tion relationships* between early precipitated phases and basaltic liquids. It may be noted that because of the complex solid solutions involved, reaction relationships may exist between early precipitated phases and basaltic liquids which are not matched by incongruent melting relationships in the simple, end-member system.

The previous discussion illustrates the constraints imposed by self-consistency arguments in the interdependent problems of upper mantle composition and basalt magma genesis. However, more positive evidence of mantle liquid composition is provided by selecting those basalts which contain xenoliths or "xenocrysts" demonstrably of high pressure origin, with density greater than that of the magma, and thus precluding the possibility of crystal fractionation of the host magma at depths less than those at which the xenolithic material was picked up. The paper by GREEN and HIBBERSON (1970) illustrates how very specific conditions of origin of some basalts can be deduced from their xenolith and xenocryst content. By selection of such basalts, it is possible to eliminate chemical variation due to low pressure fractionation and to establish a range or trend of chemical variation among basalts imposed by processes acting within the mantle (BULTITUDE and GREEN, 1968; GREEN, 1969). Basalts selected in this way are characteristically rich in olivine, have 100 Mg/(Mg + Fe^{++}) atomic ratios of 65–75 and range in normative composition from olivine basalt to olivine melilite nephelinite and kimberlite. As olivine tholeiite magmas do not contain lherzolite xenoliths, the choice of an olivine tholeiite as relevant for high pressure experimental study was made on the basis of the extensive studies of the 1959 Kilauea Iki eruption. The composition chosen for experimental study (GREEN and RINGWOOD, 1967a) was close to MACDONALD and KATSURA's (1961) estimate of a "parental magma" composition of the Kilauea Iki lava lake. It was considered to be a possible magmatic liquid composition at depths of 40–60 km. The reasons for the selection of other compositions listed in table 1 have been published previously. Compositions 6 and 9 are lherzolite-bearing

natural basalts on which the detailed high pressure crystallization experiments have not as yet been reported.

3. Crystal fractionation at high pressures in anhydrous magmas – experimental data and implications

The experimental crystallization of the compositions in table 1 shows that the nature of the liquidus phases changes with pressure, olivine giving way with increasing pressure to orthopyroxene and/or clinopyroxene and then to garnet or garnet + clinopyroxene. The compositions of liquidus and near-liquidus phases were determined by electron probe analysis. With these data and with estimates of the degree of crystallization, the directions of fractionation of the basaltic liquids have been calculated for various depths in the crust and mantle.
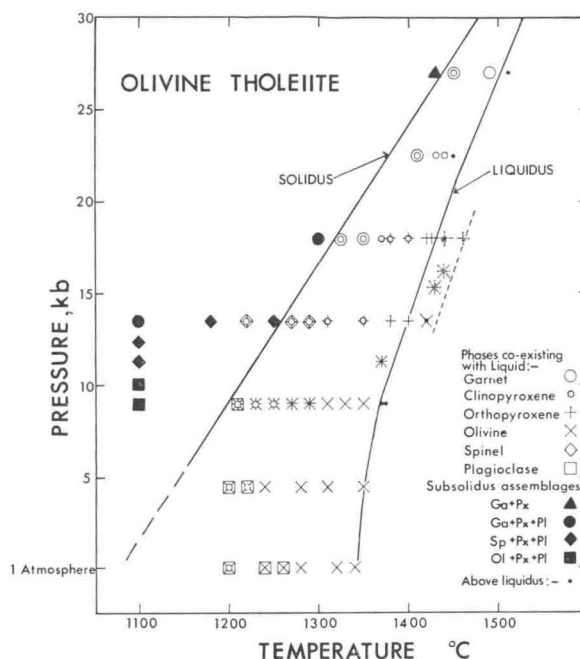

Fig. 1. Experimental crystallization of olivine tholeiite (table 1) at various pressures (GREEN and RINGWOOD, 1967a). The data for the olivine-enriched tholeiite (table 2) are shown as dotted symbols and the approximate liquidus shown by a dashed line. This composition is that of the olivine tholeiite to which has been added 5% olivine (Fo$_{20}$).

The experimental data published for the olivine tholeiite composition are reproduced in fig. 1 (GREEN and RINGWOOD, 1967a, fig. 4). Olivine is the liquidus phase at low pressure (< 10 kb), olivine and orthopyroxene

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* Such reaction relationships include

Olivine + liquid$_A$ → clinopyroxene$_{ss}$ + liquid$_B$

Orthopyroxene + liquid$_A$ $\begin{cases} → \text{clinopyroxene}_{ss} + \text{liquid}_B \\ \text{or} \\ → \text{clinopyroxene}_{ss} + \text{garnet} + \text{liquid}_C \end{cases}$

TABLE 1

Compositions of basaltic glasses used for experimental studies of crystallization at high pressures

	1 Olivine Tholeiite (GREEN and RINGWOOD, 1967a)	2 Olivine Basalt	3 Picrite	4 Auckland Id. Olivine Basalt (GREEN and HIBBERSON, 1970)	5 Alkali Basalt (GREEN and RINGWOOD, 1967a)	6 Olivine-rich basanite (Mt. Leura, Victoria) (GREEN, unpublished)	7 Olivine nephelinite (BULTITUDE and GREEN, 1968)	8 Picritic nephelinite	9 Olivine nephelinite (Scottsdale, Tasmania) (GREEN, unpublished)	10 Pyrolite (RINGWOOD, 1966)	
SiO_2	46.95	47.05	45.51	46.55	45.39	44.63	44.3	43.7	39.31	45.16	SiO_2
TiO_2	2.02	2.31	1.93	3.18	2.52	2.92	1.5	1.3	3.87	0.71	TiO_2
Al_2O_3	13.10	14.17	12.44	12.70	14.69	11.67	14.2	12.3	9.45	3.54	Al_2O_3
Fe_2O_3	1.02	0.42	0.92	2.98	1.87	2.95	0.5	1.1	5.07	0.46	Fe_2O_3
FeO	10.07	10.64	8.67	9.72	12.42	9.39	9.7	10.8	10.69	8.04	FeO
MnO	0.15	0.16	0.15	0.17	0.18	0.15	0.2	0.2	0.20	0.14	MnO
MgO	14.55	12.73	18.79	10.63	10.37	13.85	13.3	17.0	13.90	37.47	MgO
CaO	10.16	9.87	9.67	8.66	9.14	7.68	11.2	9.7	11.20	3.08	CaO
Na_2O	1.73	2.21	1.64	2.95	2.62	3.65	3.6	2.7	2.98	0.57	Na_2O
K_2O	0.08	0.44	0.08	0.95	0.78	2.00	1.0	0.8	1.53	0.13	K_2O
P_2O_5	0.21	—	0.20	0.60	0.02	1.03	0.5	0.4	2.30	0.06	P_2O_5
Cr_2O_3										0.43	Cr_2O_3
$\dfrac{100\ Mg}{Mg+Fe^{++}}$	72.0	68.1	79.4	66.2	59.8	72.5	71.0	73.8	70.0	90.0	$\dfrac{100\ Mg}{Mg+Fe^{++}}$

CIPW Norms

Lc	—	—	—	—	—	—	—	—	0.3	—	Lc
Or	0.6	2.7	0.5	5.6	4.5	11.7	6.1	4.5	8.3	1.1	Or
Ab	14.7	18.9	13.9	24.8	18.0	12.0	2.0	3.4	—	4.7	Ab
Ne	—	—	—	—	2.2	10.2	15.3	10.6	13.4	—	Ne
An	27.6	27.3	26.3	18.9	26.2	9.8	19.4	19.2	8.4	6.6	An
Di	17.0	17.6	16.5	17.7	15.7	18.7	26.4	21.7	29.1	6.7	Di
Hy	12.3	1.3	2.8	2.7	—	—	—	—	—	15.4	Hy
Ol	21.9	27.2	34.6	18.8	25.8	25.8	25.9	35.7	22.3	62.7	Ol
Ilm	3.8	4.4	3.7	6.1	4.8	5.6	2.9	2.4	6.4	1.4	Ilm
Mt	1.4	0.6	1.3	4.4	2.9	4.3	0.7	1.6	7.4	0.6	Mt
Ap	0.5	—	0.4	1.3	—	2.0	1.3	1.0	4.5	0.1	Ap
										0.7	Chr