Ultramafic Nodules from Ile Bizard Québec

-

.

.

. .

ABSTRACT

Ultramafic Nodules from Ile Bizard, Québec

by

Michael Marchand Dept. of Geological Sciences Master of Science Thesis

The Ile Bizard kimberlite, located near Montreal Canada contains numerous ultramafic nodules which are mainly websterites and lherzolites, though a few amphibole-bearing nodules and a dunite nodule have been found. The lherzolites show evidence of cooling from an assemblage of aluminous pyroxenes and olivine by the following reactions:

1) aluminous enstatite + olivine = spinel + enstatite

2) aluminous pyroxenes + spinel = pyrope + olivine The aluminum content of the enstatite indicates a temperature of approximately 1050°C and a pressure of 20 Kb for reaction (2) in a pyrolite upper mantle. This reaction has been balanced and is shown to be divariant. Since the reaction has not gone to completion the nodules must have been ejected to the surface from these conditions. Adiapiric rise of pyrolite to the 60 km. area of the mantle with subsequent magma segregation produced the websterites as cumulates and the lherzolites as residue. The heat produced by this event caused a slight amount of partial melting in the underlying material, from which the kimberlite magma was formed.

ULTRAMAFIC NODULES FROM ILE BIZARD QUEBEC

by

Michael Marchand

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Geological Sciences

McGill University

÷

1970

 \odot

TABLE OF CONTENTS

.

	page
Introduction	1
The Ile Bizard Kimberlite	
Description and Mineralogy	4
Chemical Composition	16
Conditions of Crystallization	19
Ultramafic Nodules	
Amphibole-bearing Nodules	20
Websterite Nodules	27
Lherzolite Nodules	34
Miscellaneous Nodules	55
Discussion	<i>5</i> 8
Acknowledgements	61
References	62
Appendix I - Potassium Argon Ages	68
Appendix II - Possible New Mineral	69
Appendix III - Electron Microprobe	71
Appendix IV - Petrology Collection Catalogue	72

List of Figures

Figure		page
1	Map of the Monteregian Province	3
2	Outcrop map of the Ile Bizard kimberlite	5
3	Photo of the kimberlite breccia	7
4	Photo of the porphryitic phlogopite	12
5	Photo of the zoned hydrogrossular	14
6	Photo of a globule in groundmass	15
7	Photo of an amphibole-bearing nodule	21
8	Pyroxene quadrilateral with websterite nodule pyroxenes	29
9	Triangular plot of garnet compositions	35
10	Pyroxene quadrilateral with lherzolite nodule pyroxenes	45
11	Photo of nodule 52	46
12	P,T fields of mineral assembleges in pyrolite	47
13	Photo of Nodule 1 showing s pinel to garnet reaction	49
14	Photo of Nodule 2304 showing spinel to garnet reaction	50
15	Photo of nodule 47	56

.

List of Tables

Table		page
1	Analyses of megacrysts	9
2	Analyses of groundmass minerals	10
3	Analyses of kimberlite from Ile Bizard	17
3 a	Analyses of kimberlite and alnoites	18
4	Analyses of minerals in amphibole-bearing nodules	23
5	Analyses of orthopyroxenes in websterites	31
6	Analyses of clinepyroxenes and phlogopite in websterites	32
7	Analyses of orthopyroxenes in lherzolites	36
8	" " clinopyroxenes " "	3 8
9	" " garnets " "	40
10	" " spinels " "	42
11	" " olivines " "	43
12	Table of residuals	5 2
13	Analysis of garnet from nodule 47	5 7

Introduction

The Ile Bizard kimberlite, which is situated in the Monteregian province about 15 km. west of the city of Montreal (Fig. 1), contains numerous ultramafic nodules. This thesis presents a description of the kimberlite and analyses of phenocrysts and of the co-existing minerals in a variety of these nodules, which provide the basis for interpretation of their conditions of origin in the mantle and of the history of development of this kimberlite intrusion.

The relation of the Ile Bizard kimberlite to the other Monteregian Intrusives is illustrated in Figure 1. The kimberlite is situated close to the Oka carbonatite complex and lies in an area of alnoite, alnoite breccia and diatreme breccia intrusions (Clark, 1952). As seen in Figure 1, the intrusions of the Monteregian province lie along fault trends and seem to be directly related to them. A complete description of the Monteregian province is available in Philpotts (1970) and Gold (1967).

The rocks at this kimberlite occurence have been mentioned only three times previously. In 1910 Harvie mentioned the outcrop location in his article on the breccias of the Montreal region. In 1935 Grimes-Graeme wrote a thesis on the intrusive breccias in the Montreal district in which he described the kimberlite but saw nothing of special significance in it.

Figure 1

Map of the Monteregian Province

1. Chatham-Grenville *

*

- 2. Rigaud
- 3. Carillon
- 4. Ile Cadieux
- 5. Oka
- 6. St. Monique
- 7. Ile Bizard
- 8. St. Dorothée
- 9. Visitation Island
- 10. Mount Royal
- 11. St. Helen's Island
- 12. Mount Bruno
- 13. St. Hilaire
- 14. Iberville Intrusion
- 15. Mount Johnson
- 16. Rougemont
- 17. Yamaska
- 18. Brome
- 19. Shefford

Diagram from Philpotts (1970)

* This intrusion is not part of the Monteregian province, which is of Cretaceous age, but is of Cambrian age and may be related to the tectonic activity along the St. Lawrence graben (Doig & Barton, 1968).



Clark (1952) mentioned the occurence in his work on the Montreal area. None of these investigators recognized it as kimberlite or noticed the ultramafic nodules. However, in 1966 N.H. Gray and associates recognized the outcrop as kimberlite and staked the ground. Subsequently Southern Exploration and Development acquired the ground and DeBeers optioned it, drilling several shallow holes and shipping a bulk sample back to South Africa. The milling of this sample revealed several minute diamonds (Walters, 1969; Surette, 1969) which were thought to be possibly due to contamination by previous samples in the milling system.

THE ILE BIZARD KIMBERLITE

Description and Mineralogy

The Ile Bizard kimberlite breccia occurs as a fissure intrusion (Fig. 2) extending for 60m. southward from an oval outcrop through the surrounding Beekmantown dolostone to a prominent hill of diatreme breccia that contains no igneous matrix or ultramafic nodules. The kimberlite is a very heterogeneous rock due to the variations in the numbers of xenoliths and in the mineralogy of the igneous matrix. The oval outcrop has an area of very fresh igneous matrix which is free of inclusions excepting for the ultramafic nodules which occur there in abundance. These features along with the distinctly



Figure 2

Outcrop map of Ile Bizard Kimberlite

oval shape suggest that this outcrop may be the surface expression of a pipe which fed the fissure.

The rock is quite variable in appearance due to its inhomogeneity. In places it consists mainly of the igneous matrix which is very fine-grained, light pinkish-grey in colour, and exhibits numerous lusterous cleavage flakes of phicgopite. In other places the rock consists of numerous white and green fragments in a light-grey very fine-grained igneous matrix (Fig. 3). These fragments forming the breccia consist of shale. limestone, quartzite and 'Grenville rocks' and they show all stages of alteration, the products of which commonly form concentric zones. Even the very angular fragments which have been substantially altered retain their shapes. One inclusion about 25 mm. wide consists of coarse grained calcite, fine grained phlogopite, and zoned, in shades of dark brown to berlin blue, subhedral melilite. The coarsegrained nature of the melilite indicates that a substantial thermal metamorphism took place which is further substantiated by the presence of a zone of contact metamorphism at the intrusion's edge.

Large brown pleochroic phlogopite megacrysts are common as are magnetite megacrysts (up to 6 mm. in diameter) which



Figure 3. Typical kimberlite breccia showing a variety of country rock inclusions and one ultramafic nodule. (center left)

occur as bright lusterous crystals with conchoidal fractures. An analysis of one such magnetite crystal (Table 1) shows it to be magnesium rich, whereas kimberlites normally contain magnesium rich ilmenites (Lovering & Widdowson, 1968). Less commonly black lusterous homogeneous augite crystals (Table 1) are found up to 3 cm. long. Serpentinized olivine megacrysts are common throughout. One nodule contains a phlogopite megacryst poikilitically enclosing the augite megacrysts and serpentinized olivine. The presence of these three megacrysts in a single nodule shows that they were crystallizing simultaneously from the magma.

The igneous matrix is heterogeneous due to sympathetic variations in the amount of calcite and hydrogarnet. The fresh rock from the oval outcrop contains essentially no calcite whereas in other places calcite forms up to 25 per cent of the matrix. The very fine-grained groundmass which forms the major part of the matrix consists of brown translucent masses which x-ray diffraction patterns indicate are a mixture of hydrogarnet and serpentine. An electron probe analysis was done on an area of the matrix judged to be homogeneous (Table 2, No. 4) and therefore representative of the final crystallization product of the magma. The difference of 9.3 per cent from 100 per cent may be ascribed

Analyses of Megacrysts					
	1	2	3		
Si02	-	-	51.30		
TiO2	8.04	8.04	0.64		
A1203	1.36	1.36	4.72		
Fe203	-	50.31 +	-		
FeO	77.43 *	30•59	5.19 *		
MnO	0.08	0.08	-		
MgO	4.93	4.93	17.09		
CaO	-	-	18.85		
Na 0 2	-	-	1.33		
Total	91.86	95•31	99.12		
+ Fe ₂ 0 ₃ calculated by method of Anderson (1968)					
* Total 1	Fe as FeO				
Structure	al Formulae				
Si Al iv Al vi Ti Fe 3+ Fe 2+ Mn		0.4919 0.0000 1.8553 11.6172 7.8501 0.0208	1.8860 0.1140 0.0905 0.0177 0.1596		
ng Ca Na		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	0.7425 0.0948		

Table 1

÷

-

Total

Magnetite megacryst
Magnetite megacryst with Fe₂O₃ calculated by method of Anderson (1968) cations to 32 oxygens
Augite megacryst - cations to 6 oxygens

4.0415

24.0901

		Table 2				
	Ana	lyses of	Groundmass	Minerals		
	1	2	3	4		
Si02	39.10	27.32	26.53	28.8 4		
Ti02	0.14	1. 48	1.46	0.96		
Al203	17.12	12,38	13.22	5.06		
Fe0*	3.50	9.2 8	9.01	12.02		
MgO	24.61	0.66	0.54	21.86		
CaO	0.00	40.92	4 3. 56	21.82		
Na 0	0.00	0.00	0.00	0.00		
к ₂ 0	10.90	0.00	0.00	0.00		
^{Cr20} 3	0.00	0.00	0.00	0,12		
Total	95 • 37	92.04	94.32	90 . 69		

* Total Fe as FeO

1) Phlogopite phenocryst from fresh kimberlite.

2) Zoned hydrogarnet, center.

3) Zoned hydrogarnet, edge.

4) Fine grained igneous matrix.

to volatile content which in this case is most probably water.

Phlogopite, which is a major constituent of the rock, occurs in three different modes; as the previously mentioned megacrysts, as a porphrytic constituent of the matrix, and as a fine-grained component of the groundmass. The porphrytic variety occurs as well shaped laths up to 4 mm. long (Fig. 4) and is colourless in thin section. A microprobe analysis (Table 2) shows it to be a very Fe poor variety of phlogopite. The very fine grained phlogopite which occurs as a late product in the groundmass forms tiny laths or anhedral crystals.

Magnetite, perovskite, and apatite occur as fine-grained anhedral to subhedral crystals distributed throughout the groundmass. Chrome spinel occurs similarly but is much less abundant.

In the very fresh calcite free kimberlite a highly zoned clear garnet with low birefringence is found (Fig. 5). The strong zoning must reflect some compositional change but probe analyses (Table 2) of the center and edge show only slight variations. As the analyses do not total 100 per cent it is assumed that the differences are due to water and that the variations in water content may cause the zoning. Small clear unzoned hydrogarnets are also very common in parts of the rock. Both types have edges of a brown translucent



ł

<u>3 mm</u>

Figure 4. Porphrvitic phlogopite in calcite-poor groundmass. Polarized light.

hydrogarnet which likely is of a different composition and may represent the final crystallization product of the magma or it may have formed as a result of deuteric alteration of the early hydrogarnet to a more water rich composition.

In the fine-grained matrix there are globules approximately 1 mm. in diameter (Fig. 6) consisting in part of very fine grained (.03 mm.) brown translucent hydrogarnet with the remaining material being even finer grained. The globules are often outlined by a ring of magnetite grains. The composition of the globules as indicated by a qualitative microprobe determination is a Ca-Fe-Al silicate with volatiles and a low silica content. The surrounding groundmass is a Mg=Ca-Al-K-Si phase with some volatile content. There are two possible origins for this texture, one is that these globules were lapilli of magma which cooled as a separate unit (Gold, 1963) and the other is that they were immi⁶cible melt droplets.

Ę

.02 mm

Figure 5. Highly zoned hydrogrossular. (Polarized light)



- Charles

i....

(

<u>1 m m</u>

Figure 6. Plain light view of one of the globules at center of photograph in typical calcite-poor groundmass.

Chemical Composition

Five whole rock analyses are presented in Table 3. Analysis 5 is of the very fresh xenolith free igneous matrix which is probably most representative of the kimberlite magma. The greatest variation is in the carbon dioxide and water contents of these rocks; a variation which may be attributed to original variations in the magma, to the amount of xenoliths in the sample analysed and to the effect of late stage alteration.

In table 3a the kimberlite (No. 5) is compared with other kimberlites and nearby alnoites. In general the Ile Bizard kimberlite seems to be chemically transitional between the kimberlites and the alnoites. The high water, low sodium and the high K/Na ratio, which should be near 7 for kimberlites (Dawson, 1967), makes the rock chemically more like a kimberlite than an alnoite. Mineralogically and texturally the rock is unlike the alnoites, especially with the porphryitic phlogopite, which is an obvious primary texture and is not found in any of the alnoites. Any hypothesis of this kimberlite being an altered and hydrated alnoite is thus untenable but some relationship between the alnoites and kimberlites may exist because of their chemical similarity and field association.

Table	3
-------	---

Chemical Analyses of Ile Bizard Kimberlite

	1	2	3	4	5
Si02	35.46	30.70	37.54	33.88	33. 58
Ti02	1.88	1.89	1.67	1.97	2,27
A1203	8.36	5•55	6.18	6.51	6.93
^{Fe} 2 ⁰ 3*	10,68	10.46	9.11	11.53	13.20
MgO	22.13	21.62	18.73	20,40	20,08
CaO	14.84	14.17	14.81	14.73	12.89
Na ₂ 0	•23	• 53	• 31	.48	.18
к ₂ 0	.61	1.80	1.84	2.03	•77
P205	1.07	1.01	•89	1.13	1.16
co ₂	.20	6.55	1.32	0.0	0.0
^H 2 ⁰ ±	4.52	5•73	7.54	7.35	8,76
Total	99.98	99•98	99.94	100.01	99.82
K/Na	2.7	3.4	5•9	4.2	4.3

* Total Fs as Fe₂03

- 1) Micaceous kimberlite.
- 2) Kimberlite with few xenoliths.
- 3) Kimberlite with abundant xenoliths.
- 4) Kimberlite, dark very fine-grained variety.
- 5) Kimberlite, very fresh with no xenoliths.

	Kimberlites and Alnoites				
	A	В	С	D	E
Si02	36.33	31.1	33. 58	30.85	30.27
Ti02	1.89	2.03	2.27	2.87	2.84
A1203	5.09	4.9	6.93	8.21	10.00
^{Fe} 2 ⁰ 3	7.43	-	13.20	3.33	4.88
Fe0	3.40	10.5	-	6.52	6.95
Mn0	.10	• 10	-	•21	.16
MgO	26.63	23.9	20.08	23.16	20.11
CaO	6.78	10.6	12.89	16.46	14.73
Na20	• 37	• 31	. 1 8	1.01	1.41
к <u>0</u>	2.43	2.1	•77	1.43	2.85
P205	•66	•66	1.16	1.90	•95
^{C0} 2	1.64	7.1	0.0	3.04	3.24
^H 2 ⁰ +	7.25	5•9	<u>+</u> 8 . 76	1.22	<u>+</u> 2.17
Total	99•90	99.20	99.82	100.26	100.64
K/Na	6.6	6.8	4.3	1.4	2.0

Table 3a

A - Average of 10 micaceous kimberlites (Nockolds, 1954)

B - Micaceous kimberlite (Dawson, 1967)

C - Ile Bizard kimberlite No. 5

D - Alnoite, Ile Cadieux (Bowen, 1922)

E - Alnoite, north of Ile Cadieux (Stansfield, 1923)

Conditions of Crystallization

The fine and even grain size of the groundmass and the preservation of the ultramafic nodules in the kimberlite may be interpreted as resulting from the rapid crystallization of a magma. The lack of rounding of the fragments further suggests that the intrusion process was rather gentle and was not by fluidization. The intrusion probably took place along an opening produced when the adjacent diatreme was formed.

The presence of coarse-grained melilite in the xenolith described earlier indicates a temperature of at least 720°C, the lower stability limit of akermanite over a wide range of pressures (harker & Tuttle, 1956). Walter's (1965) decomposition curves for akermanite at CO₂ pressures of 0.3 to 0.5 kb, a resonable estimate of the minimum pressure based on the depth of the present land surface below the ancient surface as given by Clark (1952), gives a temperature range of 820-900°C. The porphryitic phlogopite, which was the first mineral to crystallize, can form up to 1170°C over a pressure range of 1-40 kb in the presence of a pure water gas phase (Yoder & Kushiro, 1969). Since there was also likely a CO₂ gas phase present this temperature must have been lower and hence the temperature of intrusion was probably between 900-1150°C.

ULTRAMAFIC NODULES

Amphibole-bearing Nodules

Rounded black amphibole-bearing nodules consist of a medium-grained mosaic of interlocking amphibole and clinopyroxene (Fig. 7). In one of the nodules a large clinopyroxene crystal is embayed and dissected by the amphibole which, although perhaps indicating a reaction relationship between the clinopyroxene and the amphibole, does at least indicate the earlier occurence of clinopyroxene. The clinopyroxene which forms 20-50 per cent of the nodules is colourless and has rare exsolution lamellae of orthopyroxene. The amphibole is very strongly pleochroic in shades of deep brown and yellow and contains abundant pyrite, minor chalcopyrite and ilmenite inclusions. The high TiO₂ content of the amphibole (Table 4) shows that it is a kaersutite.

The high TiO_2 content of the nodule clinopyroxene (Table 4) suggests that it was a product of the kimberlite magma as does the kaersutite, which is commonly found in alkaline rocks. Since the clinopyroxene megacryst is also thought to be a product of the kimberlite magma these two pyroxenes are compared in table 4, where it is seen that the nodule clinopyroxene is richer in TiO₂, CaO, Al₂O₃, FeO and poorer in MgO, Na₂O, and SiO₂. Since the composition of clinopyroxenes



 γ

Figure 7. Amphibole-bearing nodule showing mosaic of kaersutite (Ks) and clinopyroxene (Cp).

in basic rocks have been shown to depend on the level of undersaturation of the host rocks (Kushiro, 1960, LeBas, 1962), these differences may reflect changing magma compositions. Data from Wilkinson (1966) for clinopyroxenes in theralites show that the relation found for the two clinopyroxenes above is a typical relationship between phenocryst (Megacryst) and groundmass (nodule) clinopyroxenes. Binns (1969) has a sequence of megacrysts that consists initially of Mg-rich clinopyroxene and terminates with a Mg-rich kaersutite and ilmenite. This suggests that the clinopyroxene megacryst was the first to crystallize with the nodule clinopyroxene forming later after the magma had changed composition somewhat and the kaersutite following closely after that.

The aluminium contents of the clinopyroxenes expressed in terms of Ca-Tschermak's (CaTs) molecule (CaAl₂SiO₆) is an indication of high pressure origin. This was experimentally shown by Clark, Schairer, and de Neufille (1962) for solid \times solution of CaTs in diopsidic clinopyroxenes and Hays (1967) found that pure CaTs is unstable below 1100°C and 11.6 Kb. While the amount of aluminum in the pyroxenes is influenced by the amount of Al₂O₃ and SiO₂ in the magma (Kushiro, 1960) it must also be controlled by the phases crystallizing from the magma. The appearance of an aluminium rich phase

	CLINOPY	ROXENES	AND AMPHIBOLE	2
si02	1 48•07	2 51.30	3 46•95	4 40•81
Ti02	1.94	0.64	2,12	3.15
A12 ⁰ 3	7.14	4.72	7•33	14. 54
Fe203	8.	a	2.96	a
FeO	6.21	5.19	4.60	9.91
MnO	nd	nd	0.10	nd
MgO	11.82	17.09	12.95	13.72
CaO	23.73	18.85	21.42	12,13
Na_20	0.68	1.33	0.69	2,12
к ₂ 0	0.00	0.00	tr	2.05
Total	99 •59	99.12	99.12	98.43
n	d = not determined	tr =	= trace a =	Total Fe as FeO

Table 4

1) Clinopyroxene from amphibole-bearing nodule

- 2) Clinopyroxene megacryst
- 3) Phenocrysts in analcime-olivine theralite, Square Top Intrusion, Nundle, New South Wales (Wilkinson, 1966)
- 4) Amphibole from amphibole-bearing nodule 37 .



Table	4	cont'	d
-------	---	-------	---

	1	2	3	4
	Cations per 6 oxygens			Cations per 23 oxygems
Si	1.7962	1.8660	1.758	5.9725
Al iv	.2038	• 1140	.242	2.0275
Al vi	.1106	•0905	.082	•4804
Ti	•0545	•0177	• 060	• 3467
Mg	. 6583	•9365	•723	2.9928
Fe 2+	• 1941	•1596	• 144	1.2129
Fe 3+	-	-	•083	-
Mn	-	-	•003	-
Ca	•9500	•7425	. 859	1.9020
Na	•0593	•0948	• 050	.0616
K	-	-	-	• 3827
XY	2 .026 8	2.0416	2.004	X 2.8863 Y 5.0328
Ca	52.7	40.4	47.4	
Mg	36.5	50.9	39•9	
Fe	10,8	8.7	12.7	

•

(eg. plagioclase, spinel, garnet) would certainly reduce the amount of Al available for the pyroxenes. The results of experimental work on an alkali basalt system (Green & Ringwood, 1967) show_that the pyroxenes become Al-rich at 11 kb and 1000° C. This^{is}_Aobviously a reflection of the absence of plagioclase and supports the view of Kushiro (1962) that the amount of CaTs in the pyroxene is due to the disappearance of plagioclase and the appearance of garnet, both of which decrease the CaTs component. Natural examples of megacrysts that have been assigned a high pressure origin are glassy black aluminous clinopyroxenes from an alkali olivine basalt (Kuno, 1964) near Taki-sima, Japan and from analcime basanites near Armidale, New South Wales (Binns, 1969).

Experimental studies on a variety of olivine normative basaltic compositions under both dry and hydrous conditions indicate that olivine and plagioclase are important liquidus phases at pressures below 10 Kb whereas pyrope-rich garnet is prominent above pressures of about 18 Kb (Green & Ringwood, 1967, Bultidude & Green, 1968). The absence of plagioclase and pyrope megacrysts along with the CaTs content of the clinopyroxene would suggest crystallization in the 10-18 Kb region for a magma of basaltic composition but the kimberlite is sufficiently different so as to possibly allow crystallization at slightly higher pressure. The amphibole, which was slightly later, may have formed at slightly lower pressures though it is stable to 30 Kb at 950°C (Gilbert, 1969).

Websterite Nodules

The websterite nodules consist of clinopyroxene and orthopyroxene with olivine and phlogopite as minor constituents in a few nodules. The orthopyroxene is a dark green aluminous enstatite (Table 5) and the clinopyroxene is a bright green aluminous chrome diopside (Table 6) usually of a dusty nature due to a slight alteration. Both pyroxenes show exsolution features of the other pyroxenes as fine lamellae parallel to (100) and in places as blebs. The most common texture in these nodules is a medium-grained, equigranular aggregate of clinopyroxene and subordinate orthopyroxene, a texture which megascopically appears to be a recrystallization of larger crystals of clinopyroxene and finer grained enstatite. In some nodules the diopside, which is more abundant than the enstatite, occurs as large crystals (phenocrysts) up to 1 cm. long in a groundmass of finer grained enstatite. Black fine-grained alteration material and more rarely phlogopite is common along the edges of the nodules and along cracks penetrating them. An analysis of this phlogopite (Table 6) shows it to have an appreciable chrome and titanium content.

The analysed pyroxenes have been plotted in the pyroxene

quadrilateral (Fig. 8) along with the temperatures on the solvus in the system diopside-enstatite at 30 Kb (Davis & Boyd, 1966). This solvus is not very sensitive to pressure and the pyroxenes in the nodules do not deviate much from the system diopside-enstatite so that the solvus temperatures can be used in a relative way to show the compositional trends with decreasing temperature.

In nodule 53 there are four analysed pyroxenes; 53a and 53c are small separate grains of clino- and orthopyroxene respectively, whereas 53b is a large clinopyroxene crystal with exsolved blebs of orthopyroxene near its margin, one of which has been analysed (53b*). Because of the several different compositions of clino- and orthopyroxenes in this nodule there could not have been equilibrium. Since there are no phenocrysts of orthopyroxene, it is possible that the composition of the clinopyroxene phenocryst was originally almost identical to 53b, there being only a very small percentage of exsolved orthopyroxene in these grains. Pyroxenes 53a and 53c may have crystallized from the residual liquid which could have been enriched in orthopyroxene relative to the original magma. The original phenocryst of clinopyroxene on cooling reached the solvus with orthopyroxene at temperatures of approximately 1100°C. However, pyroxenes



Figure 8. Analysed pyroxenes from the websterite nodules plotted in a portion of the pyroxene quadrilateral. Temperatures given are points on the diopside solvus in the system $MgSiO_3$ -CaMgSi $_2O_6$ at 30 kb (Davis & Boyd, 1966) 53a and 53c may have crystallized directly from the melt as separate clino- and orthopyroxenes or as a single phase which reached the solvus shortly after crystallization. In either case 53a and 53c stopped equilibrating at approximately 1250° C. It is possible that pyroxenes of compositions of 53a and 53c cannot equilibrate as easily as those of compositions 53b. The total Al₂O₃ and increasing Al iv/vi ratios of clinopyroxenes can be qualitatively related to increasing temperatures under isobaric conditions (Boyd & England, 1964, Kushiro, Syono, & Akimoto, 1967) and these pyroxenes illustrate this relationship: the phenocryst has a higher total Al₂O₃ showing its higher crystallization temperature while the Al iv/vi ratios of the clinopyroxenes demonstrate their relative subsolidus equilibrium temperatures.

The textures of the nodules indicate clinopyroxene was the major phase crystallizing from a magma with enstatite being a minor phase or possibly forming from a trapped pore fluid. Some of the enstatite grains may have formed by exsolution from clinopyroxene. The phlogopite would appear to be formed by reaction with the kimberlite magma since it occurs around the edges of the nodules. The high chrome and titanium contents of the phlogopite are considered the contributions of the nodule
Ta	ble	5
		_

ORTHOPYROXENES

	4	5 a	5b	26	53b'	53 c
Si02	52.53	55.24	55.19	53.86	54.06	55.12
^{Ti0} 2	0.00	0.13	0.21	0.39	0,00	0.27
A12 ⁰ 3	3.37	3.64	3.48	3.58	4.62	3.02
Fe0 *	6.69	6.97	7•53	7.03	7.02	7.36
Mn0	nd	nd	nd	nd	nd	0.14
MgO	33.61	34.43	33.55	35.46	33.24	34.89
CaO	1.00	0.90	0.78	1.26	0.00	1.26
^{Cr2⁰3}	0.33	0.50	0.63	0.19	0.38	0.32
Total	97•53	101.82	101.37	101.76	99•32	102.38
* Tot	al Fe as F	69	nd	= not dete	rmined	
Struc	tural form	mlae Cat	ions per (ó oxygens		
Si	1.8742	1.8852	1.8951	1.8476	1.8841	1.8792
Al iv	0.1258	0.1148	0.1049	0.1447	0.1159	0.1208
Al vi	0.0159	0.0316	0.0359	0.0000	0.0739	0.0005
Cr	0.0093	0.0135	0.0171	0.0052	0.0105	0,0086
Ti	0.0000	0.0033	0.0054	0 . 10 01	0.0000	0.0069
Mg	1.7873	1.7513	1.7171	1.8127	1.7268	1.7729
Fe	0.1996	0.1989	0.2162	0.2016	0.2046	0.2098
Ca	0.0382	0.0329	0.0287	0.0463	0.0000	0.0460
XY	2.0503	2.0316	2.0205	2.0678	2.0157	2.0489

- ---

		Table 6		
	CLIN	NOPYROXENES AND PH	LOGOPITE	
	Cpx 5	Cpx 5 3a	Cpx 53b	Phlog. 5
sio ₂	53.22	50.93	52.12	37.41
Ti02	0.51	0.48	0.00	4.47
A1203	4.76	4.04	6.35	15.24
FeO *	3.86	4.03	3•59	4.73
MgO	16.76	19.32	15.99	21.44
CaO	17.47	17.02	18 .60	0.00
Na_2^0	1.95	1.58	nd	0.00
к ₂ 0	0 _e 00	nd	nd	14.47
^{Cr2⁰3}	0.95	0.71	0.63	1.20
Total	99•48	98.11	97.28	98.96
* Total Fe	as FeO	nd = not d	letermined	
Structural	formulae	Clinopyroxenes: (Phlogopite: Catio	Cations per 6 cons per 22 oxyg	oxygens gens(anhydrous)
Si	1.9287	1.8805	1.9188	5.3081
Al iv	0.0713	0.1195	0.0812	2.5486
Al vi	0.1320	0.0563	0.1943	0.0000
Cr	0.0272	0.0207	0.0183	0.1346
Ti	0.0139	0.0133	0,0000	0.4770
Mg	0•9053	1.0633	0.8774	4.5343
Fe 2+	0.1170	0.1244	0.1105	0,5613
Ca	0.6783	0.6733	0.7337	0•0000
Na	0.1370	0.1131	-	0.0000
К	0.0000	-	-	2.6191
XY	2.0107	2.0645	1.9343	8.3262

and kimberlite magma respectively. The well preserved nature of the nodules and the small amount of phlogopite suggests that the nodules did not spend much time in the kimberlite magma.

Lherzolite Nodules

(

The lherzolite nodules consist of a medium- to coarsegrained mosaic of orthopyroxene and olivine with subordinate clinopyroxene and a minor amount of interstitial chrome spinel and pyrope and also a small amount of phlogopite around the edges. The orthopyroxenes are dark green aluminous enstatites (Table 7) some of which show a slight alteration and the clinopyroxenes (Table 8) are bright green chrome diopsides which inevitably show some degree of alteration giving them a dusty appearance. Both pyroxenes commonly show exsolution lamellae of the other pyroxene. The olivine is a very clear forsterite (Table 11). The chrome spinel which has a light brown colour when it occurs as discrete grains is very inhomogeneous in its chrome content which varies from 12 to 26 per cent (Table 10), commonly increasing from the center of the grain to the edge. The chrome spinel also occurs as light green platelets in both pyroxenes. The pyrope (Fig. 9) (Table 9) occurs as rims around the spinel grains. Some of the pyrope grains contain very small crystallographically orientated rods of rutile and chrome spinel and one grain was found with a two phase sulphide bleb, a Ni-Fe-As and a Cu-Fe-As sulphide. The lherzolites all have a slight but pervasive serpentinization which occurs



Figure 9. Chemical composition of the garnets from various nodules from the Ile Bizard kimberlite in terms of almandine (Alm), grossular + andradite (Gr + An), and pyrope (Py).

Table	7
-------	---

ORTHOPYROXENES

	2304a	2304b	1a	1ь	ic	23	29	52 a	52Ъ
Si02	55.11	57•47	57.73	54.51	57.72	57.48	54.24	57.77	55.50
Ti02	nd	nd	0.11	nd	0.12	0.02	0,18	nd	0.13
A1203	3.32	3.41	2.73	2.96	2.03	1.81	2.89	3.13	4.05
FeO *	5.45	5.66	5•54	5•95	6.01	5.37	7.98	6.29	6.26
Mn0	0.06	nd	nd	0.10	nd	nd	nd	nd	nd
MgO	33.02	34.22	33.42	35.81	34.05	32.70	33•73	33.41	33.23
CaO	0.43	0.76	0.60	0.54	0.45	0.43	0 <u>• 5</u> 0	0.45	0.55
^{Cr2⁰3}	0,28	0,27	0.44	0•35	0,28	0.24	0.36	0.24	0.39
Total	97.67	101.79	100.57	100,22	100.66	98.05	99.88	101.29	100.11
* Total	Fe as FeO		nd = not de	etermined					

2

•

.

			Structural	ructural Formulae Cations per 6 oxygens					
	2304a	2304Ъ	1a	1b	1c	23	29	52 a	52Ъ
Si	1.9370	1.9389	1.9674	1.8831	1.9699	2.0032	1.8946	1.9594	1.9919
Al iv	0.0630	0.0611	0.0326	0.1169	0.0301	0.0000	0.1054	0.0406	0.0881
Al vi	0.0745	0.0745	0.0770	0.0036	0.0516	0.0743	0.0136	0.0845	0.0763
Cr	0.0078	0.0072	0.0119	0.0096	0.0076	0.0066	0.0099	0,0064	0.0106
Ti	-	-	0.0028	-	0.0031	0.0005	0.0047	-	0.0034
Mg	1.7299	1.7208	1.6976	1.8439	1.7321	1 .698 6	1.7561	1,6890	1.7062
Fe	0.1602	0.1597	0.1579	0.1719	0.1715	0.1565	0.2331	0.1784	0.1803
Ca	0.0162	0.0275	0.0219	0.0200	0.0165	0.0161	0.0187	0.0164	0.203
XY	1.9885	1.9897	1.9691	2.0490	1.9824	1,9558	1.9892	1,9748	1.9972

Table 7 cont'd

	CLINOPYROXENES								
	1gm	1a	1b	1c	29a	29Ъ	52 a	52b	
Si02	51.84	52.89	54.43	54.15	50.15	51.91	52.12	52.38	
Ti02	0.30	0.94	0.47	0.31	0.79	0 . 3 8	0.55	0.41	
Al2 ⁰ 3	5.01	4.92	3.86	3.78	4 . 1 8	3.59	4.84	4.73	
FeO *	2.73	4.35	2.89	2.75	4.19	3.60	3.72	3.08	
MgO	16.07	15.34	15.60	14.89	15.35	16.12	15.50	16.22	
CaO	21.30	20.58	21,22	21.67	21.69	21.74	20.80	20.06	
Na20	nd	nd	1.54	1.60	0.67	nd	1.54	1.49	
^{Cr} 2 ⁰ 3	0.95	0.91	0.98	0.90	0.72	0.68	0.63	0.47	
Total	98.20	99•93	100.99	100.05	97.74	98.02	99.10	98.84	
* Total	Fe as Fe	nd	= not deter	mined					

.

Table 8

Table 8 cont'd

Structural Formulae Cations per 6 oxygens

.

	1gm	1a	1b	1c	29 a	29Ъ	52a	5 2 Ъ
Si	1.9062	1.9172	1.9503	1.9598	1.8806	1.9241	1.9084	1,9165
Al iv	0 .093 8	0.0828	0.0497	0.0402	0.1194	0.0759	0.0916	0.0835
Al vi	0.1223	0.1274	0.1133	0.1211	0.0653	0.0809	0.1173	0,1205
Cr	0.0276	0.0261	0.027 8	0.0258	0.0213	0.0199	0.0182	0.0136
Ti	0.0083	0.0256	0.0127	0.0084	0.0223	0.0106	0.0151	0,0113
Mg	0.8808	0.8288	0.8332	0.8033	0.8580	0.8906	0.8459	0,8846
Fe	0.0840	0 .1319	0.0866	0.0832	0.1314	0,1116	0.0955	0.0942
Ca	0.8392	0.7993	0.8147	0.8403	0.8714	0.8634	0.8160	0.7864
Na		-	0.1070	0.1123	0.0487	-	0.1093	0.1057
XY	1.9631	1.9390	1.9951	1.9944	2.0185	1.9775	2.0175	2.0163

•

Table 9

.

GARNETS

	2304	1a	1b	1c	2	13a	13ъ	13e
Si02	43.17	44 . 10	41.32	41.75	41.48	43.42	41.51	43.08
Ti0 ₂	0.18	nd	nd	0.08	nd	0.18	0.09	0.14
A12 ⁰ 3	21.47	22,12	23.83	22.08	21.83	21.77	23.30	22.54
MgO	21.32	21.59	21.54	20.53	21.48	20.33	18,91	19.77
FeO *	7•37	7.27	7.67	7•59	10.54	7•56	9.16	9.46
CaO	5.76	5.52	4.67	5.25	5.00	5•31	5.19	4.68
^{Cr2⁰3}	1.05	1.17	1.16	1.06	1.69	1.18	1.13	1.46
Total	100.32	101.77	100.19	98 . 34	102.02	99•75	99.29	101, 13
* Total	. Fe as FeO		nd = not de	termined				

.

			Structural Formulae		Cation			
	2304	1a	1b	1c	2	13a	13Ъ	13c
Si	6.0973	6.1226	5.8448	6.0186	5.8648	6.1548	5.9622	6.0696
Al iv	0.0000	0.0000	0.1552	0.0000	0.1352	0.0000	0.0378	0.0000
Al vi	3• 5 73 9	3.6195	3.8176	3.7514	3.5025	3.6370	3.9064	3.7428
Cr	0.1139	0.1284	0.1297	0.1208	0.1889	0.1322	0.1283	0.1626
Ti	0.0191	-	-	0.0087	- ,	0.0192	0.0097	0.0148
Mg	4.4883	4.4677	4.5415	4.4113	4.5267	4.2954	4.0484	4.1517
Fe	0.8705	0.8441	0.9073	0.9150	1.2463	0.8962	1.1003	1.1146
Ca	0.8716	0.8211	0.7070	0.8109	0.7574	0.8065	0.7987	0.7065

,

Table 9 cont'd

.

.

Table 10

SPINELS

	center 2	edge 2	2304	13	52
Si02	0.08	0.11	0.13	0.08	0 .1 4
Ti0 ₂	0.20	0.27	0,28	0.23	0.32
A1203	49.9 8	50.04	49.49	48.98	51 . 38
FeO *	15.05	15.16	12.50	15.45	14.08
MgO	18.31	18.65	21.45	18.00	19.17
^{Cr} 2 ⁰ 3	15.42	14.19	13.84	15.14	12.67
Total	99.04	98.42	97.69	97.88	97.76
* Total	. Fe as FeC)			
Structu	ral Formul	.8 0	Cations per	32 oxygen s	
Si	0.0174	0.2040	0.0283	0.0177	0.0305
Al iv	12.8244	12.8914	12.6962	12.7572	13.1849
Cr	2.6543	2.4524	2.381 8	2.6453	2.1811
Ti -	0.0327	0.04444	0.0458	0.0382	0.0524
Mg	5.9416	6.0763	6.9592	5.9291	6.2231
Fe	2.7402	2.7713	2.2754	2.8554	2.5638

...

The chrome content of other spinel grains are listed below:

1a	22.35		
1Ъ	25.70		
lexsol . 45	19.53 19.84	spinel exsolution in pyr	oxene

Table 11

OLIVINES

	2304	1	23	52		
Si02	40.12	40.09	40.58	38.45		
A1203	0.19	0.11	0.00	0.00		
MgO	52.35	51 . 1 6	48.91	49.05		
FeO *	8,80	9.64	9.23	9.96		
Total	101.46	101.00	98 .72	97.46		
* Total Fe as FeO						
Structural	formulae	Cat	ions per 4 o	xygens		
Si	0•9670	0.9737	1.0033	0.9713		
Al iv	0.0054	0.0031	0.0000	0.0000		
Mg	1.8806	1.8521	1.8025	1.8469		
Fe	0.1774	0.1958	0.1909	0.2104		
Atomic Ratios						
Mg	91.4	90•4	90.4	8 9 •8		
Fe 2+	8.6	9.6	9.6	10.2		

mainly along the grain boundaries.

In the pyroxene quadrilateral (Fig. 10) clinopyroxenes and orthopyroxenes from the lherzolites form distinct groups with higher Mg/Fe ratios than the websterites. This suggests that the lherzolites may be an earlier product of fractional crystallization than the websterites or alternatively that they are the refractory residue of an episode of partial melting, with the websterites forming as cumulates from this melt. The higher chrome content of the lherzolites also supports this interpretation. Comparison with Davis and Boyd's solvus temperatures indicate equilibration of the lherzolites to lower temperatures than the websterites.

Nodule 52 (Fig. 11) shows a spinel grain surrounding both olivine and orthopyroxene which may be textural evidence of the following reaction:

(m-2) MgSiO₃ · MgAl₂SiO₆ + MgSiO₄ = MgAl₂O₄ + m MgSiO₃ (Green & Ringwood, 1967)

Decreasing temperatures are indicated by this reaction since the boundary curve (Fig. 12) is nearly isothermal and by the pyroxenes which indicate equilbration temperatures considerably lower than that of the reaction.







(___:





Figure 12. Diagram illustrating the P,T fields of different mineral assembleges in pyrolite III composition. The figures 1% Al₂O₃ etc. refer to the Al₂O₃ content of orthopyroxene in equilibrium with garnet in the garnet pyrolite field. The oceanic and Precambrian shield geotherms are those illustrated by Ringwood et al (1964).

Diagram taken from Green & Ringwood p.155, 1967.

The reaction which provides the best estimate of the depth of origin of these nodules is the one which defines the boundary between the pyroxene pyrolite and the garnet pyrolite fields (Fig. 12). The idealized reaction may be written;

(MacGregor, 1968)

This reaction is well illustrated in figures 13,14 where the spinel grains are surrounded by garnet rims and olivine blebs occur between the pyroxene and garnet. This texture shows the reaction was preserved in the nodules and since analyses of both reactants and products are available, a balanced reaction was written .

Since there are five phases the reaction can only be balanced for four components. Numerous combinations of components, both inert and mobile were defined to write the balanced equation, but only a few of them gave the observed reaction. The reaction with the lowest residuals,



 $\left(\cdot \right)$



Figure 14. Nodule 2304 showing spinel surrounded by pyrope with olivine between the pyrope and enstatite.

a measure of its univariance, is:

1.93 orthopyroxene + .62 clinopyroxene + .14 spinel + Al₂0₃ + Fe₂0₃ + Mg0 =

.65 garnet + 1 olivine + FeO + $Cr_2O_3 + TiO_2 + Na_2O$ The components balanced for in this reaction are $(Al, Cr, Fe)_2O_3$, (Mg,Fe)O, CaO, SiO₂, with TiO₂ and Na₂O unbalanced. All the mineral compositions are taken from nodule 1 except for the spinel which is from nodule 2 because there were no acceptable analyses of spinel from nodule 1 available. The differences in spinel compositions between nodule 1 and nodule 2 are only in the Al and Cr contents which are treated as one component so there should be no effect on the balanced equation. Since phlogopite is also present in the nodules, it was used as an additional phase, but the resultant reaction was not the one observed in the nodules which therefore supports the textural evidence that phlogopite was a result of a later reaction.

The method of balancing an equation by simple matrix operations produces residuals (Carmichael, 1970) which are an indication of either the necessity to add or subtract elements in the system, 'mobile components', or of a divariant reaction. The zoning in the spinels shows that the high chrome residual (Table 12) indicates that the reaction is divariant. The chrome 51

Table 12

....

RESIDUALS

(+ produced, - consumed) in the reaction

Fe0	MgO	A1203	Cr203	Fe203	Ti02	Na 0 2
+.1507	1507	2143	+. 3402	1250	+.0027	+.066

Since all the oxides are balanced except for Ti and Na the residuals for any one component must be equal and opposite in sign.

has a strong tendency to remain in the spinel rather than to enter the reaction products. The residuals in FeO and MgO also indicate that the partition of these oxides has a slight contribution to the divariance of the reaction. MacGregor (1965) showed that in the system CaO-MgO-Al₂O₃-SiO₂ the reaction was univariant and Boyd (1969) suggested that chrome would complicate the reaction. Therefore, the boundary between the garnet- and pyroxene-pyrolite fields in the pyrolite system (Green & Ringwood, 1967) must be a divariant zone and not a univariant line as in Fig. 12.

This reaction is used in conjunction with Green and Ringwood's (1967) diagram (Fig. 12) of mineral assembleges for an upper mantle of pyrolite composition, which is comparable to that of the lherzolite nodules, and a value of 3.0 per cent Al_{203}^{0} in the orthopyroxene of nodule 1 to obtain a value of 1050°C and 20 kb (60 km) for the conditions where the reaction took place. The effect of the divariance of the reaction must affect these values somewhat, but the extent of this is indeterminate at the present time. Both the texture and the inhomogeneity of the chrome spinel indicate that the reaction was in progress when the nodule was quenched, suggesting a rapid emplacement from the 60 km. region of the mantle.

The final stage in the evolution of the lherzolite nodules was the formation of pyroxene and chrome spinel exsolution lamellae. This final exsolution of chrome spinel could not have occurred earlier as the spinel would have reacted to form garnet similar to the reaction above or it would have exsolved directly as garnet. Thus the chrome spinel exsolution must have taken place as the nodules were injected to crustal conditions and represent the final attempt at equilibrium under low pressure conditions. Similar exsolution features are found in an enstatite augen from a high temperature peridotite in Venezuela (Green, 1963). Green showed that the spinel exsolution was a result of disequilibrium in the high alumina augen as a result of a large change in load pressure. As a consequence of the chrome spinel exsolution in the pyroxenes, the value of 3.0 per cent Al203 used above would be increased for a homogenized pyroxene but the effect would only result in a slight increase of the pressure and temperature determined for the reaction .

Miscellaneous Nodules

龖

There are two nodules which are quite unlike the other nodules so far described. Nodule 47 consists of a finegrained equigranular aggregate of clinopyroxene and orthopyroxene with some rare grains of garnet (Fig. 15). There is an abundance of phlogopite throughout the nodule and all the grains in the nodule have dark and dusty edges suggesting a pervasive alteration. The garnet grains, which are all surrounded by an opaque border as wide as the grain itself are pyrope-almandine (Table 13) with 10 per cent less of the pyrope component than the garnets in the lherzolite nodules (Fig. 9). It seems that this nodule has undergone considerable recrystallization and alteration.

The other nodule, P 8677, is very coarse grained and consists of olivine and orthopyroxene. The orthopyroxene forms only 15 per cent of the nodule and it has no exsolution features of any sort. Serpentine is very common along grain boundaries and cracks. The nodule is a harzburgite and it may be analogous the the 'residual dunites' (Ringwood, 1969) of the upper-most mantle. 55



٠.

1 m m

Figure 15. Nodule 47 with garnet grain at center in groundmass of pyroxenes and phlogopite.

Table 13

GARNET from Nodule 47

Si02	39.87
Ti02	0.32
A12 ⁰ 3	23.57
MgO	16.46
Fe0 *	12.69
CaO	5.23
Cr2 ⁰ 3	0.12
Total	98.26
* Total	Fe as FeO

Structural Formula

-

Cations to 24 oxygens

Si		5.8783
Al	iv	0.1217
Al	vi	3•9739
Cr		0.0140
Ti		0.0355
Mg		3.6172
Fe		1.5647
Ca		0.8262

DISCUSSION

The fine-grained nature of the kimberlite, the preservation of the ultramafic nodules and the slight amount of phlogopitization along the edges of the nodules indicate that the intrusion and the cooling of the magma was a rapid process. Since the websterites and the lherzolites are compositionally and texturally quite different from the megacrysts and show evidence of disequilibrium with the kimberlite magma, it is likely that they are accidental xenoliths that were caught up in the kimberlite magma as it passed upward.

The temperatures indicated by the nodules are substantially higher than those of the Precambrian shield geotherm (Fig. 12) and they may be a result of a diapiric rise of pyrolite from depth to the required 60 km. with fractional fusion and subsequent magma segregation. As previously presented, the evidence supports the theory that the websterites were the cumulate phase formed by fractional crystallization of the magma while the lherzolites were the refractory residual phase.

The kimberlite magma must have come from below the 60 km. depth indicated by the lherzolite nodules and the absence of any pyrope phenocrysts or other pyrope-bearing nodules suggests that it must have come from immediately below the lherzolites. The presence of large unzoned clinopyroxene crystals along with olivine and phlogopite megacrysts implies the existence of a magma chamber where slow equilibrium crystallization occurred. The presence of considerable amounts of water in the kimberlite and of the phlogopite megacrysts indicates that there was water present in the mantle at these depths. Thus the chemical nature of the kimberlite magma can be accounted for by a slight amount of partial melting of an undepleted mantle which would tend to concentrate the volatile components and the 'incompatible elements' in the small amount of magma formed. After segregation of this magma into the magma chamber there would a strong tendency for the surrounding wall rock to be depleted of its 'incompatible elements' by the flow of water into the highly undersaturated liquid. Nodule 47 may represent a sample of this highly altered wall rock.

It is likely that the heat necessary to form the kimberlite magma came from the cooling of the websterite and lherzolite zone above it. This is quite reasonable since it required the area to have undergone only one thermal event and it would have provided a slight amount of heat, but just enough to cause the slight amount of partial melting necessary to form the kimberlite magma.

×)

The minute size of the diamonds that may have come from the kimberlite can be attributed to resorption by the magma during the formation of the websterites and lherzolites. In the sequence of events that has been postulated this is the only material that may have come from depths where diamond is stable.

Acknowledgements

The author thanks Dr. A.R. Philpotts who suggested and supervised the thesis. The Québec Department of Natural Resources provided a scholarship during the work and field and laboratory studies were made possible by G.S.C and N.R.C. grants to Dr. A.R. Philpotts. L. Barron assisted in the field work, J.M. Barton Jr. performed the K-Ar determinations, N.H. Gray loaned samples and provided stimulating discussion, Dr. D.M. Carmichael and W. Trzcienski instructed the author in the technique of balancing reactions, and Dr. W.H. MacLean instructed in the use of the electron microprobe.

REFERENCES

- Anderson, A.T., 1968, Oxidation of the LaBache Lake titaniferous magnetite deposit, Que.: Jour. Geol. v.76, p.528-543
- Binns, R.A., 1969, High-pressure megacrysts in basanitic lavas near Armidale, New South Wales; Amer. Jour. Sci. v. 267-A p.33-49
- Bowen, N.L., 1922, Genetic features of alnoitic rocks at Ile Cadieux, Québec: Amer. Jour. Sci. v.3, p.1-34
- Boyd, F.R., 1969, Electron-probe study of diopside inclusions from kimberlites: Amer. Jour. Sci. v.267-A p.50-69 ______ and England, J.L., 1964, The system enstatite-pyrope:

Carnegie Inst. Washington Year Book 63, p.157-161

- Bultitude, R.J. and Green, D.H., 1968, Experimental study at high pressures on the origin of olivine nephelinite and olivine melilite nephelinite magmas Earth and Planetary Sci. Letters v.3, p.325-337
- Carmichael, D.M., 1970, Intersecting isograds in the Whetstone Lake area, Ontario: Jour. Petr. v.11, p.147-181
- Clark, S.P., Schairer, J.F., and de Neufville, J., 1962, Phase relations in the system CaMgSi₂O₆-CaAl₂SiO₆-SiO₂ at low and high pressure: Carnegie Inst. Washington Year Book 61, p.59-68

62

Clark, T.H, 1952, Montreal area, Laval and Lachine map-areas: Que. Dept. Mines Geol. Report 46, 159 pp.

- Davis, B.T.C. and Boyd, F.R., 1966, The join Mg₂Si₂O₆-CaMgSi₂O₆ at 30 kb pressure and its application to pyroxenes from kimberlites: Jour. Geophy. Res., v.71, p.3567-3576
- Dawson, J.B., 1967, Geochemistry and origin of kimberlite: in Ultramafic and Related Rocks, Ed. P.J. Wyllie p.269-278
- Doig, R. and Barton Jr., J.M., 1968, Ages of carbonatites and other alkaline rocks in Québec: Can. Jour. Earth Sci. v.5, p.1401-1407
- Gilbert, M.C., 1969, Reconnaissance study of the stability of amphiboles at high pressure: Carnegie Inst. Washington Yearbook 67, p.167.170
- Gold, D.P., 1963, The relationship between the limestones and the alkaline igneous rocks of Oka and St. Hilaire, Québec: Unpub. Ph.D. thesis, McGill Univ., Montreal
- _____, 1967, Alkaline ultrabasic rocks in the Montreal area, Québec: in Ultramafic and Related Rocks, Ed. P.J. Wyllie, p.288-302



- Green, D.H., 1963, Alumina content of enstatite in a Venezuelan high-temperature peridotite: Bull. Geol. Soc. Amer., v.74, p.1397-1402
- and Ringwood, A.E., 1967, The genesis of basaltic magmas: Contr. Min. Petr. v.15, p.103-190 _____, 1967, The stability fields of

aluminous pyroxene peridotite and garnet peridotite and their relevance in upper mantle structure: Earth and Planetary Sci. Letters, v.3, p.151-160

- Grimes-Graeme, R.C.H., 1935, The origin of the intrusive igneous breccias in the vicinity of Montreal, Québec: Unpub. MSc Thesis, McGill Univ., Montreal
- Harker, R.I., and Tuttle, O.F., 1956, The lower limit of stability of akermanite (Ca₂MgSi₂O₇): Amer. Jour. Sci., v.254, p.468-478

Harvie, R., 1909, On the origin and relations of the Paleozoic breccia of the vicinity of Montreal: Trans. Roy. Soc. Can., 3rd. ser., v.3, p.249-299

Hays, J.F., 1967, Lime-alumina-silica: Carnegie Inst. Washington Yearbook 65, p.234-239

Kuno, H., 1964, Aluminum augite and bronzite in alkali olivine basalt from Taka-sima, North Kyushu, Japan,: in Advancing Frontiers in Geology and Geophysics, Hyberabad, Osmania Univ. Press, p.205-220 Kushiro, I., 1960, Si-Al relation in clinopyroxenes from

ignecus rocks: Amer. Jour. Sci. v.258, p.548-554

- _____, 1962, Clinopyroxene solid solutions in the CaAl₂SiO₆ component: Japanese Jour. Geol. Geography Trans., v.33, p.213-220
- ______, Syono, Y., and Akimoto, S., 1967, Effect of pressure on garnet-pyroxene equilibrium in the system MgSi0₃-CaSi0₃-Al₂0₃: Earth and Planetary Sci. Letters, v.2, p.400-404
- Lovering, J.F., and Widdowson, J.R., 1968, The petrological environment of magnesium ilmenites: Earth and Planetary Sci. Letters, v.4, p.310-314

_____, 1968, Mafic and ultramafic inclusions as indicators of the depth of origin of basaltic magmas; Jour. Geophy. Res., v.73, p.3737-3745

Nockolds, S.R., 1954, Average compositions of some igneous rocks: Bull. Geol. Soc. Amer. v.65, p.1007-1032

Philpotts, A.R., 1970, The Monteregian province: in The

Alkaline Rocks, ed. Sørensen, Chapt. IV, pt. 6. Ringwood, A.E., 1969, Composition and evolution of the upper mantle: in The Earth's Crust and Upper Mantle, P.J. Hart (ed.), Geophy. Monograph 13, Amer. Geophy. Union, p.1-17

- _____, MacGregor, I.D., and Boyd, F.R., 1964, Petrological consideration of the upper mantle; Carnegie Inst. Washington Yearbook 63, p.147
- Rucklidge, J. and Gasparrini, E.L., 1968, Electron Micro-Probe Analytical Data Reduction Programme; Univ. of Toronto, Dept. of Geology Pub. 24pp.
- Stansfield, J., 1923, Extension of the Monteregian petrographical province to the west and northwest: Geol. Mag. v.60, p.433-453
- Surette, R., 1969, Ten tiny Ile Bizard diamonds trigger boulder size rumors: The Montreal Star, March 22 pp. 3,5
- Walter, L.S., 1965, Experimental studies on Bowen's decarbonation series III P-T-Univariant equilibrium of the reaction : Spurrite + Monticellite = Merwinite + calcite and analysis of assembleges found at Crestmore California; Amer. Jour. Sci. v263, p.64-77

Walters, A., 1969, Private report on the Ile Bizard kimberlite to Southern Exploration and Development Corp.

Wilkinson, J.F.G., 1966, Clinopyroxene from the Square Top

4

intrusion, Nundle, New South Wales: Mineralog. Mag. v.35, p.1061-1070

Yoder, H.S. and Kushiro, I., 1969, Melting of a hydrous phase: phlogopite : Amer. Jour. Sci. v.267-A, p.558-582
Appendix I

Potassium Argon Ages

Samples run by J.M. Barton Jr. were a phlogopite megacryst, the very fresh and inclusion free sample of the igneous matrix, and an amphibole-bearing nodule. The results are presented in the table below and they confirm the Cretaceous age of the intrusion and show no evidence of excess argon.

Sample	no.	Wt. \$ K	Atoms ⁴⁰ Ar*/gm	Mean Air Correction	Age myrs.
Whole rock	5	0 . 64 ± 0.011	8.28×10^{13}	64.8	125 <u>+</u> 10
Phlogopite	2	6.35	8.85×10^{14}	44.5	125 <u>+</u> 10
Amphibole	5	1 . 17 <u>+</u> 0.009	1.55×10^{14}	34•4	119 <u>+</u> 5

* Radiogenic

K and Ar concentrations are the mean of two or more analyses

 $\lambda_{e} = 5.85 \times 10^{-11}/\text{yr}$. $\lambda_{e} = 4.72 \times 10^{-10}/\text{yr}$. 40 K/K = 0.0119%

Appendix II

POSSIBLE NEW MINERAL

A possible new high pressure mineral has been found in a lherzolite nodule. It occurs as square white single crystals in the center of a spinel grain in a polished thin section (ANU 2304) which was provided by N.H. Gray who first noticed the mineral. The size of the largest grain is 0.1 mm. on a side with another grain which is within 1 mm. being slightly smaller. The mineral is uniaxial negative with the birefringence being in the upper greys. The photo below shows its appearance and an apparently good analysis is presented below. The mineral has the stoichiometery of no known mineral though melilite is the closest to it.



 \bigcirc

Possible New Mine	ral
si0 ₂	28,08
Ti0 ₂	0.16
A1203	25.95
FeO*	0.83
MgO	0.27
ĈaÛ	44.44
^{Cr2⁰3}	0.23
Total	99•96
* Total Fe as	Fe0

.

.

.

70

Appendix III ELECTRON MICROPROBE

All the mineral analyses presented in this thesis were done on an Acton MS-64 Electron Microprobe. The raw data was then reduced to oxide percents with a computer program written by J. Rucklidge and E.L. Gasparrini (1968) at the University of Toronto which was substantially modified for the Acton probe and IBM 360-75 computer. This was accomplished with the expert help of W.H. MacLean, M. Firth and W. Trzcienski.

The use of the microprobe resulted in rapid analyses of numerous minerals; however, the results were not always favourable and consequently at least forty percent of the data Standards used were analysed silicates obtained was discarded. both synthetic and natural specimens and it was found that any silicate could be used as long as it was relatively close to the unknown in the content of the analysed element. Difficulty was encountered for considerable time in the analysis of the spinels, which contain around 50 % Al₂O₃ . It seems that when alumina is so abundant it is necessary to be especially careful and use a standard that is very close in alumina content. In general the elements Al, Mg, and Si are especially sensitive in this regard while it was found that for Mn and Cr pure metal standards could be used satisfactorily.

Appendix IV

PETROLOGY COLLECTION CATALOGUE

Locality Ile Bizard Kimberlite, P.Q.

Collected Rv Michael Marchand

Collector's No.	Location	Description	McGill No.		
	Ile Bizard	kimberlite	P 8670		
	11	micaceous kimberlite	P 8671		
	11	fine grained dyke	P 8672		
	17	kimberlite	P 8673		
	11	rt	P 8674		
	18	11	P 8675		
	17	÷t	P 8676		
	19	dunite - harzburgite nodule	P 8677		
	• • • • • • • • • • • • • • • • • • •	· · ·			
1					
		······································			
· · · · ·					

PETROLOGY COLLECTION CATALOGUE

Locality Ile Bizard Kimberlite, P.Q.

•

Collected By Michael Marchand

Collector's No.	Location	Description	McGill No.		
WR-7	Ile Bizard	Fresh kimberlite- Analysis 5	P 9296		
37	11	Amphibole-bearing nodule	P 9297		
49	11	Clinopyroxene megacryst	P. 9298		
4	11	Websterite	P 9299		
5	tt	Websterite (no hand spec.)	P 9300		
26	tt	Websterite	P 9301		
53	t)	Websterite	P 9302		
1	10	Lherzolite (garnet-spinel)	P 9303		
2	11	Lherzolite (no thin section)	P 9304		
13	11	Lherzolite	P 9305		
23	11	Lherzolite	P 9306		
29	ti	Lherzolite	P 9307		
52	Ħ	Lherzolite	P 9308		
47		Phlogopite-garnet-pyroxene	P 9309		
	note: Sample 2304 (ANU	2304) is in the petrology collection			
	at The Australian National University, Canberra, Aust.				
	· · · · · · · · · · · · · · · · · · ·				
		······································			
9					
	·				
		3	<u> </u>		

. •

.....