

PETROLOGY AND CHEMISTRY OF GARNET LHERZOLITE NODULES IN KIMBERLITE FROM SOUTH AFRICA

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ABSTRACT

The garnet lherzolite nodules in kimberlite from South Africa consist essentially of olivine, orthopyroxene, garnet, clinopyroxene, and serpentine with minor amounts of phlogopite and opaques occurring in some samples. The average chemical compositions of 41 samples are: SiO₂ 44.66%, Al₂O₃ 1.22%, total Fe as FeO 7.87%, MgO 42.94%, CaO 0.81%, Na₂O 0.155%, K₂O 0.123%, TiO₂ less than 0.10%, MnO 0.113%, Cr₂O₃ 0.352%, NiO 0.370%, Co 89 ppm, Sr 31 ppm, and Zn 42 ppm. The MgO/(total Fe as FeO) ratios of the rocks range from 4.63 to 6.14. Al₂O₃, CaO, Na₂O, MnO, Cr₂O₃, Sr, and Zn decrease while NiO increases with increasing Mg/(total Fe as FeO) ratios. The systematic chemical variations in the garnet lherzolites may be interpreted as due to different degrees of partial fusion of the undepleted upper mantle materials consisting of some members of the garnet lherzolites with relatively low MgO/(total Fe as FeO) ratios.

INTRODUCTION

In recent years, interest in the studies of mafic and ultramafic nodules in basaltic and kimberlitic rocks has been sharpened largely because these rocks may be fragments of the Earth's upper mantle. Furthermore ultramafic rocks are generally considered as having some sort of genetic relationships with basalts.

Experimental petrologists (Kushiro and Yoder, 1966; Green and Ringwood, 1967; MacGregor, 1965, 1968) have defined the sets of subsolidus mafic and ultramafic phase assemblages that can exist within well-established pressure-temperature stability fields in the upper mantle. Among the ultramafic assemblages garnet lherzolites that occur as inclusions in kimberlite pipes have been considered as potential primary upper mantle material (O'Hara, 1963; Reay, 1965). However, White (1966) suggested that lherzolite nodules in Hawaiian basaltic rocks are either residues from fusion or fragments of the infusible part of a heterogeneous mantle, chiefly because of their low potassium contents.

Further interest in ultramafic rocks is evidenced by the work of Hess (1964) who considered olivine nodules, ultramafic intrusions, and Saint Paul rocks to be potential upper mantle materials. In addition, Fisher *et al.* (1969) have studied the elemental abundances in ultramafic rocks and found wide differences in their chemical compositions. They concluded that either the mantle is chemically very heterogeneous or that none of the rock types (*i.e.*, dunites, pyroxenites, and peridotites) studied is representative of primitive mantle material. However, they indicated

that garnet peridotite nodules in kimberlites might be representative of the primary upper mantle.

Recently Kuno (1969) has compiled nearly ninety bulk chemical analyses of ultramafic nodules and found systematic variation in their chemical compositions. He suggested that the lherzolite nodules in kimberlite with relatively lower MgO/(total Fe as FeO) ratios may be the primordial mantle material and the source rock of basaltic magmas.

In the present study, forty-one garnet lherzolite nodules in kimberlite from South Africa have been petrographically and chemically studied. The origin of the rocks is discussed on the basis of these results.

PETROGRAPHY

The garnet lherzolite nodules in kimberlite were collected at Bultfontein, Wesselton, and Jagersfontein Mines near Kimberley, South Africa by I. D. MacGregor and B. T. C. Davis. The geology of the area has been discussed in detail by Williams (1932). The ultramafic nodules at these three mines are made up of harzburgite, spinel harzburgite, garnet harzburgite, wehrlite, lherzolite, spinel lherzolite, and garnet lherzolite. It is difficult to place a quantitative value on the ratio of one rock type to another in different pipes. However, a rough estimate indicates that garnet lherzolites constitute one third of the nodules at these three localities.

The size of the nodules generally ranges from 5 to 20 cm in their greatest dimensions. In general, the rocks have a hypidiomorphic equigranular texture with grain size ranging from 0.2 to 0.5 cm. Layered structures characteristic of crystal cumulates are not observed in the nodules. Some nodules have a crude planar fabric marked by the roughly planar arrangement of elongated olivine and orthopyroxene grains. Furthermore, olivine and orthopyroxene crystals in some nodules have undulatory extinction indicating the rocks have been subjected to shearing stress. Triple-point adjustment which resulted in near 120° contacts among three grains has been noted in some samples suggesting considerable subsolidus recrystallization.

The modal compositions of the samples were determined by counting at least 1500 points in relatively large thin sections under a petrographic microscope. In general, the sections are thought to be representative of the samples.

Modal analyses of these rocks (Table 1) illustrate the predominance of olivine (40–60 vol. percent) and to a lesser extent, orthopyroxene (30–40 vol. percent). The clinopyroxene and garnet contents are generally less than 8 percent of the rocks by volume. Phlogopite occurs in some samples and its abundance is usually less than 3 percent of the rock by

Table 1 Modal analyses of garnet lherzolites (in volume per cent)
normalized to 100%

	B 8	B10	B13	B14	B15	B16	B36	B37	B42	B44	
Ol	43.2	38.6	61.2	33.1	27.1	35.7	42.8	29.2	48.3	55.0	
Opx	36.3	36.1	18.3	33.1	20.6	30.8	43.4	42.4	34.8	32.4	
Cpx	1.5	1.4	0.6	0.1	2.8	2.4	2.6	0.5	3.2	1.2	
Gt	7.6	6.0	4.3	4.1	6.9	2.6	5.0	2.5	8.6	4.2	
Phl	0.2	trace			2.1						
Serp	11.2	17.9	13.9	29.6	40.3	28.5	6.2	25.4	5.0	6.6	
Op			1.7		trace				0.1	0.6	
	B47	B49	B50	B53	B54	B70	B72	B74	B82	W 8	
Ol	48.0	32.0	26.7	37.7	57.6	47.3	33.6	40.1	57.1	51.5	
Opx	32.0	20.0	33.1	41.1	21.9	26.1	45.6	35.9	31.4	29.0	
Cpx	1.9	0.9	6.8	2.8	1.4	3.9	2.3	0.5	1.4	7.8	
Gt	9.6	5.0	18.5	1.5	5.2	5.9	4.6	4.1	4.0	4.8	
Phl		1.1	1.3	0.1	0.2	0.1	0.3	2.8		1.6	
Serp	8.4	40.9	13.6	14.9	13.7	14.4	13.6	16.6	5.9	4.7	
Op	0.1	0.1		1.9		2.3			0.2	0.6	
	W13	W14	W17	W20	W22	W31	W34	W35	W36	W43	W48
Ol	60.3	21.5	45.4	48.5	56.3	62.3	37.3	51.8	49.9	40.1	50.4
Opx	31.5	41.4	26.9	27.8	36.7	27.5	38.1	39.6	25.2	37.2	26.5
Cpx	0.8	12.8	1.5	7.2	2.9	1.2	0.6	0.7	7.3	1.5	6.7
Gt	4.2	10.7	5.5	10.9	0.5	6.8	2.8	4.9	7.2	3.8	11.3
Phl	0.4	0.1	1.1	0.4	1.9	0.7		1.7		1.1	0.4
Serp	1.9	11.7	19.4	5.2	1.7	1.4	21.2	0.9	10.0	15.9	4.7
Op	0.9	1.8	0.2			0.1		0.4	0.4	0.4	
	W61	W65	J21	J25	J33	J34	J41	J47	J70	J87	
Ol	46.7	56.8	53.0	57.7	50.7	46.6	40.0	77.5	53.2	58.7	
Opx	31.7	25.5	33.5	30.5	32.3	24.3	51.2	10.3	40.5	24.8	
Cpx	3.3	1.4	0.5	1.4	0.6	0.8	0.9	5.2	1.3	0.3	
Gt	6.6	11.0	1.7	9.3	0.7	10.8	2.2	5.8	2.8	6.7	
Phl	0.4					4.2		0.3		0.4	
Serp	10.5	5.3	11.3	1.1	15.7	13.3	5.7	0.9	2.0	9.1	
Op	0.8							0.2			

Ol: Olivine; Opx: Orthopyroxene; Cpx: Clinopyroxene; Gt: Garnet;
Phl: Phlogopite; Serp: Serpentine; Op: Opaques

B, W and J denote samples from Bultfontein, Wessleton and Jagersfontein
Mines respectively.

volume. Petrographic descriptions of the mineral components of the rocks are given in the following:

Olivine: it occurs as pale grass greenish, subhedral to anhedral grains with numerous veinlets of fibrous serpentine. In some cases over half of the olivine may be replaced by an aggregate of serpentine but the associated orthopyroxene and clinopyroxene are relatively unaffected by the alteration. Garnet inclusions have been noted in some olivine grains. The olivines have compositions varying from $Fo_{87}Fa_{13}$ to $Fo_{93}Fa_7$.

Orthopyroxene: orthopyroxene occurs as pale greenish brown, subhedral to anhedral grains which occasionally contain veinlets of serpentine. Poikilitic texture is generally lacking however, some orthopyroxenes have narrow intergrown lamellae that may be exsolved clinopyroxenes. In some samples orthopyroxenes are partially altered to phlogopite. The compositions of orthopyroxenes generally vary from $\text{En}_{88} \text{Fs}_{12}$ to $\text{En}_{96} \text{Fs}_4$.

Clinopyroxene: clinopyroxene is characterized by its bright emerald green color. It is generally anhedral, interstitial and smaller in size than the associated olivine and orthopyroxene which suggests that clinopyroxene grew in a restricted environment. In some specimens the clinopyroxene contains narrow intergrown lamellae that may be exsolved clinopyroxene of another kind. MacGregor and Carter (1970) reported that clinopyroxene in garnet peridotite from Roberts Victor Mine varies in composition from $\text{Di}_{88} (\text{En-Fs})_3 \text{Jd}_9$ to $\text{Di}_{77} (\text{En-Fs})_9 \text{Jd}_{14}$.

Garnet: it occurs as reddish brown rounded grains or as inclusions in olivine. The edges of the garnet are frequently altered to dark kelyphitic aggregates which are tentatively identified as chlorite + phlogopite + spinel(?). Unit cell and index of refraction data suggest that the garnet is pyrope rich ($\text{Py}_{75} \text{Al}_{12} \text{Gr}_{13}$).

Phlogopite: phlogopite generally occurs as pleochroic brown to straw yellow interstitial materials. In many cases, it may represent the alteration product of orthopyroxene and garnet. However, some relatively large subhedral plates of phlogopite may be of primary origin.

Opagues: they occur as anhedral grains or as alteration products associated with serpentine in cracks or along grain boundary. No attempts have been made to investigate the opagues in detail.

CHEMISTRY

The samples used in the chemical analysis were prepared as follows: 1) Fresh parts of the rocks were crushed into pea size pieces (200–300 grams) using a hammer. 2) Rock pieces were washed with double distilled water three times and dried under heat lamps. 3) 200–300 gram rock pieces were ground into powders (grain size generally between 100 and 200 meshes) in an Al_2O_3 Spex mill. The powdered samples are generally considered to be representative of the bulk samples due to their relatively larger weight.

The chemical analyses were carried out with a Perkin-Elmer Model 303 atomic absorption spectrophotometer. Ten artificial standards of garnet lherzolitic compositions were carefully prepared from Johnson and Matthey spectrographically pure chemicals and were used to construct the working curves. U. S. Geological Survey rock standards DTS-1 and PCC-1 were used as references.

All the elements except silicon were analyzed using the solutions prepared by dissolving 1.0000 gm of rock powders in a mixture of distilled HNO_3 and ultrapure HF. In case of silicon determinations the solutions were prepared by NaOH fusion of 0.0500 gm rock powders in nickel crucibles followed by water leaching and HCl acidification (modified from Shapiro and Brannock, 1962).

The instrumental settings for the analyses are those listed in Perkin-Elmer Analytical Methods for Atomic Absorption Spectrophotometry. Nitrous oxide was used for the determinations of Si, Al, Mg, Ca, Ti, and Sr.

Duplicate analyses on seven samples indicate the following precision: Si $\pm 4\%$, Al $\pm 3\%$, Fe $\pm 2\%$, Mg $\pm 2\%$, Ca $\pm 2\%$, Na $\pm 2\%$, K $\pm 1\%$, Ti $\pm 3\%$, Mn $\pm 1\%$, Cr $\pm 3\%$, Ni $\pm 3\%$, Co $\pm 3\%$, Sr $\pm 3\%$ and Zn $\pm 2\%$ of the amounts present. The results of the chemical analyses are listed in Table 2. The range and average of 41 analyses are as follows: SiO₂ 41.80–47.00% (avg. 44.66%), Al₂O₃ 0.53–2.21% (avg. 1.22%), total Fe as FeO (hereafter referred to as Σ FeO) 7.10–9.17% (avg. 7.87%), MgO 38.00–45.80% (avg. 42.94%), CaO 0.35–

Table 2 Chemical data of garnet lherzolites
(all analyses in weight percent except where indicated in ppm)

	B 8	B10	B13	B14	B15	B16	B36	B37	B42	B44
SiO ₂	42.70	43.00	43.90	41.90	41.80	42.00	46.00	42.70	45.30	43.50
Al ₂ O ₃	0.70	0.93	0.93	0.93	1.51	1.17	1.46	1.05	1.28	1.22
Σ FeO	8.25	7.80	7.35	7.35	7.43	7.88	7.55	7.55	7.80	7.88
MgO	45.60	44.40	44.20	44.92	43.60	44.00	41.72	44.40	43.08	44.92
CaO	0.50	0.65	0.35	0.35	0.60	0.60	0.90	0.45	0.80	0.70
Na ₂ O	0.087	0.142	0.200	0.056	0.151	0.128	0.145	0.118	0.091	0.078
K ₂ O	0.086	0.062	0.550	0.027	0.102	0.053	0.102	0.043	0.036	0.037
TiO ₂	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MnO	0.100	0.100	0.093	0.093	0.100	0.100	0.117	0.086	0.117	0.106
Cr ₂ O ₃	0.277	0.279	0.312	0.291	0.407	0.318	0.444	0.291	0.401	0.359
H ₂ O	0.452	0.369	0.401	0.401	0.369	0.401	0.340	0.426	0.363	0.369
Co (ppm)	104.5	91.5	95.5	95.5	86.5	87.5	76.5	93.0	87.5	91.5
Sr (ppm)	23	22	62	10	22	17	37	15	23	25
Zn (ppm)	52	50	34	46	42	44	36	42	48	42
Subtotal	98.752	97.750	98.286	96.318	96.069	96.650	98.778	97.114	99.268	99.169
MgO/ Σ FeO	5.35	5.69	6.01	6.11	5.87	5.58	5.53	5.88	5.52	5.70

	B47	B49	B50	B53	B54	B70	B72	B74	B82	W 8
SiO ₂	44.50	43.50	44.50	44.40	44.40	43.30	44.60	44.90	46.00	46.00
Al ₂ O ₃	1.22	0.93	2.21	1.05	1.28	1.40	1.28	0.93	1.17	1.87
Σ FeO	7.88	7.88	8.05	7.50	7.62	8.50	7.62	7.43	7.10	8.20
MgO	43.60	42.60	39.40	43.60	43.60	42.60	43.08	43.08	43.60	40.80
CaO	0.70	0.42	2.80	0.60	0.42	0.93	0.60	0.42	0.45	1.45
Na ₂ O	0.119	0.073	0.405	0.152	0.091	0.262	0.185	0.138	0.097	0.236
K ₂ O	0.062	0.123	0.057	0.077	0.022	0.320	0.043	0.078	0.058	0.094
TiO ₂	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MnO	0.113	0.100	0.127	0.110	0.106	0.137	0.110	0.093	0.093	0.127
Cr ₂ O ₃	0.378	0.262	0.470	0.322	0.365	0.343	0.389	0.363	0.342	0.413
H ₂ O	0.369	0.417	0.324	0.385	0.401	0.369	0.369	0.385	0.385	0.363
Co (ppm)	87.5	99.5	86.5	85.0	90.0	91.5	90.0	82.5	82.5	78.5
Sr (ppm)	18	17	81	33	20	58	22	20	41	43
Zn (ppm)	44	52	42	38	40	57	38	44	40	42
Subtotal	98.941	96.305	98.343	98.196	98.305	98.161	98.276	97.817	99.295	99.553
MgO/ Σ FeO	5.53	5.41	4.89	5.81	5.72	5.01	5.65	5.80	6.14	4.98

Table 2 continued

	W13	W14	W17	W20	W22	W31	W34	W35	W36	W43	W48
SiO ₂	44.90	44.90	43.60	45.80	45.30	44.80	45.10	45.40	43.90	44.00	45.90
Al ₂ O ₃	0.53	1.22	1.05	1.46	1.69	0.99	0.93	1.11	1.46	1.22	1.46
EPeO	7.50	8.20	8.12	8.50	8.12	7.75	7.50	7.50	8.58	7.75	8.20
MgO	45.80	38.00	43.08	41.20	42.60	44.68	42.60	44.40	42.60	43.60	41.68
CaO	0.35	4.65	0.80	1.32	1.02	0.60	0.35	0.40	1.25	0.45	1.02
Na ₂ O	0.118	0.600	0.081	0.223	0.200	0.137	0.066	0.194	0.192	0.087	0.147
K ₂ O	0.170	0.031	0.066	0.170	0.203	0.133	0.042	0.220	0.048	0.112	0.270
TiO ₂	<0.1	0.15	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MnO	0.100	0.127	0.110	0.133	0.123	0.110	0.103	0.113	0.133	0.117	0.127
Cr ₂ O ₃	0.213	0.621	0.357	0.389	0.413	0.295	0.313	0.332	0.339	0.355	0.332
NiO	0.426	0.312	0.401	0.356	0.350	0.385	0.356	0.369	0.363	0.363	0.356
Co (ppm)	89.0	71.0	91.5	87.5	81.0	90.0	86.5	96.8	107.3	95.5	99.5
Sr (ppm)	23	78	23	49	35	30	15	23	41	17	40
Zn (ppm)	25	50	47	40	46	36	32	36	48	38	48
Subtotal	99.707	98.661	97.665	99.551	100.019	99.88	97.360	100.038	98.865	98.054	99.492
MgO/EPeO	6.11	4.63	5.31	4.85	5.25	5.77	5.68	5.92	4.97	5.63	5.08

	W61	W65	J21	J25	J33	J34	J41	J47	J70	J87
SiO ₂	46.00	45.80	45.60	46.00	46.10	46.20	47.00	44.60	46.90	44.70
Al ₂ O ₃	1.28	1.11	1.28	1.63	1.40	1.34	1.40	1.40	0.81	0.81
EPeO	8.00	7.80	7.75	8.25	8.25	8.25	7.62	9.17	7.30	8.05
MgO	41.68	43.76	42.60	42.40	41.20	40.80	41.68	42.60	42.60	44.00
CaO	1.07	0.45	0.45	0.65	0.60	0.60	0.40	1.20	0.40	0.45
Na ₂ O	0.226	0.109	0.075	0.085	0.284	0.140	0.069	0.179	0.054	0.123
K ₂ O	0.045	0.080	0.123	0.082	0.258	0.275	0.177	0.080	0.288	0.112
TiO ₂	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MnO	0.127	0.117	0.113	0.133	0.120	0.130	0.117	0.123	0.106	0.110
Cr ₂ O ₃	0.459	0.355	0.353	0.417	0.305	0.329	0.318	0.357	0.330	0.239
NiO	0.385	0.356	0.340	0.356	0.340	0.299	0.340	0.375	0.324	0.356
Co (ppm)	100.5	103.0	91.5	94.5	90.0	94.0	91.5	113.5	76.0	100.5
Sr (ppm)	28	25	13	20	46	43	22	17	30	33
Zn (ppm)	34	36	37	35	32	48	34	69	40	36
Subtotal	99.272	99.937	98.684	100.003	98.857	98.363	99.121	100.084	99.112	98.950
MgO/EPeO	5.21	5.61	5.50	5.14	4.99	4.95	5.47	4.65	5.84	5.47

Subtotal = SiO₂ + Al₂O₃ + EPeO + MgO + CaO + Na₂O + K₂O + MnO + Cr₂O₃ + NiO

4.65% (avg. 0.81%), Na₂O 0.054–0.600% (avg. 0.155%), K₂O 0.022–0.550% (avg. 0.123%) TiO₂ less than 0.10–0.15% (avg. <0.10%), MnO 0.086–0.137% (avg. 0.113%), Cr₂O₃ 0.213–0.621% (avg. 0.352%), NiO 0.299–0.452% (avg. 0.370%), Co 71–114 ppm (avg. 89 ppm), Sr 10–81 ppm (avg. 31 ppm), and Zn 25–69 ppm (avg. 42 ppm).

A systematic variation in chemical composition of the garnet lherzolites has been noted in the ternary plot of MgO-ΣFeO-CaO (Fig. 1). The author has found no correlation between the degree of serpentinization and CaO content of the rocks (see Table 1 and Table 2) suggesting that the variation in CaO is essentially related to the variation of chemistry and/or abundance of clinopyroxenes in the rocks.

The $\text{MgO}/\Sigma\text{FeO}$ ratios of the 41 garnet lherzolites vary from 4.63 to 6.14. Despite the limited range of the ratio, consistent variation trends have been found in the plots of Al_2O_3 , CaO , Na_2O , MnO , Cr_2O_3 , NiO , Sr , and Zn versus $\text{MgO}/\Sigma\text{FeO}$ ratios of the rocks (Fig. 2 and Fig. 3). With the exception of nickel all the elements mentioned above tend to decrease with increasing $\text{MgO}/\Sigma\text{FeO}$ ratios. The negative correlation between Cr_2O_3 and $\text{MgO}/\Sigma\text{FeO}$ is probably due to the concentration of chromium in clinopyroxene (Carter, personal communication) which tends to decrease with increasing $\text{MgO}/\Sigma\text{FeO}$ ratio.

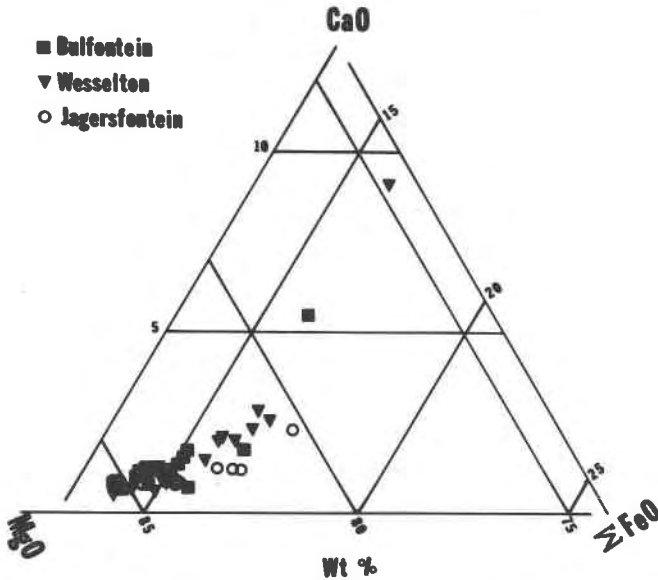


FIG. 1. $\text{MgO}-\Sigma\text{FeO}-\text{CaO}$ variations in garnet lherzolites from South Africa.

It should be mentioned that no correlation has been noted between K_2O and $\text{MgO}/\Sigma\text{FeO}$ ratios of the rocks suggesting that potassium of the rocks may have been involved in a complex history. As mentioned before, petrographic evidences suggest that some phlogopites may represent alteration products of orthopyroxene and garnet. However, it is uncertain whether the alteration has resulted from reactions that occurred in the kimberlitic liquids during the upward transport of the nodules or whether it has resulted from reactions that occurred within the upper mantle prior to the kimberlitic intrusion. It should be noted that Kushiro *et al.* (1967) suggested that phlogopite can be formed in the upper mantle down to 150–200 km if the water pressure is equal to or nearly equal to total pressure and if potassium is available.

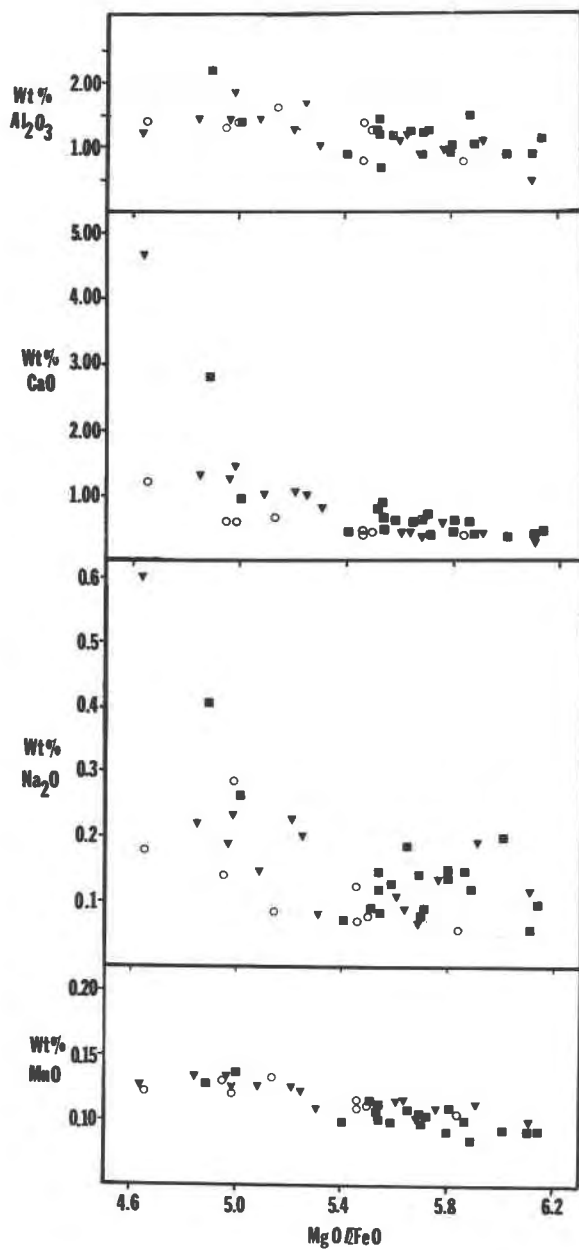


FIG. 2. Al_2O_3 , CaO , Na_2O and MnO vs. $MgO/\Sigma FeO$ ratios for garnet lherzolites from South Africa. Symbols same as Fig. 1.

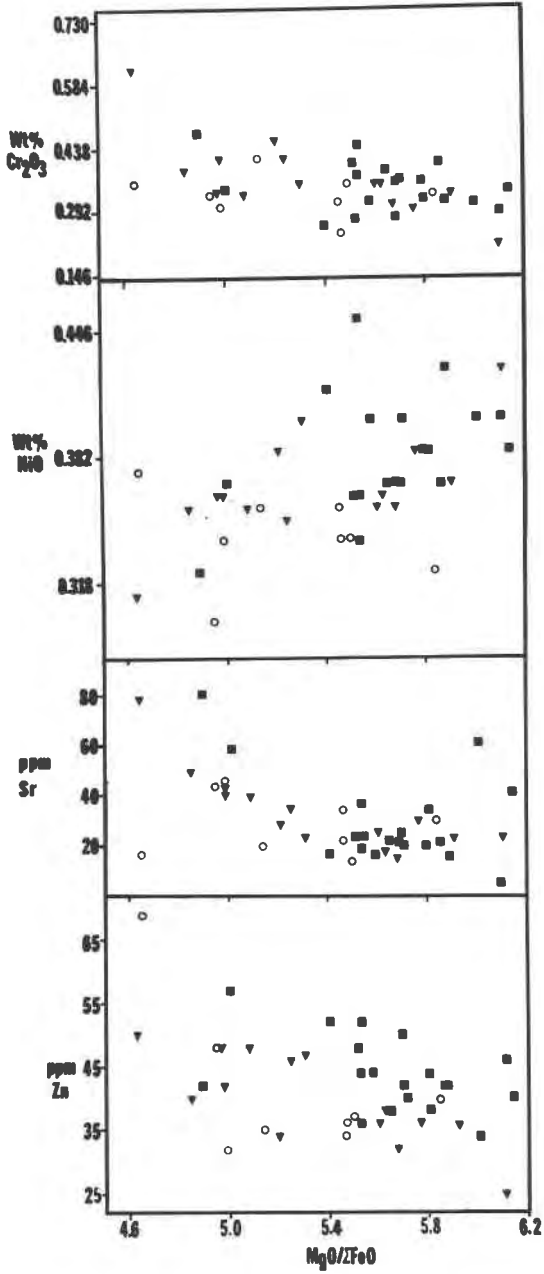


FIG. 3. Cr_2O_3 , NiO, Sr and Zn vs. $MgO/\Sigma FeO$ ratios for garnet ilmenites from South Africa. Symbols same as Fig. 1.

TABLE 3. CHEMICAL COMPOSITIONS OF THE UPPER MANTLE
ESTIMATED BY VARIOUS AUTHORS

	1	2	3	4	5
SiO ₂	44.95	44.05	43.56	45.16	44.20
Al ₂ O ₃	1.57	2.80	2.36	3.54	2.70
ΣFeO	8.48	8.17	8.67	8.45	8.29
MgO	40.30	40.98	41.53	37.47	41.30
CaO	2.49	2.49	2.51	3.08	2.40
Na ₂ O	0.352	0.21	0.32	0.57	0.25
K ₂ O	0.085	0.03	0.005	0.13	0.0015
TiO ₂	0.10	0.14	0.04	0.71	0.10
MnO	0.128	0.14	0.10	0.14	0.15
Cr ₂ O ₃	0.459	0.36	0.40	0.43	0.30
NiO	0.342	n.d.	0.34	0.20	0.20
Co (ppm)	89.6	n.d.	n.d.	n.d.	n.d.
Sr (ppm)	56	n.d.	n.d.	n.d.	n.d.
Zn (ppm)	50	n.d.	n.d.	n.d.	n.d.

1. Average of four garnet lherzolites with MgO/ΣFeO ratios less than 4.90 (this paper).
2. Mantle peridotite (Kushiro and Kuno, 1963, Table 1, column 5a).
3. Hess' Type C peridotite (Hess, 1964, Table 2, column 1).
4. Ringwood's pyrolite (Ringwood, 1966).
5. Undepleted upper mantle estimated by Harris et al. (1967, Table 2, column 3).

Analyses in Wt% except where indicated in ppm

n.d.: not determined

Since Kuno (1969) indicated that the lherzolite nodules in kimberlite with relatively low MgO/ΣFeO ratios may be the primordial mantle material, the author has calculated the average chemical composition of four garnet lherzolites (B50, J47, W14, and W20) with MgO/ΣFeO ratios less than 4.90 (Table 3, column 1).

The upper mantle compositions estimated by Kushiro and Kuno (1963), Hess (1964), Ringwood (1966), and Harris *et al.* (1967) are also listed in Table 3 (column 2, 3, 4 and 5) for comparison.

It is interesting to note that the chemical compositions of the upper mantle estimated by various authors are generally similar except for potassium which shows wide range of variation.

DISCUSSION

Various hypotheses have been proposed for the origin of ultramafic nodules in basaltic and kimberlitic rocks. Wyllie (1967, p. 327) summarized the interpretations into four major categories: 1) The nodules represent xenoliths picked up within the Earth's crust. 2) The nodules are cumulates from primary basaltic magma formed as bottom cumulates in temporary reservoirs or formed marginally during upward flow. 3) The nodules represent primary mantle material. 4) The nodules are residual mantle material after extraction of basalt.

MacGregor (1968), based on experimental data in the four components system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$, indicated that the stability range at solidus temperature for garnet peridotite is 18 to 55 kilobars corresponding to a probable depth of origin of 60 to 180 km. The conclusion reached by MacGregor strongly suggests that the garnet lherzolite nodules analyzed in the present study are of upper mantle rather than crustal origin.

The consistent variation trends (Figs. 1, 2, and 3) discussed before suggest that the nodules are probably genetically related by crystal-liquid equilibrium. Although the chemical variations may be interpreted as due to crystal accumulation from primary basaltic magma yet several textural evidences observed by the author apparently fit the criteria argued by White (1966, p. 305) as not favoring an origin of crystal accumulation:

- 1) No mineralogical layering is developed within the garnet lherzolite nodules.
- 2) Modes of cumulative rocks generally vary widely but those of garnet lherzolites do not.
- 3) Poikilitic pyroxenes, a distinctive feature in many cumulative rocks, are generally lacking in the garnet lherzolites.

It should be mentioned that the four garnet lherzolites (B50, J47, W14, and W20) with $\text{MgO}/\Sigma\text{FeO}$ ratios less than 4.90 generally have higher Al_2O_3 , ΣFeO , CaO , Na_2O , MnO , Sr , and Zn and lower MgO and NiO contents as compared with other garnet lherzolites analyzed in the present study. These four garnet lherzolites are the most undepleted samples studied and may represent the primordial upper mantle material and the source rock of basaltic magmas. Continuous extraction of basaltic magmas from the undepleted upper mantle material upon partial fusion would leave residues increasingly enriched in magnesium and nickel but depleted in aluminum, iron, calcium, sodium, manganese, strontium, and zinc. The mineral assemblages of the residues would probably change from olivine+orthopyroxene+small amounts of clinopyroxene (*i.e.*,

lherzolites with relatively higher $MgO/\Sigma FeO$ ratios) through olivine + orthopyroxene (harzburgite) to olivine (dunite). The author suggests that the chemical range and the systematic chemical variations found in the garnet lherzolites studied may be interpreted as due to different degrees of partial fusion of the primordial upper mantle material consisting of garnet lherzolites with relatively low $MgO/\Sigma FeO$ ratios.

An important point in the discussion of upper mantle composition is whether liquid depletion has occurred. It might be argued that all the materials sampled have undergone some degree of partial fusion so that estimates of the composition of actual primordial upper mantle should make allowance for the removed liquid (Harris *et al.*, 1967).

Ringwood's pyrolite model (1966), which assumes an upper mantle composition equivalent to 3 parts Alpine peridotite and 1 part Hawaiian olivine tholeiite, has been corrected for liquid removal. However, most of the upper mantle compositions listed in Table 3 were estimated without liquid correction which resulted in the relatively low potassium content as compared with the pyrolite model.

The author suggests that the wide variation of potassium in the estimated upper mantle compositions may be interpreted as due to secondary introduction of potassium into some of the primordial upper mantle materials. As mentioned before, whether the introduction occurred in the upper mantle or near the surface is still uncertain.

It should be noted that the chemical compositions of the four garnet lherzolites (B50, J47, W14, and W20) with relatively low $MgO/\Sigma FeO$ ratios generally do not fall within the dominant compositions of the 41 samples studied. This points out the danger to deduce primordial upper mantle composition using dominant ultramafic rock composition compiled from literature without appropriate petrological and chemical considerations.

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