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## EXPERIMENTAL DUPLICATION OF CONDITIONS OF PRECIPITATION OF HIGH-PRESSURE PHENOCRYSTS IN A BASALTIC MAGMA

D. H. GREEN and W. HIBBERSON

*Department of Geophysics and Geochemistry, Australian National University, Canberra*

An olivine basalt from the Auckland Islands contains partially resorbed "xenocrysts" of orthopyroxene, clinopyroxene and minor olivine. Electron probe microanalyses of these crystals confirm their similarity to near-liquidus crystals obtained experimentally in tholeiitic and alkali olivine basalts at high pressures. A high pressure experimental study of the host olivine basalt demonstrates that orthopyroxene and clinopyroxene are near-liquidus phases at 11-18 kb but the degree of solid solution between the pyroxenes crystallized from the dry magma is much greater than that observed in the natural pyroxenes. Addition of water to the experimental runs results in lowering of the liquidus of the basalt and in the appearance of orthopyroxene, clinopyroxene and olivine as near-liquidus phases at 13-18 kb, 1130-1230 °C. A close correspondence between chemical compositions of the natural "xenocrysts" and the experimental near-liquidus pyroxenes and olivine is obtained and the conditions of the precipitation of the "xenocrysts" from their host magma are inferred to be near 14-16 kb and 1200 °C. The host magma contained ~2% H<sub>2</sub>O at these conditions to produce the requisite depression of the liquidus. The "xenocrysts" are regarded as high pressure phenocrysts giving natural evidence of high pressure magmatic fractionation controlled largely by separation of orthopyroxene.

### 1. Introduction

Recent experimental studies on the melting behaviour of natural basalts at high pressures have led to the formulation of hypotheses of magma generation and fractionation at depths in the mantle. To test such hypotheses we require evidence from the natural basalts themselves on their pre-eruption history. Many basalts have suffered low pressure fractionation to various degrees, so that their chemical compositions bear little relation to the compositions of liquids originally existing at depth. This is particularly true of tholeiitic basalts. However, among the undersaturated basalts, some alkali olivine basalts, olivine basanites, olivine nephelinites etc. contain high density lherzolite and pyroxenite xenoliths of high pressure mineralogy. These liquids have clearly not fractionated by crystal settling at shallow depths (less than those from which the xenoliths were acquired) and their rapid movement to the surface provides minimal opportunity for contamination by digestion of crustal material. Many of these lherzolite-bearing magmas also contain large single crystals ("xenocrysts") including clinopyroxene, olivine, orthopyroxene, spinel and amphibole. These "xeno-

crysts" (with the exception of olivine) were out of equilibrium with the magma during the final stages of crystallization and show evidence of resorption and reaction. It is a reasonable hypothesis that these crystals are the liquidus or near-liquidus phases of their host magma at depths greater than or similar to those at which the magmas picked up the lherzolite xenoliths. This hypothesis can be experimentally tested for any given magma and "xenocryst" assemblage and if it can be demonstrated that there are unique P, T conditions at which the host magma has liquidus or near-liquidus phases which match the observed xenocrysts in mineralogy and chemical composition, then these P, T conditions may be those at which the magma batch was held, however briefly, allowing some crystallization before final rapid movement to the surface. Although this characterization of P, T environment for the "magma-xenocryst" assemblage does not identify the initial source-region of the magma batch, it does demonstrate a compositional point and a fractionation trend and process which was operating at depth in the particular magma batch. In this way evidence from the natural rocks can be used to evaluate and test rival hypotheses of magma generation and fractionation within the mantle.

An olivine basalt from Mt. Eden plug, Auckland Id., Southern Ocean, was collected and examined by Dr. J. B. Wright\* and the presence of both orthopyroxene and clinopyroxene as large, vitreous, corroded crystals was noted. The basalt also contains lherzolite inclusions with the typical olivine, enstatite, clinopyroxene and pale brown spinel assemblage but the "xenocrysts" contrast in size and colour with crystal fragments detached from these xenoliths.

## 2. Chemical compositions of xenocrysts and host magmas

Several features of the chemical and normative composition (table 1) of the host magma are worthy of comment. The norm contains a small amount of hypersthene but falls within the alkali basalt field using the

TABLE 1

Chemical composition of olivine basalt, Mt. Eden plug, Auckland Id. Otago University No. 19594, A.N.U. No. 2900. Analyst E. Kiss, A.N.U.

SiO <sub>2</sub>	46.55	
TiO <sub>2</sub>	3.18	CIPW Norm
Al <sub>2</sub> O <sub>3</sub>	12.70	Or 5.6
Fe <sub>2</sub> O <sub>3</sub>	2.98	Ab 24.8
FeO	9.72	An 18.9
MnO	0.17	Di 17.7
MgO	10.63	Hy 2.7
CaO	8.66	Ol 18.8
Na <sub>2</sub> O	2.95	Ap 1.3
K <sub>2</sub> O	0.95	Ilm 6.1
P <sub>2</sub> O <sub>5</sub>	0.60	Mt 4.4
H <sub>2</sub> O <sup>+</sup>	0.67	
CO <sub>2</sub>	0.24	Normative feldspar
Cr <sub>2</sub> O <sub>3</sub>	0.06	Or <sub>11</sub> Ab <sub>51.5</sub> An <sub>37.5</sub>
NiO	0.04	D.I. = 30.4
CoO	0.01	
	100.11	
<hr/>		
$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$ (atomic ratio)	= 66.2	

criteria of POLDERVAART (1964). Petrographically it is an alkali olivine basalt in that olivine occurs as both phenocrysts and crystallites, co-precipitating with the clinopyroxene and with no evidence of a reaction relationship with the liquid. The composition also lies within the Hawaiian alkali olivine basalt field on an Na<sub>2</sub>O+K<sub>2</sub>O vs SiO<sub>2</sub> diagram. The basalt is an example illustrating the continuity of composition between the nepheline-normative alkali olivine basalts and hy-

\* Ahmadu Bello University, Zaria, Nigeria.

persthene normative olivine tholeiites (YODER and TILLEY, 1962 p. 353). It lies close to the "plane of critical undersaturation" of the latter authors.

The normative plagioclase composition is andesine (Ab<sub>58</sub>An<sub>42</sub>) and is more typical of hawaiite composition than alkali olivine basalt if a comparison is made with Hawaiian lavas (MACDONALD and KATSURA, 1964). However the low SiO<sub>2</sub> content and high Mg/(Mg+Fe<sup>++</sup>) ratio of the basalt is typical of alkali olivine basalts and alkali picrites. Except for normative feldspar composition, the host basalt falls close to the alkali olivine basalt point in all the criteria used by TILLEY and MUIR (1964) in their characterization of members of the alkali olivine basalt to trachyte magma series. The term "olivine basalt" is used in this paper for the magma but affinities to alkali olivine basalts are recognized. The points of similarity to some hawaiites are noted and may be linked to data (unpublished) showing that some hawaiites are magmas formed within the deep crust or mantle ( $P \geq 8$  kb) and that not all hawaiites can be regarded as products of alkali olivine basalt fractionation in shallow magma chambers.\*

The compositions of the large phenocrysts present in the magma have been determined using the electron probe microanalyzer and empirical calibration curves based on analyzed minerals and synthetic glasses (cf. GREEN and RINGWOOD, 1967a). Analyses of several crystals and of different areas within one crystal demonstrated small but real variations in composition - the most magnesian and most iron rich compositions obtained for both pyroxenes are listed in table 2. The orthopyroxene and clinopyroxene (table 2) have a high degree of mutual solid solution (i.e. high CaO in orthopyroxene, low CaO in clinopyroxene). They differ in this respect from the co-existing pyroxenes of lherzolite inclusions in basalts (ROSS, FOSTER and MYERS, 1954) and are also more iron-rich than the lherzolite assemblages (olivines, enstatites and clinopyroxenes with  $100 \text{ Mg}/(\text{Mg} + \text{Fe}^{++}) = 92-89$ ).

The contrast between the clinopyroxene "xenocryst" compositions and the composition of the recrystallised outermost rim, presumed to be in equilibrium with the basalt magma during crystallization at or near the surface, is clearly shown in table 2. The recrystallized rim is markedly different in TiO<sub>2</sub> content, CaO content and hypersthene solid solution, and shows smaller differences in Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> contents.

Chemical  
olivine x

SiO<sub>2</sub>  
TiO<sub>2</sub>  
Al<sub>2</sub>O<sub>3</sub>  
Fe<sub>2</sub>O<sub>3</sub>  
FeO  
MgO  
CaO  
Na<sub>2</sub>O

Molecular  
ratios

100 Mg  
Mg+Fe<sup>++</sup>

Partial a  
a) Olivine  
(Ca<sub>4</sub>N

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2. Zone  
basalt

b) Olivine  
edge

1. Cent  
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TABLE 2

Chemical compositions of orthopyroxene, clinopyroxene and olivine xenocrysts in olivine basalt. Analyses by electron probe microanalyzer

	Orthopyroxene		Clinopyroxene		Recrystallized rim	
SiO <sub>2</sub>	56.0	56.0	54.6*	52.9*	50.5	
TiO <sub>2</sub>	0.2	0.3	0.45	0.65	2.2	
Al <sub>2</sub> O <sub>3</sub>	3.0	3.6	3.4	4.3	2.8	
Fe <sub>2</sub> O <sub>3</sub>	—	—	—	—	1.3*	
FeO	8.1	8.6	5.9	6.5	6.7	
MgO	31.6	31.0	20.7	19.1	14.2	
CaO	2.1	2.1	16.0	15.6	21.9	
Na <sub>2</sub> O	<0.1	<0.1	0.7	0.7	0.5	
	101.1	101.7	101.7	99.7	100.1	
Molecular ratios	Ca	4	4	32	33	46
	Mg	84	83	59	56	41
	Fe	12	13	9	11	13
$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$	87.4	86.5	86.2	84.0	79.1	
Partial analyses of olivines						
a) Olivine partially enclosed by orthopyroxene xenocryst (Ca <sub>4</sub> Mg <sub>84</sub> Fe <sub>12</sub> )						
	FeO	CaO	Al <sub>2</sub> O <sub>3</sub>	$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$		
1. Part against orthopyroxene	12.8	0.1	0.1	86.9		
2. Zoned edge against basalt	28.9	0.3	0.6	67.2		
b) Olivine phenocryst - continuously zoned, strongly zoned on edge						
1. Centre	18.8	—	—	80.0		
2. Outer edge	29.6	—	—	66.5		

\* Values calculated from other elements assuming normal pyroxene molecules in solid solution.

A single olivine grain was observed to be partially enclosed by an orthopyroxene "xenocryst" and has closely similar Mg/Mg+Fe<sup>++</sup> value to the orthopyroxene (table 2). The crystal is not significantly zoned except at the margin contacting the basalt where a sharp compositional gradient leads to more iron-rich olivine with a minimum Mg/(Mg+Fe<sup>++</sup>) value of 67.2. An euhedral olivine phenocryst has a core composition of Fo<sub>80</sub> with very sharp marginal zoning to at least Fo<sub>66.5</sub> at the outer edge.

### 3. Experimental study of the crystallization behaviour of the olivine basalt

*Anhydrous conditions:* The experimental methods used have been described previously (GREEN and RING-

WOOD, 1967a, 113-117). The starting material for the runs was a glass prepared from the analysed basalt and rechecked after fusion for FeO and Fe<sub>2</sub>O<sub>3</sub> content. The effect of Fe-loss to the platinum capsule, previously shown to be of minor importance (op. cit. p. 115-117) and not significantly affecting the sample mineralogy, has been further minimised by shorter run times. As a further confirmatory measure, some runs were carried out in graphite capsules demonstrating the same sequence of appearance of phases at 13.5 kb. Runs in both platinum and graphite at 13.5 kb and at 1330 °C and 1320 °C all yielded orthopyroxene+clinopyroxene+liquid. The similarity of degree of crystallization and of the 100 Mg/(Mg+Fe<sup>++</sup>) values (83.0) of the clinopyroxenes in both 1330 °C and 1320 °C runs in graphite suggests that there is no actual difference in degree of crystallization between these runs. The more magnesian compositions of the pyroxenes from the run in platinum at 1330 °C may be due to this run being nearer the liquidus or to some iron loss. The latter effect may also have caused the appearance of orthopyroxene (100 Mg/(Mg+Fe<sup>++</sup>) = 86.4) alone in the one hour run at 1325 °C. Microdetermination of FeO (10.3%) and Fe<sub>2</sub>O<sub>3</sub> (0.97%) in the 30 min. run at 13.5 kb 1320 °C in platinum confirms the relatively small change in chemical and normative composition produced by iron loss within the run times used. Microprobe methods and the accuracy of analyses are as previously described (GREEN and RINGWOOD, 1967a).

The crystallization behaviour of the Auckland Island olivine basalt is almost identical to that of the olivine basalt studied by GREEN and RINGWOOD (1967a). Comparison of the compositions shows higher normative olivine and Al<sub>2</sub>O<sub>3</sub> in the previous composition but otherwise very similar chemical and normative compositions. Details of experimental runs are given in table 3. Olivine is the liquidus phase at 9 kb and is joined by clinopyroxene as the second phase. At 13.5 kb orthopyroxene and clinopyroxene occur together near the liquidus. Orthopyroxene is the major phase, or possibly the only phase on the liquidus, but at lower temperatures, clinopyroxene is more abundant. At 18 kb clinopyroxene appears to be the liquidus phase and orthopyroxene probably appears over a very restricted lower temperature interval. In comparison with the previous data on olivine basalt (GREEN and RINGWOOD, 1967) the present composition has a slightly more re-

TABLE 3  
Experimental crystallization of Auckland Island olivine basalt at various pressures and temperatures

Pressure (kb)	Temperature (°C)	Time (mins)	Sample capsule	Results
<i>A. Dry conditions</i>				
9.0	1280	30	Pt	Olivine+glass. Very near liquidus
9.0	1260	30	Pt	Olivine+clinopyroxene+glass
11.3	1320	30	Pt	Above liquidus
11.3	1310	30	Pt	Clinopyroxene+rare orthopyroxene+minor olivine. Clinopyroxene with rare parallel growth of orthopyroxene
13.5	1350	30	Pt	Above liquidus
13.5	1330	30	Pt	Uncommon orthopyroxene and clinopyroxene+glass. Very near liquidus
13.5	1330	60	Graphite	Clinopyroxene+orthopyroxene+glass Clinopyroxene > orthopyroxene
13.5	1325	60	Pt	Orthopyroxene+glass
13.5	1320	30	Pt	Clinopyroxene+rare orthopyroxene+glass Cpx ≫ Opx
13.5	1320	60	Graphite	Clinopyroxene+orthopyroxene+glass Cpx > Opx
13.5	1300	30	Pt	Clinopyroxene+minor orthopyroxene+glass (~30% crystallization)
18.0	1380	60	Graphite	Above liquidus
18.0	1370	60	Graphite	Clinopyroxene+glass. Cpx may be quench
18.0	1360	60	Graphite	Clinopyroxene+possible rare orthopyroxene+glass
<i>B. "Wet" conditions</i>				
13.5	1200	30	Pt	Olivine+glass. Very near liquidus
13.5	1190	30	Pt	Olivine+orthopyroxene+glass. Opx > ol
13.5	1180	30	Pt	Olivine+orthopyroxene+glass. Opx ≫ ol
13.5	1160	30	Pt	Olivine+orthopyroxene+clinopyroxene+glass. Opx > Cpx. Minor olivine. Possible amphibole
13.5	1150	30	Pt	Olivine+orthopyroxene+clinopyroxene+glass
13.5	1130	30	Pt	Olivine+orthopyroxene+amphibole+glass. Clinopyroxene not certain
18.0	1260	30	Pt	Orthopyroxene+glass. Very near liquidus
18.0	1240	30	Pt	Orthopyroxene+clinopyroxene+glass. Opx > Cpx
18.0	1200	30	Pt	Orthopyroxene+clinopyroxene+glass. Orthopyroxene and clinopyroxene intergrowths well developed Opx ≈ Cpx
<i>C. Controlled Water Contents</i>				
15.3	1200	20	Pt	With 3% H <sub>2</sub> O. Above liquidus
14.4	1200	30	Pt	With 2% H <sub>2</sub> O. Above liquidus
14.4	1170	30	Pt	With 2% H <sub>2</sub> O. Orthopyroxene+clinopyroxene+rare olivine. Opx common
15.3	1200	20	Pt	With 2% H <sub>2</sub> O. Rare large orthopyroxene, no definite olivine.
15.3	1170	30	Pt	With 2% H <sub>2</sub> O. Common orthopyroxene and possible rare olivine

stricted field of orthopyroxene crystallization. The analytical data on the pyroxene compositions (table 4) demonstrate a very high degree of hypersthene solid solution in the clinopyroxene and somewhat lower Al<sub>2</sub>O<sub>3</sub> contents in both pyroxenes than those observed in the previous olivine basalt. The clinopyroxenes have compositions suggestive of very magnesian pigeonites but comparison with the sub-calcic (9-10% CaO) clinopyroxenes previously obtained experimentally does not provide any evidence as yet for a compositional break

between augites, sub-calcic augites and compositions near to pigeonite. The coexistence of orthopyroxenes with slightly varying CaO content with this range of clinopyroxene compositions suggests that we are dealing with the "roof" of the two-pyroxene miscibility gap, the orthopyroxene side being "steep" (i.e. CaO content varies only slightly with temperature and with Mg/(Mg+Fe<sup>++</sup>) ratio) while the clinopyroxene side in contrast is "shallow" and the hypersthene solid solution rapidly increases for small increases in temperature

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TABLE 4

Compositions of phases crystallized from the olivine basalt under dry conditions in sealed platinum capsules or in graphite capsules with "dry" (talc+boron nitride) furnace assemblies

Pressure (kb)	11.3	13.5	13.5				
Temperature (°C)	1310	1330	1320				
Sample capsule	Platinum	Platinum	Graphite				
Time	30 mins	30 mins	60 mins				
Phases present Analyzed phase	Ol+Cpx+Glass		Opx+Cpx+Glass		Opx+Cpx+Glass		
	Olivine	Clino- pyroxene	Ortho- pyroxene	Clino- pyroxene	Ortho- pyroxene	Clino- pyroxene	
SiO <sub>2</sub>	40.0*	53.5*	55.0*	54.4*	54.0*	53.0*	
TiO <sub>2</sub>	—	(0.6) <sup>+</sup>	0.4	0.5	0.4	0.7	
Al <sub>2</sub> O <sub>3</sub>	<0.2	3.9	4.1	3.8	4.0	4.0	
Fe <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	—	
FeO	14.2	9.4	8.4	8.1	10.3	9.9	
MgO	45.5*	27.2*	29.9*	27.9*	28.9*	27.0*	
CaO	0.3	5.3	2.2	5.1	2.4	5.2	
Na <sub>2</sub> O	—	(0.2) <sup>+</sup>	<0.05	0.2	<0.05	0.25	
Molecular proportions	{Ca	0.4	10.5	4.5	10.0	4.5	10.5
	{Mg	84.8	75.0	82.5	77.5	79.7	74.5
	{Fe	14.8	14.5	13.0	12.5	15.8	15.0
100 Mg Mg+Fe <sup>++</sup>	85.1	83.6	86.3	86.0	83.3	83.0	

\* Calculated value.

<sup>+</sup> Value assumed from analyses of similar clinopyroxenes.

or decreases in Mg/(Mg+Fe<sup>++</sup>) ratio. A similar effect is evident in the simple system diopside-enstatite (DAVIS and BOYD, 1966) and is reported for the system hedenbergite-ferrosilite at 20 kb by LINDSLEY (this volume).

"Wet" Conditions: Apparatus for sealing of water in the small high pressure capsules was not available when the majority of the experiments were carried out so that the techniques of running with an unknown but fairly reproducible water contents were followed (BULTITUDE and GREEN, 1968). Approximately 1 mgm (~5%) of water was added to the sample and the platinum capsule crimped but not welded. The high pressure furnace assembly used a simple talc cylinder (see GREEN and RINGWOOD, 1967b fig. 1) in which dehydration of the talc and use of open (non-welded) platinum capsules had previously (GREEN and RINGWOOD, 1964) produced a depression of the liquidus of an olivine tholeiite composition by approximately 100 °C. Use of these techniques produced a depression of the liquidus of the olivine basalt of about 130 °C at 13.5 kb and 100 °C at

18 kb. It might be anticipated that runs with this technique would yield rather random points between liquidus and solidus but in fact the careful repetition of the same run procedure produced a series of runs at 13.5 kb and 18 kb in which the order of decreasing temperature is also the order of increasing degree of crystallization as illustrated by the regular sequence of appearance of phases, and the regular decrease of the ratio 100 Mg/(Mg+Fe<sup>++</sup>) in the phases. These data suggest that the technique produces similar but unknown activity of water in the experimental runs. Several later experiments carried out with sealed Pt capsules and known water contents yielded crystallization products consistent with the previous work and showing that the observed depression of the liquidus required water contents of 2-3% (table 3). The earlier technique of running with appreciable but unknown water activity has been criticized by O'HARA (1968) and KUSHIRO (1968) but the data obtained on this particular composition give no grounds for suspecting change of sample composition by transport of components in an aqueous phase either moving into or out of the sample capsule.

TABLE 5

Compositions of analyzed crystals obtained in crystallization of olivine basalt at 13.5 kb and 18 kb under "wet" conditions i.e. lowering of liquidus by  $\sim 120^\circ\text{C}$  by the addition of water.

Phase	Temperature ( $^\circ\text{C}$ )	100 Mg Mg+Fe <sup>++</sup> (atomic ratio)	Molecular proportions			Weight per cent	
			Ca	Mg	Fe	Al <sub>2</sub> O <sub>3</sub>	CaO
<b>A. At 13.5 kb</b>							
Olivine	1200	86.9	0.2	86.7	13.1	<0.2	0.2
Olivine	1190	86.9	0.2	86.7	13.1	<0.2	0.2
Orthopyroxene		90.0	3.4	87.1	9.6	1.7	1.8
Olivine	1180	84.8	0.2	84.6	15.2	<0.2	0.2
Orthopyroxene		88.1	3.6	85.2	11.3	1.7	1.9
Olivine	1160	81.4	0.2	81.2	18.6	<0.2	0.2
Orthopyroxene		84.3	4.0	81.2	14.8	4.4	2.0
Clinopyroxene		no consistent analyses					
Olivine	1150	80.0	0.3	79.8	19.9	<0.2	0.3
Orthopyroxene		83.3	4.0	80.0	16.0	4.3	2.0
Clinopyroxene		83.3	32.0	56.6	11.3	6.1	$\geq 15.2$
Olivine	1130	81.0	0.2	80.8	19.0	<0.2	0.2
Orthopyroxene		82.8	4.0	79.5	16.5	4.5	2.0
Amphibole		not analyzable					
<b>B. At 18 kb</b>							
Orthopyroxene	1260	89.3	3.8	85.9	10.3	2.4	2.0
Orthopyroxene	1240	86.1	3.9	82.8	13.3	2.5	2.0
Clinopyroxene		83.5	30.4	58.0	11.6	5.5	$\geq 14.0$
Orthopyroxene	1200	85.6	3.9	82.3	13.8	3.1	2.0
Clinopyroxene		83.2	35.5	53.4	11.1	5.9	16.2
<i>Coexisting orthopyroxene and clinopyroxene</i>							
		13.5 kb 1150 $^\circ\text{C}$		18 kb 1240 $^\circ\text{C}$		18 kb 1200 $^\circ\text{C}$	
		Opx	Cpx	Opx	Cpx	Opx	Cpx
SiO <sub>2</sub>		51.1*	51.7*	55.3*	52.8*	54.9*	52.3*
TiO <sub>2</sub>		—	0.6	0.4	0.7	0.4	0.7
Al <sub>2</sub> O <sub>3</sub>		4.5	6.1	2.5	5.5	3.1	5.9
FeO		10.4	6.9	8.8	6.8	9.1	6.4
MgO		29.4*	19.3*	30.9*	19.2*	30.5*	17.5*
CaO		2.0	$\geq 15.2$	2.0	$\geq 14.0$	2.0	16.2
Na <sub>2</sub> O		—	0.3	—	1.0	—	1.0

\* Calculated values.

The depression of the liquidus of the olivine basalt to 1200  $^\circ\text{C}$  at 13.5 kb resulted in appearance of olivine as the liquidus phase, closely followed by orthopyroxene and joined by clinopyroxene as the third phase. At 1130  $^\circ\text{C}$ , amphibole may replace clinopyroxene as the latter was not definitely identified. It may also be noted that the olivine coexisting with amphibole at 1130  $^\circ\text{C}$  is more magnesian than that at higher temperature. Olivine is present throughout the crystallization interval studied but remains a minor phase and does not per-

ceptibly increase in abundance, in contrast with the large increase in abundance of the orthopyroxene and clinopyroxene. The orthopyroxene analyses (table 5) show CaO contents consistently lower than those obtained from orthopyroxenes at 1320–1330  $^\circ\text{C}$ . Al<sub>2</sub>O<sub>3</sub> contents in the higher temperature orthopyroxenes are low but increase in the 1160–1130  $^\circ\text{C}$  runs. The clinopyroxene analyzed at 1150  $^\circ\text{C}$  has higher Al<sub>2</sub>O<sub>3</sub> content than coexisting orthopyroxene and, most significantly, has a very much higher CaO content than the

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clinopyroxenes analyzed from 1320 °C and 1330 °C runs.

The experimental runs at 18 kb yielded orthopyroxene as the liquidus phase, joined by clinopyroxene at lower temperatures. Orthopyroxene is slightly more magnesian than coexisting clinopyroxene and has lower Al<sub>2</sub>O<sub>3</sub> content (cf. GREEN and RINGWOOD, 1967a). The clinopyroxene compositions have CaO contents of 14–16%. The most reliable clinopyroxene analyses obtained from the runs were those at 18 kb, 1200 °C; in most runs the crystals were smaller than orthopyroxene and with quench outgrowths and were analyzed with difficulty. The Na<sub>2</sub>O contents of the clinopyroxenes in equilibrium with the olivine basalt liquid increase with increasing pressure – thus in both the dry and “wet” runs at 13.5 kb, the clinopyroxenes contained 0.2–0.3% Na<sub>2</sub>O with apparently slightly lower contents in the higher temperature clinopyroxenes. At 18 kb however the clinopyroxenes contain 1.0% Na<sub>2</sub>O, probably in jadeite solid solution.

A puzzling feature of the compositions listed in table 5 is that olivine has a consistently lower 100 Mg/(Mg+Fe<sup>++</sup>) ratio than co-existing orthopyroxene in the “wet” runs. This differs from the pattern previously obtained at 9 kb, 1290–1250 °C (GREEN and RINGWOOD 1967a) where olivine has essentially the same 100 Mg/(Mg+Fe<sup>++</sup>) ratio as co-existing orthopyroxene. Except for the 13.5 kb, 1150 °C run, co-existing pyroxene pairs have clinopyroxene with lower 100 Mg/(Mg+Fe<sup>++</sup>) ratio than coexisting orthopyroxene. The differences are very small at 13.5 kb, 1320–1330 °C i.e. where the compositional differences between the two pyroxenes are relatively small, but are larger in the 18 kb, 1240–1200 °C runs. The partition coefficients for Fe and Mg between pyroxene pairs in natural rocks are such that the clinopyroxene is relatively enriched in magnesium although for magnesian igneous pyroxene pairs the coefficients approach unity. The apparent reversal of this trend in the experimental runs may in part be due to appreciable Fe<sup>+++</sup> contents (not determinable by microprobe analyses) in the clinopyroxenes or may be a real feature of the high temperature of equilibration of these assemblages.

*Comparison of natural xenocryst compositions with experimentally crystallized phases:* The experiments under dry conditions show that olivine, orthopyroxene and

clinopyroxene (the three natural xenocryst phases) occur together on the liquidus at 11.3 kb, 1310 °C; the two pyroxenes occur without olivine on the liquidus at 13.5 kb and olivine occurs on the liquidus at 9 kb. The analyzed synthetic phases are similar or slightly lower in 100 Mg/(Mg+Fe<sup>++</sup>) value than the natural xenocryst phases and it is probable that accurate matching of this parameter could be obtained at 11–12 kb and appropriate temperature (1310–1320 °C). However, the analyzed clinopyroxene at 11.3 kb and the pyroxene pairs at 13.5 kb are very different in composition from the natural pyroxenes, particularly in the extremely sub-calcic nature of the clinopyroxene and the slightly higher CaO content of the synthetic orthopyroxene.

Comparison of tables 2 and 5 shows that the natural pyroxene compositions are very closely matched by analyzed pyroxenes from “wet” runs at 13.5 kb and 18 kb. CaO contents in both pyroxenes, TiO<sub>2</sub> contents, 100 Mg/(Mg+Fe<sup>++</sup>) ratios and Na<sub>2</sub>O contents are closely matched. In detail the Na<sub>2</sub>O content of the natural clinopyroxenes (0.7%) is between the values for the 13.5 kb (0.3) and 18 kb (1.0) clinopyroxene; the CaO content of the natural orthopyroxene is slightly greater and the CaO content of the more Fe-rich natural clinopyroxene slightly lower than the 18 kb, 1200 °C pyroxene pair. These differences suggest that a pressure of 14–16 kb and a temperature slightly above 1200 °C would yield near-liquidus pyroxenes identical to the natural xenocrysts. It may be noted also that while olivine precedes orthopyroxene in the crystallization sequence at 13.5 kb, and is absent at 18 kb, it should occur together with orthopyroxene on the liquidus at about 15 kb. The natural pyroxenes encompass a small range in 100 Mg/(Mg+Fe<sup>++</sup>) ratio and thus represent crystal/liquid equilibria over a small range of P, T conditions such as might be anticipated in a cooling magma chamber or in a static or slow moving feeder dyke. The range of experimental conditions in the wet melting experiments appears to exceed the range required to produce the observed compositional variations.

#### 4. Conclusions

The experimental study of the crystallization of the Auckland Id. olivine basalt has shown that the olivine basalt can precipitate, as near-liquidus phases, crystals which closely match the observed partly resorbed “xe-

nococrysts" within the basalt. This matching of liquidus and xenocryst phases in chemical composition and in paragenesis can only be achieved experimentally over a very small P, T range. In particular, the possible temperature of precipitation is rather closely fixed by the observed degree of solid solution between co-existing pyroxenes and the load pressure at precipitation may be deduced from the relative roles of pyroxene or olivine as liquidus phases and by the Na<sub>2</sub>O content of the clinopyroxene. It is considered that the "xenocrysts" are not of accidental origin but are cognate, high-pressure phenocrysts precipitated from the host olivine basalt at depths of around 50–55 kms, (load pressure 14–16 kb) and a temperature close to 1200 °C. These conditions of precipitation require that the basalt liquidus was depressed about 130 °C below the dry liquidus – this is consistent with the presence of approximately 2% water within the magma at the depth of precipitation of the crystals.

The inferred high pressure phenocrysts have lower 100 Mg/(Mg+Fe<sup>++</sup>) values than that inferred for parental mantle material or those values present in lherzolite or garnet peridotite xenoliths (100 Mg/(Mg+Fe<sup>++</sup>) ~88–92). Thus the composition of the Auckland Id. olivine basalt is not considered to be that of a direct partial melt from mantle peridotite but rather to be a liquid produced from some more primitive parent magma by fractional crystallization at depths ≥ 50 km. While it is not possible to unequivocally deduce the nature of this parent magma, the Auckland Id. olivine basalt magma provides natural evidence of a process of fractional crystallization operating at about 50 km depth and "quenched" by the rapid eruption of both liquid and precipitating phases. This fractionation trend is dominated by pyroxene separation and in particular, by orthopyroxene. Although olivine accompanies the near-liquidus pyroxenes in the experiments, it is volumetrically a minor percentage of the precipitated material i.e. the precipitated material would be olivine-poor pyroxenite and not peridotite mineralogy. In chemical composition, the estimated crystal extract at

14–16 kb is very similar to that deduced for the olivine basalt and alkali olivine basalt by GREEN and RINGWOOD (1967a). The calculated fractionation trend at 14–16 kb, ~1200 °C, deduced for the Auckland Id. olivine basalt predicts more hypersthene-normative, tholeiitic compositions as parental to the observed host basalt and predicts nepheline-normative alkali olivine basalts as lower temperature derivative liquids from the host basalt. The data support and extend the conclusions of GREEN and RINGWOOD (1964, 1967a) on the dominant role of orthopyroxene and orthopyroxene+clinopyroxene crystallization at 13–18 kb in producing a spectrum of basaltic liquids from olivine tholeiite to basanite. It has been demonstrated that it is possible to characterize in a rather unequivocal manner, the P, T conditions and water content of some magmas within the upper mantle, prior to rapid extrusion.

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