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The major element geochemistry
of some ultrabasic inclusions from the
Lashaine volcano, Northern Tanzania.

Being a thesis presented by
David Guy Powell
to the University of St. Andrews
in application for the degree of
Master of Science.



Certificate.

I certify that DAVID GUY POWELL has been engaged in research for four terms at the University of St. Andrews, that he has fulfilled the requirements of Ordinance No.51 and that he is qualified to submit the accompanying thesis in application for the degree of Master of Science.

I certify that the following thesis is based on the results of research carried out by me, that it is my own composition and that it has not previously been presented for a higher degree.

The major element geochemistry of some ultrabasic
inclusions from the Lashaine volcano, Northern Tanzania.

by D.G. Powell

Introduction.

The Neogene volcanic rocks of Northern Tanzania are divided into two groups, the Older Extrusives and the Younger Extrusives. The Older Extrusives are lavas of the continental olivine basalt association consisting of olivine basalts, trachybasalts, trachytes and phonolites. They are the products of central type volcanoes, the more mobile basic members having spread out to form extensive lava plateaux well away from the eruptive centres. Some of the olivine basalts are known to contain peridotitic nodules. In lower Pleistocene times these older lavas were broken up by a phase of faulting and, following this faulting, the Younger Extrusives were erupted from much smaller central volcanoes. Eruptions were highly explosive and the volcanoes are dominantly pyroclastic. The associated lavas are ultrabasic feldspathoidal types and carbonatite is found at many centres.

In the area south and west of Arusha numerous small cones stand up above the faulted lava plateau, many of these being formed of lapilli or red welded scoria. Some of these cones consist of carbonate-rich pyroclastics containing ejected blocks of unusual rock types. These cones belong to the Younger Extrusives and their extremely youthful topography suggests that their formation was very recent.

The rocks under consideration occur as ejected blocks in the Lashaine volcano, a small prominent volcano rising some 700 ft. above the plains south

of Monduli. The tuff and agglomerate ring surrounding the crater is strongly asymmetric due to greatest deposition of ejectamenta on the western side. The hill itself measuring 3000 ft. by 2500 ft. is oval in plan and appears to have been built in two stages (Dawson 1964). First an asymmetric cone of red welded scoria was formed similar to many others in the area; this was followed by a phase of highly explosive activity during which calcite-rich tuffs and agglomerates were deposited on top of the red scoria with outward dips up to 50°. These pyroclastics consist of bedded calcium carbonate forming up to 70% of the rock and include blocks of country-rock olivine basalt, red scoria, crystalline gneissose rocks and ultrabasic igneous rocks. The gneissose and ultrabasic rocks are round or disc shaped and Dawson (1964) recognised within the ultrabasics olivine, augite, diopside, enstatite, phlogopite, biotite, hornblende, pyrope and spinel. These ultrabasic rocks were provisionally classified as lherzolites, harzburgites, peridotites and garnet peridotites. The general shape and mineralogy of the peridotites in particular were believed by Dawson (1964) to be strongly reminiscent of the cognate xenoliths found in kimberlite pipes in South Africa and in Russia. The object of the present study was to ascertain whether, in their chemistry, the ultrabasic nodules at Lashaine have more in common with the peridotite nodules associated with the earlier olivine basalt activity of the Older Extrusives or have more affinities with peridotitic blocks and garnet peridotites from known kimberlite pipes.

Description of the rock types.

The ultrabasic nodules are ovoid in shape and have fairly smooth surfaces. Three of them are shown in Fig. 1. The largest is about one foot long by eight

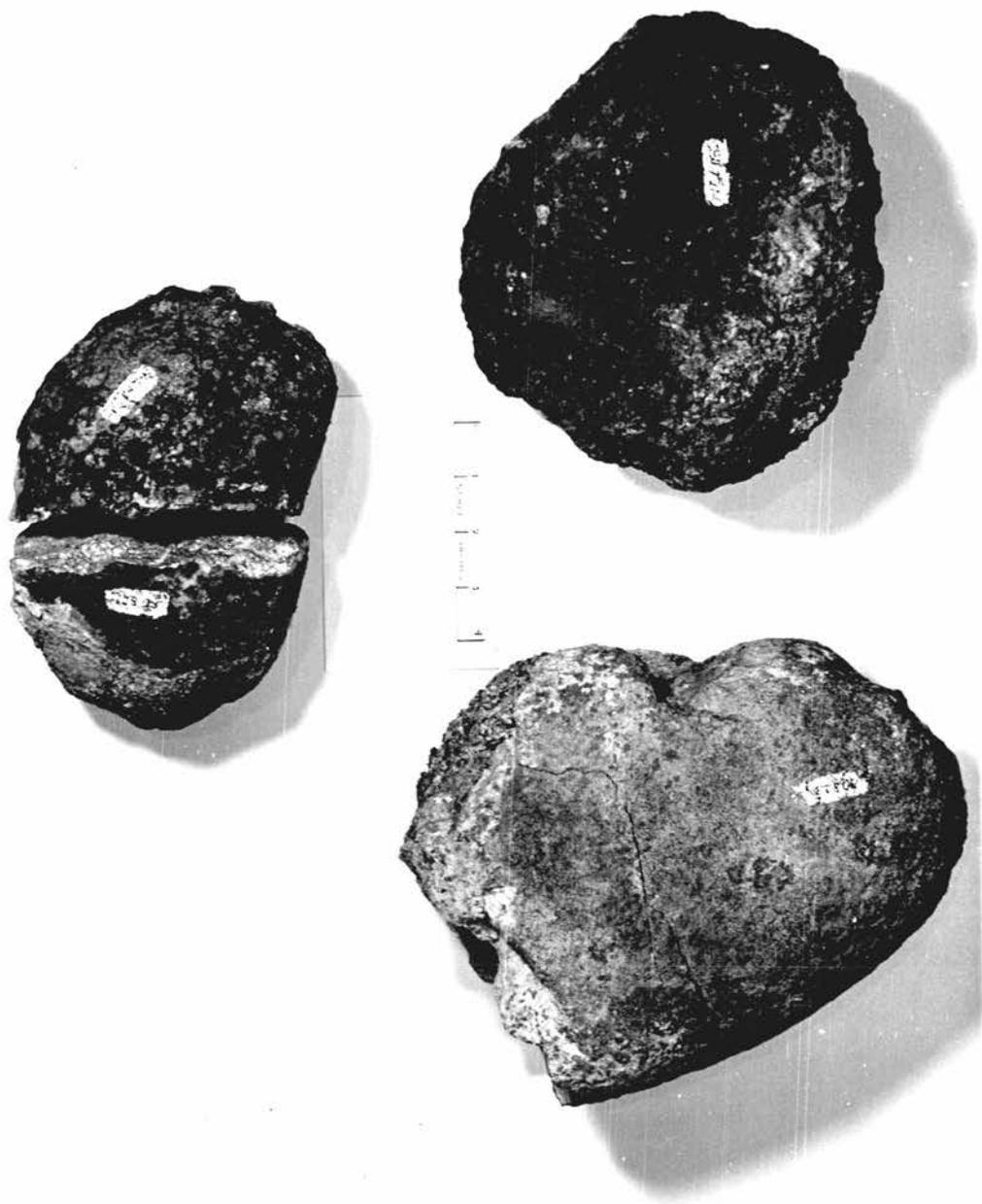


Fig. 1. Three ultrabasic nodules, showing discoidal form.

inches across. The minerals occur as large grains and show no signs of alteration. There is no obvious layering of the minerals and no cumulate type textures are shown although a layered lherzolite has been found at Lashaine. The rocks themselves are representative of five different types: BD 730 is a garnet peridotite with the mineralogical composition olivine, orthopyroxene, clinopyroxene, and garnet; BD 771 is a lherzolite with olivine, orthopyroxene and clinopyroxene; BD 806 is a mica dunite comprising olivine and phlogopite; BD 821 is a wehrlite, dominantly olivine with subsidiary chrome diopside, and BD 822 is a spinel harzburgite containing olivine, orthopyroxene and spinel present as large euhedral crystals.

For ease of reference the following code will be used;

Lashaine peridotite - LP, Lashaine wehrlite - LW etc. Thus the olivine from the Lashaine lherzolite will be referred to as LL/ol., and the clinopyroxene from the Lashaine wehrlite as LW/cpx., etc.

Methods.

a. Mineral separation.

A sample of each rock was crushed and two separate fractions were collected, one of particle size less than 80 mesh and one of particle size greater than 80 but less than 48. The mineral separations were carried out on the second fraction. A quarter of each fraction was further ground to less than 200 mesh for the bulk rock analysis.

During separation of the minerals standard methods were used. In the case of the mica dunite the mica was separated from the olivine by flotation in bromoform. In most of the other cases separation was carried out by means of

electromagnetic separation in a Franz isodynamic separator. During this it was found that chrome diopside was easily separated from the olivine and orthopyroxene.

The separation of olivine from orthopyroxene in BD 730, BD 771, and BD 822 presented the greatest problem. The mixture was heated with 2:1 HCl:H₂O for an hour and a half. After this treatment the orthopyroxene remained unchanged but the grain size of the olivine was reduced. The reduction in size enabled a good separation to be obtained on the Franz.

The garnet present in BD 730 has highly developed kelyphite rims. A concentration of garnet with kelyphite was obtained from the original crushed mixture by flotation in Clerici's solution. Unfortunately an efficient separation of clean garnet from garnet kelyphitised in varying degrees could not be effected by the same method, the kelyphitised grains having a variety of densities. A sample of clean garnet was finally obtained from the concentrate by hand picking using a vacuum pipette. In all other cases also the final concentrates of olivine, orthopyroxene and clinopyroxene were finally cleaned by hand picking.

A spinel rich fraction of BD 822 was easily obtained on the Franz Separator. The resulting mixture, contaminated with olivine and orthopyroxene, was heated with hydrofluoric acid for two hours and the remaining impurities were removed on this separator.

b. Determination of physical properties.

The specific gravities of all minerals were measured using a 10 ml. specific gravity bottle.

The refractive index of the garnet only was measured by immersion in methylene iodide - sulphur mixture. The refractive index of the liquid was measured on an Abbe refractometer.

The cell-edge length of the garnet and spinel was determined using X-ray powder photographs.

X-ray data

Extensive use was made both of X-ray powder photographs and X-ray diffractograms. The powder photograph technique was used to determine the length of the cell edge for the spinel in BD 822, the garnet in BD 730 and for the spinel present in the kelyphite rims on the garnet. Too little of this second spinel was available for a chemical analysis to be performed on it.

A powder photograph of the mica of BD 806 was taken to enable an attempt at identification to be made. The measured d spacings agree tolerably well with the values quoted for hydrobiotite of 1st. or 2nd. degree alternation in Mikeev V.I., "X-ray patterns of minerals".

Powder photographs of all the olivines were taken in an attempt to determine the mol.% of forsterite by the method of Jambor and Smith (1964). For this method the d spacing of the 174 line is calculated. The results obtained by this method are tabulated below with those obtained by other methods for purposes of comparison.

X-ray diffraction was also used to determine the olivine compositions following the method described by Yoder and Sahama (1957) whereby the position of the olivine 130 reflection is determined using the 111 silicon reflection as an internal standard.

Results yielded by both methods are below compared with those derived from chemical analysis.

Sample	Jambor & Smith	Yoder & Sahama	Analysis
BD 730	93.9	90.8	89.8
BD 771	92.7	86.4	89.7
BD 806	87.1	78.8	78.2
BD 821	96.3	90.2	84.3
BD 822	96.3	90.8	88.1

As can be seen, the results obtained from the powder photographs are consistently much higher than those from the other two methods. Cu radiation was however used in this work whereas $\text{FeK}\alpha_1$ radiation was used in the published description. The difference in the distances measured may be large enough to introduce sufficient error to account for the discrepancies. Yoder and Sahama (op. cit.) state that the error in an individual estimate of composition is of the order of ± 4 mol.% for the composition range being considered here. It will be noted that the results obtained by diffraction agree within these limits with those produced by analysis.

Methods of chemical analysis.

The samples of rocks and separated minerals upon which chemical analyses were to be performed were ground in an agate mortar to a mesh size of less than 200.

Prior to the determination, by classical gravimetric techniques (following sodium carbonate fusion) of SiO_2 , R_2O_3 , CaO and MgO the sample was dried at 110°C overnight, enabling H_2O^- to be determined. MnO, TiO_2 , P_2O_5 and total iron as Fe_2O_3 were all determined colourimetrically. FeO was determined classically by titration with standard potassium dichromate solution using diphenylamine indicator after decomposition in oxygen-free environment by

hydrofluoric acid. In the analyses of the bulk rocks reported the Al_2O_3 was found by difference from the value obtained for the R_2O_3 group. In the mineral analyses the aluminium was determined colourimetrically at a pH of 4.8 - 5.0 utilising the yellow colour of the complex formed with 8-hydroxyquinoline in a chloroform solution, the iron, which would interfere, being restricted to the water layer as the 2:2 dipyridyl complex.

The chromium and nickel values reported in the rock analyses were determined by atomic absorption spectroscopy. Chromium in the minerals was determined by fusion of 50 mgm. of the sample with sodium hydroxide and sodium peroxide in a nickel crucible, boiling the residue with 10% ethyl alcohol and comparing the optical density of the filtered solution with that of standard potassium dichromate solution.

The solutions of garnet and spinel on which MnO , TiO_2 and Fe_2O_3 were determined were obtained by fusing samples of the minerals with a mixture of lithium fluoride and boric acid and digesting the residue with concentrated sulphuric acid. Solutions of all other minerals and the rocks were prepared by digestion with hydrofluoric and perchloric acids.

In all cases sodium and potassium were determined by flame photometry.

Major element chemistry of rocks and minerals.

The analyses of the five rocks under discussion are presented in Table 1 with their associated norms. The analyses of all the minerals comprising the rocks together with their structural formulae are given in Tables 2 - 8. In the following description each rock or group of rocks will be considered in comparison with published details of rocks of the same type and their constituent minerals. Thus Table 9 presents the analyses of the garnet peridotite being

TABLE I.

	<u>Bulk rocks.</u>						<u>Bulk rock norms</u>				
	<u>BD 730</u>	<u>BD 771</u>	<u>BD 821</u>	<u>BD 822</u>	<u>BD 806</u>		<u>BD 730</u>	<u>BD 771</u>	<u>BD 821</u>	<u>BD 822</u>	<u>BD 806</u>
SiO ₂	44.37	40.47	40.53	42.41	39.28	Or.	0.41	-	0.41	0.40	2.15
Al ₂ O ₃	1.33	2.80	2.77	2.41	1.08	Ab.	1.65	-	-	1.20	1.29
TiO ₂	0.08	0.22	0.19	0.04	0.39	An.	1.65	3.85	4.48	1.81	0.65
Cr ₂ O ₃	n.d.	0.32*	0.21*	0.24*	n.d.	Di.	3.71	-	-	-	0.86
Fe ₂ O ₃	2.44	0.49	0.56	0.87	2.28	Hy.	21.11	-	-	9.64	5.71
FeO	6.42	7.02	7.16	5.38	13.78	Ol.	69.82	92.76	92.77	85.69	87.28
MgO	42.14	45.12	44.74	46.48	38.48	Mag.	1.54	0.30	0.41	0.60	1.51
MnO	0.09	0.09	0.10	0.10	0.22	Il.	0.10	0.30	0.30	-	0.54
NiO	n.d.	0.35*	0.35*	0.18*	n.d.	Leu.	-	0.61	0.30	-	-
CaO	1.45	1.58	1.70	0.50	0.41	Ne.	-	1.21	0.61	-	-
Na ₂ O	0.25	0.39	0.20	0.19	0.21	Chrom.	-	0.20	0.10	0.10	-
K ₂ O	0.14	0.25	0.21	0.14	0.50	2CaO.SiO ₂	-	0.76	0.61	-	-
H ₂ O ⁺	0.39	0.23	0.31	0.30	0.73	Cor.	-	-	-	0.55	-
H ₂ O ⁻	0.13	0.19	0.22	0.11	0.24						
P ₂ O ₅	0.05	0.00	0.05	0.00	0.04						
L.O.I.	0.25	0.26	0.27	0.24	1.89						
	<u>99.53</u>	<u>99.78</u>	<u>99.57</u>	<u>99.59</u>	<u>99.53</u>		<u>99.99</u>	<u>99.99</u>	<u>99.99</u>	<u>99.99</u>	<u>99.99</u>

* by atomic absorption.

n.d. not determined.

TABLE 2.Olivines.

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 806</u>	<u>BD 821</u>	<u>BD 822</u>
SiO ₂	40.79	40.10	37.15	40.74	40.66
TiO ₂	0.07	0.11	0.12	0.08	0.04
FeO	10.04	10.02	20.51	14.69	11.51
MgO	49.35	49.61	42.20	44.57	47.95
CaO	0.00	0.17	0.00	0.08	0.07
H ₂ O ⁻	0.07	0.01	0.12	0.04	0.01
MnO	0.09	0.08	0.15	0.06	0.06
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
	100.41	100.10	100.25	100.26	100.30
Mol.%Fo.	89.8	89.7	78.2	84.3	88.1
Fa.	10.2	10.3	21.8	15.7	11.9
Fe/Mg.	0.114	0.115	0.278	0.186	0.135
$\frac{\text{Fe}}{\text{Fe}+\text{Mg}}$	0.102	0.103	0.218	0.157	0.119
Sp.gr.	3.361	3.334	3.439	3.339	3.305

TABLE 3.

Enstatites.

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 822</u>
SiO ₂	55.81	^{55.03} 54.57	55.32
TiO ₂	0.04	0.25	0.09
Al ₂ O ₃	1.54	1.24	1.67
FeO	7.43	7.62	^{6.47} 5.95
MgO	34.38	33.67	34.68
CaO	0.52	0.56	0.24
H ₂ O ⁻	0.03	0.01	0.02
MnO	0.06	0.08	0.07
Cr ₂ O ₃	0.23	1.10	0.90
	<hr/>	<hr/>	<hr/>
	100.04	^{99.56} 99.10	^{99.46} 98.94
En	89.3	88.8	91.3
Of	10.7	11.2	8.7

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 822</u>
Sp. gr.	3.270	3.241	3.221
Structural formulae on the basis of 6 oxygens.			
Si.	1.934	1.920	1.927
Al.	0.062	0.051	0.071
Ti.	0.002	0.008	0.002
Cr.	0.004	0.029	0.025
Fe ²⁺ .	0.214	0.224	0.171
Mn.	0.002	0.002	0.002
Mg.	1.787	1.777	1.812
Ca.	0.019	0.023	0.008
<u>Fe³⁺</u>			
Mg.	0.120	0.126	0.094
<u>Fe³⁺</u>			
Fe ³⁺ +Mg.	0.107	0.112	0.086
Total R ₂ O ₃	1.64	1.98	2.38
mol. %.			

TABLE 4.
Chromite diopside.

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 821</u>
SiO ₂	51.56	53.86	51.94
Al ₂ O ₃	2.76	2.56	2.66
TiO ₂	0.25	0.58	0.58
Fe ₂ O ₃	1.22	1.57	2.01
FeO	1.46	1.62	1.70
MgO	17.18	16.60	16.95
MnO	0.11	0.08	0.10
CaO	21.52	17.94	19.66
Na ₂ O	1.56	2.27	1.33
K ₂ O	0.09	0.10	0.22
H ₂ O ⁻	0.00	0.00	0.03
Cr ₂ O ₃	1.90	3.04	2.33
	<hr/>	<hr/>	<hr/>
	99.61	100.22	99.51
Total Fe as FeO	2.56	3.03	3.51

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 821</u>
Sp. gr.	3.313	3.270	3.247
Structural formulae on the basis of 6 oxygens.			
Si.	1.898	1.958	1.905
Ti.	0.006	0.017	0.018
Al.	0.119	0.109	0.114
Cr.	0.057	0.087	0.066
Fe ^{III}	0.035	0.044	0.057
Fe ^{II}	0.044	0.048	0.053
Mn.	0.002	0.002	0.002
Mg.	0.950	0.898	0.933
Ca.	0.849	0.698	0.772
Na.	0.110	0.161	0.092
K.	0.004	0.004	0.009
Fe	0.083	0.102	0.118
Mg			
Fe	0.077	0.093	0.105
Fe+Mg.			
Ca	0.47	0.44	0.45
Ca+Mg.			

Calculation of end members.

Cr Jd + Ac	5.88	8.74	9.04	5.22
Hd.	4.75	5.29	5.47	5.67
Di.	82.13	68.31	70.63	79.64
En.	7.24	14.37	14.86	6.58
Tsch.	-	-	-	2.27
Fe ₂ O ₃	-	-	-	0.62
SiO ₂	-	3.28	-	-

a. b.

a - includes residual silica, b - recalculated excluding silica.

TABLE 5.Chrome diopside norms.

	<u>BD 730</u>	<u>BD 771</u>	<u>BD 821</u>
Orthoclase.	0.45	0.45	0.91
Albite.	1.36	10.95	8.22
Anorthite.	0.23	-	0.68
Nepheline.	4.76	-	0.68
Diopside.	86.85	71.84	79.50
Olivine.	3.97	3.76	6.51
Magnetite.	0.57	-	0.23
Haematite.	0.17	-	0.63
Ilmenite.	0.17	0.34	0.91
Chromite.	1.47	2.28	1.71
Acmite.	-	3.42	-
Hypersthene.	-	6.04	-
Perovskite.	-	0.57	-
Na ₂ O.SiO ₂	-	0.34	-
	<hr/>	<hr/>	<hr/>
	100.00	99.99	99.98



	<u>BD 730</u>
SiO ₂	40.13
Al ₂ O ₃	22.36
TiO ₂	0.19
Fe ₂ O ₃	0.60
FeO	6.29
MgO	21.02
MnO	0.06
CaO	7.59
H ₂ O ⁻	0.07
Cr ₂ O ₃	2.18
	<hr style="width: 10%; margin-left: auto; margin-right: 0;"/>
	100.49
Sp. Gr.	3.657
n 19°C	1.743
a Å	11.486

Structural formula on the basis of 24 oxygens.

	5.73		
	0.27	-----	6.00
	3.48		
Cr	0.24		
Fe ^{III}	0.07		
Ti	0.03	-----	3.82
Mg	4.49		
Fe ^{II}	0.75		
Mn	-		
Ca	1.16	-----	6.40

Excess of R^{II} elements may be explained by the observed presence of substantial inclusions of olivine in the garnet.

Calculation of end members.

	% bulk analysis.	% garnet fraction.
Pyrope.	60.2	66.8
Uvarovite.	5.9	6.5
Grossular.	13.2	14.6
Almandine.	10.8	12.0
Forsterite.	8.8	
Fajalite.	<u>1.0</u>	-----
	99.9	99.9

	<u>BD 822</u>
SiO ₂	0.05
Al ₂ O ₃	15.66
TiO ₂	2.86
Fe ₂ O ₃	13.92
FeO	6.88
MgO	15.89
MnO	0.36
CaO	1.42
Cr ₂ O ₃	43.65
H ₂ O ⁻	0.17
	<hr/>
	100.86
Sp. Gr.	4.291
a Å	8.213

BD 730*

8.059

TA
E

Si
Al
Cr
Fe³⁺
Ti
Mg
Fe²⁺
Mn
Ca

Structural formula on the basis of 32 oxygens.

Si	0.015		
Al	4.528		
Cr	8.438		
Fe ³⁺	2.558		
Ti	0.529	----	16.07
Mg	5.836		
Fe ²⁺	1.411		
Mn	0.088		
Ca	0.367	----	7.70

* Spinel from kelyphite rim round garnet BD 730.

TABLE 8

	<u>Mica.</u>		<u>Structural formula on the basis of 24</u>		
	<u>BD 806</u>	<u>A.</u>		<u>oxygens.</u>	
SiO ₂	36.06	37.30	Si	5.809	
Al ₂ O ₃	12.86	13.30	Al	2.191	---- 8.00
			Al	0.237	
TiO ₂	4.07	4.21	Ti	0.495	
Fe ₂ O ₃	6.86	7.09	Fe ⁺⁺⁺	0.822	
FeO	4.84	5.01	Fe ⁺⁺	0.644	
MnO	0.03	0.03	Mn	-	
MgO	17.19	17.78	Mg	4.147	---- 6.34
CaO	3.78	2.23	Ca	0.374	
Na ₂ O	0.35	0.36	Na	0.112	
K ₂ O	10.62	10.98	K	2.186	---- 2.67
F	0.18	0.19	F	0.093	
H ₂ O ⁺	1.29	1.33	OH	1.382	---- 1.47
H ₂ O ⁻	0.17	0.18			
CO ₂	<u>1.27</u>	<u>1.27</u>			
	99.57	99.99			
O =	<u>0.07</u>				
	99.50				

A -- Recalculated wt. % after CO₂ and an equivalent amount of CaO have been taken out as calcite.

TABLE 9

	<u>Garnet peridotites.</u>							
	1.	2.	3.	4.	5.	6.	7.	8.
SiO ₂	44.37	42.30	41.49	42.95	45.15	44.5	43.60	47.58
TiO ₂	0.08	0.14	0.15	0.04	0.15	0.15	0.04	0.19
Al ₂ O ₃	1.33	2.42	2.55	0.88	2.39	2.55	2.40	6.68
Fe ₂ O ₃	2.44	1.92	3.55	2.63	0.27	1.5	1.00	0.69
Cr ₂ O ₃	n.d.	0.48	0.53	0.40	0.09			0.43
FeO	6.42	7.30	5.74	7.82	6.35	7.3	7.80	6.51
MgO	42.14	41.26	35.69	40.97	42.21	41.7	41.50	27.50
MnO	0.09	0.16	0.11	0.15	0.12	0.14	0.10	0.14
NiO	n.d.			0.32				0.33
CaO	1.45	1.93	3.20	2.20	2.08	2.25	2.50	7.94
Na ₂ O	0.25			0.19	0.24	0.25	0.32	0.82
K ₂ O	0.14			0.02	nil.	0.015	0.005	0.02
P ₂ O ₅	0.05			0.003	0.03			0.003
H ₂ O ⁺	0.39			1.20	0.65			1.08
H ₂ O ⁻	0.13	0.27	0.98		0.12			
L.O.I.	0.25	1.36	5.45					
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>			<hr/>
	99.53	99.59	99.48	99.75	99.85			99.91

1. BD 730 garnet peridotite, Lashaine, new analysis.
2. Garnet peridotite, Bohemian massif, Fiala (1966).
3. Garnet peridotite, Bohemian massif, Fiala (1966).
4. Garnet-dunite, Tafjord, Norway, Mercy & O'Hara (1965).
5. Garnet peridotite inclusion in kimberlite, Basutoland, Dawson (1962).
6. Estimate of upper mantle composition, White (1967).
7. Hess' type C peridotite.
8. Garnet-lherzolite, Almklovdalen, O'Hara & Mercy (N.69) (1963).

TABLE 10.

Analyses of garnets.

	1.	2.	3.	4.	5.	6.	7.
SiO ₂	40.13	42.13	42.29	42.44	41.20	41.78	41.62
TiO ₂	0.19	0.74	0.43	0.52	0.19	0.17	0.98
Al ₂ O ₃	22.36	21.48	22.34	22.24	23.11	22.26	20.88
Cr ₂ O ₃	2.18	1.73	1.61	1.98	0.80	2.32	1.69
Fe ₂ O ₃	0.60	0.91	0.33	1.56	1.59	1.91	1.68
FeO	6.29	7.65	8.04	4.75	10.40	7.08	8.37
MnO	0.06	0.34	0.43	0.16	0.41	0.45	0.14
MgO	21.02	20.74	20.20	21.53	17.96	20.13	18.86
CaO	7.59	4.34	4.41	4.99	4.55	4.60	5.98
Na ₂ O		0.21	0.15		0.05	0.04	
K ₂ O		0.02	0.01		tr.	tr.	
H ₂ O ^m	0.07						0.12
	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>	<hr/>
	100.49	100.29	100.24	100.08	100.26	100.74	100.32
n.	1.743	1.746	1.747	1.742-6	1.742	1.744	1.755
a.	11.486				11.534	11.534	
Fe/Mg.	0.182	0.229	0.231		0.369	0.244	
D.	3.657						3.73

1. BD 730 garnet peridotite, Lashaine, new analysis.
2. Garnet peridotite, Bohemian massif, J. Fiala (1966).
3. Garnet peridotite, Bohemian massif, J. Fiala (1966).
4. Garnet peridotite inclusion in kimberlite, Basutoland, J.B. Dawson (1962).
5. Garnet-lherzolite, Almklovdaalen, M.J.O'Hara & E.L.P. Mercy N. 69 (1963).
6. Garnet-lherzolite inclusion in kimberlite, S. Africa, M.J.O'Hara & E.L.P. Mercy A 3 (1963).
7. Kimberlite pipe Geophysicheskaya, Yakutia, Bobrievich (1959).

studied, BD 730 or LP, together with those of six other garnet peridotites and one estimated composition, the peridotites originating in Bohemia, Norway and South Africa.

Garnet peridotite BD 730.

Of the five selected rocks the garnet peridotite BD 730 has the highest silica content, this is reflected in the presence in the norm of the lowest percentage of olivine and the highest percentage of hypersthene, the rock containing over 20% of normative hypersthene.

The most noteworthy differences exposed are the relatively low values for aluminium and calcium. In the high content of magnesium BD 730 is most like the Basutoland peridotite (Dawson 1962). Indeed in overall composition this specimen provides the closest comparison to BD 730, differing markedly only in having higher aluminium and lower ferric iron content. In these latter respects BD 730 is more closely akin to the specimen from Tafjord, Norway (Mercy and O'Hara 1964).

Garnet peridotite BD 730.

1. Olivine.

The analysis of LP/ol is compared in Table 11 with those of olivines from garnet peridotites occurring in Bohemia (2 & 3), Norway (4), and S. Africa (5).

It has been assumed that all the iron is present as ferrous iron, and this assumption has been made for all the olivines. The molar percentages of the fayalite and forsterite components are given together with the relative densities. The values found for individual components of LP/ol are easily embraced within the variation range of the analyses offered for comparison.

TABLE 11.

Analyses of olivines, (garnet peridotites)

	1.	2.	3.	4.	5.
SiO ₂	40.79	40.28	40.28	n.d.	n.d.
TiO ₂	0.07	0.03	0.05	0.08	0.03
Al ₂ O ₃		0.19	0.19	0.30	0.04
Cr ₂ O ₃		0.02	nil.	0.03	0.01
Fe ₂ O ₃		0.96	0.98		
FeO	10.04*	8.91	9.32	10.54*	8.05*
MnO	0.09	0.14	0.12	0.10	0.10
CaO	nil.	0.10	0.25	0.20	0.08
NiO		0.49	0.40	0.53	0.43
MgO	49.35	48.85	48.08	47.08	50.24
H ₂ O ⁻	0.07				
	<hr/>	<hr/>	<hr/>		
	100.41	99.87	99.67		
Sp. gr.	3.361	3.392	3.384	-	-
Mol. % Fa.	10.2	10.1	10.6	11.2	8.2
Mol. % Fo.	89.8	89.9	89.4	88.8	91.8
Fe/Mg.	0.114	0.112	0.119	0.126	0.090

1. BD 730 garnet peridotite, Lashaine, new analysis.
2. Garnet peridotite, Bohemian massif, J. Fiala (1966).
3. Garnet peridotite, Bohemian massif, J. Fiala (1966).
4. Garnet-lherzolite, Almklovdalen, M.J.O'Hara & E.L.P. Mercy. N 69 (1963).
5. Garnet-lherzolite inclusion in kimberlite, S. Africa, M.J.O'Hara & E.L.P. Mercy. A 3 (1963).

The Fe/Mg ratio is close to that of the samples from the Bohemian massif but considerably lower than the value given for the Norwegian specimen and higher than that from S. Africa.

Estimates of the forsterite content of the olivines were made using two different X-ray methods. The results obtained are compared with each other and with those derived from analysis on earlier pages.

2. Orthopyroxene.

The analyses of LP/opx and those from comparable rocks are given in Table 12. Once again all the iron is assumed to be in the divalent state, for this, and all subsequent, orthopyroxenes. From the structural formulae presented in Table 12 it will be seen that there is a cation deficiency in the Z group similar to that found by O'Hara and Mercy (1963) and Ross et al., (1954). The suggestion has been put forward that at high pressures there may be a solid solution at the orthopyroxene - olivine contact, (Boyd and England 1960).

Except in the high level of chromium compared with that in the sample from Norway there is little variation between LP/opx and the others shown. The Aluminium content is low compared with that found in inclusions in basalts, see Table 16. This contrasts with the experimental results of Boyd and England (1960) which indicate that the aluminium content of orthopyroxenes in a high pressure environment in the presence of an aluminium component might be high.

The Fe/Mg ratio of the sample under investigation is in reasonable agreement with the others given, with the exception of the low value obtained for the S. African sample.

TABLE 12

Structural formulae of orthopyroxenes from garnet peridotites on the basis of 6 oxygens.

	1.	2.	3.	4.	5.
Si	1.934	1.951	1.941	1.976	1.967
Al	0.062	0.036	0.047	0.024	0.033
Al		0.006	0.018	0.020	0.027
Ti	0.002	0.004	0.004	0.002	0.002
Cr	0.004	0.012	0.004	0.002	0.004
Fe ^{III}		0.014	0.021		
Fe ^{II}	0.214	0.183	0.175	0.212	0.142
Mn	0.002	0.005	0.003	0.002	0.003
Mg	1.787	1.764	1.737	1.752	1.813
Ca	0.019	0.035	0.055	0.009	0.009
Fe/Fe+Mg	0.107				

Analyses of orthopyroxenes, (garnet peridotites)

	1.	2.	3.	4.	5.
SiO ₂	55.81	56.38	56.02	n.d.	n.d.
TiO ₂	0.04	0.16	0.21	0.09	0.07
Al ₂ O ₃	1.54	1.04	1.60	1.08	1.53
Cr ₂ O ₃	0.23	0.42	0.15	0.08	0.17
Fe ₂ O ₃		0.54	0.82		
FeO	7.43*	6.33	6.05	7.49*	5.05*
MnO	0.06	0.17	0.11	0.10	0.11
MgO	34.38	34.21	33.64	34.73	36.22
CaO	0.52	0.94	1.48	0.26	0.24
H ₂ O ⁻	0.03				
	100.04	100.19	100.08		

* total iron calculated as FeO.

Sp. gr.	3.270	3.297	3.289	-	-
Mol. % Of.	10.7	10.1	10.2	10.8	7.3
Mol. % En.	89.3	89.9	89.8	89.2	92.7
Fe/Mg.	0.120	0.112	0.113	0.121	0.078

1. BD 730 garnet peridotite, Lashaine, new analysis.
2. Garnet peridotite, Bohemian massif, J. Fiala (1966).
3. Garnet peridotite, Bohemian massif, J. Fiala (1966).
4. Garnet-lherzolite, Almklovdalen, M.J.O'Hara & E.L.P. Mercy N 69 (1963).
5. Garnet-lherzolite inclusion in kimberlite, S. Africa, M.J. O'Hara & E.L.P. Mercy A 3 (1963).

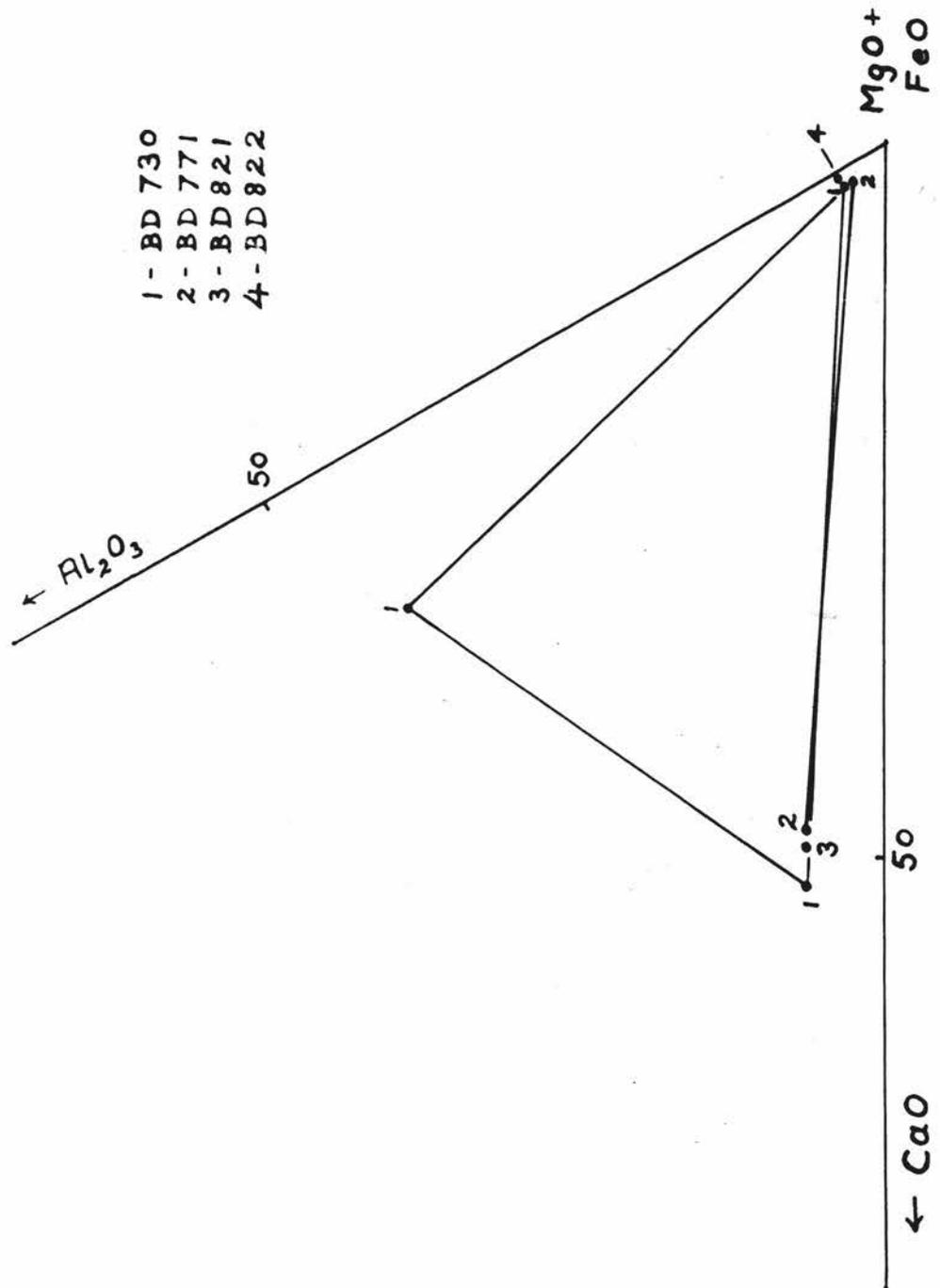


Fig. 2. Composition of minerals.

1. Minerals of BD 730; garnet, ortho- and clinopyroxenes.
2. Minerals of BD 771; ortho- and clinopyroxenes.
3. Clinopyroxene of BD 821.
4. Orthopyroxene of BD 822.

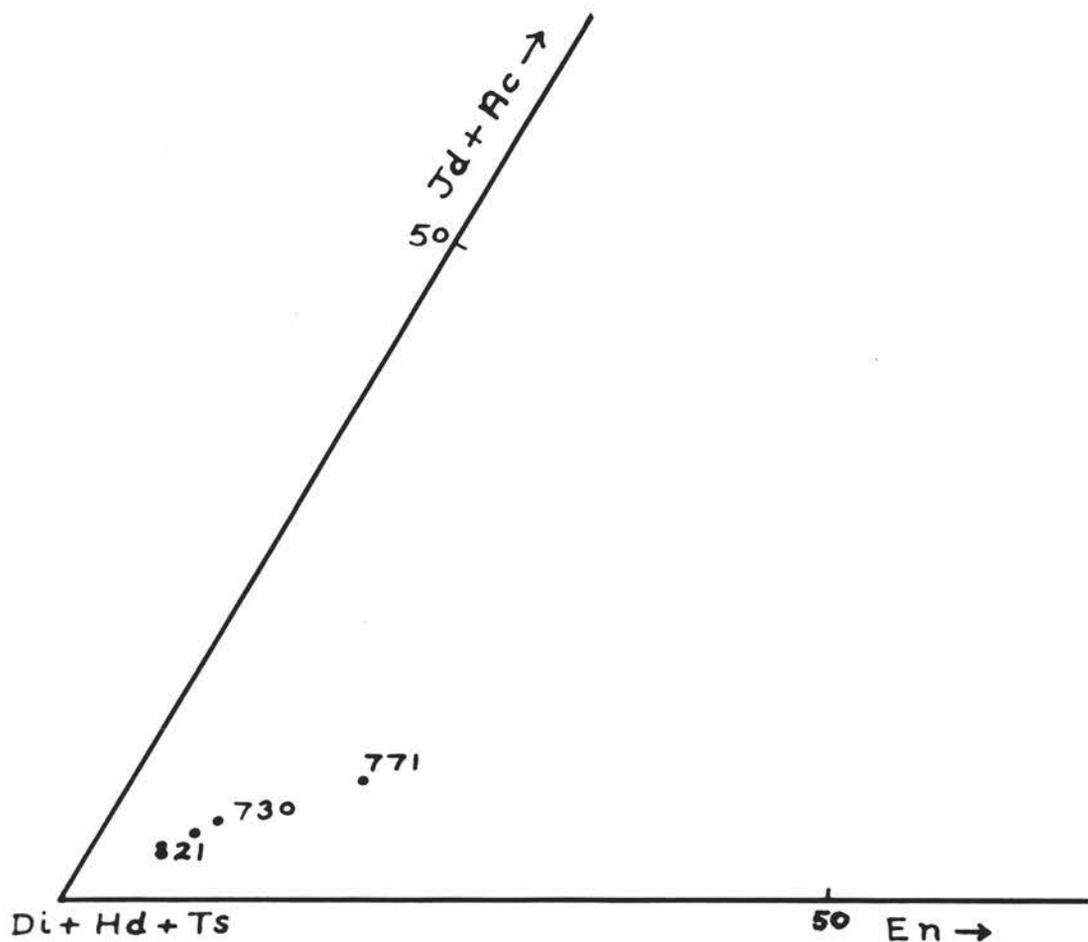


Fig. 3. Compositions of the clinopyroxenes in terms of the end members; enstatite, jadeite plus acmite, diopside plus hedenbergite plus Tschermakite.

3. Clinopyroxenes.

The analysis and relative density of LP/cpx is given in Table 13 together with comparative data. The corresponding structural formulae and Fe/Mg ratios also appear in Table 13.

The chromium content is notably higher than that of the Norwegian and Basutoland specimens, being in closest agreement with the clinopyroxene of the kimberlite inclusion (5). The level of aluminium is also high, particularly when compared to the Basutoland sample. The Fe/Mg ratios, calculated on the basis of the total iron content are similar in all cases.

The compositions of all three clinopyroxenes studied, from BD 730, BD 771 and BD 821, are shown in terms of the end members Jadeite + Acmite, Diopside + Hedenburgite + Tschermakite, Enstatite in Fig. 3, calculated by the method recommended by Yoder & Tilley (1962). The norms are also given in Table 5.

4. Garnet.

The composition of LP/gr together with the refractive index and Fe/Mg ratio, is given with comparative data in Table 10. The structural formula and composition in terms of end members are shown in Table 6. The garnet was seen to contain inclusions of olivine of varying sizes and this fact is held to explain the excess of divalent elements in the structural formula.

The titanium in the specimen from BD 730 is at a similar level to that in the Norwegian and S. African samples but is much lower than for the Bohemian and Basutoland pyropes. The chromium value for LP/gr is directly comparable to that for the garnets derived from inclusions in kimberlite both from S.

Structural formulae of clinopyroxenes from garnet peridotites
on the basis of 6 oxygens.

	1.	2.	3.	4.	5.
Si	1.898	1.918	1.924	1.968	1.961
Ti	0.006	0.007	0.013	0.005	0.005
Al	0.119	0.087	0.111	0.092	0.102
Cr	0.057	0.033	0.030	0.020	0.045
Fe ^{III}	0.035	0.014	0.005	0.027	0.037
Fe ^{II}	0.044	0.071	0.087	0.047	0.039
Mn	0.002	0.002	0.003	0.002	0.002
Mg	0.950	0.960	0.969	0.857	0.885
Ca	0.849	0.859	0.810	0.893	0.801
Na	0.110	0.110	0.076	0.094	0.126
K	0.004				
Fe/Mg	0.083	0.088	0.095	0.086	0.086
Fe/Fe+Mg	0.077				

Analyses of clinopyroxenes, (garnet peridotite)

	1.	2.	3.	4.	5.	6.
SiO ₂	51.56	52.71	53.17	54.20	53.90	54.61
TiO ₂	0.25	0.25	0.48	0.18	0.20	0.23
Al ₂ O ₃	2.76	2.02	2.60	2.15	2.40	1.30
Cr ₂ O ₃	1.90	1.14	1.05	0.69	1.55	0.92
Fe ₂ O ₃	1.22	0.50	0.19	0.98	1.34	1.14
FeO	1.46	2.34	2.87	1.55	1.28	3.02
MnO	0.11	0.08	0.09	0.05	0.08	0.10
MgO	17.18	17.72	17.98	15.89	16.39	20.88
CaO	21.52	22.05	20.91	22.90	20.57	16.20
Na ₂ O	1.56	1.56	1.08	1.34	1.80	1.28
K ₂ O	0.09	0.05	0.03	0.01	0.02	0.12
H ₂ O ⁺						0.41
H ₂ O ⁻	nil.					0.07
	99.61	100.42	100.45	99.94	99.53	100.28
Sp.gr.	3.313	3.329	3.317	-	-	-

1. BD 730 garnet peridotite, Lashaine, new analysis.
2. Garnet peridotite, Bohemian massif, J. Fiala (1966).
3. Garnet peridotite, Bohemian massif, J. Fiala (1966).
4. Garnet-lherzolite, Almklovdalen, M.J.O'Hara & E.L.P. Mercy N 69 (1963).
5. Garnet-lherzolite, inclusion in kimberlite, S. Africa, M.J.O'Hara & E.L.P. Mercy A 3 (1963).
6. Garnet peridotite inclusion in kimberlite, Basutoland, J.B. Dawson (1962).

Africa and Basutoland, but is a good deal higher than the chromium in the Bohemian and Norwegian garnets. The manganese level of LP/gr is very low and the calcium value high when compared to the other examples presented. The value of the Fe/Mg ratios varies quite widely, with the value for LP/gr being lower than the others.

Non-garnetiferous peridotites.

The next group of rocks to be considered consists of three non-garnetiferous peridotites, a lherzolite BD 771, a wehrlite BD 821 and a harzburgite BD 822, containing spinel. The analyses of these rocks appear in Table 14 and their norms in Table 1. The harzburgite, BD 822, shows a lower value for calcium than the other two, as might be expected in the absence of any clinopyroxene, and a lower value for iron.

The composition of each mineral in these rocks will be discussed in comparison with the corresponding mineral from similar rock types occurring as inclusions in basaltic rocks. The source of the comparative data is, "Ultramafic inclusions in basaltic rocks from Hawaii" R.W. White (1966). The various minerals are also compared in Tables 2 - 5 with those of the garnet peridotite BD 730.

The mica dunite BD 806, will be discussed separately later.

There is a conspicuous lack of data in the published literature concerning non-garnetiferous peridotitic inclusions in kimberlite.

Lherzolite.

1. Olivine.

The analysis of LL/ol. is compared in Table 15 with those of olivines from lherzolites present as inclusions in basaltic rocks. The molar percentages of fayalite and forsterite are given.

TABLE 14.

Analyses of three peridotite inclusions.

SiO ₂	40.47	40.53	42.41
Al ₂ O ₃	2.80	2.77	2.41
TiO ₂	0.22	0.19	0.04
Cr ₂ O ₃	0.32*	0.21*	0.24*
Fe ₂ O ₃	0.49	0.56	0.87
FeO	7.02	7.16	5.38
MgO	45.12	44.74	46.48
MnO	0.09	0.10	0.10
NiO	0.35*	0.35*	0.18*
CaO	1.58	1.70	0.50
Na ₂ O	0.39	0.20	0.19
K ₂ O	0.25	0.21	0.14
P ₂ O ₅	nil.	0.05	nil.
H ₂ O ⁺	0.23	0.31	0.30
H ₂ O ⁻	0.19	0.22	0.11
L.O.I.	0.26	0.27	0.24
	<hr/>	<hr/>	<hr/>
	99.78	99.57	99.59

- | | | |
|----|-------------------------------|-----------------|
| 1. | BD 771 lherzolite, Lashaine. | } new analyses. |
| 2. | BD 821 wehrlite, Lashaine. | |
| 3. | BD 822 harzburgite, Lashaine. | |

TABLE 15.

Analyses of olivines from lherzolites.

	1.	2.	3.	4.	5.
SiO ₂	40.10				
TiO ₂	0.11	0.00		0.00	
Al ₂ O ₃	n.d.			0.00	
Cr ₂ O ₃	n.d.			0.00	
FeO*	10.02	9.6	9.9	9.8	11.1
MnO	0.08	0.15	0.17	0.15	0.15
NiO	n.d.	0.39	0.39	0.38	0.37
MgO	49.61	48.9	49.6	48.7	47.9
CaO	0.17	0.06	0.07	0.13	0.06
H ₂ O ⁻	0.01				
	<hr/>				
	100.10				
Mol. % Fa.	10.3	13.7	14.1	13.9	15.7
Mol. % Fo.	89.7	85.3	86.5	85.1	83.6
Fe/Fe+Mg	0.103	0.100	0.101	0.101	0.115

1. BD 771 lherzolite, Lashaine, new analysis.
 2. 25.9)
 3. 33b.18) lherzolite inclusions in basaltic rocks from Hawaii,
 4. 82b.2) R.W. White (1966).
 5. 138b.1)

There is a marked uniformity of composition for all five samples with respect to the major constituents, iron and magnesium. Small differences occur however in the levels of manganese, where LL/ol. is low, and of calcium, it being somewhat higher than for those derived from basaltic inclusions.

The Fe/Fe+Mg ratio of LL/ol. is in close accord with the other examples given.

2. Orthopyroxene.

Table 16 shows the composition of LL/opx in comparison with the orthopyroxenes originating in the same rocks as the olivines discussed in the last section, and the clinopyroxenes mentioned below.

The magnesium and iron values are in close agreement for all five examples quoted, the calcium levels are also reasonably close. The greatest differences occur in the amounts of aluminium and chromium. The aluminium content of LL/opx is very much lower than those of the others and the chromium content is a great deal higher.

The values of the Fe/Fe+Mg ratios are reasonably uniform throughout.

3. Clinopyroxene.

The analysis of LL/cpx is given in Table 17 together with those for clinopyroxenes from inclusions in basaltic rocks.

As for the orthopyroxenes the aluminium and chromium values show the greatest divergence. Once again the aluminium of LL/cpx is much lower than the others whereas the chromium is four times the concentration of the next highest example quoted (2). The iron values are fairly uniform but magnesium is slightly more abundant in LL/cpx sample. The calcium of this specimen is at a slightly lower level than the others.

TABLE 16.

Analyses of orthopyroxenes from lherzolites.

	1.	2.	3.	4.	5.
SiO ₂	54.57				
TiO ₂	0.25	0.07	0.08	0.10	0.20
Al ₂ O ₃	1.24	3.3	4.4	3.9	5.4
Cr ₂ O ₃	1.10	0.29	0.34	0.32	0.38
FeO*	7.62	6.20	6.4	6.4	7.1
MnO	0.08	0.15	0.15	0.15	0.15
NiO			0.09	0.10	
MgO	33.67	33.8	33.2	33.1	32.2
CaO	0.56	0.60	0.81	0.62	0.76
Na ₂ O				0.11	0.12
H ₂ O ⁻	0.01				
Fe/Fe+Mg	0.112	0.093	0.097	0.098	0.110

1. BD 771 lherzolite, Lashaine, new analysis.
2. 25.9)
3. 33b.18) Lherzolite inclusions in basaltic rocks from Hawaii,
4. 82b.2) R.W. White (1966).
5. 138b.1)

TABLE 17.

Analyses of clinopyroxenes from lherzolites.

	1.	2.	3.	4.	5.
SiO ₂	53.86				
TiO ₂	0.58	0.35	0.52	0.47	0.80
Al ₂ O ₃	2.56	5.5	6.9	6.2	7.3
Cr ₂ O ₃	3.04	0.77	0.73	0.70	0.61
Fe ₂ O ₃	1.57				
FeO	1.62	2.6*	3.0*	3.1*	3.4*
MnO	0.08	0.09	0.09	0.09	0.10
NiO			0.04	0.06	
MgO	16.60	15.3	14.8	14.7	14.3
CaO	17.94	20.7	19.6	18.7	19.0
Na ₂ O	2.27	1.2	1.8	1.7	1.9
K ₂ O	0.10		0.0	0.0	0.0

100.22

* total iron as FeO.

Fe/Fe+Mg	0.093	0.087	0.103	0.106	0.119
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1. BD 771 lherzolite, Lashaine, new analysis.
2. 25.9)
3. 33b.18) lherzolite inclusions in basaltic rocks from Hawaii,
4. 82b.2) R.W. White (1966).
5. 138b.1)

The Fe/Fe+Mg ratios are fairly constant.

Wehrlite.

1. Olivine.

LW/ol. is given in composition, in Table 18, in comparison with olivines of wehrlites found included in basalt. The molar percentages of fayalite and forsterite are also shown.

In composition these olivines are less uniform than those of the lherzolites. In particular LW/ol. sample is richer in magnesium and contains less iron than the other examples. The manganese is low in LW/ol. but the calcium values are fairly uniform.

Although the Fe/Fe+Mg value for LW/ol. falls within the spread of the others, the spread is considerably larger than that for the olivines of the lherzolites.

2. Clinopyroxene.

The analysis of LW/cpx. see Table 19, exhibits once again the trait noted in the lherzolite described above for the aluminium to be much lower and the chromium to be much higher in concentration than for the pyroxenes from similar rock types occurring as inclusions in basalts. The magnesium level is slightly higher for LW/cpx. and the low iron content of the mineral is reflected in the low value of the Fe/Fe+Mg ratio.

Although the titanium level of LW/cpx. is a little below that of the others given the difference is slight, and the same is true for calcium and manganese.

Harzburgite.

1. Olivine.

The analysis of LH/ol. is presented in Table 20 together with those of

TABLE 18.

Analyses of olivines from wehrlites.

	1.	2.	3.	4.	5.
SiO ₂	40.74				
TiO ₂	0.08				
FeO*	14.59	22.5	18.8	16.5	17.4
MnO	0.06	0.27	0.23	0.22	0.25
NiO		0.15		0.33	0.25
MgO	44.57	38.0	41.1	43.1	42.3
CaO	0.08	0.11	0.10	0.08	0.10
H ₂ O ⁻	0.04				
	<hr/>				
	100.26				
Mol. % Fa.	15.7	31.9	26.6	23.3	24.6
Mol. % Fo.	84.3	66.2	71.7	75.2	73.8
Fe/Fe+Mg	0.186	0.250	0.204	0.176	0.187

1. BD 821 wehrlite, Lashaine, new analysis.

2. 124s.1

3. 168c.3

4. 212.2

5. 212g

} wehrlite inclusions in basaltic rocks from Hawaii,
R.W. White (1966).

TABLE 19.

Analyses of clinopyroxenes from wehrlites.

	1.	2.	3.	4.	5.
SiO ₂	51.94				
TiO ₂	0.58	1.8	2.0	0.68	0.75
Al ₂ O ₃	2.66	6.8	7.4	2.9	3.1
Cr ₂ O ₃	2.33	0.12	0.22	0.80	0.73
Fe ₂ O ₃	2.01				
FeO	1.70	8.4*	6.7*	5.7*	5.5*
MnO	0.10	0.15	0.13	0.12	0.14
NiO		0.03			
MgO	16.95	13.6	13.5	15.7	15.7
CaO	19.66	19.3	20.4	21.1	20.8
Na ₂ O	1.33	0.75	0.61	0.44	0.40
K ₂ O	0.22	0.0		0.0	0.0
H ₂ O ⁻	0.03				

	99.51				

* total iron as FeO.

Fe/Fe+Mg	0.105	0.256	0.217	0.170	0.165
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1. BD 821 wehrlite, Lashaine, new analysis.
 2. 124s.1)
 3. 168c.3) wehrlite inclusions in basaltic rocks from Hawaii,
 4. 212.2) R.W. White (1966).
 5. 212g)

TABLE 20.

Analyses of olivines from harzburgites.

	1.	2.	3.	4.	5.
SiO ₂	40.66				
TiO ₂	0.04				
FeO*	11.51	9.0	8.5	12.2	13.2
MnO	0.06	0.13	0.13	0.17	0.18
NiO		0.37	0.39	0.47	0.41
MgO	47.95	49.2	49.6	46.8	45.8
CaO	0.07	0.11	0.07	0.10	0.10
H ₂ O ⁻	0.01				
	<hr/>				
	100.30				
Mol. % Fa.	11.9	12.7	12.0	17.2	18.8
Mol. % Fo.	88.1	85.9	86.5	81.6	79.8
Fe/Fe+Mg	0.119	0.093	0.096	0.127	0.140

1. BD 822 harzburgite, Lashaine, new analysis.
 2. 30.1)
 3. 30.2) harzburgite inclusions in basaltic rocks from Hawaii,
 4. 168b.2) R.W. White (1966).
 5. 168b.3)

olivines from similar rocks occurring as inclusions in basalt. The molar percentages of fayalite and forsterite are given. The manganese of LH/ol. is rather lower than in the others, but, with this exception, the values for all the other elements fall within the spread of values obtained for the examples chosen. The same is true for the Fe/Fe+Mg ratio.

2. Orthopyroxene.

2 The analyses, shown in Table 21, of LH/opx. together with comparative data, indicate that whereas the tendency to low aluminium and high chromium in the pyroxenes being studied when compared to pyroxenes derived from inclusions in basalts is maintained, the discrepancies are much less pronounced than was the case for the lherzolites.

The manganese and calcium levels in LH/opx. are low, but those for titanium, iron and magnesium are comparable to those of the other examples. The Fe/Fe+Mg ratios are also in fairly good agreement.

3. Spinel.

The analysis of LH/SP. is given in Table 7, with its structural formula.

An interesting feature of this analysis is the fairly high titanium figure. The value reported for ferrous iron was arrived at by recalculation from the total iron result.

Mica Dunite.

1. Olivine.

The analysis of LD/ol. is given in Table 2 together with those of the other olivines investigated. This is the only olivine not coexisting with a pyroxene. Marked differences are apparent in the levels of several elements. The much higher iron content of LD/ol. is reflected in the high molar percentage

TABLE 21.

Analyses of orthopyroxenes from harzburgites.

	1.	2.	3.	4.	5.
SiO ₂	55.32				
TiO ₂	0.09	0.07	0.00	0.22	0.23
Al ₂ O ₃	1.67	4.1	2.4	2.1	2.4
Cr ₂ O ₃	0.90	0.58	0.50	0.73	0.50
FeO*	5.95	5.9	5.4	7.9	8.4
MnO	0.07	0.14	0.14	0.17	0.17
NiO			0.10	0.13	0.10
MgO	34.68	32.6	34.2	32.0	31.4
CaO	0.24	1.1	0.87	1.4	1.4
H ₂ O ⁻	0.02				
Fe/Fe+Mg	0.086	0.093	0.082	0.122	0.131

1. BD 822 harzburgite, Lashaine, new analysis.
 2. 30.1)
 3. 30.2) harzburgite inclusions in basaltic rocks from Hawaii,
 4. 168b.2) R.W. White (1966).
 5. 168b.3)

of fayalite and the correspondingly high Fe/Fe+Mg ratio. The manganese value is also high. In silica and magnesium LD/ol. is poorer than any of the other olivines examined.

2. Mica.

The analysis of LD/m. appears in Table 8. The second column (A) represents the recalculated analysis after the carbon dioxide has been taken out with an equivalent amount of CaO as calcite. This step was taken because in thin section cavities within the mica grains were seen to be rimmed by calcite. The values found for both titanium and calcium are fairly high. The structural formula in Table 8 reveals that the proportion of F+OH is low, suggesting formation in a high pressure environment.

Review of the Hypotheses on the origin of ultrabasic xenoliths.

The origin of ultrabasic inclusions in basaltic and kimberlitic rocks has preoccupied many authors over a number of years. Ross, Foster and Myers (1954), after a chemical investigation of several olivine-rich inclusions in basaltic rocks, conclude that these nodules "are derived from the peridotite zone of the earth's crust and that most of them at least came directly from that zone." The upper surface of this zone is believed by them to represent the Mohorovicic discontinuity. Among the arguments they cite against the nodules being direct differentiates from basaltic magmas are: the improbability of nodules of pure olivine, pure enstatite and dominantly chrome diopside being simultaneously formed; the large size of most mineral grains not being indicative of direct crystallisation from a basaltic magma; and the fact that the high chromium content of the pyroxenes of the inclusions would represent an improbable concentration from a basaltic magma.

O'Hara and Mercy (1963) in a later study of garnet peridotites conclude that only the garnet peridotite nodules included in kimberlite "can be representative of the unmodified composition of the upper mantle", and that peridotite nodules in basalt "may be a fundamental part of the process whereby alkali basalt and melilitite basalt are derived by partial fusion of garnet peridotites in the mantle".

Harris (1966) proposes that ultramafic nodule inclusions represent mantle fragments from a pyroxene-peridotite layer and a deeper garnet peridotite layer.

R.W. White (1966) after an extensive study of ultramafic inclusions in basaltic rocks from Hawaii, argues that "it is unlikely that lherzolite inclusions are fragments of homogeneous primary mantle equivalent to that from which basaltic magma is produced. "But", he continues, "I know of no good arguments why they cannot be either a residue of fusion or fragments of infusible portions of heterogeneous mantle, and in either case be unlike the material from which basaltic magmas are produced".

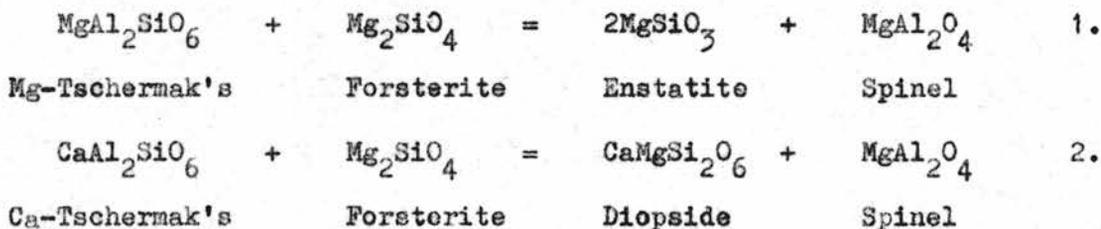
A statistical treatment of a compilation of chemical analyses by I.G. White (1967) provides evidence that the majority of ultrabasic rocks were not derived by crystal accumulation processes from liquids but are solid samples of the upper mantle. These statistics also indicate that partial fusion of peridotites has occurred and, depending on the degree of fusion, a range of intermediates between original peridotite and pure olivine residue is possible. In view of this, evidence derived from phase studies of synthetic and natural mixtures will be discussed later.

Sobolev and Sobolev (1964), working on the inclusions in the kimberlites of northern Yakutia, found "xenoliths with garnet peridotite passing into eclogite and olivine passing into spinel harzburgite", pointing to the conclusion that these are not magmatic segregations but fragments from a body having a banded or stratified structure. They also postulate a mechanism for transformations in ultrabasic and basic rocks as the pressure changes and further mention will be made of this.

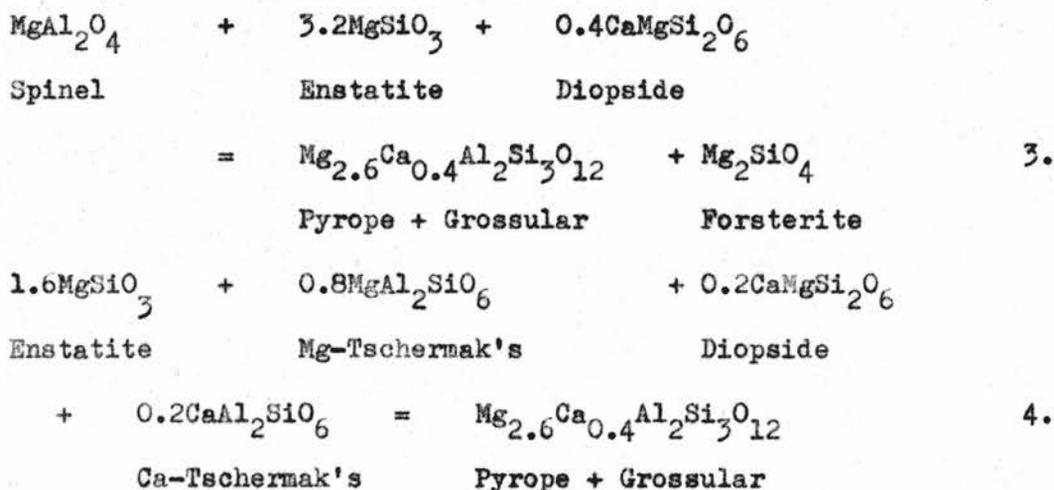
The solubility of alumina in enstatite has been investigated as a function of pressure and temperature. Boyd and England (1960) working with a temperature of 1400°C and a pressure of 18.2 kilobars (kb) found that the solubility limit for Al_2O_3 in enstatite was in the region 14-19%. The same authors later found (1963) that the alumina content of enstatite in equilibrium with pyrope is a function of both temperature and pressure. The solubility of Al_2O_3 in enstatite is less than 5% at 1100°C and 30kb. pressure but increases to 16% at 1650°C at the same pressure. An increase in pressure greatly reduces the solubility of Al_2O_3 in enstatite in the presence of pyrope to about 2% at 1100°C and 40kb. pressure. MacGregor and Ringwood (1964), working on the natural system enstatite - pyrope confirmed the general observations on the synthetic system outlined above. However they found that at 1500°C a natural orthopyroxene at equilibrium has more R_2O_3 component than synthetic enstatite at equilibrium under the same conditions. This difference, however, decreases with increasing pressure and becomes negligible at pressures greater than 50kb. After studying aluminous diopsides in the three-phase assemblage, diopside solid solution + forsterite + spinel,

MacGregor (1965) concludes that the Al_2O_3 content of diopsides also decreases with increasing pressure at constant temperature.

Results of an investigation into the melting and phase relations in a natural peridotite carried out by Ito and Kennedy (1967) led the authors to the conclusion that a low pressure mineral assemblage of olivine + orthopyroxene + clinopyroxene + chrome spinel is stable up to 23kb. The formation of spinel from an olivine - pyroxene mixture may, they suggest, be accounted for by supposing that an increase in pressure makes reactions 1 and 2 advance to the right, thereby producing spinel and less aluminous pyroxenes.



At about 23kb. and $1350^\circ C$, garnet appeared and co-existed with chrome spinel up to a pressure of approximately 27kb. when the spinel disappeared. They propose the following reactions to account for the appearance of garnet.



The assemblage olivine, orthopyroxene, clinopyroxene and garnet was stable to the highest pressure investigated by these authors.

MacGregor (1964) investigating the reaction



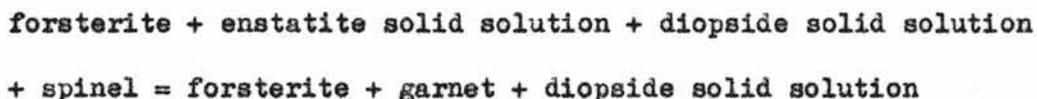
found that it proceeded under pressure - temperature conditions embodied in the equation

$$T = 0.0546P - 173 \quad (P \text{ in bars})$$

giving a pressure of about 27.8kb. at 1350°C, a value in good agreement with the results of Ito and Kennedy.

These results are at variance with those of Ringwood, MacGregor and Boyd (1964) who postulate a higher temperature and pressure as being necessary to produce pyrope from a pyroxene of the composition of that used by Ito and Kennedy.

MacGregor (1965) working with the synthetic system $\text{MgO}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ found that at a temperature of 1300°C garnet first appeared at about 21kb. He deduced from this that the effect of CaO in the production of garnet is to enable the reaction



to proceed at a lower pressure than the reaction



Thus garnet would appear at a relatively lower pressure in a two pyroxene peridotite than in a peridotite with only orthopyroxene.

MacGregor (1965) goes on to say that at 1300°C the four phase field of forsterite + diopside solid solution + enstatite solid solution + garnet, i.e. garnet peridotite, is stable from 21kb. to at least 65kb. This then sets approximate lower limits to the stability field of the garnet.

Other workers have used the chemical compositions of other minerals as a guide to the conditions under which they achieved equilibrium.

Boyd (1966) and Davis and Boyd (1966) describe how the extent of solid solution of enstatite in diopside may be used as an indicator of the temperature at which the pyroxene pair reached equilibrium. They show that this indicator is independent of pressure up to 1400°C. However, uncertainty as to the extent of exsolution during eruption from the mantle and the effect of elements such as aluminium, iron and chromium on the solid solution cast doubts upon the validity of estimates derived by this method.

The presence of appreciable amounts of jadeite in the diopside from the garnet peridotite might indicate a high pressure of crystallisation. Dobretsov (1962) states that pure jadeite is stable only at pressures greater than 12,000 atmospheres, and Bell and Davis (1965) terminate their study of the temperature - composition section for jadeite - diopside with the conclusion that the effect of solid solution of diopside on the stability of jadeite is negligible.

Bartholomé (1962) utilised the iron - magnesium ratios of coexisting mineral phases to find the approximate temperature at which these minerals achieved equilibrium. He expressed the equilibrium reaction between ortho- and clinopyroxenes by the equation

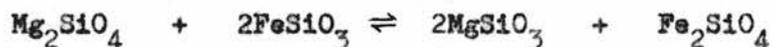


and, assuming that the reacting pyroxenes form ideal solid solutions, he derived an expression for the temperature dependent equilibrium constant;

$$K_p = (\text{Fe}^{\text{II}}/\text{Mg})_{\text{opx}}/(\text{Fe}^{\text{II}}/\text{Mg})_{\text{cpx}}.$$

The dependence of K_p on temperature he expressed in a graphical form.

By an analogous method the same author deduced the equilibrium constant of the olivine - orthopyroxene reaction



to be

$$K_p = (\text{Fe}''/\text{Mg})_{\text{ol}} / (\text{Fe}''/\text{Mg})_{\text{oPx}}^2$$

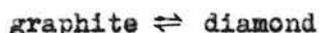
This value he also found to be temperature dependent, and he, once again, plotted the dependence graphically.

Several authors have noted that the structural formulae of their analysed orthopyroxenes show a cation sum in excess of the expected four per formula unit. Boyd and England (1960) note that the ratio R''/Si gives values greater than one for enstatites in olivine bearing rocks. Mercy and O'Hara (1965) attribute this discrepancy to a small extent of solid solution of potential olivine molecule in orthopyroxene. They further state that the discrepancy for pyroxenes from inclusions in basalt is rather larger than for the garnet peridotites they cite and conclude that the garnet peridotites equilibrated at relatively lower temperatures.

It appears that a garnet peridotite would be stable at pressures of about 21kb. at 1300°C or 25kb. at temperatures of around 1200°C. These values would represent the lower limit of stability.

Boyd and MacGregor (1964) postulate that if the upper mantle is composed of peridotite, there will be a layer of spinel peridotite below the Mohorovicic discontinuity and garnet peridotite at greater depth. The thickness of this spinel peridotite layer will, they suppose, depend on the geothermal gradient and the thickness of the overlying crust. Thus, this

layer will be thin or absent altogether under the continents. In support of this view they point out that kimberlites, on their way up from the mantle, collect fragments of the crustal and mantle rocks through which they pass and among these inclusions garnet peridotites are relatively common but spinel peridotites are rare. Kimberlites erupt principally in Precambrian shield areas, and superposition of the Precambrian shield geotherm on the phase diagram for the equilibrium



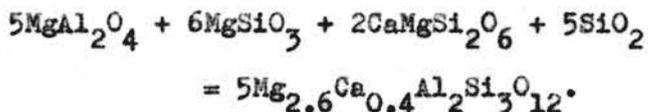
indicates that within the field of diamond stability a solubility of 1-2% Al_2O_3 in enstatite is to be expected.

To the problem of the origin of the spinel peridotite inclusions found in basalts these authors offer three possible solutions. They might be primary mantle rocks from the spinel peridotite layer, the products of inversion of primary garnetiferous rocks or samples of a layer formed by crystal accumulation from basaltic magma in the uppermost part of the mantle.

As a result of a later study of the stability fields of spinel and garnet peridotites in the synthetic system $\text{MgO-CaO-Al}_2\text{O}_3\text{-SiO}_2$, MacGregor (1965) states that in continental areas at depths greater than 10km. most peridotite compositions fall within the garnet peridotite stability field. The conclusion he draws from this is that the spinel peridotites in continental regions, with normal geothermal gradients, have not formed by inversion from a high pressure garnet bearing assemblage but that they must have formed directly, at high temperature and pressure, on the low pressure side of the equilibrium boundary between spinel and garnet peridotites. It would seem

therefore, that spinel peridotite probably formed by fractional crystallisation of basaltic magmas in or near the base of the crust. They do not represent a primary upper mantle composition.

Sobolev and Sobolev (1964) describe some xenoliths found in the kimberlite of northern Yakutia. Xenoliths with a banded stratiform structure were common, in particular "xenoliths with garnet peridotite passing into eclogite and with olivine passing into spinel harzburgite" were found. The indications are that these were not derived from magmatic segregations but represent fragments of a body having a banded or stratified structure. Their observations of garnet overgrowths on spinel grains are interpreted as positive evidence of replacement. They propose a two stage process for the changes brought about by an increase of pressure on ultrabasic rocks. The first stage taking place at pressures of 3-10kb. is the replacement of the anorthite - olivine paragenesis by the spinel - diopside paragenesis. This is followed by a garnetisation process which, neglecting the iron, chromium and presence of aluminium in the pyroxenes, may be represented by



It will be noted that this reaction proceeds with the absorption of SiO_2 and if none is available compensation occurs by the transition of enstatite into olivine. Thus in the absence of enstatite spinel will survive. A decrease of pressure may be held to account for the fusion reactions responsible for the formation of kelyphitic rims around the garnets of peridotites. These authors therefore conclude that the xenoliths examined by

them were formed by the metamorphism of solid rocks at increased pressure.

The relationship between garnet and non garnetiferous peridotites.

After working on strontium isotope and alkali element abundances in ultramafic rocks, Steuber and Murthy (1966) conclude that their data support the idea of possible derivation of basalt from the partial fusion of garnet peridotite but not from the ultramafic inclusions found in basalts. It would therefore seem profitable to examine the changes observed during the partial fusion of garnet peridotite.

Yoder, Tilley and Schairer (1963) find that most magnesium-rich pyroxene compositions or assemblages melt with olivine on the liquidus, thereby enriching the liquid in silica relative to pyroxene. This observation agrees with the results of work by Davis and England (1963) who found that the relationship

$$T = 4.77P + 1898$$

governs the melting of forsterite up to 47kb. pressure. This gives a value of about 2025°C as the melting point of forsterite at 30kb. Thus it would be expected that any extraction by partial fusion would leave the residue enriched in olivine. The incongruent melting of enstatite to forsterite plus liquid disappears at pressures greater than 5kb. (Davis 1963, Boyd and England 1963) and so has no relevance at the pressures envisaged for the upper mantle. O'Hara (1963), working on the melting of garnet peridotite at 30kb. found that the assemblage forsterite, garnet, clinopyroxene and a trace of orthopyroxene, crystallised at 30kb. and 1500°C from the mixture 25% diopside, 50% pyrope and 25% forsterite, melted at 1600°C to forsterite, abundant enstatite and liquid. He also observed that the garnet molecule is readily

soluble in clinopyroxenes and orthopyroxenes at high temperatures and it seems likely that many natural garnet peridotites are represented by an olivine-spinel-two pyroxene assemblage at the beginning of melting, the pyroxenes being enriched in Al_2O_3 , Fe_2O_3 and Cr_2O_3 . The residuum after partial fusion of garnet peridotite is likely therefore to be garnet free. Others (Boyd and England 1962) have noted that at pressures below 36kb. pyrope melts incongruently, principally to spinel and liquid. Further work by O'Hara (1963) on the join diopside - pyrope at 30kb. shows that at $1600^{\circ}C$ and 30kb. the mixture 45% diopside and 55% pyrope crystallises to clinopyroxene and garnet, but at $1612.5^{\circ}C$ and $1625^{\circ}C$ the same original mixture yields orthopyroxene, clinopyroxene and liquid. Work on a natural peridotite by Ito and Kennedy (1967) reveals that at 20kb. the order of melting was first clinopyroxene, then spinel, with orthopyroxene disappearing at $1750^{\circ}C$. Above this temperature only olivine coexisted with the liquid. At 40kb. the first liquid formed at about $1570^{\circ}C$ with clinopyroxene melting immediately above the solidus and garnet melting within 50° of the solidus. O'Hara and Mercy (1963) propose as a possible partial fusion model of garnet peridotite

8 garnet + 18 clinopyroxene + 8 hypersthene + 24 olivine

undergoing partial melting to give

5 garnet + $14\frac{1}{2}$ clinopyroxene + 2 hypersthene + $28\frac{1}{2}$ olivine

with a liquid of normative content

3 An + $1\frac{1}{2}$ Ab + 2 Di + 3 Hy.

In his statistical analysis I.G. White (1967) provides evidence, from the shape of the histograms, of the depletion in silica, alumina, lime, soda and potash and enrichment of magnesium and iron oxides in the rocks examined by him. Such a result would be expected if these rocks represent the residual rocks after some liquid segregation has occurred.

Discussion of Results(a) Pyroxenes.

It is apparent that the aluminium content of all the orthopyroxenes and clinopyroxenes derived from inclusions in basaltic rocks is greater than that of the corresponding pyroxenes of the Lashaine inclusions. The chromium level on the other hand is much higher in the pyroxenes being investigated here.

In the low variation of Al_2O_3 content, the Lashaine clinopyroxenes agree more with the data of Boyd (1966) for kimberlite pyroxenes than with that for the alpine peridotites (Peters 1968).

The clinopyroxenes do not show any systematic reflection of the bulk composition of the rocks. For instance, the bulk rock BD 730 is the most silica saturated but, on the other hand, its chrome diopside is nepheline normative. BD 771 however is very silica undersaturated (containing nepheline, leucite, and calcium orthosilicate in the bulk rock norm), yet the clinopyroxene in it has excess of silica expressed as normative hypersthene. The silica undersaturated bulk rock BD 821 contains nepheline normative chrome diopside.

(b) Olivines.

The olivines from the non-garnetiferous peridotites are similar to olivines from both garnet-peridotites and peridotite-xenoliths from basaltic rocks.

(c) Element partition.

The partition of the elements between coexisting mineral phases is expressed graphically in Figs. 4 to 14. In Figs. 4 to 13 the data plotted are directly compared with those presented by R.W. White (1966) for lherzolites found as inclusions in basaltic rocks.

The iron-magnesium distribution, expressed as the ratio $Fe/Fe+Mg$, is plotted for various coexisting mineral pairs in Figs. 4, 5 and 6. These plots, with the single exception of the olivine - clinopyroxene pair of BD 821 (Fig. 5), fall within the area enclosing the values determined by White (1966). The distribution of aluminium between coexisting orthopyroxenes and clinopyroxenes is plotted in Fig. 7. The values obtained for the two rocks containing two pyroxenes fall at the extreme lower end of the limits for those examined by White (1966). Although the pyroxenes being examined here are poor in aluminium, the same is not true of chromium (see Fig. 8). Both the clinopyroxenes coexisting with orthopyroxenes are rich in chromium and the plots obtained fall outside the boundary found by White (1966).

Figs. 9 - 13 show the plots of weight percentage of various oxides against those of total iron expressed as FeO. The areas embracing the results found by White (1966) are marked and, with few exceptions, the plots obtained from this work fall within the corresponding areas. One exception is seen in the MnO/FeO diagram, Fig. 12, where the plot for the olivine of BD 806 falls well outside the area for lherzolithic olivines, but since BD 806 is a mica dunite this discrepancy is not altogether unexpected. A further noteworthy exception, to the agreement observed in these diagrams between data obtained in this study and those of White (1966), is found in Fig. 13, where all three orthopyroxenes and three of the olivines from Lashaine are shown to be relatively rich in iron.

The distribution of Fe^{2+} and Mg^{2+} between coexisting olivines and orthopyroxenes is illustrated in Fig. 14, using the method of plotting adopted by Ramberg and DeVore (1951). In the lherzolite BD 771 and garnet peridotite

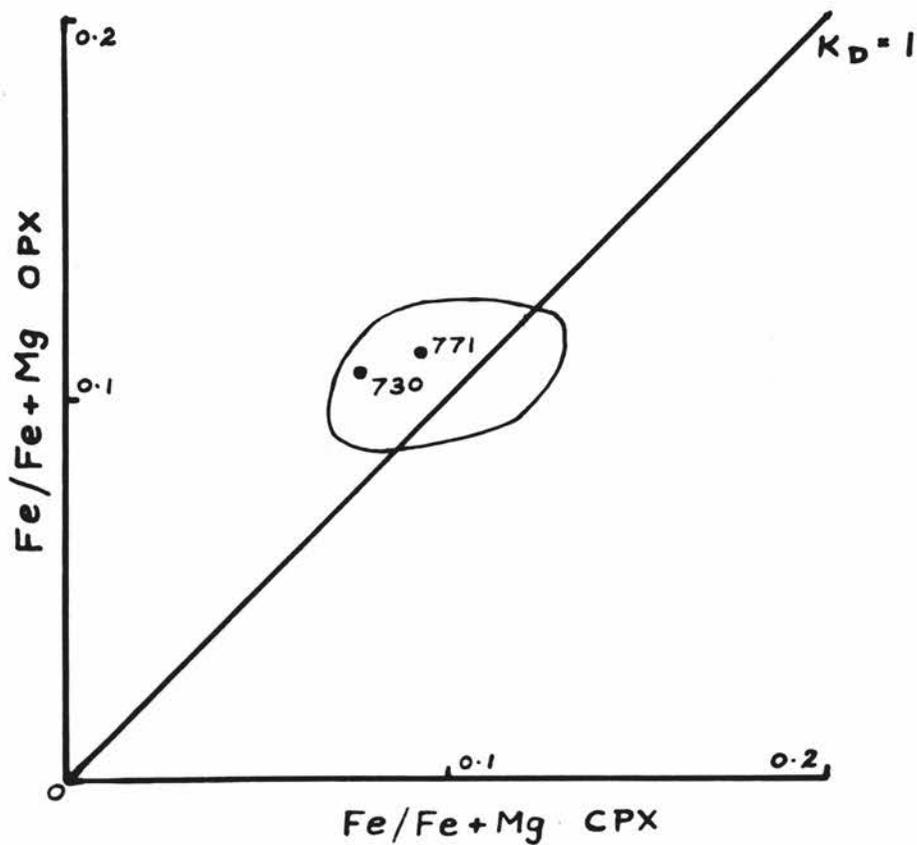


Fig. 4. Variation of the ratio $\text{Fe}/\text{Fe}+\text{Mg}$ in coexisting ortho- and clinopyroxenes.

The delineated area includes the plots obtained by R.W. White (1966) for lherzolites in his work on inclusions in basaltic rocks.

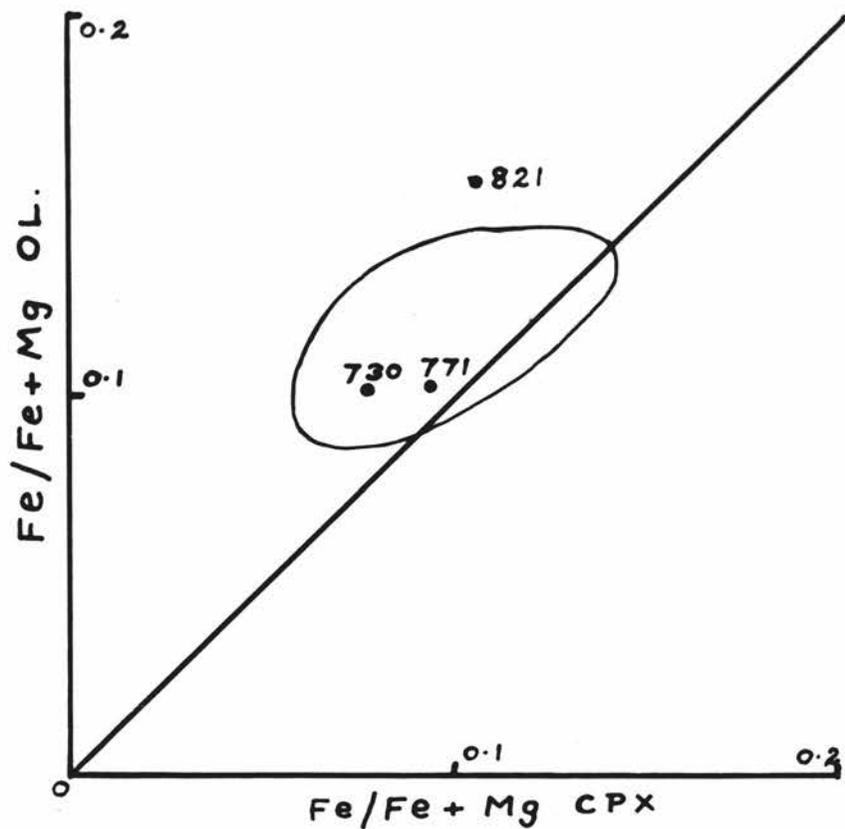


Fig. 5. Variation of the ratio $\text{Fe}/\text{Fe}+\text{Mg}$ in coexisting olivines and clinopyroxenes.

The delineated area includes the plots obtained by R.W. White (1966) for lherzolites in his work on inclusions in basaltic rocks.

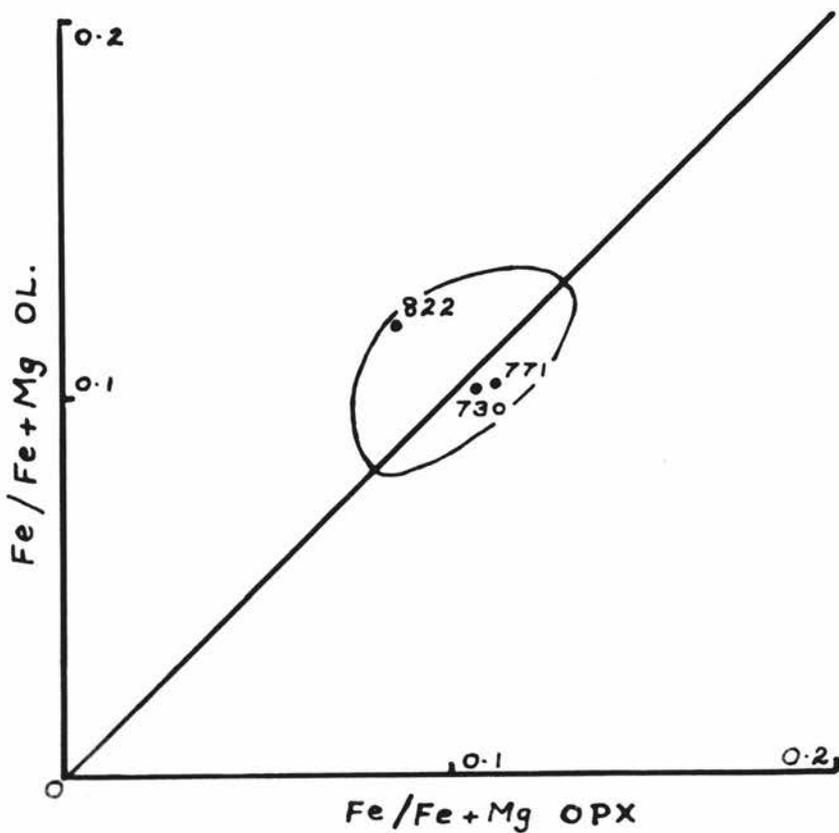


Fig. 6. Variation of ratio $Fe/Fe+Mg$ in coexisting olivines and orthopyroxenes.

The delineated area includes the plots obtained by R.W. White (1966) for lherzolites in his work on inclusions in basaltic rocks, and also plots obtained from the data of Ross et al., (1954).

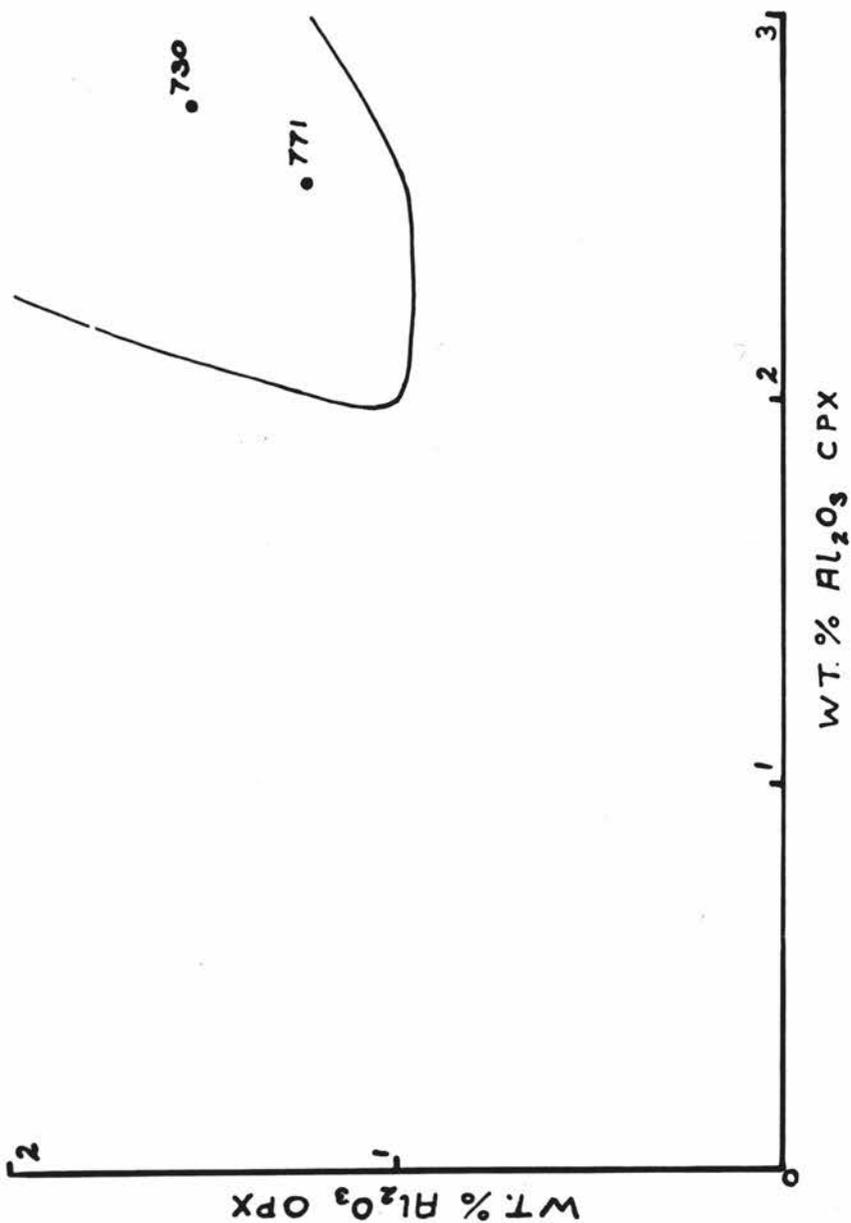


Fig. 7. Variation of wt. % Al₂O₃ in coexisting ortho- and clinopyroxenes.

The delineated area covers data on lherzolites from R.W. White (1966).

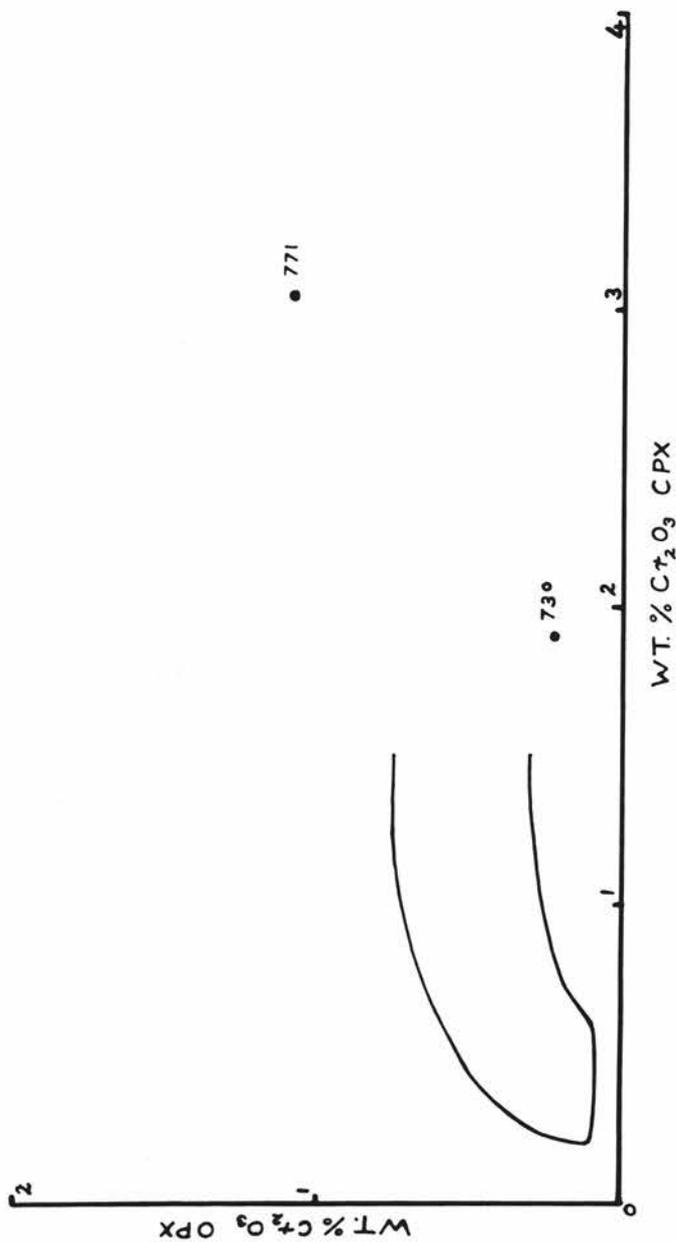


Fig. 8. Variation of wt. % Cr₂O₃ in coexisting ortho- and clinopyroxenes.

The delineated area covers data on lherzolites from R.W. White (1966).

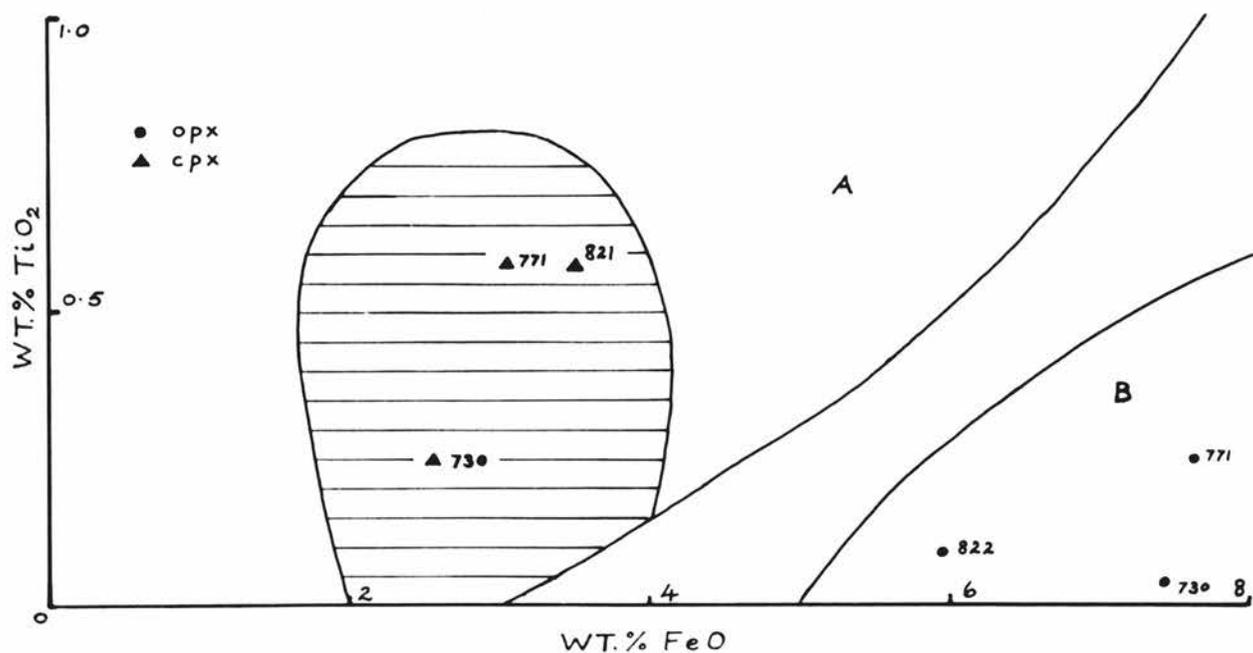


Fig. 9. Variation of wt. % TiO₂ with total iron as FeO in ortho- and clinopyroxenes.

Shaded area covers clinopyroxenes in lherzolites, area A covers all clinopyroxenes, area B covers orthopyroxenes in lherzolites. Data from R.W. White (1966).

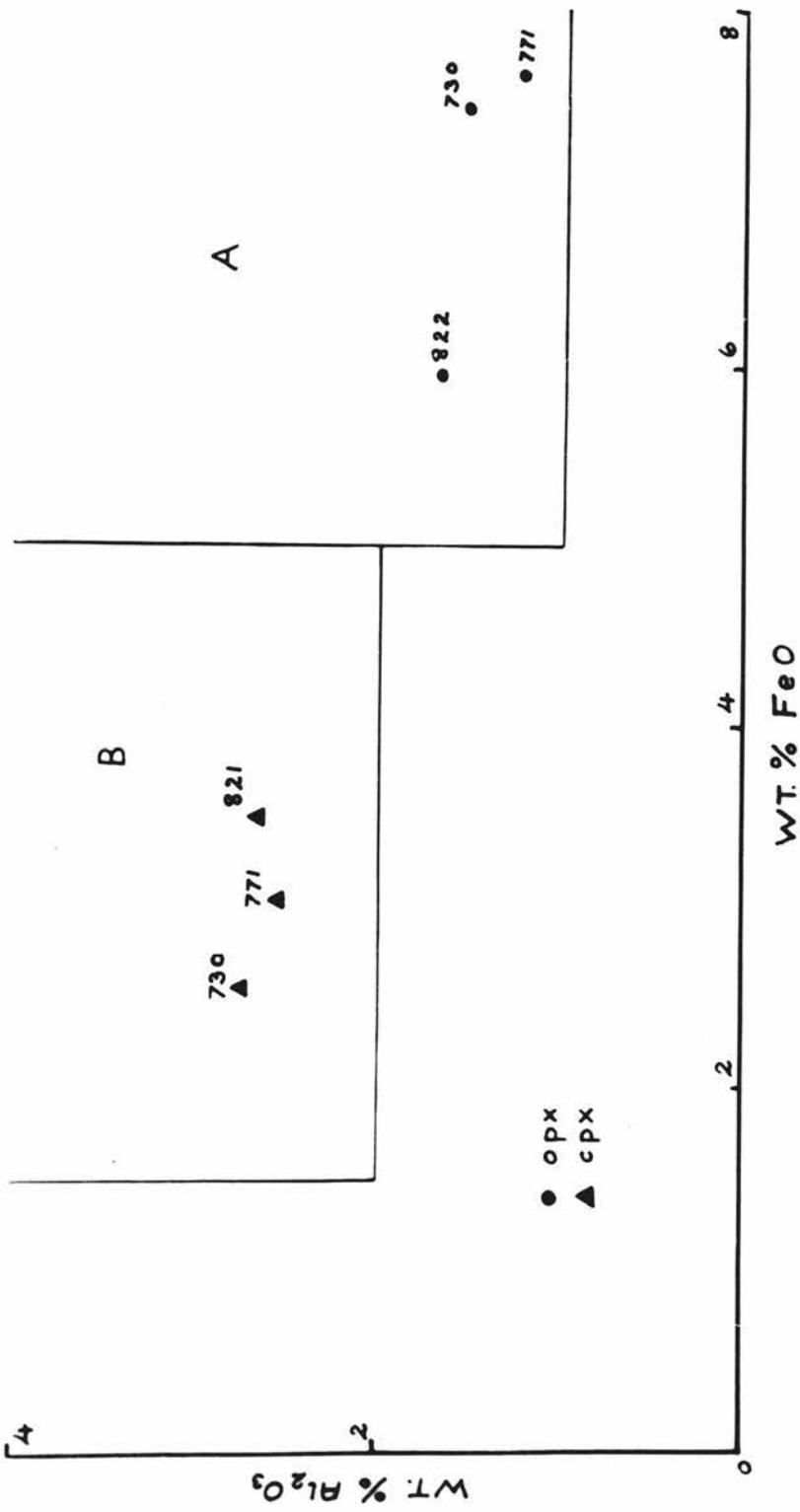


Fig. 10. Variation of wt. % Al₂O₃ with total iron as FeO in ortho- and clinopyroxenes.

Area A covers orthopyroxenes from Iherzolites, area B covers clinopyroxenes in Iherzolites. Data from R.W. White (1966).

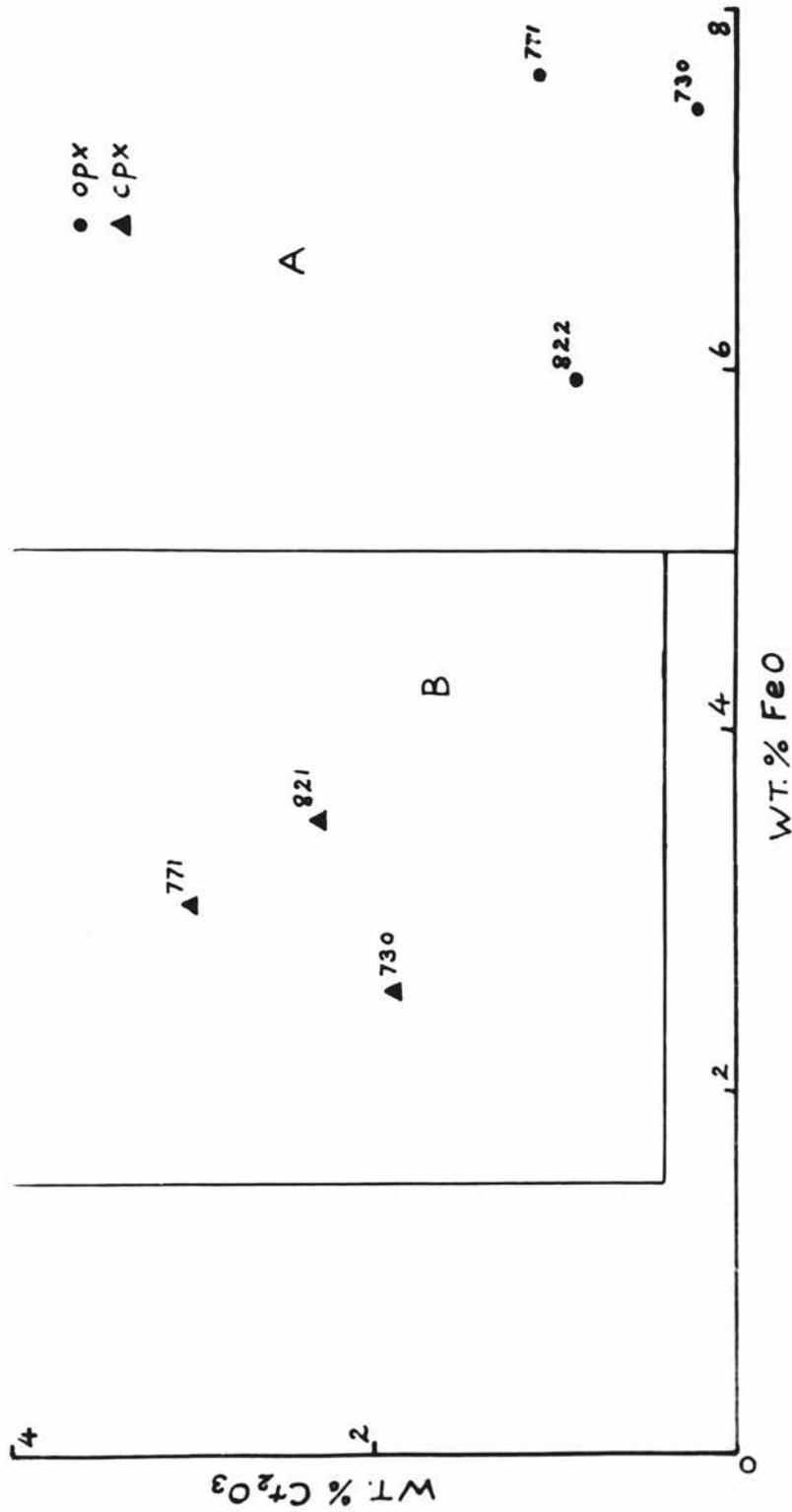


Fig. 11. Variation of wt. % Cr₂O₃ with total iron as FeO in ortho- and clinopyroxenes. Area A covers orthopyroxenes in lherzolites, area B covers clinopyroxenes in lherzolites. Data from R.W. White (1966).

Fig. 12. (see over). Variation of wt. % MnO with total iron as FeO in olivines, ortho- and clinopyroxenes.

Area A covers clinopyroxenes in lherzolites,
area B covers orthopyroxenes in lherzolites,
area C covers olivines in lherzolites.
Data from R.W. White 1966.

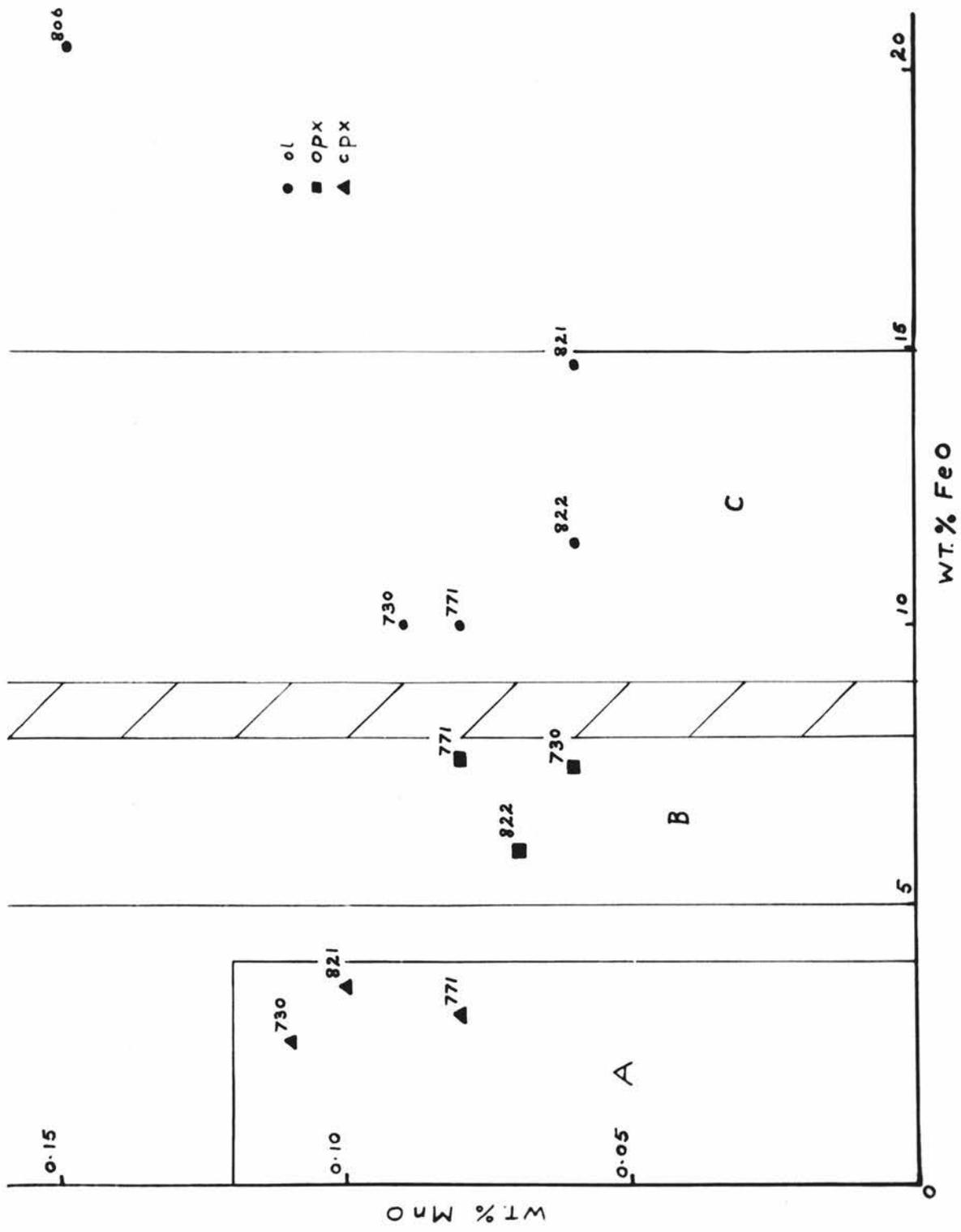


Fig. 13. (see over) Variation of wt. % CaO with
total iron as FeO in olivines and orthopyroxenes.

Area A covers orthopyroxenes in lherzolites,
area B covers olivines in lherzolites.
Data from R.W. White 1966.

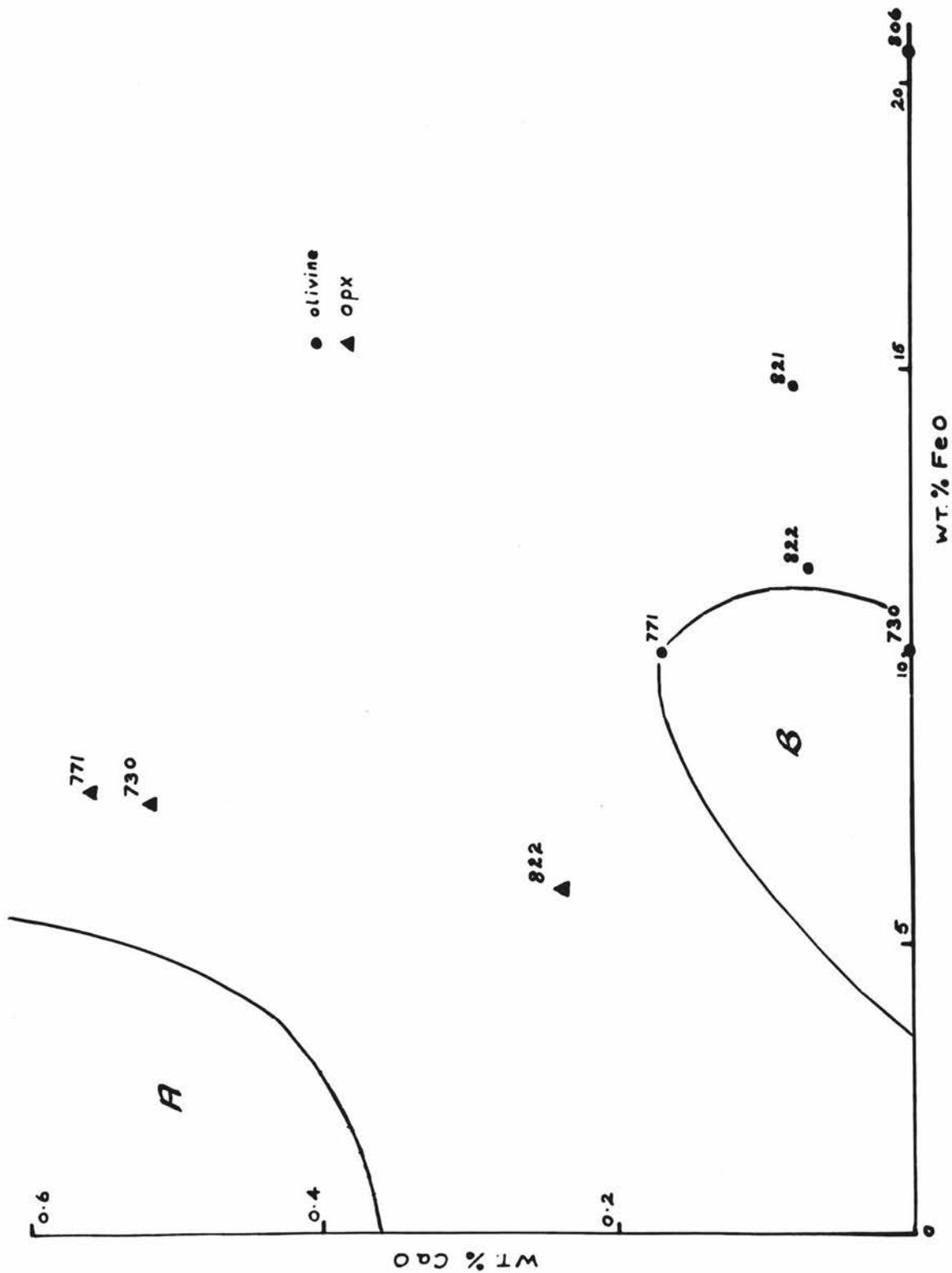
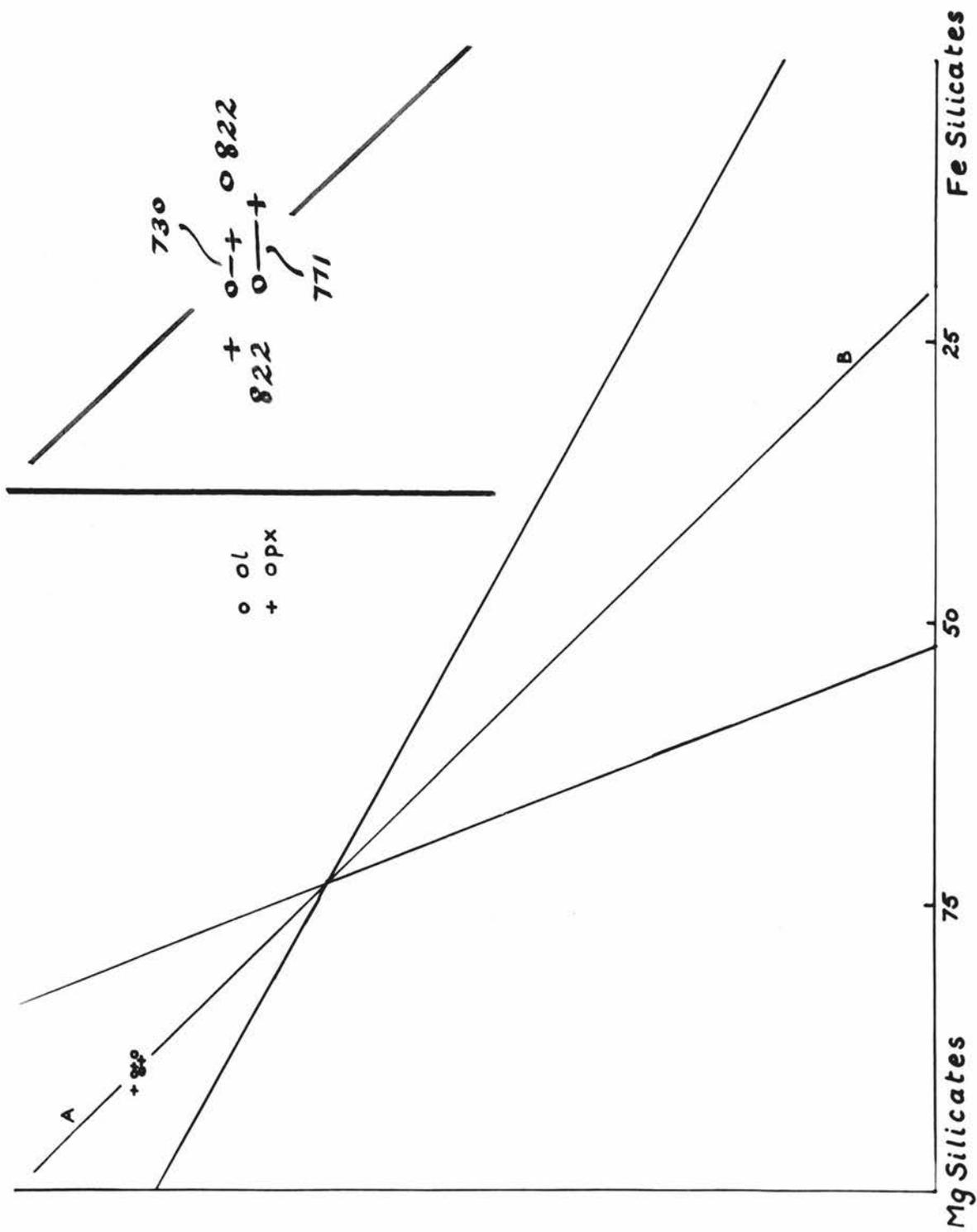


Fig. 14. (see over) Illustrating the distribution of Fe²⁺ and Mg²⁺ in coexisting olivines and orthopyroxenes.

The plots are arranged such that the mid-line bisects the tie lines drawn between coexisting pairs. The two boundary lines indicate the limits of compositions found by Ramberg and DeVore who utilize this method of plotting. "The distribution of Fe²⁺ and Mg²⁺ in coexisting olivines and pyroxenes". J. Geol. 59, 1951.



BD 730, the olivine has a higher Mg/Fe ratio than the coexisting enstatite. In the spinel harzburgite BD 822, the reverse is true. (This high Mg content of the orthopyroxene is also brought out in Fig. 6). This variation in Mg/Fe partition is consistent with data obtained on other highly magnesian rocks, and has apparently no genetical significance. However, the bulk rock BD 822 has a higher Mg/Fe ratio than the other two, so the inference is that the high Mg/Fe ratio of the orthopyroxene is a reflection of the bulk chemistry of the rock.

The pressure and temperature of formation of the Lashaine peridotites.

In the light of work on phase relations, including especially experiments carried out at the Geophysical Laboratory in Washington and the ideas this work has generated, it is proposed to discuss the composition of the ultrabasic nodules forming the subject of this study.

Although the rock samples under discussion fall into four different groupings, (the mica dunite, BD 806, will be discussed later) namely a garnet peridotite, a lherzolite, a wehrlite and a spinel harzburgite, according to the preponderance or absence of certain minerals, a comparison of the analyses of the mineral types shows a similarity of composition throughout all four rocks. Moreover, these rocks were all found as nodule inclusions in a carbonate matrix and they bear a far greater resemblance, in the analyses of their constituent minerals, to the ultrabasic inclusions found in kimberlite than to the nodules found in basalts. In particular the aluminium content of the pyroxenes is uniformly low by comparison with the basalt inclusions, and the chromium content is high.

Approximate limits for the conditions under which the garnet peridotite BD 730 could have reached equilibrium may now be proposed. Application of the methods used by Bartholome (1962) to BD 730 gives the result of approximately 1100°C as the temperature of equilibrium when the coexisting pyroxenes are considered, and about 1200°C using the olivine-orthopyroxene equilibrium.

If this figure of 1200°C is inserted in the equation

$$T = 0.0546P - 173 \quad (P \text{ in bars})$$

deduced by MacGregor and referred to earlier, the value obtained for the pressure of equilibrium of the system



is about 25kb.

In terms of its end-members, the composition of the garnet from BD 730 (see Table 6) shows certain similarities to the one quoted by Green and Ringwood (1967) as appearing on the liquidus of an olivine basalt at 27kb. They give its composition as almandine 17.2, pyrope 68.3, grossular 14.5.

The structural formulae of the orthopyroxene of BD 730 shows a cation sum in excess of the expected four per formula unit (see Table 3). As mentioned earlier a possible explanation of this is that the garnet peridotites equilibrated at temperatures lower than those at which the inclusions in basalt achieved equilibrium.

The method of Davis and Boyd (1966) gives a value of 950-1000°C as the temperature of formation of the pyroxenes of BD 730.

Any attempt to interpret the data accumulated about BD 822 in the light of any of the models discussed in the review is fraught with uncertainties. The alumina level of the enstatite is low, between 1 and 2%, but as this enstatite

is not in equilibrium with pyrope, perhaps the low Al_2O_3 level is indicative of a low temperature of equilibration. Since there is no coexisting clinopyroxene the temperature of formation cannot be estimated by a method involving solid solution of enstatite in diopside. However the departure of the cation sum from the ideal value of four is rather less for this enstatite than for the orthopyroxene of BD 730, which might indicate a relatively lower temperature of formation. Spinel is present rather than pyrope which is indicative of equilibration at a relatively lower pressure. On the other hand the absence of a calcium bearing component ensures that garnet will not appear until a pressure has been reached higher than that necessary for garnet production in a two pyroxene system. The textural aspect of the spinel as large, euhedral crystals would seem to testify against their being formed by inversion from a garnet as the spinels usually found in kelyphite rims are very much smaller. The presence of a nodule in a kimberlite from Yakutia exhibiting a change from an olivine to a spinel harzburgite seems to indicate that the specimen BD 822 is from part, perhaps the upper part, of a banded stratiform mass, not derived from magmatic segregations.

In the light of the evidence discussed in the review section the rocks BD 771 and BD 821 will be considered. BD 771 is a lherzolite containing olivine, enstatite and chrome diopside, BD 821 is a wehrlite composed of olivine and chrome diopside. The olivines of both rocks are similar to the olivine of the garnet peridotite BD 730 with the BD 821 sample having a slightly higher Fe/Mg ratio. The enstatite of BD 771 is low in Al_2O_3 in common with the other enstatites analysed (see Table 3). Table 3 reveals from the structural formulae that the BD 771 enstatite is slightly depleted in alumina and enriched to a marked degree in chromium when

compared to BD 730. Contrasting the clinopyroxenes of BD 730 and BD 771 (Table 4) it can be seen that the diopside of BD 771 shows depletion in alumina and lime and enrichment in chromium and iron oxides. Application of the various geothermometric methods to the diopside (cf. Boyd 1966), coexisting pyroxene pair, and coexisting orthopyroxene and olivine (cf. Bartholome 1962), yields the three results for the temperature of equilibration; 1050-1100°C, 1250°C and 1200°C respectively. A comparison of the clinopyroxenes of BD 821 and BD 730 shows the BD 821 diopside to be depleted in alumina and lime and enriched in chromium and iron oxides.

It would appear that both BD 771 and BD 821 could be samples of a residue left after partial fusion of garnet peridotite. The pyroxenes could have dissolved the garnet below the solidus thereby becoming enriched in aluminium, iron, chromium and possibly calcium only to lose a proportion of the aluminium and calcium when a state of partial fusion was reached.

As was mentioned earlier the large euhedral crystals of spinel present in BD 822 suggest that they were not formed by the kelyphitisation of garnet. Perhaps they were crystallised from a liquid coexisting with olivine and orthopyroxene after partial fusion of garnet peridotite, the crystallisation taking place at relatively low pressure.

The mica dunite.

Boyd (1966) lists phlogopite among the primary minerals of kimberlite and points out that the occurrence of diamond among these minerals makes their origin in the upper mantle almost unequivocal. Kushiro et al., (1967), found that phlogopite breaks down to garnet and an unidentified mineral at

pressures higher than at least 40kb. at about 1200°C. Since the breakdown temperature of magnesium phlogopite in a silica deficient environment is very high, the nodule BD 806, consisting of olivine and phlogopite, could be a sample from a layer of a stratiform body on the Russian model (cf. Sobolev and Sobolev).

A layered lherzolite found at Lashaine but not examined here also lends tentative support to the Russian model. The presence of a potassium-bearing phase under these conditions is interesting in view of the evidence of Seifert and Schreyer (1968) who find that mixtures of forsterite and enstatite show partial melting in the pressure range 1-5kb. at approximately 550-700°C if small amounts of K_2O are added in the presence of excess H_2O . However, the proportion of hydroxyl in the mica of BD 806 is low.

Summary of conclusions.

1. Except for BD 806, the bulk chemistry of the rocks under examination is closely similar. Their constituent minerals are also chemically similar.
2. With the exception of the high iron content of the olivine of BD 806 the olivines exhibit a very narrow compositional range.
3. The Al_2O_3 content of the enstatites is lower than that of enstatites from inclusions in basalts but similar to those found as inclusions in kimberlites.
4. The clinopyroxenes, in their chromium to aluminium ratio, are more akin to those from peridotitic inclusions in kimberlites than to those from peridotitic inclusions in basalts.

On the basis of previously established data, together with the conclusions enumerated above, the indications are that there is more

similarity of the ultramafic inclusions from Lashaine with those from kimberlites than with those from basalts.

5. The fact that this suite of xenoliths includes mica-dunite (BD 806) supports recent views on upper mantle heterogeneity.
6. The existence of peridotitic nodules of the kimberlitic type in a carbonatite tuff cone is consistent with the view that there is a close relationship between kimberlites and carbonatites.

There is a lack of published analyses of non-garnetiferous peridotites found as inclusions in kimberlites. More of these analyses would allow work of a statistical nature similar to that carried out by I.G. White (1967) to proceed and the mode of formation of this type of inclusion might thereby be clarified.

If, as O'Hara and Mercy (1963) conclude, the garnet peridotites found in kimberlite are representative of the unmodified composition of the upper mantle, it is of interest to know whether or not the non-garnetiferous inclusions are representative of various stages of partial fusion of the upper mantle. This line of reasoning has been adopted here but many more analyses are required before a satisfactory statistical treatment can be attempted.

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