

Composition and structure of the Kaapvaal lithosphere, southern Africa

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Abstract—Bulk and mineral analyses have been used to calculate modes for 24 peridotite xenoliths from the Kaapvaal craton. Large samples for bulk analysis, weighing 0.5–1.0 kg, were prepared to avoid the effects of heterogeneities in grain distribution that are commonly present on a scale of several centimeters. These and comparable data obtained by COX *et al.* (1987) are used as a basis for speculation about the igneous and tectonic processes through which the craton has formed.

Peridotites with low equilibration temperatures (<1100°C) that comprise rigid lithosphere within the craton are strongly depleted in Fe and moderately depleted in diopside and garnet but are relatively rich in modal enstatite. They have a range in modal olivine of 45–80 weight percent but have an average olivine content (61 weight percent) that is approximately the same as that of hypothetical fertile peridotite, such as pyrolite. Peridotites with high equilibration temperatures (>1100°C), believed to underlie the low-temperature suite, are characterized by higher modal olivine than is present in the low-temperature rocks, combined with lower Mg/(Mg + Fe) and more abundant diopside and garnet. The average composition of high-temperature peridotite from the Premier kimberlite in the central part of the craton is more fertile in elements concentrated in basalt than that of high-temperature peridotite from the southern margin of the craton. The more depleted high-temperature peridotites have compositions that are similar to residual oceanic peridotites.

The low-temperature peridotites may have originated as residues of partial fusion events that occurred at pressures above 50 kbar. Their wide range of modal olivine might be the product of cumulate processes. Alternatively the compositions of these peridotites may reflect primordial compositions or events associated with accretion and core formation.

The high-temperature peridotites are speculated to have originated in an oceanic plate subducted beneath the southern margin of the Kaapvaal craton possibly at the time of formation of the Namaqua-Natal mobile belt, approximately 1 b.y. ago. Subsequent to subduction these oceanic(?) peridotites have been heated to temperatures in the range 1100–1500°C, and converted to rocks having the mechanical properties of asthenosphere.

INTRODUCTION

UNDERSTANDING of the igneous and tectonic processes by which cratons have formed has traditionally been sought through study of the greenstone belts and gneisses that comprise their crustal caps. It is now appreciated, however, that cratons have mantle roots extending to depths substantially greater than the base of oceanic lithosphere. The concept of craton roots had been developed by JORDAN (1978, 1979) who proposed that the density imbalance resulting from cooler temperatures in the mantle beneath continents was compensated by a greater degree of magmatic depletion of the subcontinental mantle. He has interpreted seismic evidence to suggest that craton root zones depleted in basaltic components may extend below the lithosphere to depths as great as 400 km.

Evidence in support of the existence of craton roots has also come from studies of kimberlite xenoliths and of diamond occurrences and inclusions. Regularities in temperatures and depths of equilibration estimated for kimberlite xenoliths erupted in southern Africa have been interpreted

to reflect an asthenosphere–lithosphere boundary that shelves from a depth of 180 km beneath the Kaapvaal craton to 140 km beneath the western and southern mobile belts (*e.g.*, BOYD and NIXON, 1978). Coarse peridotites with equilibration temperatures that are predominantly below 1100°C are interpreted to be characteristic of the lithosphere whereas peridotites with higher equilibration temperatures are commonly deformed and are believed to have originated in the asthenosphere (BOYD, 1987). Occurrences of diamonds and of associated subcalcic garnet xenocrysts in southern Africa also appear related to the presence of a thickened lithosphere (BOYD and GURNEY, 1986). The base of the Kaapvaal lithosphere contains peridotites as old as the crustal rocks that form the cap (KRAMERS, 1979; RICHARDSON *et al.* 1984), and by the late Archaean the thermal gradient within the craton was similar to that estimated from present-day heat flow (BOYD and GURNEY, 1986; POLLACK and CHAPMAN, 1977). How the Kaapvaal and other cratons formed, however, remains a matter for investigation and speculation.

Major element studies of xenoliths of mantle origin included in kimberlites have primarily been carried out by electron probe analysis of constituent minerals. Data obtained in these studies have become a basis for thermobarometry and the development of mantle stratigraphies for the Kaapvaal and other cratons. Additional insights relating to ultimate igneous origin of these rocks can be obtained, however, by investigations of modal and bulk chemical variations. Modes estimated by O'HARA *et al.* (1963) for a small suite of garnet peridotite xenoliths from kimberlites showed them to be distinctively enstatite-rich. MATHIAS *et al.* (1970) used modes to demonstrate the unique compositional ranges of peridotite, pyroxenite and eclogite xenoliths from Kaapvaal kimberlites and provided an average mode for garnet lherzolite (Table 1). MAALOE and AOKI (1977) used bulk analyses and modes to demonstrate differences in average composition between spinel peridotite and garnet lherzolite xenoliths, the former being primarily from basaltic volcanics and the latter from kimberlites. Their average mode for garnet lherzolite includes the data of MATHIAS *et al.* (1970) and is close to the values given by the latter authors (Table 1). A distinction between low- and high-temperature peridotites was not made in previous modal studies. The low-temperature peridotites are considerably more abundant, however, and the similarity between the earlier average modes for garnet peridotite and the average for low-temperature peridotite obtained in the present work (Table 1) is thus concordant. COX *et al.* (1987) have used modal data determined on large peridotite xenoliths to show that diopside and garnet in these rocks may have exsolved from Mg-rich pyroxene in ultra-coarse harzburgites that crystallized near the dry solidus.

Modal and chemical data for twenty-four large peridotite xenoliths from the Kaapvaal craton that

have been obtained in the present investigation are combined with comparable data for thirteen xenoliths analyzed by COX *et al.* (1987) as a basis for speculation about the igneous history of the craton. The desirability of having large analytical samples, explained hereafter, has constricted the choice of localities; most of the xenoliths studied in the present work are from the Jagersfontein and Letseng-la-Terai kimberlites with a lesser number from the Premier, Frank Smith, Mothae and Monastery kimberlites. Those studied by COX *et al.* (1987) are primarily from Bultfontein (Kimberley). Both high- and low-temperature garnet peridotites and one spinel peridotite are included. Detailed petrographic and electron probe data for these specimens are given in an Appendix that can be obtained on request from Boyd.

APPROACH

Modes for peridotite xenoliths have been determined by calculation from bulk and mineral analyses with a computer program (LSPX) written by Felix Chayes. With this approach estimates of modal composition can be obtained for substantially larger volumes of rock than is possible by point-counting with thin sections or slabs.

Most peridotite xenoliths erupted in kimberlites are free of mineral banding and other large-scale segregations, having textures that most visibly reflect variable deformation. Heterogeneities in mineral distribution are, nevertheless, present in most specimens and it is difficult to obtain bulk analyses and modes that represent true compositions on a xenolith scale (10–30 cm). COX *et al.* (1987) have demonstrated that the fabrics of peridotite xenoliths from the Kaapvaal craton consist of clusters of olivine grains interspersed with clusters of enstatite, diopside and garnet. Heterogeneities in distribution of a particular mineral produced by clustering are commonly on a scale that is approximately 2–3 cm. In some instances, however, heterogeneities exceed 3 cm, as can be seen in tracings of slabs cut from two of the specimens analyzed in the present study (Figure 1).

A sample of peridotite weighing 90 g has a volume equivalent to a cube 3 cm on an edge. Many bulk analyses of peridotite xenoliths have carried out on analytical samples that were smaller than 90 g and it now appears that variations between these analyses may be due in part to small scale heterogeneities of the kind described by COX *et al.* (1987). Samples weighing approximately 500 g were used by them for bulk analyses. Analytical samples with minimum weights near 500 g and ranging up to 950 g were prepared in the present investigation.

Xenolith samples were pulverized incrementally, beginning with a jaw crusher equipped with steel plates, then a pulverizer equipped with mullite ceramic plates followed by crushing in a shatterbox having an alumina grinding container so that all the resulting particles were less than 180 μm in diameter. Contamination via the crushing method is less than 0.1 weight percent Al_2O_3 and Fe_2O_3 . The sample powders were split with a stainless steel sample splitter until a 10 to 15 g aliquot of powder remained. Initial samples were split into four aliquots of this volume with each being analyzed to establish homogeneity.

Table 1. Comparison of published average modes for garnet lherzolite with average modes obtained in the present study for low- and high-temperature garnet peridotite from the southern Kaapvaal, weight percent.

	MATHIAS <i>et al.</i> (1970)	MAALOE and AOKI (1977)	Southern Kaapvaal	
			Low-T	High-T
OLV	64	62	62	75
OPX	27	30	31	16
GAR	7	5	5	6
CPX	3	2	2	3

Abbreviations: OLV—olivine, OPX—orthopyroxene, GAR—garnet, CPX—clinopyroxene.

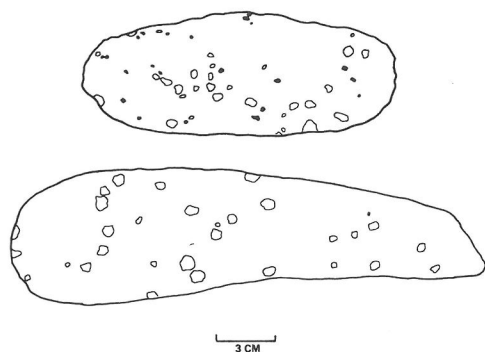


FIG. 1. Tracings of garnet and diopside grain distribution in slabs of two high-temperature lherzolite xenoliths from the Jagersfontein kimberlite pipe; top is FRB 997C and bottom is FRB 1031. Garnet grains are open and diopside grains are solid. Diopside is not shown in the tracing of 1031 because it has insufficient color contrast for consistent identification in the sawed face.

For XRF analysis, whole rock powder was mixed with $\text{Li}_2\text{B}_4\text{O}_7$, diluted with LiI solution to reduce the viscosity, and fused into a homogeneous glass disc. Working curves were determined by analyzing a suite of forty-two geochemical rock standards, data for each having been compiled by ABBEY (1983). Standards PCC-1, DTS-1, and NIM-P were prepared and analyzed as unknowns; the results essentially matched their published analyses.

Ferrous iron was titrated by a modified REICHEN and FAHEY (1962) method and loss on ignition (LOI) was determined by heating an exact aliquot (~ 1 g) of the sample at 900°C for one hour. Trace element briquettes were prepared by mixing 1.0000 g of whole rock powder with 0.50000 g of pure microcrystalline cellulose and pressing the mixture into a pellet. The mass absorption data correction method of HOWER (1959) was used for data reduction. The above standards together with BHVO-1 were prepared and analyzed as unknowns and the results agreed well with the published values.

Electron microprobe analyses were made on thin sections with supplemental grain mounts, employing techniques and standards long in use at the Geophysical Laboratory (FINGER and HADIDIACOS, 1972). Analyses of 5–8 grains were sufficient to establish average compositions for most minerals, but more detailed analysis was carried out on phases with marginal metasomatic alterations. Bulk analyses for the 24 xenoliths are given in Table 2; electron microprobe analyses, weights of individual analytical samples and petrographic descriptions are contained in an unpublished Appendix that will be supplied by Boyd on request.

METASOMATIC EFFECTS

Serpentine, phlogopite and fine-grained phases comprising kelyphite have crystallized subsequent to the primary igneous events in which the rocks studied were formed. Marginal zoning and minor amounts of secondary crystals of olivine, enstatite, diopside and spinel that are spatially associated with mica have also been found in several of the low-

temperature peridotites from Jagersfontein. The serpentine and kelyphite are present in varying concentrations in virtually all the xenoliths and they appear to have developed by reaction of primary phases in the presence of introduced H_2O . In calculating modes from chemical analyses on an H_2O -free basis the presence of serpentine and kelyphite have been ignored. The formation of phlogopite, however, has involved the introduction of elements in addition to water and has occurred with both the consumption and growth of anhydrous phases (Table 3). Evaluation of these effects is required for determination of primary modes.

Five low-temperature peridotites from Jagersfontein contain several percent of phlogopite that primarily forms intergranular lenticles and clots. The grain size of the mica is predominantly of the order of 0.1 mm, but coarser flakes with a poikilitic habit are present in several of the peridotites. The phlogopite has commonly crystallized in contact with enstatite and envelopes all grains of garnet; it is not found along contacts between olivine grains.

Small amounts of secondary olivine and enstatite are present in the margins of some primary grains in association with interstitial mica. The occurrence of the zoned margins is erratic and they appear to have formed by alteration of primary grains rather than as overgrowths. Marginal zones in olivine are 50–100 μm thick. Enstatite is not zoned in some occurrences where zoning of olivine is present. Secondary diopside in mica forms subhedral granules ranging up to 0.3 mm. Secondary spinel occurs both as mantles on primary grains and as granules in mica.

Secondary phases are uniformly enriched in Ti and Fe. In addition, secondary enstatite is enriched in Ca, whereas secondary diopside is depleted in this element. These pyroxene relations may indicate that the zoning developed with increasing temperature associated with kimberlite magmatism, although compositional inhomogeneities are clear evidence that an approach to equilibrium was imperfect. Granules of secondary diopside and spinel in mica are relatively depleted in Al, perhaps because of concomitant crystallization of the Al-rich mica.

Comparison of bulk analyses calculated from the modes and primary mineral analyses with analyses of whole-rock samples shows that the principal elements introduced along with H_2O in the formation of phlogopite and other secondary phases are K, Na, Ti, and Fe (Table 3). Additional evidence for the introduction of Ti and Fe can be obtained by comparison of the compositions of secondary anhydrous phases with primary values (Table 4). The

Table 2. Bulk analyses for garnet peridotite xenoliths and one spinel peridotite from the Kaapvaal craton, southern Africa. Weight percent.

Spec	1 FRB- 1007	2 FRB- 1008	3 FRB- 1012	4 FRB- 1031	5 FRB- 1033	6 FRB- 76	7 FRB- 999	8 FRB- 1009	9 FRB- 447	10 FRB- 448	11 FRB- 135	12 FRB- 492
SiO ₂	42.52	43.44	41.54	40.68	41.57	41.49	43.08	43.26	40.51	41.11	46.17	45.62
TiO ₂	0.07	0.16	0.15	0.08	0.16	0.17	0.11	0.07	0.31	0.02 ₆	0.00	0.00
Al ₂ O ₃	0.80	1.14	1.16	1.69	1.02	1.80	0.94	1.61	1.42	0.79	1.49	1.60
Fe ₂ O ₃	2.08	2.02	2.94	3.39	1.70	2.34	2.18	2.42	2.77	1.57	1.24	0.91
FeO	3.78	4.11	5.01	3.53	6.08	5.62	4.60	4.70	6.04	5.97	4.66	5.15
MnO	0.10	0.11	0.13	0.12	1.14	0.13	0.12	0.13	0.12	0.12	0.11	0.12
MgO	44.38	42.74	42.53	40.47	43.99	41.92	43.36	41.01	40.82	44.41	43.00	42.88
CaO	0.53	0.71	0.85	1.03	0.94	1.30	0.68	0.96	1.20	0.40	0.56	0.77
H ₂ O	0.08	0.13	0.06	0.06	0.07	0.08	0.12	0.16	0.10	0.04	0.06	0.20
K ₂ O	0.22	0.44	0.03 ₂ *	0.01 ₃	0.01	0.02 ₆	0.21	0.28	0.14	0.05 ₂	0.01	0.17
P ₂ O ₅	0.02	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.04	0.00 ₃	0.00	0.05
L.O.I.	5.70	5.31	5.98	9.37	4.34	4.90	4.69	5.14	6.65	5.48	2.30	1.96
Total	100.28	100.32	100.38 ₂	100.43	100.02 ₈	99.78 ₆	100.11	99.76	100.12	99.97 ₁	99.60	99.43
Fe ₂ O ₃ ^T	6.29	6.60	8.52	7.32	7.97	8.60	7.30	7.65	9.50	8.22	6.43	6.64
RB	13	26	6	2	5	2	6	13	4	2	1	4
Sr	55	92	17	15	15	25	48	76	128	20	8	55
Ba	142	80	42	30	16	51	55	67	936	63	11	52
Y	16	17	14	7	29	15	18	11	4	2	3	6
Zr	18	6	21	16	20	22	12	12	19	2	16	25
V	14	24	33	33	29	52	27	33	72	31	28	23
Ni	2180	1998	2168	2044	2262	2154	2067	1961	2257	2380	2177	2156
Cr	1970	2499	2601	2500	2750	2826	2491	2511	2272	2666	2696	2673

absolute magnitudes of these differences in bulk composition, however, are small and most of the components of phlogopite have been supplied by solution and recrystallization of primary phases rather than by subsolidus introduction.

Calculated modes that include analyzed mica differ systematically from those calculated on a mica-free basis. For all five mica-bearing peridotites from Jagersfontein that have been analyzed, the mica-present modes contain less enstatite and garnet and more diopside than the mica-absent modes (*e.g.*, Table 2). These differences are interpreted to indicate that the mica-forming reaction was:

garnet + enstatite + fluid →

phlogopite + diopside

This conclusion is supported by the textural evidence; mica in the Jagersfontein rocks is found most commonly in contact with enstatite and it appears to replace garnet. The development of secondary diopside is manifest in some specimens by crystallization of fine-grained crystals in mica. Sec-

ondary diopside is also present as a component of secondary enstatite. The suggested reaction is concordant with inferences based on studies of metasomites from the Kimberley pipes (ERLANK *et al.*, 1986).

The primary peridotite compositions are of particular interest in the present study. Accordingly, the modal values used are calculated on a mica-free basis. These calculated primary modes, however, contain substantially more garnet and enstatite and somewhat less diopside than the actual modes for specimens that are relatively rich in phlogopite. Both mica-free and mica-included modes are listed for such specimens in the unpublished Appendix, available on request from Boyd.

MODAL RESULTS

Values of modal olivine calculated for 500–1000 g analytical samples of coarse Mg-rich peridotites with equilibration temperatures below 1100°C have a range of 45–80 weight percent with a broad maximum near 60 (Figure 2). The dispersion is greater

Table 2. (Continued)

Spec	13 FRB- 983	14 FRB- 997B	15 FRB- 997C	16 FRB- 1003A	17 PHN- 4254	18 PHN- 4257	19 PHN- 4258	20 PHN- 4259	21 PHN- 4265	22 PHN- 4274	23 PHN- 5267	24 PHN- 5268
SiO ₂	43.05	41.87	40.55	40.32	44.29	44.56	43.24	45.84	46.82	44.41	43.57	42.26
TiO ₂	0.05	0.10	0.10	0.10	0.03 ₁	0.08 ₁	0.04	0.06 ₆	0.00 ₆	0.00 ₇	0.03	0.11
Al ₂ O ₃	1.13	2.00	1.10	0.51	0.99	1.36	0.74	1.63	1.52	0.91	1.80	0.86
Fe ₂ O ₃	1.66	1.72	2.64	2.61	2.06	1.87	2.03	1.30	1.27	1.61	1.78	2.63
FeO	4.80	6.90	4.88	5.34	3.41	4.26	3.96	4.62	4.30	4.14	5.55	4.79
MnO	0.11	0.13	0.12	0.13	0.10	0.11	0.10	0.11	0.11	0.10	0.13	0.10
MgO	44.60	39.77	42.75	44.80	43.77	42.55	44.87	42.57	41.96	43.28	41.44	44.46
CaO	0.44	1.45	0.49	0.31	0.32	0.52	0.14	0.76	0.67	0.40	1.94	0.42
Na ₂ O	0.10	0.11	0.07	0.08	0.03	0.08	0.03	0.08	0.08	0.06	0.13	0.09
K ₂ O	0.23	0.05	0.01	0.03	0.03 ₂	0.08 ₁	0.02 ₅	0.03 ₄	0.02 ₈	0.02	0.12	0.07 ₄
P ₂ O ₅	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
L.O.I.	3.96	5.75	7.12	5.91	5.09	4.37	4.62	3.34	3.20	4.68	3.08	4.44
Total	100.14	99.87	99.84	100.05	100.15 ₃	99.83 ₂	99.79 ₅	100.29 ₀	99.96 ₄	99.61 ₇	99.57	100.25 ₄
Fe ₂ O ₃ ^T	7.00	9.40	8.07	8.56	5.86	6.61	6.44	6.44	6.06	6.22	7.96	7.96
Rb	8	1	<1	2	<1	3	1	2	<1	1	4	5
Sr	39	21	7	14	21	16	11	12	2	16	27	29
Ba	84	43	9	43	28	38	21	9	15	18	120	184
Y	3	5	3	2	8	5	7	7	1	13	5	4
Zr	13	24	13	21	7	12	10	12	1	6	6	2
V	21	49	35	24	20	26	20	27	31	19	45	46
Ni	2327	2048	2297	2350	2123	2098	2330	2090	1924	2128	2136	2323
Cr	2190	2379	2295	1791	2978	2412	2413	2558	2704	2217	2853	2068

Garnet peridotites:

1–5, 7, 8, 13–16: Jagersfontein

6, 9, 10: Frank Smith

11: Mothae

17, 18,, 20–22: Letseng-la-Terai

23, 24: Premier

Spinel peridotite:

19: Letseng-la-Terai

* Values in subscripts have lesser significance

for previous data based on analytical samples much smaller than 500 g and this relationship is believed due to the influence of small scale heterogeneities on the older data. These rocks are enstatite-rich with as much as 30–40 weight percent enstatite (Figure 3) but the amounts of garnet and diopside are commonly less than 5–10 weight percent. The average olivine content of the low-temperature peridotites is 61 weight percent, a value near that calculated for hypothetical, more Fe-rich, fertile lherzolite compositions such as pyrolite (57 weight percent; RINGWOOD, 1982).

The deformed, more Fe-rich peridotites with equilibration temperatures above 1100°C are more olivine-rich and enstatite-poor than the low-temperature rocks. Modal enstatite for the high-temperature peridotites from the southern Kaapvaal is predominantly less than 20 weight percent and barely overlaps the range for the low-temperature peridotites (Figure 3). There are differences in modal ranges for these minerals however, between the high-temperature suite from the Premier mine in the central part of the craton and suites from lo-

calities near the southern margin of the craton, including northern Lesotho, Kimberley and Jagersfontein (Figure 4). The Premier suite has a broader range of modal olivine with an average of 66 weight percent, whereas suites from the southern Kaapvaal have an average of 76 weight percent olivine. Most of the Premier analyses were carried out on samples of restricted size (DANCHIN, personal communication). Nevertheless, the pronounced difference in *average* modal olivine is unlikely to be related to sample size although small scale heterogeneities can affect the range of values found.

Plots of modal olivine against Mg/(Mg + Fe) of olivine illustrate the pronounced contrast in ranges of Mg/(Mg + Fe) between the Mg-rich low-temperature peridotites and the relatively more Fe-rich high-temperature rocks (Figure 5). A value of 0.915 for Mg/(Mg + Fe) of olivine divides the two groups with only a few exceptions.

Garnet is commonly more abundant than diopside in both the high- and low-temperature peridotites (Figure 6). The high-temperature peridotites contain more diopside and garnet on the average

Table 3. Calculated modes of garnet, lherzolite xenolith FRB 1007, Jagersfontein, together with a comparison of the analysed bulk composition with bulk compositions calculated from the mineral analyses and modes, both with and without mica, weight percent.

Modes	No mica	With mica
Olivine	70.2	70.3
Enstatite	23.9	22.8
Garnet	2.4	0.8
Diopside	1.8	2.2
Spinel	0.3	0.3
Phlogopite	—	2.8
Totals	98.6	99.2

Bulk composition	Analyzed	Calculated	
		No mica	With mica
SiO ₂	44.81	44.80	44.80
TiO ₂	0.07	0.00	0.05
Al ₂ O ₃	0.84	0.81	0.83
Cr ₂ O ₃	0.30	0.28	0.29
FeO	5.95	6.09	6.01
MnO	0.10	0.09	0.08
MgO	46.76	46.73	46.74
CaO	0.56	0.57	0.56
Na ₂ O	0.08	0.04	0.07
K ₂ O	0.24	0.00	0.26
NiO	0.29	0.25	0.26
Totals	100.00	99.66	99.95

than do the low-temperature rocks, although there is much overlap in their ranges. The Premier high-temperature suite includes a larger number of more garnet- and diopside-rich lherzolites than do the suites for the southern Kaapvaal.

DISCUSSION

Metasomatism

The fine grain size and textural relations of the phlogopite and other secondary phases in the Jagersfontein peridotites studied in this investigation are evidence that the metasomatism occurred as a part of the kimberlite magmatic event. The association of the mica with marginal zoning of adjacent enstatite and olivine is further evidence of a late-stage metasomatism. It is unlikely that such zoning, involving Fe, persisted for long periods of time (SMITH and BOYD, 1987a,b). Secondary diopside in these rocks is less calcic than the primary phase, whereas secondary enstatite contains increased Ca. These secondary minerals are inhomogeneous and have not equilibrated; nevertheless, these relations may be evidence of mica formation in an environment of rising temperature, possibly during eruption. Other examples of metasomatism believed to

be associated with kimberlite magmatism include dunites from the Kampfersdam pipe at Kimberley that have secondary enrichments of Fe (BOYD *et al.*, 1983), and mineralization of peridotites from the Matsoku pipe, Lesotho (HARTE and GURNEY, 1975).

Modal scatter

The compositions of residues of varying degrees of isobaric depletion of a given fertile parent should form a trend of increasing modal olivine with increasing Mg/(Mg + Fe). Plots of modal olivine against Mg/(Mg + Fe) for both the low- and high-temperature Kaapvaal peridotites show considerable scatter (Figure 5). Many low-temperature peridotites contain even less olivine than hypothetical fertile peridotite compositions, such as pyrolite or

Table 4. Compositions of minerals in a coarse, low-temperature garnet lherzolite from the Jagersfontein kimberlite pipe, FRB 1008, weight percent.

	Primary				
	OLV	OPX	CPX	SPN	GAR
SiO ₂	41.6	47.6	55.6	0.07	41.9
TiO ₂	<0.03	<0.03	<0.03	0.04	<0.03
Al ₂ O ₃	<0.03	0.75	1.46	17.09	22.4
Cr ₂ O ₃	<0.03	0.18	0.94	51.2	2.32
Fe ₂ O ₃	—	—	—	2.81	—
FeO	6.87	4.36	1.21	12.9	7.99
MnO	0.05	0.11	0.08	0.08	0.50
MgO	52.7	37.3	17.2	13.7	20.4
CaO	<0.03	0.17	22.7	<0.03	5.15
Na ₂ O	n.d.*	<0.03	1.00	n.d.	<0.03
NiO	0.48	n.d.	0.05	0.04	n.d.
Totals	101.6	100.5	100.2	98.2	100.6

	Secondary				
	OLV	OPX	CPX	SPN	MICA
SiO ₂	40.8	57.4	55.1	0.13	38.7
TiO ₂	<0.03	0.30	0.59	3.82	2.27
Al ₂ O ₃	<0.03	0.48	0.94	6.97	14.9
Cr ₂ O ₃	0.03	0.20	1.07	52.7	1.65
Fe ₂ O ₃	—	—	—	6.04	—
FeO	9.78	6.29	3.38	14.7	3.79
MnO	0.11	0.15	0.18	0.37	0.03
MgO	50.3	35.7	19.3	13.7	23.0
CaO	0.06	0.60	18.6	<0.03	<0.03
Na ₂ O	n.d.	0.05	1.05	n.d.	0.35
K ₂ O	n.d.	n.d.	n.d.	n.d.	9.53
NiO	0.39	0.11	0.04	0.16	0.19
Totals	101.5	101.3	100.3	98.6	94.4

* n.d. is not determined

Abbreviations: OLV—olivine, OPX—orthopyroxene, CPX—clinopyroxene, SPN—spinel, GAR—garnet

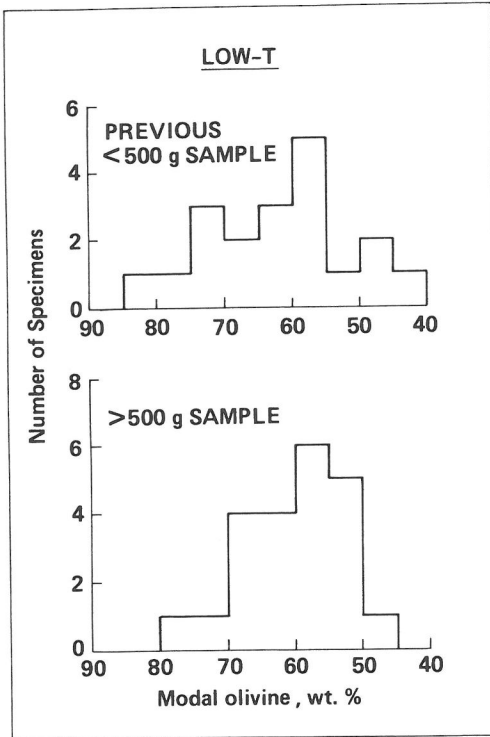


FIG. 2. Histograms of modal olivine contents of low-temperature garnet peridotite xenoliths from the Kaapvaal craton. New data calculated from analyses of samples larger than 500 grams are from this report and from COX *et al.* (1987). Previous data for smaller analytical samples are calculated from analyses given by NIXON and BOYD (1973); COX *et al.* (1973); CARSWELL *et al.* (1979) and DANCHIN (1979).

1611. The compositions of the Kaapvaal peridotites thus appear to have been modified by some process or combination of processes other than simple depletion. Pressure has a significant effect on the position of the Fo-En liquidus boundary, discussed hereafter, and large differences in the depth of partial melting could lead to variations in the proportions of olivine and enstatite in the residues. These variations, however, would not be expected to include modal olivine proportions less than that of fertile peridotite.

Any modal proportion of olivine and enstatite independent of $Mg/(Mg + Fe)$ could form in a cumulate process, but would require relatively high degrees of partial melting. Layering is uncommon in peridotite xenoliths from kimberlites. Nevertheless, the size of the nodules is small and these rocks have undergone subsolidus recrystallization. The possibility that some of the wide variation in modal olivine is due to cumulate origin seems worth consideration.

Exsolution

Diopside and garnet are the first phases to melt in peridotite at moderate pressures within the garnet stability field (*e.g.*, MYSEN and KUSHIRO, 1977). The reasons for the widespread occurrence of both these phases in Mg-rich, strongly depleted Kaapvaal peridotites are thus not immediately obvious. The pseudo-eutectic in the system Diopside-Forsterite-Pyroxene has a composition near the mid-point on

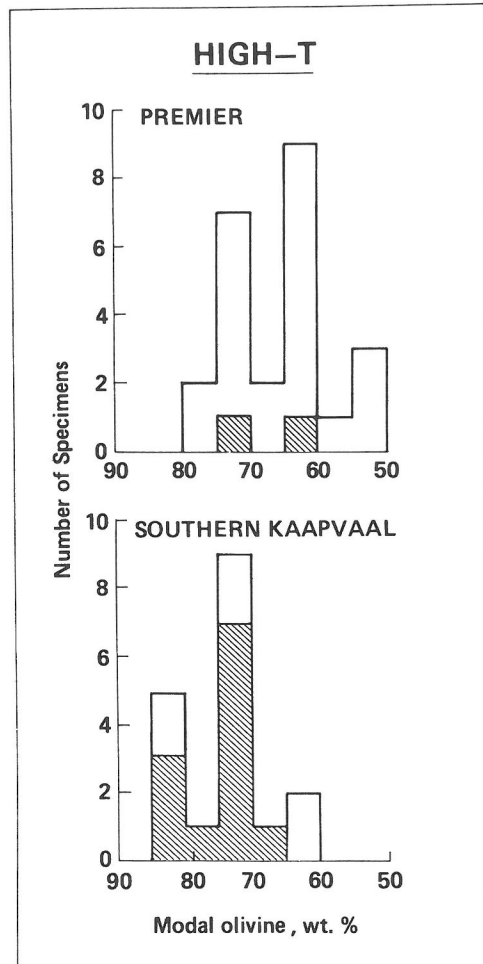


FIG. 3. Histograms of modal olivine contents of high-temperature garnet peridotite xenoliths from the Kaapvaal craton. Specimens from the Premier pipe in the central part of the craton are distinguished from those erupted in other pipes which occur along the southern margin of the craton; specimens from the southern Kaapvaal include xenoliths from the northern Lesotho suite, Jagersfontein, and Frank Smith. Data for analytical samples larger than 500 grams are shaded and are from this report and from COX *et al.* (1987). Previous data for smaller analytical samples are calculated from analyses given by NIXON and BOYD (1973) and DANCHIN (1979).

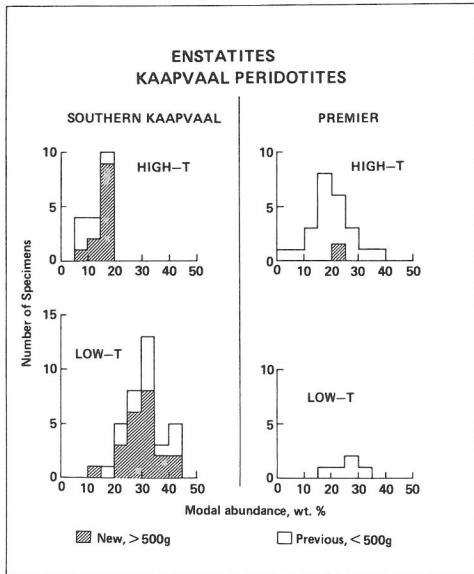


FIG. 4. Histograms of modal enstatite contents of Kaapvaal peridotites. Sources of the data are given in the legends for Figures 2 and 3.

the Diopside–Pyrope join at 40 kbar, (DAVIS and SCHAIRER, 1965) and residual liquids formed near the solidus would be expected to crystallize in approximately equal proportions of diopside and garnet. Garnet commonly is in excess (Figure 6), however, and the occurrence of substantial numbers of garnet harzburgites may be evidence that some garnet is a residual phase. Low-temperature peridotites in particular must have cooled from primary crystallization temperatures to ambient temperatures

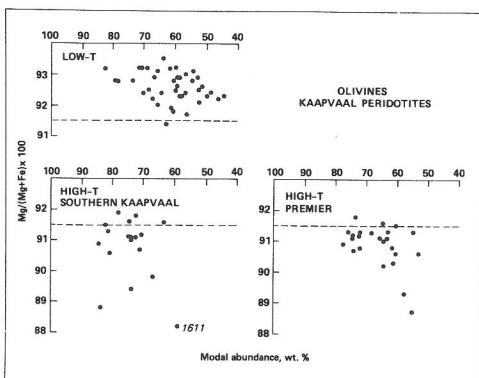


FIG. 5. Plots of $Mg/(Mg + Fe)$ of olivine against modal olivine for garnet peridotite xenoliths from the Kaapvaal craton. Sources of the data are given in the legends for Figures 2 and 3. The point for fertile lherzolite PHN 1611 is distinguished. The dashed line is provided for reference and is drawn at an Mg value of 91.5 in all three plots.

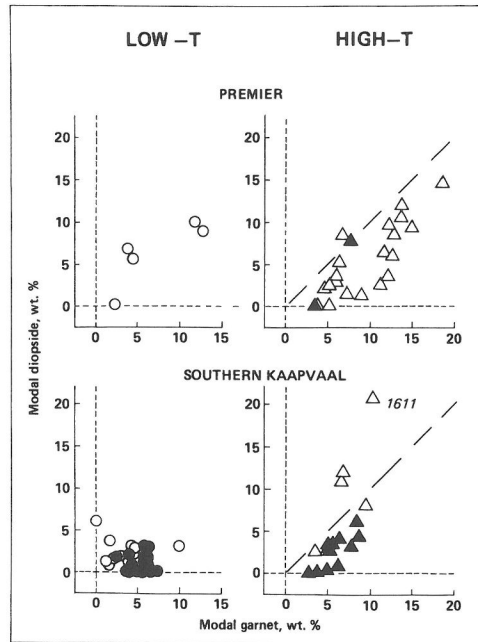


FIG. 6. Plots of modal diopside against modal garnet for Kaapvaal peridotite xenoliths. Solid points are for modal values calculated from analyses of samples larger than 500 grams (this report and COX *et al.*, 1987). Previous data from smaller samples are shown as open points. The point for fertile lherzolite PHN 1611 is identified. The dashed line at a 1:1 ratio is for reference.

and some of the diopside and garnet in them must have exsolved.

Exsolution may have been the dominant process in generating the small amounts of garnet and diopside that are commonly present in the low-temperature peridotites (DAWSON *et al.*, 1980; COX *et al.*, 1987). Orthopyroxene is eliminated in the melting interval of fertile peridotite (*e.g.*, PHN 1611) at pressures above 40 kbar (TAKAHASHI *et al.*, 1986). The clinopyroxene that crystallizes at higher pressures, however, is an Mg-rich pigeonitic phase with 6–7 weight percent CaO (GREEN *et al.*, 1986). This phase may have been the parent for the enstatite-rich clusters of pyroxene and garnet that are commonly present in low-temperature peridotites (COX *et al.*, 1987).

Exsolved phases initially form lamellae and blebs, but with recrystallization they coalesce as interstitial grains. Exsolution textures are relatively abundant in eclogites and pyroxenites but only rare examples have been found in lherzolites (DAWSON and SMITH, 1973). COX *et al.* (1987) suggest that the rarity of exsolution features in peridotites is due to the lesser strength of olivine and the relatively

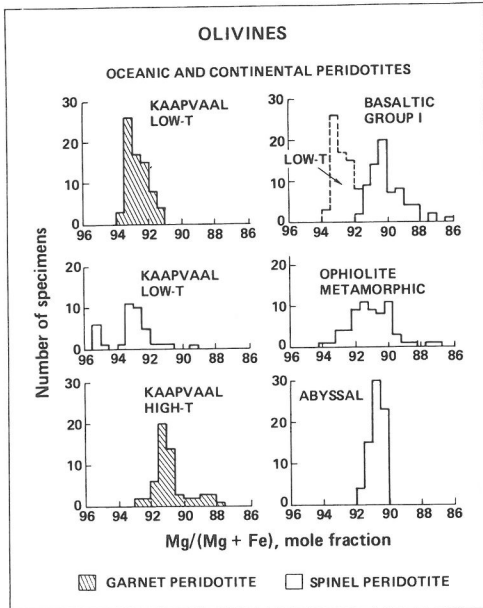


FIG. 7. Values of $Mg/(Mg + Fe)$ for olivines in peridotite xenoliths from the Kaapvaal craton, Group I (Cr-diopside) basaltic xenoliths and peridotites from oceanic lithosphere. Spinel and garnet peridotites are distinguished. The outline of the low-temperature Kaapvaal histogram is reproduced in the basaltic Group I plot for easy comparison. This figure is reproduced from BOYD (1987) with the addition of data for Kaapvaal spinel peridotites.

greater ease with which olivine-bearing rocks are deformed and recrystallized.

Compositional comparisons

Both the high- and low-temperature peridotites are depleted in basaltic elements relative to hypothetical fertile peridotite (*e.g.*, pyrolite) and thus

both suites may be residues. Nevertheless, marked differences in their compositional ranges are evidence that the two are products of different magmatic processes. The abundance of olivine and the relative concentrations of Fe and of elements concentrated in diopside and garnet are commonly-used indices of depletion. These indices appear decoupled, however, in contrasting the compositional variations of the two Kaapvaal suites.

The low-temperature peridotites are enstatite-rich, containing an average of 31 weight percent modal enstatite in comparison to 16 weight percent for the high-temperature suite from the southern Kaapvaal and 20 weight percent for the high-temperature peridotites from the Premier mine in the central part of the craton. The high-temperature rocks are proportionately richer in olivine, but contrary to expected depletion relations they are also richer in Fe and are variably richer in diopside and garnet (Tables 1 and 5). Most high-temperature peridotites are markedly richer in Ti but there is a large dispersion of values for Ti in these rocks and it is possible that it has been irregularly introduced in the initial stages of kimberlite magmatism (BOYD, 1987; SMITH and BOYD, 1987a,b).

Peridotites with compositions characteristic of the low-temperature Kaapvaal suite may be confined to Archaean cratons. The high-temperature Kaapvaal peridotites, however, are strikingly similar in composition to peridotites from oceanic and orogenic regions. Comparison of $Mg/(Mg + Fe)$ for olivines in low- and high-temperature Kaapvaal peridotites with values for abyssal peridotites, tectonites from ophiolites, and Cr diopside-bearing (Group 1) spinel lherzolite xenoliths from basaltic volcanics (Figure 7) shows that both spinel and garnet peridotites in the low-temperature suite forming the craton lithosphere are the most Mg-rich, with

Table 5. Modes and bulk chemical compositions of high-temperature peridotite xenoliths and depleted oceanic peridotites. See text for method of calculation of garnet facies modes of oceanic rocks, weight percent.

	High-T premier	High-T S. Kaapvaal	Abyssal average Dick and Fisher (1984)	MORB residue Green <i>et al.</i> (1979)
OL	66	75	79	75
OPX	20	16	13	17
GAR	9	6	5	6
CPX	5	3	4	3
Mg No*	909	911	908	917
TiO ₂	0.24†	0.13	0.02	0.04
Cr ₂ O ₃	0.30†	0.37	0.22	0.58
NiO	0.25†	0.30	0.22	0.32

* Mg no. is $Mg/(Mg + Fe) \times 100$ olivine, mole percent

† Values from Danchin (1979)

Abbreviations: OL—olivine, OPX—orthopyroxene, CPX—clinopyroxene, GAR—garnet

Mg/(Mg + Fe) predominantly greater than 0.920. Olivines from the underlying high-temperature peridotites, oceanic peridotites and those from Group 1 (Cr-diopside) basalt xenoliths are more Fe-rich, having Mg/(Mg + Fe) primarily in the range 0.880–0.920. More detailed comparisons of the compositions of high-temperature peridotites with those originating in oceanic lithosphere can be made utilizing modes as well as bulk chemical analyses. To facilitate this comparison, modes for the average composition of abyssal peridotites (DICK and FISHER, 1984) and a hypothetical MORB residue (model D, GREEN *et al.*, 1979) have been calculated as garnet peridotites (Table 5). Mineral compositions for these calculations were chosen by matching Mg/(Mg + Fe) of olivine in individual high-temperature peridotites with comparable values for the abyssal average and MORB model.

There is a striking similarity in mode between the high-temperature peridotite xenoliths from the southern Kaapvaal and the oceanic residues (Table 5). Comparably depleted rocks are included in the Premier high-temperature suite but the presence of more fertile peridotites at Premier causes the average to differ and the similarity is not as great.

Origin of low-temperature peridotites

The characteristics of the low-temperature peridotites that are particularly distinctive are Mg/(Mg + Fe) of olivine in the range above 0.920 and values for modal enstatite in the range 20–45 weight percent. Residues produced in the generation of basalt at relatively low pressures in oceanic environments have less modal enstatite and are commonly less magnesian (Table 5). There is, however, a possibility that the low-temperature peridotites are products of melting at high pressures. HERZBERG and O'HARA (1985) have proposed that peridotite melting may become eutectic-like at high pressures and they suggest that mantle peridotites may have originated as liquids rather than residues. Liquids and residues have similar compositions in eutectic-like melting, but the fact that the low-temperature peridotites have higher Mg/(Mg + Fe) than all other peridotite groups (*e.g.*, Figure 7) makes it appear more likely that they are residues. Alternatively, their compositions might reflect primordial compositions or early Archean events.

Olivine and enstatite comprise over 90 weight percent of the mode of most low-temperature peridotites. If speculation that much of their diopside and garnet has exsolved is correct (see above), many of them were composed entirely of olivine and an Mg-rich pyroxene solid solution at the time of their

igneous crystallization. Experiments have shown that the composition of the eutectic in the system $\text{MgSiO}_3\text{--Mg}_2\text{SiO}_4$ shifts from a position near enstatite toward forsterite with increasing pressure in the range up to 30 kbar (KUSHIRO, 1968; CHEN and PRESNALL, 1975). The magnitude of the eutectic shift with increasing pressure decreases at pressures above 30 kbar and the extrapolated eutectic composition appears unlikely to become more forsterite-rich than 30 mole percent at pressures over 100 kbar (KATO and KUMAZAWA, 1985). The pseudobinary eutectic in the system $\text{CaMgSi}_2\text{O}_6\text{--Mg}_2\text{SiO}_4$ also shifts toward forsterite with increasing pressure, but experiments and calculations suggest that the shift may be much greater, extending almost to forsterite composition at pressures above 100 kbar (HERZBERG, 1983).

The phase relations determined for these binary systems are concordant with the discovery that the compositions of liquids formed by small degrees of partial fusion of natural peridotites become more forsterite-rich as pressures are increased to 140 kbar (TAKAHASHI and SCARFE, 1985). Nevertheless, enstatite is replaced by an Mg-rich clinopyroxene containing 6–7 weight percent CaO in the melting interval of fertile peridotite at pressures above 40 kbar (GREEN *et al.*, 1986; TAKAHASHI *et al.*, 1986). Variation in the position of the liquidus boundary between this phase and forsterite as a function of pressure is not yet known.

Removal of small amounts of more forsterite-rich melts at high pressures would leave residues that were more enstatite-rich than those formed at lower pressures. The phase boundary shifts are in the right direction to permit interpretation of the low-temperature peridotites as high-pressure residues; it is possible that the shifts are also of the right magnitude, but insufficient experimental data are available at present to test this hypothesis.

The crystallization ages of the low-temperature peridotites are not known but they are probably greater than 3.3 b.y., the oldest age determined for diamonds believed to have crystallized in the craton root (RICHARDSON *et al.*, 1984). It is conceivable that the compositions of these ancient peridotites reflect primordial compositions or events associated with accretion and core-formation.

Tectonic considerations

Similarity in composition of the high-temperature Kaapvaal peridotites to residues of MORB formation may be evidence that they are the remains of subducted oceanic lithosphere originally formed at pressures near or below 10 kbar. Beneath the

rigid block composed of low-temperature peridotites, the oceanic rocks have been heated and transformed to peridotites having the mechanical properties associated with the asthenosphere. A subduction system is speculated to have developed along the southern margin of the craton during the formation of the Namaqua-Natal mobile belt approximately 1 b.y. ago. This model is consistent with the crustal geology in that rocks overthrust on the Kaapvaal craton have been interpreted as obducted oceanic crust (MATTHEWS, 1972). Analogous subduction from the south in Mesozoic time has been suggested as a precursor to kimberlite eruption (SHARP, 1974; HELMSTAEDT and GURNEY, 1982). A subducted origin for eclogite xenoliths in Kaapvaal kimberlites has been proposed on the basis of $^{16}\text{O}/^{18}\text{O}$ relations (MACGREGOR and MANTON, 1987) and appears consistent with the model suggested here.

The configuration of Mg- and enstatite-rich low-temperature peridotites overlying olivine-rich high-temperature peridotites is gravitationally stable. The density of average low-temperature peridotite is estimated to be 3.32 g/cm^3 in contrast to 3.38 g/cm^3 for average high-temperature peridotite and 3.39 g/cm^3 for fertile garnet lherzolite, PHN 1611 (BOYD and MCCALLISTER, 1976).

The petrologic model for the Kaapvaal mantle is consistent with more general, geophysical models developed by ANDERSON (1987) and by JORDAN (1978, 1979). In Anderson's model for the continental mantle, rigid lithosphere composed of depleted peridotite extends to a depth of 150 km. Between 150 and 200 km there is a decrease in seismic velocity that is interpreted to reflect a high thermal gradient accompanied by a change in composition to more fertile peridotite. Below about 200 km the velocities plot close to a 1400°C adiabat for olivine-rich rock and heat transfer is believed to be convective. Jordan's model has a root zone of depleted peridotite extending to a greater depth of 300–400 km, well beneath the lithosphere-asthenosphere boundary.

The transition between low-temperature and high-temperature peridotites is interpreted as the lithosphere-asthenosphere boundary (BOYD and GURNEY, 1986) and its depth beneath the Kaapvaal craton is estimated to be 175–200 km (FINNERTY and BOYD, 1987), in agreement with geophysical estimates. The depth interval represented by the high-temperature peridotites, however, is not more than a few tens of kilometers. The depth of the deeper transition to fertile peridotite is not represented in xenolith suites thus far discovered. Thus, present petrologic results cannot be used to resolve

the difference between the models of Jordan and Anderson.

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