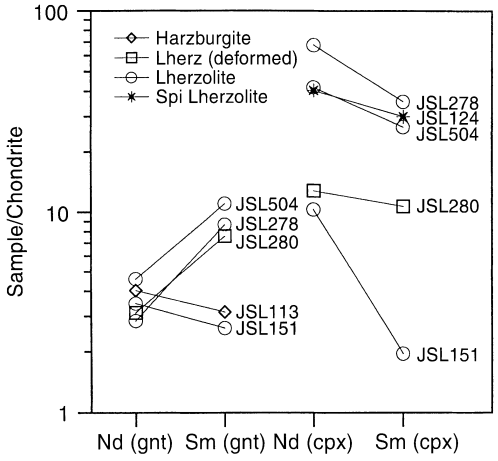

Fig. 6 Chondrite-normalised Nd and Sm concentrations in garnet and clinopyroxene from the Letlhakane peridotite xenoliths selected for isotopic study. Sample numbers indicated

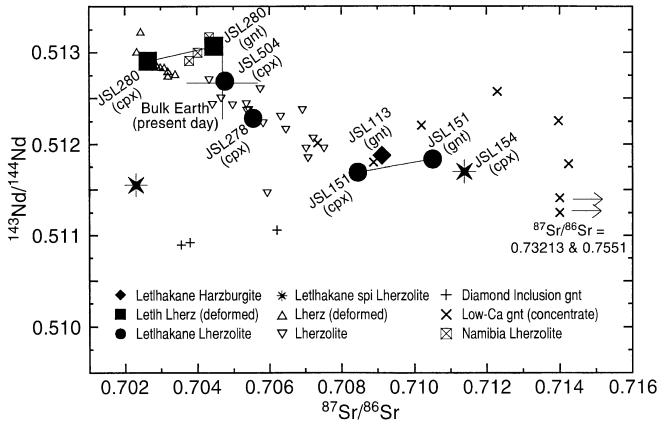

Fig. 7 Present day Sr-Nd plot of clinopyroxene in peridotite xenoliths from southern Africa. Data from Letlhakane (this study) as well as Menzies and Murthy (1980), Jones (1984), Richardson et al. (1985), Waters (1987), Hops (1989) and Walker et al. (1989). Sample numbers for Letlhakane xenoliths indicated

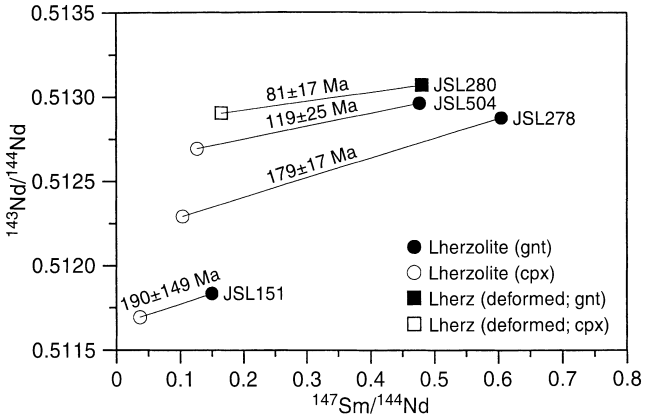

Fig. 8 Present day isochron diagram for garnet and clinopyroxene from Letlhakane peridotite xenoliths. Calculated two-point ages indicated. Errors on ages calculated from the minimum and maximum statistical run error (2 sigma) on the ^{143}Nd / ^{144}Nd ratio

On the basis of present-day garnet and clinopyroxene $^{143}Nd/^{144}Nd$ isotopic compositions it is clear that constituent minerals in all the coarse garnet lherzolite xenoliths are not in isotopic equilibrium (Table 2, Fig. 8). This is adequately explained by radiogenic decay of ^{147}Sm since pipe emplacement in the case of samples JSL151 and JSL504 as they define garnet-clinopyroxene ages which are within error of the pipe emplacement age (Fig. 8). However, on a Sm-Nd isochron diagram xenolith JSL278 yields a garnet-clinopyroxene age which is significantly older than the rest of the xenoliths (Fig. 8). This correlates with a relatively low calculated *P-T* condition of equilibration for this xenolith (Fig. 5) and might indicate that the xenolith isotope systematics have been only partially reset during residence in the comparatively lower temperature mantle environment from which this xenolith derives.

Depleted mantle Nd model ages of 1061 Ma and 1171 Ma are calculated for clinopyroxene from xenoliths JSL278 and JSL151 respectively.

Spinel lherzolite xenoliths

Clinopyroxenes in the two spinel-bearing lherzolite xenoliths analysed both have very unradiogenic $^{143}Nd/^{144}Nd$ isotopic compositions, while Sr isotopic compositions are variable, ranging from unradiogenic $^{87}Sr/^{86}Sr$ (0.702302) in the case of xenolith JSL124 to radiogenic $^{87}Sr/^{86}SR$ (0.711390; Fig.7). These isotopic

characteristics require pervasive light rare earth element enrichment in the xenoliths, followed by diffusive re-equilibration with an heterogeneously distributed phase with a high Rb/Sr ratio (e.g. phlogopite) during subsequent mantle or crustal storage.

A depleted mantle Nd model age of 3165 Ma is calculated for clinopyroxene from xenolith JSL124

Discussion

The Letlhakane kimberlite pipes have produced samples of a wide selection of peridotitic materials, ranging from fertile garnet lherzolites to depleted garnet harzburgites and unusual spinel lherzolites. The absence of peridotite xenoliths at Orapa and their abundance at Letlhakane may be the result of weathering. The Orapa kimberlite has not been significantly eroded and crater facies kimberlite is still preserved. In this crater lake environment the rapid decomposition of olivine and orthopyroxene is likely, leading to xenolith disaggregation. Garnet and clinopyroxene are more resistant to weathering, leading to preferential preservation of eclogite xenoliths at Orapa. In contrast, Letlhakane contains only small remnants of diatreme facies kimberlite (and relatively little crater facies material). Deeper levels of the pipe are therefore accessible to mining and there is consequently an increased likelihood for the preservation and recovery of peridotite xenoliths.

The presence of the GP, GPP and PP metasomatic sequence (Erlank et al. 1987) of peridotite xenoliths at Letlhakane and the similarity of mineral compositions to those from the Kimberley xenolith suite is noteworthy. It is therefore evident that metasomatism is also a feature of the mantle below Letlhakane. However, the advanced stages of metasomatism are absent as no peridotites containing any primary textured amphibole have been found. This is apparently also the case at many other localities (Erlank personal communication 1992) on the Kaapvaal craton.

A comparison of the Letlhakane pressure-temperature array with data from the Kaapvaal craton and Siberia (e.g. Finnerty and Boyd 1987; Carswell and Gibb 1987) indicates only minor differences between these localities (Stiefenhofer 1993). The peridotite xenoliths from Letlhakane closely resemble those from northern Lesotho, Frank Smith, Jagersfontein and Premier Mine in that coarse peridotites as well as high temperature, deformed peridotite xenoliths are represented, with highest temperatures of equilibration recorded in the deformed xenoliths. However, it is noticeable that unlike xenoliths erupted on the Kaapvaal craton, there is a continuum in pressure/temperature estimates for the low-T peridotites through to 6 GPa. Boyd et al. (1993) proposed that the gap that is often present between low-T and high-T xenoliths is occupied by low-Ca garnet harzburgites but this is clearly not the case at Letlhakane. The Letlhakane xenolith suite is evidently also another locality where hot, deformed peridotite xenoliths occur. This contrasts with the presence of cold deformed xenoliths (and absence of hot deformed xenoliths) at localities such as the Kimberley pipes (Boyd and Nixon 1978). A number of the Letlhakane cold coarse peridotite xenoliths plot well into the diamond stability field and this is compatible with the diamondiferous nature of the intrusions.

Mantle xenoliths entrained from beneath crust of Phanerozoic, Proterozoic and Archaean age display a considerable range in neodymium isotopic composition (Menzies 1990 a,b). The most unradiogenic Nd isotopic compositions and most radiogenic Sr isotopic compositions are restricted to xenoliths from Archaean lithosphere (Hawkesworth et al. 1990; Menzies 1990 a,b). Enriched domains dominate the xenolith suites entrained from within the Archaean lithosphere as represented by garnet peridotites and silicate inclusions in diamond with an age 3.2–3.3 billion years (Richardson 1990) and this is believed to be a by-product of age and mixing processes. Overall the Archaean lithosphere xenolith database (Menzies 1990a; Fig. 7) points to the passage of a considerable amount of time since its formation producing isotopic heterogeneity from initial elemental heterogeneity, and possible mixing of an originally depleted protolith with small volume melt fractions such that a spread of isotopic data results with time (Richardson 1990; Menzies 1990 a,b). Significantly, cold coarse textured peridotite xenoliths from the Louwrensia and Gibeon Townlands kimberlites in Namibia do not show the unradiogenic Nd isotopic compositions seen in xenoliths from the Kaapvaal (Jones 1984; Fig. 7). The major element compositions of peridotite xenoliths from these off-craton kimberlites are intermediate between the compositions of peridotites from on-craton kimberlites and oceanic peridotites (Hoal et al. 1995). The absence of Archaean Re-Os model ages from the Namibian peridotites suggests an age of lithosphere formation which is significantly younger than that of the Kaapvaal lithosphere (Pearson et al. 1994; Hoal et al. 1995), and this is consistent with the observations of Menzies (1990a,b). The radiogenic Sr and unradiogenic Nd isotopic compositions of the Letlhakane harzburgite and coarse textured lherzolite xenoliths (Fig. 7) are comparable to isotopic data for xenoliths from the Kaapvaal craton, and are totally unlike the xenoliths from Namibia. This is therefore taken as evidence for xenolith derivation at Letlhakane from an Archaean cratonic root which has survived convective disruption.

The isotope chemistry of the one analysed hot deformed Letlhakane peridotite xenolith is very similar to that of other high temperature deformed peridotite xenoliths from Cretaceous kimberlites (Walker et al. 1989; Pearson et al. 1995a) and indicates a depleted mantle source analogous to that of mid ocean ridge basalts or HIMU (e.g. Zindler and Hart 1986). However, high temperature lherzolites are more deficient in basaltic elements than model fertile mantle (Boyd 1987) and as such they may also have been produced by melt extraction (Walker et al. 1989). Osmium isotope data

indicate that this melt extraction either occurred later than that which formed the low-temperature peridotites, or that they formed at the same time but that the high-temperature lherzolites have been pervasively re-enriched in basaltic elements and Re by transient melts (Walker et al. 1989; Pearson et al. 1995 a,b). This infiltration may have imposed the depleted mantle-like Sr-Nd isotopic signature on high-temperature lherzolites.

Spinel peridotites are of widespread occurrence in xenolith suites of the Kaapvaal craton, having been collected at over a dozen localities in South Africa and Lesotho (Boyd 1989). Their proportions in individual xenolith suites vary widely from small to amounts approaching those of garnet peridotites. Carswell et al. (1984) recognised the existence of five spinel-bearing peridotite xenolith groups in Lesotho. Groups 1 and 2 are characterised by Fe-rich olivine (e.g. Fo_{80-88}) and Al and Cr spinels (e.g. Cr/Cr + Al = 0.07 – 0.38). Group 3 xenoliths contain Cr spinels (Cr/Cr + Al = 0.25 – 0.48) with magnesian olivines Fo_{91-93} and orthopyroxenes (En_{93-94}). Group 4 nodules have similar whole rock compositions to Group 3 xenoliths but contain coexisting Cr pyrope garnet with magnesiochromite spinel (Cr/Cr + Al > 0.60), magnesian olivines (Fo_{92-94}) and low Al_2O_3 orthopyroxenes (0.99 – 1.21 wt%). Group 5 spinel-bearing peridotite xenoliths have extremely depleted whole rock chemical compositions and contain highly magnesian olivines (Fo_{93-95}), low Al_2O_3 orthopyroxenes (0.36 – 1.05 wt%), magnesiochromite spinels (Cr/Cr + Al = 0.69 – 0.80) and no garnet. Carswell et al. (1984) concluded that the Group 1 and Group 2 xenoliths represent basaltic cumulates of lower crustal origin and assigned the Group 3–5 xenoliths to the upper mantle. The olivine mineral chemistry and modal olivine content of Kaapvaal spinel peridotites from Premier, Kimberley, Frank Smith and Letseng (similar to the Group 3 and Group 4 spinel peridotites of Carswell et al. 1984) clearly overlap with that of low-temperature garnet peridotites from the Kaapvaal (Boyd 1989). These data suggest a common origin for both spinel and garnet-bearing Kaapvaal peridotites. The broadly similar mineral chemistry of the Letlhakane spinel peridotites to the xenoliths of Boyd (1989) and the Groups 3 and 4 xenoliths of Carswell et al. (1984) is indicative of a shared petrogenetic history. The unradiogenic Nd and radiogenic Sr isotopic composition of clinopyroxene in Letlhakane spinel peridotite JSL154 is comparable to the isotopic composition of other Kaapvaal garnet lherzolites, perhaps indicating that Letlhakane spinel peridotites and garnet peridotites are petrogenetically related. However, the isotopic composition of clinopyroxene in Letlhakane spinel peridotite xenolith JSL 124 (both unradiogenic $^{87}Sr/^{86}Sr$ and unradiogenic $^{143}Nd/^{144}Nd$) is not typical of other Kaapvaal lherzolites and is only matched by the isotopic composition of low-Ca garnet inclusions in diamond (Richardson et al. 1984). In this instance similarities in isotopic composition are also to be found in crustal material such as the Lewisian gneisses (Hamilton et al. 1979) and the Lashaine granulites (Cohen et al. 1984) as well as other $^{87}Sr/^{86}Sr$ depleted granulites (Ben Othman et al. 1984). It is therefore concluded that the Letlhakane spinel peridotites are most likely to be mantle-derived, but that the possibility of a crustal origin can not be entirely excluded.

Conclusions

The conclusions of this study are summarised as follows:

(1) Coarse low-temperature peridotite xenoliths, hot deformed peridotite xenoliths, subcalcic garnet harzburgites and spinel-bearing peridotite xenoliths comprise the ultramafic suite at the Letlhakane kimberlite pipe in Botswana. In terms of petrography and mineral chemistry the xenolith suite is very similar to other xenolith suites from the Kaapvaal craton. However, the advanced stages of mantle metasomatism (as evidenced by the appearance of metasomatic amphibole) are not seen in the xenolith suite. Spinel peridotites at Letlhakane are also very similar to those reported from kimberlites on the Kaapvaal, but contain coarse, anhedral spinel which contrasts with the presence of spinel-orthopyroxene symplectites in the Kaapvaal specimens.

(2) It is noticeable that unlike xenoliths erupted on the Kaapvaal craton, there is a continuum in pressure/depth estimates for the low-T peridotites through to 6 Gpa. The calculated P-T conditions of equlibration of the xenoliths define a 40 mW/m^2 continental geotherm and are consistent with the presence of a thick lithospheric keel below Letlhakane which extends into the diamond stability field.

(3) The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotopic composition of a Letlhakane hot deformed peridotite xenolith indicates a depleted mantle source. In contrast, the cold coarse lherzolite xenoliths as well as a depleted (low-Ca) harzburgite xenolith analysed show isotopic evidence of time averaged trace element and light rare earth element enrichment, reflecting long term storage in a cratonic root. The observed unradiogenic $^{143}Nd/^{144}Nd$ and radiogenic $^{87}Sr/^{86}Sr$ isotopic compositions are consistent with an Archaean age for this lithosphere.

(4) It is concluded that the Letlhakane kimberlites are underlain by Archaean mantle which is related to the Zimbabwe craton. The Proterozoic Magondi Belt is therefore a superficial tectonic feature which is not rooted in the mantle.

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