

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