

281

GREE-DH 70-1321

A REVIEW OF EXPERIMENTAL EVIDENCE ON THE  
ORIGIN OF BASALTIC AND NEPHELINITIC MAGMAS

D. H. GREEN

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

*Reprint from: PHYS. EARTH PLANET. INTERIORS*



NORTH-HOLLAND PUBLISHING COMPANY - AMSTERDAM

## A REVIEW OF EXPERIMENTAL EVIDENCE ON THE ORIGIN OF BASALTIC AND NEPHELINITIC MAGMAS

D. H. GREEN

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

Geological and petrological arguments are used to select those basaltic compositions which have been directly derived from the upper mantle with minimum opportunity for crystal fractionation or for contamination within the crust. The experimental study of the crystallization of these magmas at high pressures, under both anhydrous and hydrous conditions provides evidence of genetic links between magma types. These studies also provide data necessary to evaluate a major constraint on "primary" magmas, i.e. that magmas derived by direct partial melting of the upper mantle must have olivine and enstatite among their liquidus phases at the P, T conditions of magma segregation. The characteristic magma derived from either direct partial melting (~20–25%) of pyrolite or fractional crystallization of olivine-rich tholeiite at depths of 15–35 km is high alumina olivine tho-

leite. At 35–70 km partial melting of anhydrous pyrolite or fractional crystallization of olivine-rich tholeiite or tholeiitic picrite produces a series of liquids from olivine-rich tholeiite through olivine basalt and alkali olivine basalt to basanite (~25% Ol, ~5% Ne). With availability of water in the pyrolite source or during crystal fractionation, the pyrolite solidus is depressed. This produces changes in the subsolidus mineralogy and in the nature of liquids formed by low degrees of partial melting or by extensive crystal fractionation of less undersaturated magmas. Olivine nephelinites and basanites may be generated by small degrees of melting of water-bearing (0.1–0.2% H<sub>2</sub>O) pyrolite at ~50–70 km and olivine melilite nephelinites, olivine-rich nephelinites and olivine-rich basanites form in a similar way, as hydrous magmas at 70–100 km depth.

### 1. Introduction

The processes of generation of basaltic magmas within the earth's mantle involve crystal-liquid equilibria in chemically complex systems at pressures at least up to 30 kb. The availability of solid media high pressure apparatus (BOYD and ENGLAND, 1960) and the application of the electron probe microanalyser to the chemical analysis of complex phases synthesized at high pressure, have resulted in important advances in the study of basalt genesis in recent years. With the ability to quantitatively study the behaviour of natural, complex basalt compositions at high pressures, the need to attempt extrapolations from simple 3 and 4 component systems to the behaviour of natural basalts has largely disappeared, although the intrinsic value of studies of simple systems has not diminished. However, working with natural basalts involves a large element of choice and a dependence on geological and petrological arguments to select those basaltic compositions which are of direct mantle derivation and thus readily justify, on petrogenetic grounds, the study of their crystallization behaviour at high pressures.

In studies of basalts where the chemical composition of a magma is the principal concern, it is convenient to adopt a normative (i.e. indirect chemical) classification rather than a modal (mineralogical) classification. The nomenclature used is as follows:

*Tholeiite*: basalt with normative hypersthene;

*Quartz tholeiite*: basalt with normative hypersthene and quartz;

*Olivine tholeiite*: basalt with normative hypersthene and olivine, hypersthene > 3%;

*Olivine basalt*: with normative olivine and with 0–3% normative hypersthene; no normative nepheline;

*Alkali olivine basalt*: with normative olivine and nepheline; nepheline < 5%;

*Basanite*: basalt with normative olivine, nepheline and albite and with nepheline > 5%, albite > 2%;

*Olivine nephelinite*: basalt-like composition with major normative olivine and nepheline; albite < 2%, normative orthoclase and/or leucite but no normative larnite;

*Olivine melilite nephelinite*: basalt-like composition with normative olivine, nepheline, leucite and larnite. The principal variation between the above magma

types is the degree of silica saturation. Most workers recognize continuity and transition in chemical composition between the various basalts. Silica content decreases from 47–49% in the olivine tholeiites to <38% in olivine melilite nephelinite, whereas alkalis ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) increase and CaO also increases, particularly in the nephelinitic compositions. A further variation in basalt compositions is apparent in the recognition of distinctive high-alumina basalts (TILLEY, 1950; KUNO, 1960). These are aphyric basalts with normative olivine and either normative hypersthene or low normative nepheline contents but with  $\text{Al}_2\text{O}_3$  contents distinctly higher (at 16–20%  $\text{Al}_2\text{O}_3$ ) than “normal” olivine tholeiites or alkali olivine basalts of similar  $\text{SiO}_2$  and  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  contents (KUNO, 1960).

The following review does not attempt to be comprehensive and in particular, recent papers by KUSHIRO (1968), ITO and KENNEDY (1968), O'HARA and YODER (1967) contain relevant experimental data, and illustrate other approaches to the problems of basalt genesis. The paper is mainly concerned with summarizing data and presenting inferences from those experimental studies with which the author has been associated and also with rebuttal of recent criticism of earlier papers.

## 2. Constraints on magma composition in the upper mantle

The geophysical and petrological arguments for a peridotitic composition for the upper mantle are considered to be compelling. It is assumed that the average mantle composition, in regions unaffected by earlier extraction of basaltic or other liquids, is that of a peridotite capable of providing 20–30% of basaltic liquids, or 40% of picritic liquids, by partial melting leaving residual olivine and enstatite. This is the rationale of the “pyrolite” model (RINGWOOD, 1962; GREEN and RINGWOOD, 1963; and RINGWOOD, 1966). It is emphasized that the concept of pyrolite is a general one but the actual calculation of a specific “pyrolite” composition will change with improved knowledge of liquid-residue relationships in the upper mantle. Thus the “pyrolite” composition calculated by GREEN and RINGWOOD (1963) utilized NOCKOLDS' (1954) average basalt and highly refractory dunite, whereas RINGWOOD's (1966) calculation taking into account the studies in basalt crystallization at high pressures, utilized

a Hawaiian tholeiite as the basaltic liquid and an enstatite-peridotite as the residue. The particular proportions of basalt and residual peridotite were chosen to yield compositions similar in major elements to a class of peridotites (high temperature peridotites, lherzolite nodules in basalts and in kimberlites) which are of mantle derivation and cannot be less refractory than the parental material for basalts. The deduced pyrolite composition was also compared with the mantle composition inferred from the chondritic earth model.

The acceptance of a pyrolite composition for the upper mantle imposes a major constraint on basalt compositions in that liquids derived by partial melting of the mantle must be in equilibrium, at their depth of magma segregation, with residual minerals of pyrolite. The choice of an eclogite composition for the upper mantle would impose very different constraints on partial melting but these can be shown to be inconsistent with natural basalts and their high pressure crystallization products. The subsolidus mineralogy of pyrolite has been investigated experimentally (GREEN and RINGWOOD, 1967b, and this volume) and some data also obtained on partial melting of pyrolite. From these data we can infer that at very low degrees (1–3%) of melting, magmas would be in equilibrium with olivine, enstatite, clinopyroxene and plagioclase at low pressures; olivine, aluminous enstatite, aluminous clinopyroxene  $\pm$  spinel\* at intermediate pressures; and olivine, enstatite, clinopyroxene and garnet at high pressures. With increasing degree of melting, minerals enter the melt in proportions and sequence dependent on the P, T conditions, until at high degrees (>15–20%) of melting, only olivine and enstatite remain as residual phases. A self-consistent model for basalt genesis from a pyrolite mantle thus requires that basaltic liquids which are unfractionated products of direct partial melting should include olivine and enstatite as liquidus phases at pressures and temperatures matching those of their origin. Magmas which segregate from residual peridotite and begin to fractionate by removal of liquidus crystals at the depth of magma segregation may yield liquids which do not have olivine and orthopyroxene as liquidus phases, provided that there are reac-

\* The presence or absence of spinel at the solidus depends sensitively upon the bulk composition and on the solidus temperature, i.e. whether the solidus is depressed by the presence of water or not.

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<sup>++</sup>) 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.

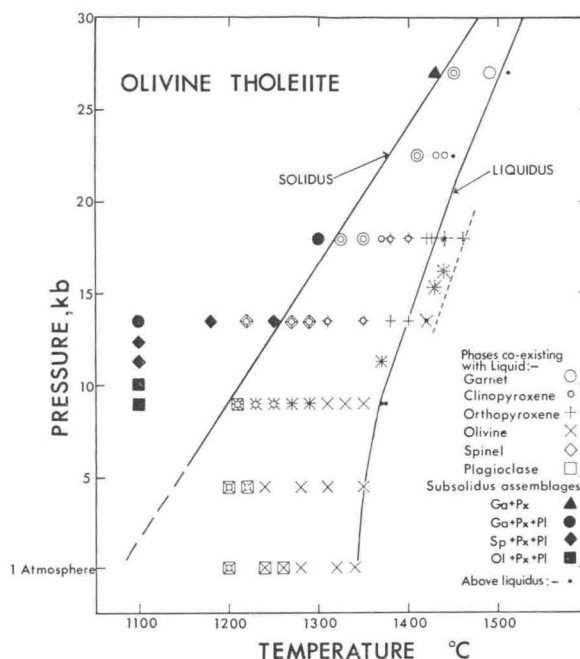


Fig. 1. Experimental crystallization of olivine tholeiite (table 1) at various pressures (GREEN and RINGWOOD, 1967a). The data for the olivine-enriched tholeiite (table 2) are shown as dotted symbols and the approximate liquidus shown by a dashed line. This composition is that of the olivine tholeiite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

\* Such reaction relationships include  
 Olivine + liquid<sub>A</sub> → clinopyroxene<sub>SS</sub> + liquid<sub>B</sub>  
 Orthopyroxene + liquid<sub>A</sub> { → clinopyroxene<sub>SS</sub> + liquid<sub>B</sub>  
 or  
 → clinopyroxene<sub>SS</sub> + garnet + liquid<sub>C</sub>

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

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 (GREEN and RINGWOOD, 1967a)	3 Picrite (GREEN and RINGWOOD, 1967a)	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 (GREEN, unpublished)	9 Olivine nephelinite (Scottsdale, Tasmania) (GREEN, unpublished)	10 Pyrolite (RINGWOOD, 1966)	
SiO <sub>2</sub>	46.95	47.05	45.51	46.55	45.39	44.63	44.3	43.7	39.31	45.16	SiO <sub>2</sub>
TiO <sub>2</sub>	2.02	2.31	1.93	3.18	2.52	2.92	1.5	1.3	3.87	0.71	TiO <sub>2</sub>
Al <sub>2</sub> O <sub>3</sub>	13.10	14.17	12.44	12.70	14.69	11.67	14.2	12.3	9.45	3.54	Al <sub>2</sub> O <sub>3</sub>
Fe <sub>2</sub> O <sub>3</sub>	1.02	0.42	0.92	2.98	1.87	2.95	0.5	1.1	5.07	0.46	Fe <sub>2</sub> O <sub>3</sub>
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 <sub>2</sub> O	1.73	2.21	1.64	2.95	2.62	3.65	3.6	2.7	2.98	0.57	Na <sub>2</sub> O
K <sub>2</sub> O	0.08	0.44	0.08	0.95	0.78	2.00	1.0	0.8	1.53	0.13	K <sub>2</sub> O
P <sub>2</sub> O <sub>5</sub>	0.21	—	0.20	0.60	0.02	1.03	0.5	0.4	2.30	0.06	P <sub>2</sub> O <sub>5</sub>
Cr <sub>2</sub> O <sub>3</sub>										0.43	Cr <sub>2</sub> O <sub>3</sub>
100 Mg Mg+Fe <sup>++</sup>	72.0	68.1	79.4	66.2	59.8	72.5	71.0	73.8	70.0	90.0	100 Mg Mg+Fe <sup>++</sup>
<i>CIPW Norms</i>											
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

TABLE 2

Experimental crystallization at high pressures of an olivine tholeiite composition prepared from olivine tholeiite (table 1 column 1) and olivine (Fo<sub>90</sub>) mixed in proportions 95:5 = olivine tholeiite:olivine. Also experimental runs on olivine tholeiite (table 1, column 1) in graphite rather than Pt capsules. All runs in graphite capsules under "dry" conditions.

Pressure (Kb)	Temperature (°C)	Time (mins)	Products	Comments
<i>Olivine tholeiite + olivine (Fo<sub>90</sub>)</i>				
13.5	1420	30	Ol+glass	Many small olivine crystals
15.3	1430	30	Ol+Opx+glass	Many small olivine and fewer but much larger orthopyroxene crystals
16.2	1440	30	Opx+Ol+glass	Rare small olivine and more common, much larger orthopyroxene
18.0	1460	30	Opx+glass+quench	Rare orthopyroxene
18.0	1440	30	Opx+glass+quench	More common orthopyroxene, possible clinopyroxene
18.0	1420	30	Opx+Cpx+quench	Cpx > Opx
<i>Olivine tholeiite</i>				
9	1360	30	Ol+glass	Many small olivine crystals
13.5	1380	30	Opx+glass	Large orthopyroxene crystals
13.5	1360	30	Opx+Cpx+glass	Cpx > Opx

occur together on the liquidus at approximately 11.3 kb and orthopyroxene is the liquidus phase at 13–18 kb, followed by clinopyroxene and garnet at higher pressures. Although fig. 1 includes only runs in Pt capsules, the problem of Fe-loss and sample composition change was previously evaluated and shown to be of minor significance. This has been further checked by runs in graphite capsules at 9 kb and 13.5 kb confirming the role of olivine at 9 kb and orthopyroxene at 13.5 kb as liquidus phases (table 2). The data on the olivine tholeiite composition suggest that crystal fractionation of olivine tholeiitic magmas at 13–18 kb will be dominated by orthopyroxene separation. Analyses of the orthopyroxenes crystallized and estimation of the degree of crystallization enabled the calculation of derivative liquids – the fractionation trend was shown to lead very directly from hypersthene-normative olivine tholeiite through olivine basalt to alkali olivine basalt compositions. The effectiveness of orthopyroxene crystallization throughout this spectrum of compositions was confirmed by detailed experiments on the olivine basalt and alkali olivine basalt compositions (table 1) (GREEN and RINGWOOD, 1967a). Although these compositions had orthopyroxene as a liquidus phase at 13–18 kb, they were undersaturated in olivine and thus these three experimentally-studied compositions could not be direct partial melting products of a pyrolite mantle at 13–18 kb (although the olivine tholeiite and possibly the alkali basalt could be such partial melting products at

11.3 kb – see GREEN and RINGWOOD, 1967a). On the other hand, the picrite composition (table 1), which is closely similar to the olivine basalt composition except for substantially greater olivine content, has olivine as the liquidus phase at 13.5 kb and 18 kb and orthopyroxene appears some 20–30 °C below the liquidus. Thus, bearing in mind the similarities of the olivine basalt and picrite compositions and their relationships to the olivine tholeiite and alkali olivine basalt compositions, it was inferred (GREEN and RINGWOOD, 1967a, page 166) that liquids derived by partial melting of the pyrolite source at 13–18 kb should be slightly richer in olivine than the chosen basalt series, but not so rich as the picrite composition. In spite of the earlier discussion, O'HARA (1968) has strongly criticized the hypotheses of crystal fractionation and of partial melting presented by Green and Ringwood, on the grounds that the chosen basalts were not possible partial melting products from a mantle peridotite. O'Hara's paper implies that it is not possible to deduce or extrapolate data from specific basalt compositions to slightly dissimilar compositions without the device of reduction of complex systems to 3 or 4 component "model" systems, which then can be understood in terms of the simple system. To further demonstrate the correctness of the previous deductions, crystallization experiments have been carried out on a new glass prepared from a mix of olivine tholeiite (table 1) and olivine (Fo<sub>90</sub>) in proportions 95:5 (yielding a composition with 25.8% nor-

mative olivine, 11.7% hypersthene, 16.2% diopside etc.). The results of these experimental runs are listed in table 2 – olivine precedes orthopyroxene at 13.5 kb, the two phases occur together on the liquidus at 15–16 kb (cf. the 11.3 kb run on the original tholeiite) and orthopyroxene is the liquidus phase at 18 kb. A composition of olivine tholeiite and olivine mixed in 92:8 proportions should yield olivine and orthopyroxene on the liquidus at 18 kb and would contain 28.2% normative olivine, 11.3% hypersthene etc. The previous analytical data on the olivine and orthopyroxene from the olivine tholeiite show 100 Mg/(Mg + Fe<sup>++</sup>) ratios consistent with the values attributed to pyrolite.

Although the above discussion should clarify questions on the nature of liquids in equilibrium with residual olivine and enstatite at 9–18 kb, there remains a major divergence of opinion on the nature of crystal fractionation in batches of magma separated from residual peridotite at 13–18 kb or derived from deeper levels and partially crystallizing in the 13–18 kb pressure range. GREEN and RINGWOOD (1967a) considered that crystal fractionation in this region would be dominated by orthopyroxene in olivine tholeiite and olivine basalt magmas and by orthopyroxene and subcalcic clinopyroxene in alkali olivine basalt magmas. The role of olivine was incorrectly ignored in the sections on crystal fractionation (fig. 10, GREEN and RINGWOOD, 1967a). On the other hand, O'HARA (1968, p. 92–93) asserts that olivine is the major phase precipitating from possible magmas in this depth region, with lesser orthopyroxene and clinopyroxene. O'HARA (1968 p. 93) considers that the spinel-lherzolite inclusions in nepheline-normative magmas are cognate accumulates in relation to their host magmas, and that their precipitation is an essential part of the process by which some hypersthene normative magmas become nepheline normative. The basis for inferring a cognate origin for spinel-lherzolite xenoliths was given in O'HARA and MERCY (1963, p. 283–286) and expanded in O'HARA (1968b) but does not withstand critical examination of the assumptions involved nor consideration of additional data on lherzolite assemblages and their conditions of equilibration (GREEN and RINGWOOD, 1967a, 181–184). In addition, later work involving isotopic and trace element studies (LEGGO and HUTCHISON, 1969; GREEN *et al.*, 1968; KLEEMAN *et al.*, 1969; COOPER and GREEN, 1969; KLEEMAN and COOPER, 1970) has

demonstrated that typical lherzolite inclusions are of accidental origin and represent mantle fragments of very much greater age than their host magmas. Some lherzolites are still capable of yielding basaltic magmas by partial melting i.e. they are not residues or accumulates from much earlier basaltic magma episodes (KLEEMAN *et al.*, 1969).

If a magma segregates from residual olivine and enstatite and then begins to cool and fractionally crystallize then olivine will indeed be a liquidus phase at the depth of segregation or at shallower depths. However, this does not imply nor require that olivine is volumetrically a *major* phase in the precipitate material. The basalt is a complex, multi-component system, in which the cooling liquid will continuously react with precipitated olivine (if it is not removed from the liquid), converting it to more Fe-rich olivine. The *amount* of olivine present in the total precipitate, may, however, increase rapidly or imperceptibly, or it may decrease – the latter effect would require a reaction relationship such as has been observed at 9 kb ( $m \text{ olivine}_1 + \text{liquid}_A \rightleftharpoons n \text{ olivine}_2 + \text{clinopyroxene} + \text{liquid}_B$  ( $m > n$ ) GREEN and RINGWOOD, 1967a, pp. 128, 129, 143)) but for which there is no unequivocal evidence at 13–18 kb. The published experimental data on the various compositions and the data included herein on the olivine-enriched tholeiite show clearly that olivine will be a minor phase in the range of accumulates from basaltic magmas fractionally crystallizing near their depth of segregation at 13–18 kb – these precipitates would range from olivine-poor orthopyroxenite to olivine-poor pyroxenites. If a tholeiitic magma segregates from residual material at 18 kb, moves rapidly to 13 kb and then begins to crystallize, then the initial precipitate will be olivine, and orthopyroxene would only appear after approximately 5% crystallization. Further precipitation would be dominated by orthopyroxene or, at lower temperatures, clinopyroxene. These precipitates from basaltic magmas must have lower 100 Mg/(Mg + Fe<sup>++</sup>) ratios than the corresponding phases in the residual peridotite\*. The iron-enrich-

\* "Xenocrystal" and "xenolithic" material matching the anticipated precipitates from basaltic magmas includes the Salt Lake Crater pyroxenites and garnet pyroxenites (GREEN, 1966; JACKSON and WRIGHT, this volume) and other similar examples (see paper by IRVING and GREEN, 1970). The processes of crystal accumulation are themselves complex in that the bulk composition of an accumulate will depend on the presence or absence

ment trend in basalt fractionation is a fundamental constraint on the amount of fractional crystallization, particularly of olivine, possible in attempting to relate one basalt magma type to another and all basalts to an ultimate equilibrium with mantle peridotite (with olivine  $\sim$  Fo<sub>90</sub>). This forms a principal objection to O'HARA'S (1968, p. 118) requirement of very high-grades of crystallization (40% olivine separation or 50% eclogite + 40% olivine separation from picritic parents for tholeiitic and alkali olivine basalt magmas respectively) since microprobe data on a variety of compositions have shown that olivine, clinopyroxene and orthopyroxene separation strongly enrich (and garnet slightly enriches) liquids in Fe relative to Mg. O'Hara's models and arguments utilize projections and simple system analogies in which Fe and Mg are treated as equivalent. These models must finally be translated into actual magma and mineral compositions and the generalized, qualitative "trends" be evaluated in simple, multicomponent calculations. The evidence from natural lherzolite-bearing alkali basalts, basanites, olivine nephelinites and olivine melilite nephelinites shows that this whole spectrum of compositions of mantle derivation is remarkably magnesian, posing some difficulty in invoking even the relatively small degrees of crystallization required by the GREEN and RINGWOOD (1967a) crystal fractionation models and favouring direct partial melting hypotheses.

The implications of the crystallization studies under dry conditions are summarized in the upper part of fig. 2, amended from fig. 10 (GREEN and RINGWOOD, 1967a) in recording the minor role of olivine in crystal fractionation at 13–18 kb. The diagram illustrates the spectrum of magma compositions and the nature of accumulate minerals which may be derived by crystallization of a parental olivine tholeiite magma at 30–70 km depth. The maximum degree of undersaturation developed by dry fractionation appears to be a basanitic liquid with  $\sim$ 5% normative nepheline, further fractionation being controlled by garnet and clinopyroxene with little change in the degree of under-

of entrapped liquid. Assuming elimination of entrapped liquid in very slow accumulation (WAGER and WADSWORTH, 1960) the anticipated accumulates include dunites ( $<$ Fo<sub>89</sub>) and olivine-poor pyroxenites but not spinel lherzolites (Fo<sub>88</sub>–Fo<sub>92</sub>). CARTER (1966) reports preliminary data on xenolithic materials in basalt which reflect very well the divergence in Mg/(Mg+Fe<sup>++</sup>) ratios between residual and precipitate material in basalt genesis.

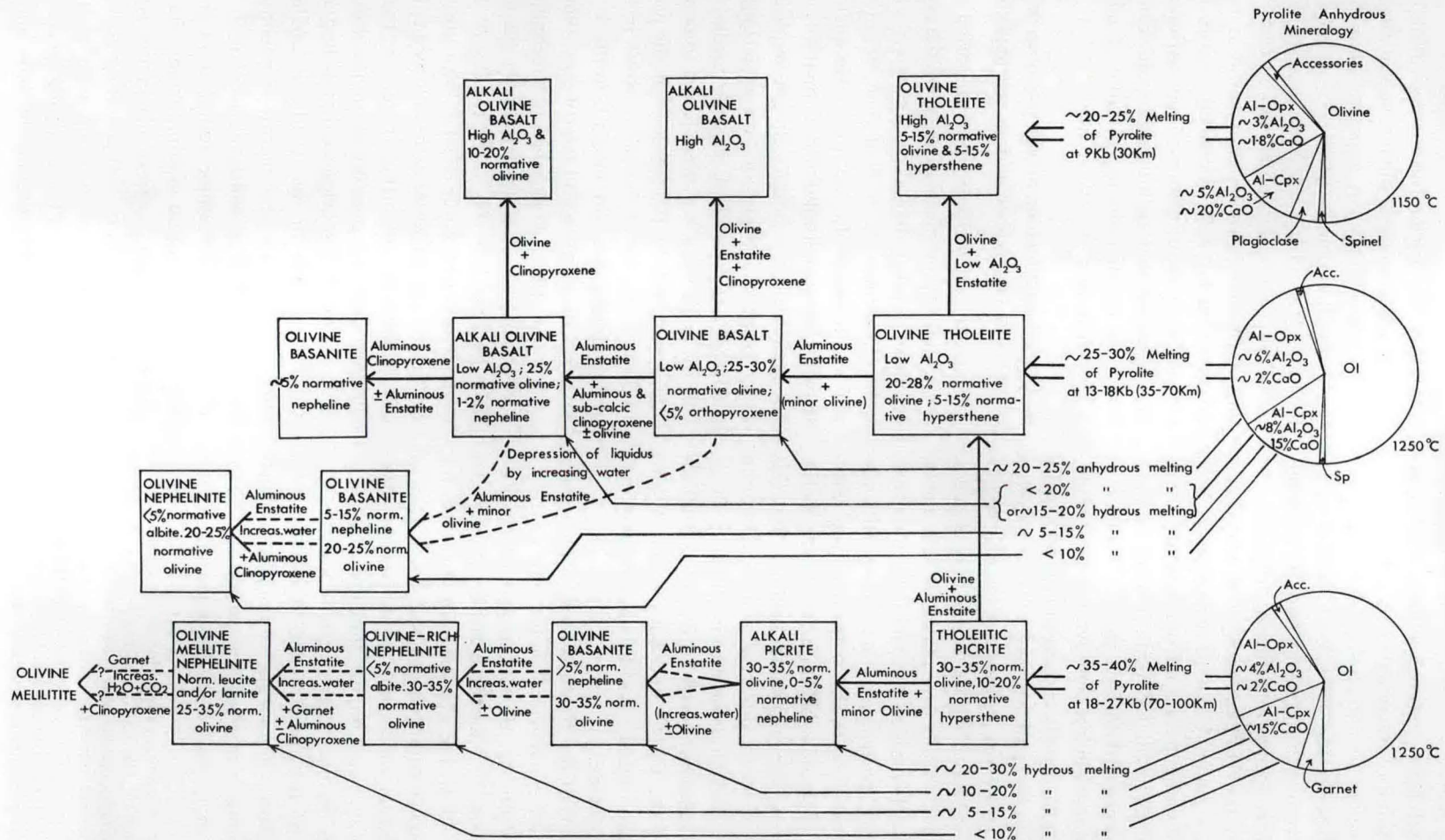
saturation. No mechanism for derivation of more nepheline-rich basanites, olivine nephelinites or olivine melilite nephelinites was apparent from the dry melting studies and detailed studies of the dry melting behaviour of the olivine-rich basanite, olivine nephelinite and picritic nephelinite compositions (table 1) revealed only olivine, clinopyroxene and garnet as liquidus phases up to 40 kb with calculated fractionation trends athwart the natural compositional variation and with no suggestion that such liquids could form in equilibrium with residual olivine, enstatite,  $\pm$  clinopyroxene  $\pm$  garnet from a pyrolite source.

#### 4. Crystal fractionation at high pressures in the presence of water - experimental data and implications

BULTITUDE and GREEN (1968) reported a reconnaissance study of the effects of water on the crystallization of olivine nephelinite and picritic nephelinite compositions (7, 8, table 1). At that time, a suitable welding unit and technique for sealing known quantities of water within the small solid media apparatus capsules was not available to the authors. Simple empirical methods, using graphite capsules or "open" (crimped, but not welded) Pt capsules and pressure media (talc) which dehydrate during a run, were found to depress the dry liquidi of basalts by  $100^\circ \pm 20^\circ$  C in the pressure range 13–30 kb. The use of "open" capsules in the presence of dehydrating pressure media is not new (YODER and TILLEY, 1962; GREEN and RINGWOOD, 1964c; O'HARA and YODER, 1967). Using the same techniques but also adding water (5–25%) to the sample, the basalt liquidi were lowered 200–300 °C in the 13–30 kb pressure range. The most notable effect of lowering of the liquidi by the presence of water is the enlargement of the field of crystallization of orthopyroxene at the expense of clinopyroxene and possibly of olivine. BULTITUDE and GREEN (1968) found evidence that orthopyroxene plays a dominant role in the fractional crystallization of olivine nephelinite and picritic nephelinite compositions at 18–27 kb at temperatures of 1150 °C–1300 °C. The possibility of sample composition change by Fe loss and by migration of components, via an aqueous phase, either into or out of the sample container was recognized (op. cit. p. 328) and attempts were made to eliminate this factor by using both Pt and graphite containers, by use of boron-nitride spacers rather than ceramic or pyrophyllite and by bulk analyses for Si,



PARTIAL MELTING OF PYROLITE AND  
FRACTIONATION OF BASALTIC MAGMA AT VARIOUS PRESSURES



D. H. GREEN

Fig. 2. Diagrammatic synthesis of relationships between basalt magma types. The rectangular boxes denote magmas related by crystal fractionation processes operating at various depth or pressure regimes. They are also derived by possible partial melting processes from a pyrolite source. The approximate mineralogy of the pyrolite source at 1150 °C, 9 kb; 1250 °C, 15 kb and 1250 °C, 27 kb is shown. This is not necessarily the immediate subsolidus mineralogy involved in the melting processes – both the mineralogy and the temperature of the solidus will be dependent on  $P_{H_2O}$ ,  $P_{Load}$  relationships.

Al, Fe, Mg and Ca of important runs using the electron microprobe (5–10 $\mu$  beam size). Orthopyroxene was produced under appropriate P, T conditions in all the variations of technique employed and the microprobe analyses showed that any sample compositional change could only have been of minor or of very selective character (Na<sub>2</sub>O was not determined). KUSHIRO (1969) considered that the stated precautions against composition change did not eliminate the possibility of selective leaching of alkalis and this is indeed a general criticism of the technique of running in unsealed capsules. O'HARA (1968, p. 104) assumed that the sequence of runs in order of decreasing temperature at any one pressure should also be a sequence of decreasing Mg/Fe ratio in olivines and orthopyroxenes and ignored the effects of varying water contents (BULTITUDE and GREEN, p. 329); on this basis, O'Hara considered that compositional changes had occurred. At 22.5 kb and between 1200–1300 °C, the reported sequence of crystallization of the picritic nephelinite is liquid  $\rightarrow$  olivine + liquid  $\rightarrow$  olivine + orthopyroxene + liquid  $\rightarrow$  olivine + orthopyroxene + garnet + liquid  $\rightarrow$  olivine + orthopyroxene + garnet + clinopyroxene + liquid\*. Amphibole reported in runs above 18 kb is probably entirely quench. The above sequence is that of increasing degree of crystallization and decreasing Mg/(Mg + Fe<sup>++</sup>) ratio of analyzed phases (comparing runs in Pt or graphite capsules independently) but is not the sequence of decreasing temperature. No crystal-liquid reaction relationships are required by the data although the relative proportions of phases suggests that there may be a partial reaction of orthopyroxene or orthopyroxene + olivine with liquid to precipitate garnet and clinopyroxene with increasing degree of crystallization. O'HARA's (1968) rejection of the reconnaissance study of the role of water in these highly undersaturated compositions is not substantiated by the arguments he used or the data originally presented, but may rest on a simple belief in the inadequacy of the precautions taken to eliminate minor compositional change.

A study of the crystallization of the olivine-rich basanite composition (table 1) under dry conditions yielded olivine as the liquidus phase up to 22.5 kb but clinopyroxene was on the liquidus at 1470 °C, 27 kb, (GREEN 1969 and unpublished data). Depression of the liquidus by permitting access of water from the talc pressure medium or by adding small drops of water to unsealed Pt and graphite capsules yielded orthopyroxene as a major near-liquidus phase at 18–27 kb in the temperature range 1200–1300 °C. Later experiments on the same composition have utilized welded Pt capsules containing known quantities of water. These techniques prevent the possibility of change in sample composition by selective leaching of alkalis, migration of silica etc. and the effect of Fe-loss has been shown to be of minor significance (cf. GREEN and RINGWOOD, 1967a, c). The major role of orthopyroxene as a near-liquidus phase has been confirmed at 22–27 kb using the sealed capsules (see also GREEN and HIBBERSON, 1970). The liquidus temperature at 27 kb was  $\sim$ 1340 °C with 2% H<sub>2</sub>O and  $\sim$ 1270 °C with 4.5% H<sub>2</sub>O. The sequence of appearance of phases is olivine (minor) joined by orthopyroxene or by orthopyroxene + clinopyroxene. At lower temperatures orthopyroxene reacts with liquid to yield clinopyroxene and garnet and the assemblage is olivine (minor) + clinopyroxene + garnet + liquid. Microprobe analyses of the phases have been carried out and will allow the calculation of fractionation trends. Similar experiments on the picritic nephelinite and olivine nephelinite (table 1, column 7) using sealed capsules are in progress but the presence of orthopyroxene in the melting interval has not as yet been confirmed by electron microprobe data. Nevertheless the data obtained on the olivine-rich basanite and olivine basalt compositions (table 1, column 4) (GREEN and HIBBERSON, 1970) demonstrate that selective leaching and compositional change were not responsible for the appearance of orthopyroxene in these compositions and seem unlikely to be of significance in the earlier runs using the same techniques.

The data demonstrate that, provided water is available in the source regions of basaltic magmas, fractional crystallization by the separation of orthopyroxene as the major crystallizing phase, extends over the compositional range from olivine tholeiite to olivine rich basanite (<12% Ab, >10% Ne) and most probably to olivine nephelinite. In olivine-rich compositions, olivine is a co-precipitating phase and either clinopyroxene or garnet is the third phase to appear depending on P, T conditions and bulk magma composition.

The data demonstrate that, provided water is available in the source regions of basaltic magmas, fractional crystallization by the separation of orthopyroxene as the major crystallizing phase, extends over the compositional range from olivine tholeiite to olivine rich basanite (<12% Ab, >10% Ne) and most probably to olivine nephelinite. In olivine-rich compositions, olivine is a co-precipitating phase and either clinopyroxene or garnet is the third phase to appear depending on P, T conditions and bulk magma composition.

\* BULTITUDE and GREEN (1968, table 3, column 3) inadvertently omitted "olivine" as a coexisting phase with orthopyroxene and garnet at 22.5 kb, 1270 °C.

sition. The effect of fractional crystallization by separation of major orthopyroxene is to rather rapidly deplete the residual liquid in  $\text{SiO}_2$ , while enriching it in CaO and alkalis. The chemical variation accords well with the natural trend in mantle-derived basalts from alkali olivine basalt to olivine melilite nephelinites (BULTITUDE and GREEN, 1968). The more undersaturated basanite and olivine nephelinite compositions appear to be attainable only at deeper levels ( $> 18$  kb or 70 km) from more picritic parent magmas. The most undersaturated product of this fractionation pattern appears to be olivine melilite nephelinite derived by separation of aluminous orthopyroxene + pyrope-almandine garnet  $\pm$  minor olivine from picritic nephelinite magma at  $\sim 27$  kb. The inferred processes and products of basalt fractionation at various pressures under both "wet" and dry conditions are summarized in fig. 2 (cf. GREEN and RINGWOOD, 1967a, fig. 10; GREEN, 1969, fig. 3). A major deduction from experiments with hydrous and anhydrous natural basalts, (although such experiments are still largely in the exploratory stage) is that basanites (with  $> 10\%$  nepheline) olivine nephelinites and olivine melilite nephelinites are hydrous magmas containing at least 2–5%  $\text{H}_2\text{O}$  at their depth of origin in the mantle. Less undersaturated magmas may also be hydrous, e.g. the Auckland Id. olivine basalt (table 1) contained  $\sim 2\%$   $\text{H}_2\text{O}$  near its depth of origin (GREEN and HIBBERSON, 1970). These hydrous magmas would form at temperatures of 100–200 °C below their anhydrous solidi and in their movement to the surface would be expected to separate a vapour phase at some depth; to precipitate amphibole and phlogopite if crystallized at some depth without escape of the vapour phase and to have characteristically explosive eruptive character – these features may be observed in the extremely undersaturated magma suite. The source of water for magma genesis of this type must lie in the upper mantle and the interrelationship of this aspect of magma genesis and chemical fractionation of the upper mantle is discussed in a later section.

### 5. Partial melting in the mantle

A specific model composition for the source regions of basalt, the "pyrolite" composition of RINGWOOD (1966), is used in the following discussion (table 1, column 10) although it recognized that some inhomogeneity must be expected. The stability fields of plagioclase

pyrolite, pyroxene pyrolite, spinel + pyroxene pyrolite and garnet pyrolite have been experimentally determined (GREEN and RINGWOOD, 1967b, 1970), and preliminary data also obtained on the stability amphibole in pyrolite composition at high pressures. In considering partial melting of pyrolite, we are concerned with the nature of the phases on the solidus, the extent of depression (if any) of the solidus by fluid pressures in the region and the sequence and proportions of phases entering the liquid at temperatures above the solidus. The microprobe analyses of the liquidus and near-liquidus phases of the basalts and of the pyrolite near-solidus assemblages are very similar and it is possible to apply the data from the experimentally amenable crystallization studies of the basalts to evaluate processes of partial melting at various depths. This has been done for anhydrous pyrolite assemblages by GREEN and RINGWOOD (1967a) and for hydrous conditions by BULTITUDE and GREEN (1968) and GREEN (1969). The inferred relationships are illustrated in fig. 2.

Tholeiitic magmas are derived by rather large degrees of partial melting of the pyrolite source. At depths of 15–35 km, magmas developed from an anhydrous pyrolite source involve melting of olivine + enstatite + clinopyroxene + plagioclase + spinel ( $\text{Cr}_2\text{O}_3$ -rich). With 20–25% melting, leaving residual olivine, low-Al enstatite and rare clinopyroxene, the liquids are tholeiitic but typically with high  $\text{Al}_2\text{O}_3$  contents (15–17%  $\text{Al}_2\text{O}_3$ ) and with normative olivine contents of 5–10% (15–25 km) or 10–15% (25–35 km). At depths of 35–70 km, the mineralogy of the pyrolite source would be olivine, aluminous enstatite, aluminous clinopyroxene and possibly rare aluminous spinel. Tholeiitic magmas result if the degree of melting is sufficient to eliminate clinopyroxene from the residual phases i.e. 25–35% melting. These tholeiitic magmas contain 15–28% normative olivine, are of low-alumina type (11–13%  $\text{Al}_2\text{O}_3$ ), and if they fractionate during movement towards the earth's surface, will trend towards high-Al tholeiites at 20–30 km or directly towards quartz-tholeiites at less than 10 km. At 70–100 km depth, melting at the anhydrous pyrolite solidus again involves olivine and aluminous pyroxenes, liquids are richer in olivine than those at lower pressures and tholeiitic picrites (30–35% normative olivine) are produced by very high degrees of partial melting (35–40%). At shallower levels tholeiitic picrites may fractionate and derivative liquids move

along the tholeiite → alkali olivine basalt trend at 35–70 km; tholeiite → high Al basalt trend at 20–30 km or tholeiite → quartz tholeiite trend at < 10 km.

With lower degrees of partial melting, liquids must be in equilibrium not only with residual olivine and enstatite, but also with clinopyroxene and, at the beginning of melting, with plagioclase (low pressure), possibly spinel (intermediate pressures) or with garnet (high pressures, > 100 km depth). At depths ~35 km, low degrees of partial melting (< 20%) would produce liquids of high alumina character, with ~47–50% SiO<sub>2</sub>, and probably with small normative hypersthene or small normative nepheline contents, and with normative olivine (10–15%) and high normative plagioclase. Some magmas classed as hawaiites but containing xenoliths and xenocrysts of high pressure origin may originate in this manner (KUNO, 1964). At depths of 35–70 km under dry conditions, liquids coexisting with olivine, aluminous enstatite and sub-calcic, aluminous clinopyroxene range from basanite with ~5% nepheline to alkali olivine basalts and these magma types would be produced by up to 20% melting of the pyrolite source. Melting to 20–25% of the source pyrolite would eliminate sub-calcic clinopyroxene from the residue and produce olivine basalts. At depths of 70–100 km, lower degrees of partial melting (< 30%) of anhydrous pyrolite would probably produce alkali picrites in equilibrium with olivine, aluminous enstatite and aluminous, sub-calcic clinopyroxene.

If small quantities of water (0.1–0.2%) are present in the source pyrolite then the subsolidus mineralogy will differ from that in fig. 2 in containing 5–15% hornblende or ~3% phlogopite. The stability of amphibole is limited to relatively shallow depths in the mantle < 100–120 km (GREEN and RINGWOOD, 1967c, p. 806; LAMBERT and WYLLIE, 1968) and at deeper levels, amphibole may be replaced by phlogopite and/or a fluid phase. The presence of water in hydrous minerals or in a fluid phase (which may contain a large CO<sub>2</sub> content, ROEDDER, 1965) will cause lowering of the pyrolite solidus and important changes in the mineralogy undergoing partial melting. Amphibole and phlogopite are inferred to melt incongruently to olivine, pyroxenes ± garnet and a liquid phase because of the high (≥ 10%) solubility of water in basalt melts at these pressures and temperatures. Lowering of the pyrolite solidus to ~1200 °C means that garnet may occur on

the solidus at depths > 80 km and also the composition of clinopyroxene at the solidus will be much more Ca-rich (16–18% CaO) and lower in alumina than the clinopyroxene at the anhydrous solidus (~10% CaO) (GREEN and RINGWOOD, 1967a, 1967b; GREEN and HIBBERSON, 1970). Because of the temperature-sensitive nature of the pyroxene solid solution, the proportions of enstatite and clinopyroxene on the solidus will also differ for wet melting.

The experimental confirmation of the role of enstatite on the olivine basanite liquidus and the reconnaissance studies showing a similar role for enstatite and for garnet in the olivine nephelinite and picritic nephelinite compositions suggest that these highly undersaturated liquids may also be partial melting products of pyrolite under wet melting conditions. It is inferred that small percentages (< 10%) of liquid formed at 200–300 °C below the anhydrous solidus at 80–120 km will be in equilibrium with olivine, orthopyroxene, garnet and minor clinopyroxene. Such liquids will be of olivine melilite nephelinite character. With increasing degree of melting, all clinopyroxene, much garnet and orthopyroxene and minor olivine enter the melt changing it to olivine nephelinite composition with residual olivine, enstatite ± minor garnet. It is emphasized that the melting process involves a continuous re-equilibration process between changing basaltic liquid and changing solid solutions and may also involve discontinuous melting relations such as  $m$  clinopyroxene<sub>1</sub> + liquid<sub>A</sub> →  $n$  orthopyroxene +  $p$  clinopyroxene<sub>2</sub> + liquid<sub>B</sub>; or garnet + liquid<sub>A</sub> → orthopyroxene + liquid<sub>B</sub>.

At depths < 80 km, garnet is probably not involved in the wet melting of pyrolite and liquids produced with low degrees of partial melting (< 10%) at 200 °C below the anhydrous pyrolite solidus will be olivine nephelinites, ranging with increasing degrees of partial melting, through olivine-rich basanites to alkali olivine basalts (fig. 2). The sequence of magmas derived by wet melting at 35–70 km will be lower in olivine than the sequence from olivine melilite nephelinite to alkali picrite at > 80 km. In the movement of such liquids towards the surface, any crystallization which occurs at shallower depths will involve separation of olivine. Clinopyroxene or amphibole may either join or replace olivine as the liquidus phase as such crystallization proceeds; replacement of olivine will occur if, as is likely, reaction relationships exist between these phases and oliv-

ine + liquid in these particular undersaturated compositions.

Fractional crystallization and the movement of the hydrous undersaturated magmas towards the surface are two processes which will tend to develop supersaturation of the liquid in the volatile components (possibly  $H_2O + CO_2$  mainly). A condition will commonly be reached at which separation of a fluid phase occurs – this will have important implications to the transport properties of the magma, the nature of its interaction with the wall-rock environment, the possibility of concentration of elements in the fluid phase and of precipitation of solid phases from the separated fluid phase. At very shallow depths, rapid expansion of a separated fluid phase may initiate explosive eruption. It is suggested that the correlation of magma type with type of xenolithic inclusion [i.e. low P assemblage or high P assemblage (WHITE, 1966; MACGREGOR, 1968; JACKSON and WRIGHT, 1970)] is not indicative of cognate relationship between magma and xenolith nor directly indicative of the depth at which magma segregates from its source material, but is a direct consequence of the water or water +  $CO_2$  (“volatile”) content of the magma and the depth at which vesiculation occurs in a magma. Thus it is inferred that olivine nephelinite or alnoitic magmas containing mineral assemblages indicative of 15–18 kb pressure, contained higher water contents and vesiculated at deeper levels than alkali olivine basalts or hawaiites containing xenoliths or xenocrysts indicative of pressures < 10 kb.

#### 6. Wall-rock reaction and selective element enrichment

Trace element concentration and ratios, while not appreciably affecting the modal or normative mineralogy nor the petrographic classification of a basalt, nevertheless provide important information and constraints on possible inter-relationships between various basalt magma types. In their application of hypotheses of olivine tholeiite and alkali olivine basalt inter-relationships, which were based on major element contents, GREEN and RINGWOOD (1967a, 167–169) considered that the known eruptive sequence and petrology of Hawaiian volcanoes could be interpreted in terms of crystal fractionation of parental olivine tholeiite magmas. The degree of crystallization (dominantly of aluminous enstatite) of the olivine tholeiite was calculated to be ~30%. However examination of the abundances

of some minor elements (K, Ti, P) and trace elements (Rb, Sr, Cs, Ba, U, Th, Zr, Hf and lighter rare earths) in the Hawaiian alkali olivine basalt and tholeiitic series showed enrichment factors in the alkali olivine basalt which were much greater than those predicted from the inferred crystal fractionation. A similar conclusion applies to basalts in general, i.e. these elements (“incompatible elements” of GREEN and RINGWOOD, 1967a) are frequently much more abundant in the undersaturated magmas than predicted by the simple crystal fractionation relationships or differences in degree of partial melting outlined in the previous sections. It was suggested that this group of elements may be highly enriched in a fractionating magma by a process of “wall rock reaction” in which cooling and crystallization of a magma involved complementary processes of reaction and extraction of the lowest melting fraction from the wall-rock. Wall-rock reaction was envisaged as a highly selective contamination of a magma by its wall-rock environment. The incompatible elements were considered to be present in the pyrolite source mainly in accessory minerals such as phlogopite, apatite, ilmenite and, by incongruent melting of these phases or by their entry into the lowest melting liquids, the incompatible elements could be highly enriched in such liquids.

GAST (1968) has given a detailed analysis of the behaviour of trace elements during partial melting with particular reference to two subclasses of basaltic magmas – the oceanic-ridge or abyssal tholeiites and, the alkaline basalts of central volcanoes of oceanic regions. Hawaiian tholeiitic rocks are not adequately considered in GAST's paper but are treated in more detail by HUBBARD (1969) and the latter paper brings out more clearly the inter-relationships of trace-element and major element geochemistry and geographic features. GAST (1968) concurs with GREEN and RINGWOOD (1967a) that fractional crystallization is inadequate to explain the differences in trace element abundances but presents arguments against the wall-rock reaction process on the grounds of inadequacy of the mechanism. GREEN and RINGWOOD (1967a) attempted to work within the framework of a single parental mantle composition and did not pursue the incompatibility between their pyrolite composition (0.71%  $TiO_2$ , 0.13%  $K_2O$ ) based on Hawaiian tholeiite (RINGWOOD, 1966) and the parental mantle (0.3–0.4%  $TiO_2$ , 0.03–0.05%  $K_2O$ ) in-

ferred from the oceanic ridge tholeiite (GREEN and RINGWOOD, 1967a, p. 171). GAST (1968) elaborated the minor and trace element data clearly distinguishing the oceanic-ridge tholeiites from alkali olivine basalts and attributed these differences to different source compositions (page 1077) and differences in degrees of partial melting; the alkali olivine basalts being derived with a small degree of melting (3–7%) from a more primitive, trace element-rich source (e.g. pyrolite of table 1) and the oceanic ridge tholeiites (15–30% melting) being derived from a partially depleted source, already chemically modified by previous partial melting of small extent. The weight of trace element data, particularly rare earths, and isotopic data, is considered to favour Gast's interpretation requiring variable source composition as well as variation in conditions of melting. GREEN (1968, p. 848–850) briefly reviewed the minor element abundances in a variety of basalts and inferred mantle inhomogeneity in accessory minerals such as phlogopite, apatite etc. on both local and regional scale. Recent data on lherzolite inclusions in basalts supports these conclusions on mantle inhomogeneity (GREEN *et al.*, 1968; LEGGO and HUTCHISON, 1968; KLEEMAN *et al.*, 1969) and suggests that in the lherzolite inclusions we are seeing examples of selectively depleted parental mantle material.

The recognition of the important role of water in the genesis of the undersaturated basalts has implications for processes of wall-rock reaction and trace element fractionation. The presence of a limited quantity of water (e.g. 0.1–0.2%) in the source region will cause melting well below the anhydrous solidus but there will be a considerable temperature range through which the degree of melting will remain small (<5%), liquids being basanite, olivine nephelinite or olivine melilite nephelinite. Such liquids will, following GAST (1968), have enriched and fractionated "incompatible" element contents as a direct consequence of partial melting. Liquids developed with higher degrees of partial melting, particularly if sufficient to eliminate clinopyroxene or garnet from the residual phases, will be of alkali olivine basalt\*, olivine basalt or olivine tholeiite type and would be expected to show decreasing abundances and fractionation in incompatible elements.

\* The conclusion of GREEN and RINGWOOD (1967a, p. 166) on dry partial melting to produce alkali olivine basalt magma should be clarified to state that liquids produced by up to 20% melting will

If hydrous minerals such as phlogopite, amphibole etc. are stable in the upper mantle then there exist conditions with  $P_{\text{H}_2\text{O}}^{\text{wall-rock}} \leq P_{\text{fluid}}^{\text{wall-rock}} \leq P_{\text{Load}}$ . If a body of magma, undersaturated in water, moves through or into a region of mantle containing hydrous phases then  $P_{\text{H}_2\text{O}}^{\text{magma}}$  may be less than  $P_{\text{H}_2\text{O}}^{\text{wall-rock}}$  and the hydrous phases may be rendered unstable in the new conditions. Breakdown of the hydrous phases produces water and other volatiles moving into the magma and modifying it. The presence of a separate fluid phase (possibly  $\text{CO}_2 + \text{H}_2\text{O}$ ) may permit selective migration of elements from wall rock to magma – those elements formerly substituting in the amphibole or phlogopite but not compatible with pyroxenes and olivine may migrate in this way\*\*. Thus the role of water (and  $\text{CO}_2$  etc.) may be an important one in allowing selective migration of elements without significant change in major element abundances.

The crystal fractionation of a magma body from a high temperature anhydrous liquid to a lower temperature hydrous magma is not a closed system process but involves chemical interaction of the magma with its wall rock environment. The original concept of wall rock reaction (GREEN and RINGWOOD, 1967a) is expanded to include movement of a fluid phase containing trace element concentrations, or trace element diffusion through a fluid phase from wall rock to magma. Important evidence for wall-rock reaction processes operating at shallow depths may be inferred from isotopic studies showing isotopic changes in the late stage liquids of "closed" magma chambers. Such evidence may be more difficult to find for mantle processes where smaller isotopic differences would be expected.

Variations in degrees of partial melting of a pyrolite source from <5% to ~15–20% will produce liquids of alkaline type with highly to moderately fractionated trace element abundances (GAST, 1968). Olivine basalts and tholeiites of Hawaiian type would be produced from the same source by  $\geq 20$ –30% melting but the oceanic ridge tholeiites and some Hawaiian tholeiites are derived from a source region already depleted in

be alkali olivine basalts at 10–20 kb. Alkali olivine basalts (~5% nepheline) formed by small degrees of melting under dry conditions should thus show fractionated and enriched trace-element abundances.  
\*\* FREY (1970) has described evidence for a "wall-rock reaction" type of process leading to selective movement of lighter REE from a metamorphic aureole (amphibole  $\rightarrow$  pyroxenes) into high-temperature peridotite in which more magnesian amphibole is stable.

some elements. The high-alumina olivine tholeiites of the oceanic ridges require approximately 20% melting and magma segregation at shallower depths than alkali olivine basalt or Hawaiian tholeiite.

## 7. Conclusions

The problems of chemical and mineralogical composition of the upper mantle and the petrogenesis of basaltic magmas are interdependent. The acceptance of a peridotitic upper mantle composition, in which olivine (55–70%) and enstatite (15–30%) are major phases, imposes a major constraint on the compositions of liquids which may be derived by partial melting of the mantle. A most productive method of investigation of these interdependent problems has been the determination of the nature and composition of liquidus and near-liquidus phases of natural basalts under various P, T conditions and the parallel investigation of the mineralogy of pyrolite, the potential mantle source rock, under the same P, T conditions.

The composition of a basaltic magma within the mantle is determined initially by the partial melting and magma segregation process i.e. for a given mantle composition the liquid composition is determined by the P, T,  $P_{H_2O}$  conditions at which the magma segregates from residual crystals. These parameters will also control the degree of partial melting and the nature and proportions of residual crystalline phases. Following segregation, a batch of magma may have opportunity for cooling and crystal fractionation at various depths leading to further diversification of magma compositions or in some cases to obliteration of chemical characteristics which would identify the primary source conditions of a magma. Crystal fractionation of a magma near its depth of origin or at shallower depths cannot always be considered as a closed system process but involves reaction with its wall-rock environment. Wall-rock reaction causes highly selective contamination of magmas with "incompatible elements" by processes of extraction of small percentages of the low melting fraction or by element migration in or through a fluid phase [possibly ( $H_2O + CO_2$ ) rich].

Tholeiitic magmas are derived by rather large degrees of melting of the peridotitic source rock. At depths of 15–35 km, magmas developed by 20–25% melting leaving residual olivine, low-Al enstatite and minor clinopyroxene, are tholeiitic with distinctively high  $Al_2O_3$

contents (15–17%  $Al_2O_3$ ) and low normative olivine (5–10% at 15–25 km or 10–15% olivine at 25–35 km). In this pressure range, magmas resembling high- $Al_2O_3$  hawaiites may be produced with smaller degrees of melting or by partial crystallization at 15–35 km of Mg-rich olivine basalts.

At depths of 35–70 km, partial melting of pyrolite under dry conditions is inferred to produce magmas ranging from basanite (~5% Ne, 25% Ol) with small degrees of melting through alkali olivine basalts, olivine basalts (25–30% Ol) to olivine tholeiites (10–15% Hy, 15–30% Ol). Magmas are nepheline normative if clinopyroxene remains among the residual phase, i.e. up to ~20% melting of pyrolite; and olivine basalt and olivine tholeiite ( $Al_2O_3$  ~ 12–13%) leave residual olivine and aluminous enstatite only. As an alternative to direct partial melting of pyrolite, the higher temperature olivine tholeiite may yield lower temperature alkali olivine basalt or possibly basanite by crystal fractionation at 35–70 km. Because of possible reaction relationships between precipitated phases and the basaltic liquid, more extreme fractionation will produce liquids unlike those produced by small degrees of melting of the original pyrolite source. Data are insufficient to fully evaluate this aspect.

At depths of 70–100 km, dry melting of pyrolite probably produces liquids ranging from alkali picrite to tholeiitic picrite (30–35% olivine) leaving residual olivine, aluminous enstatite and possibly aluminous clinopyroxene.

There appears to be no satisfactory process of generating the extremely undersaturated basanite, olivine nephelinite or olivine melilite nephelinite magmas by either partial melting of anhydrous pyrolite or crystal fractionation of less undersaturated basaltic magmas under dry conditions. Suggestions of crystallization of very large amounts of "eclogite" (garnet + clinopyroxene) and olivine from picritic parent magma (O'HARA, 1968) are as yet inadequately defined but imply marked Fe-enrichment (relative to Mg) in the undersaturated magmas – this is not observed in the natural magmas. This suggested mechanism also implies that the highly undersaturated magmas cannot form as direct partial melting products from the mantle.

The data obtained on the role of water in the fractional crystallization of basaltic magma at high pressure lead to the inference, that in the presence of water,

there is a continuous fractionation or partial melting sequence from essentially anhydrous olivine tholeiite (20–30% melting) to olivine nephelinite (2–5% water, <5% melting) at 50–70 km depth and from tholeiitic picrite, through olivine-rich basanite to olivine-melilite nephelinite (<5% melting) at 70–100 km depth. The hydrous olivine nephelinite, olivine-rich basanite, and olivine melilite nephelinite magmas form at temperatures of 100–250 °C below the dry pyrolite solidus – this has the effect of bringing partial melting into the garnet pyrolite stability field so that early formed liquids at 30 kb, the olivine melilite nephelinites, are in equilibrium with residual olivine, orthopyroxene and garnet. The presence of 0.1–0.2% H<sub>2</sub>O (and possibly similar or larger CO<sub>2</sub> contents) would play an essential role in producing small amounts of very undersaturated liquids at temperatures well below the anhydrous pyrolite solidus and at depths near the low velocity zone.

#### Acknowledgments

The author is grateful to A. E. Ringwood and A. J. Irving for critically reading the manuscript. The invaluable technical assistance of W. Hibberson in carrying out experimental high pressure runs and of E. H. Pedersen in preparing polished mounts is gratefully acknowledged.

#### References

- BOYD, F. R. and J. L. ENGLAND (1960) *J. Geophys. Res.* **65**, 741.
- BULTITUDE, R. J. and D. H. GREEN (1968) *Earth Planet. Sci. Letters* **3**, 325.
- CARTER, J. L. (1966) *Ann. Rept. South-West Centre Adv. Studies, Dallas, Texas* 65–66, 11.
- COOPER, J. A. and D. H. GREEN (1969) *Earth Planet. Sci. Letters* **6**, 69.
- FREY, F. A. (1970) *Phys. Earth Planet. Interiors* **3**, 323.
- GAST, P. W. (1968) *Geochim. Cosmochim. Acta* **32**, 1057.
- GREEN, D. H. (1966) *Earth Planet. Sci. Letters* **1**, 414.
- GREEN, D. H. (1968) in: H. H. Hess and A. Poldervaart, eds., *Basalts: the Poldervaart treatise on rocks of basaltic composition*, Vol II (Wiley-Interscience) 835.
- GREEN, D. H. (1969) Upper Mantle Symposium, Prague 1968; *Tectonophysics* **7**, 409.
- GREEN, D. H. and W. HIBBERSON (1970) *Phys. Earth Planet. Interiors* **3**, 247.
- GREEN, D. H., J. W. MORGAN and K. S. HEIER (1968) *Earth Planet. Sci. Letters* **4**, 155.
- GREEN, D. H. and A. E. RINGWOOD (1963) *J. Geophys. Res.* **68**, 937.
- GREEN, D. H. and A. E. RINGWOOD (1964) *Nature* **201**, 1276.
- GREEN, D. H. and A. E. RINGWOOD (1967a) *Contr. Mineral. Petrol.* **15**, 103.
- GREEN, D. H. and A. E. RINGWOOD (1967b) *Earth Planet. Sci. Letters* **3**, 151.
- GREEN, D. H. and A. E. RINGWOOD (1967c) *Geochim. Cosmochim. Acta* **31**, 767.
- GREEN, D. H. and A. E. RINGWOOD (1970) *Physics Earth Planet. Interiors* **3**, 359.
- HUBBARD, N. J. (1969) *Earth Planet. Sci. Letters* **5**, 346.
- IRVING, A. J. and D. H. GREEN (1970) *Phys. Earth Planet. Interiors* **3**, 385.
- ITO, K. and G. C. KENNEDY (1968) *Contr. Mineral. Petrol.* **19**, 177.
- JACKSON, E. D. and T. L. WRIGHT (1970) in press.
- KLEEMAN, J. D., D. H. GREEN and J. F. LOVERING (1969) *Earth Planet. Sci. Letters* **5**, 449.
- KLEEMAN, J. D. and J. A. COOPER (1970) *Phys. Earth Planet. Interiors* **3**, 302.
- KUNO, H. (1960) *J. Petrol.* **1**, 121.
- KUNO, H. (1964) in: *Advancing Frontiers in Geology and Geophysics* (Osmania Univ. Press), Hyderabad 205.
- KUSHIRO, I. (1968) *J. Geophys. Res.* **73**, 619.
- KUSHIRO, I. (1969) Discussion to papers at Upper Mantle Symposium, Prague, 1968; *Tectonophysics* **7**, 423.
- LEGGO, P. J. and R. HUTCHISON (1968) *Earth Planet. Sci. Letters* **5**, 71.
- MACDONALD, G. A. and J. KATSURA (1961) *Pacific Sci.* **15**, 358.
- MACGREGOR, I. D. (1968) *J. Geophys. Res.* **73**, 3737.
- NOCKOLDS, S. R. (1954) *Geol. Soc. Amer. Bull.* **65**, 1007.
- O'HARA, M. J. (1968) *Earth Sci. Rev.* **4**, 69.
- O'HARA, M. J. (1968b) in: P. J. Wyllie, ed., *Ultramafic Rocks* (Wiley, N.Y.) 393.
- O'HARA, M. J. and E. J. MERCY (1963) *Trans. Roy. Soc. Edinburgh* **45**, 251.
- O'HARA, M. J. and H. S. YODER (1967) *Scottish J. Geol.* **3**, 1.
- RINGWOOD, A. E. (1962) *J. Geophys. Res.* **67**, 857, 4473.
- RINGWOOD, A. E. (1966) in: P. M. Hurley, ed., *Advances in Earth Science* (M.I.T. Press) 287.
- TILLEY, C. E. (1950) *Quart. J. Geol. Soc. London* **106**, 37.
- ROEDDER, E. (1965) *Amer. Mineralogist* **50**, 1746.
- WAGER, L. R. and W. J. WADSWORTH (1960) *J. Petrol.* **1**, 73.
- WHITE, R. W. (1966) *Contr. Min. Petrol.* **12**, 245.
- YODER, H. S. and C. E. TILLEY (1962) *J. Petrol.* **3**, 342.