

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 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 ≥ 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,