7. TRACE ELEMENTS IN BASALTS — WALL-ROCK REACTION AND SOURCE INHOMOGENEITY

In the preceding discussion, the emphasis has been on the major element composition of basaltic magmas, since this determines the mineralogy and forms the basis of classification of basaltic rocks. In attempting to relate olivine tholeiitic and alkali olivine basalt magmas by crystal fractionation or different degrees of melting of a pyrolite source, Green and Ringwood (1967b) noted that there was a group of elements including K, Ti, P, Ba, Sr, Rb, Zr, Hf, U, Th, Pb, and the lighter rare earth elements, which show enrichment factors in Hawaiian alkali olivine basalts which are greater than would be produced by 30% crystallization of a parental olivine tholeiite or the difference between 20% melting (alkali olivine basalt) and 30% melting of the pyrolite source rock. These highly enriched elements ("incompatible elements") are those which do not substitute readily in the major minerals of the upper mantle, but probably form rare accessory phases. These elements are expected to be strongly partitioned into any melt fraction, so that for partial melting in excess of about 5% their concentration should closely reflect the %-melting and source composition only, and be essentially independent of the relative proportions of olivine, enstatite and clinopyroxene remaining in the residue.

Green and Ringwood (1967b) suggested an additional mechanism of concentrating incompatible elements in a fractionating magma by a process called 'wall-rock reaction'. In this process, it was envisaged that a body of magma could, under some conditions, cool by reaction with, and solution of, the lowest melting fraction of any wall-rock material with which it was in contact. This process was considered to be an important one for bodies of magma in a region of little temperature contrast between magma and wall-rock (i.e. a magma body near its depth of segregation from source pyrolite or for a large magma body with a relatively long residence time in the crust and undergoing crystal fractionation at low pressures). The latter aspect of wall-rock reaction was applied particularly to the fractionated and 'incompatible element enriched' quartz tholeiites of Tasmania and Antarctica.

With the recognition that the genesis of the undersaturated basanites, nephelinites, etc. (the magma with the highest enrichment factors for the incompatible elements) requires the presence of water, a further factor in selective element enrichment was suggested (Green 1969a, b). If hydrous accessory minerals such as phlogopite, amphibole, apatite, etc. are stable in the upper mantle then there exist conditions with $P_{H_2O}^{\text{wall-rock}} < P_{\text{fluid}}^{\text{wall-rock}} \leq P_{\text{solid}}$ A body of magma moving through such an environment may be very undersaturated in water and $P_{H_2O}^{\text{magma}}$ may be less than $P_{H_2O}^{\text{wall-rock}}$. Hydrous phases in the wall rock may break down under the influence of the neighbouring magma and water may migrate into the magma.. The concept of wall rock reaction was modified to include the movement of a fluid phase containing incompatible element concentrations or diffusion of incompatible elements through a fluid phase from wall-rock to magma.

In an important paper, Gast (1968) discussed the trace-element enrichment in basalt magmas derived by partial melting, and showed that the strongly enriched 'incompatible element' contents of alkali olivine basalts, basanites, etc. would result if these magmas were produced by

very low degrees of melting (3 - 7%) of their source peridotite. Olivine tholeiites from the mid-oceanic ridge environments, with very low potassium and other incompatible element contents, were regarded as derived by 20 - 30% melting of a source rock which had previously suffered partial melting. Hawaiian olivine tholeiites, enriched in incompatible elements when compared with many oceanic ridge olivine tholeiites, were grouped with the alkali olivine basalts as products of smaller degrees of partial melting. This suggested relationship is inconsistent with figs. 4 and 6. Fig. 6 could reasonably account for the differences between Hawaiian magma types on the basis of different degrees of partial melting (provided alkali olivine basalts are in general formed by up to 20% melting, and commonly much less than this) of a pyrolite source rock, but the same source rock could not also yield the oceanic tholeiites (high-alumina olivine tholeiites) with their characteristically depleted incompatible element contents, by 15 - 20% melting in a single-stage process.

Consideration of incompatible element variations between rocks which are essentially similar in major element content, leads to the concept of inhomogeneity in incompatible element contents in the source region. Gast's (1968) suggestion of 2-stage melting, the first extracted melt being of small volume but highly enriched in incompatible elements, may be important. An additional suggestion has been made that the upper mantle source region may be vertically zoned in incompatible element concentrations (Green 1970) due to upward migration within the low velocity zone of a fluid phase. This fluid phase is envisaged as water-rich and possibly CO_2-rich, or possibly, a very small, water-rich, silicate melt fraction. The presence of a free fluid phase within the low velocity zone may permit the upward migration of incompatible elements, which do not readily substitute in olivine, pyroxenes, or garnet, until they are 'fixed' by entering a small silicate melt fraction in the upper part of the low velocity zone. In this way, source regions with 'depleted' and 'enriched' patterns of incompatible element abundance could be developed in the lower or upper part respectively of the low velocity zone. The particular tectonic or dynamic mechanism of partial melting (i.e. mantle diapirism, 'fault' tapping of the low velocity zone etc.) would determine which source region was involved in magma production.

8. CONCLUSIONS

The understanding of basalt magma genesis and of upper mantle composition are mutually dependent problems and both require a close integration of studies of geochemical and geophysical aspects of natural basalts, and experimental studies under simulated (P, T, P_{H_2O}) upper mantle conditions. I have, in this lecture, developed a model of basalt genesis in which the source composition (pyrolite) is regarded as essentially homogeneous in major elements but inhomogeneous or chemically zoned in content of incompatible elements and accessory minerals. The low velocity zone of the upper mantle is interpreted as a region in which, due to the instability of amphibole in pyrolite containing 0.1 - 0.2% H_2O at depths in excess of 80 - 100 kilometres, there is a very small ($<5\%$) degree of partial melting. The nature of this liquid fraction is highly undersaturated olivine nephelinite or olivine melilitite. Ascent and extrusion of basaltic magmas may occur when the low velocity zone is tapped rather directly