

phases were dominantly very magnesian olivine, with much smaller quantities of aluminous enstatite and/or sub-calcic, aluminous clinopyroxene. This type of mineral accumulate is possible from magmas such as the olivine basalt, olivine tholeiite or picrite compositions at pressures around 5–10 kb. We might expect such accumulative rocks to be initially inhomogeneous, possibly ranging from dunite to pyroxenite and also controlled in their bulk chemistry by the presence or absence of trapped, interprecipitate magma. Later cooling would be accompanied by exsolution of Al_2O_3 from aluminous pyroxenes to form spinel, exsolution of orthopyroxene from subcalcic clinopyroxene and could give rise to the observed mineralogy of the nodules. This hypothesis may be applicable to a limited degree but must rest on a postulated earlier history of the nodules which cannot be directly and unequivocally deduced from the present observed chemistry and mineralogy of the nodules.

The second hypothesis has been adopted by KUSHIRO and KUNO (1963) with calculations of the degree of partial melting needed to extract basalts of average Hawaiian and Japanese types from average lherzolite nodule composition. KUSHIRO and KUNO (1963) show that only 2–9% of basalt magma could be extracted from the lherzolite before one or more of the oxides TiO_2 , P_2O_5 or K_2O goes to zero. Approximately 8% of an average high- Al_2O_3 , oceanic tholeiite (ENGEL, ENGEL and HAVENS, 1965) could be extracted before TiO_2 and Na_2O of the average nodule composition used by KUSHIRO and KUNO go to zero. These small degrees of partial melting seem incompatible with the relatively high $\text{Mg}/\text{Mg} + \text{Fe}^{++}$ ratios of some basaltic liquids and pose mechanical difficulties in segregating such a small liquid fraction from residual crystals. The difficulties in obtaining basaltic chemistry, particularly the contents of incompatible elements such as K, U, Th etc. are even more formidable if average nodule compositions (e.g. VILMINOT, 1965) rather than selected individual nodules are used as model parental material.

The third hypothesis has been advocated by de ROEVER (1961, 1963), O'HARA and MERCY (1963) and OXBURGH (1964a, b) and is supported by the very low K_2O (MORGAN and GOODE, 1966), TiO_2 , P_2O_5 and, to a lesser extent, Na_2O , contents of the lherzolite nodules. Referring to the previous discussion of partial melting in the mantle, the nature of residual peridotite will differ considerably depending on whether an olivine tholeiite or alkali olivine basalt magma is extracted. The appreciable Na_2O , CaO and Al_2O_3 contents and the opx:cpx ratios of 3:1 or 2:1 in very many lherzolites imply that, if the nodules are residua after basalt extraction, the magma extracted was of alkali olivine basalt type and not of olivine tholeiite type. The presence of glass (with crystallites of olivine, clinopyroxene and plagioclase) apparently developed at the expense of clinopyroxene + spinel in some Australian lherzolite inclusions, implies that at least some inclusions are capable of yielding a liquid fraction at magmatic temperatures and cannot be regarded as completely refractory residues. The third hypothesis, i.e. that lherzolite nodules are residual mantle from which a basaltic magma has been extracted, is probably valid for many lherzolite nodules. The previous arguments indicate that the magma extracted from pyrolite to yield compositions of the lherzolite nodules is of alkali olivine basalt rather than olivine tholeiite type. With this type of limitation the third hypothesis passes transitionally into the fourth, i.e. that

lherzolite nodules are "residual" in character only in their content of incompatible elements but have not suffered a general partial melting process. The fourth hypothesis has been suggested by HESS (1964) and further discussed by RINGWOOD (1966a) and GREEN (1967). The hypothesis postulates that lherzolite nodules are "residual", in comparison with pyrolite in their contents of elements such as K, Ba, U, Th, Rb, Sr, Zr, Ti, P and to a lesser extent, Na and the rare earths. The selective depletion in these elements, with little change in Ca, Al, Fe etc. could be a consequence of the process of wall-rock reaction previously discussed. Thus, fragments of pyrolite included in alkali olivine basalt magma would be expected to lose any very low melting fraction into the magma — it is assumed that this low melting fraction will be highly enriched in the incompatible elements K, Ba, U, Th, Rb, Sr, Zr, P and Ti. Of the major minerals of the lherzolite, clinopyroxene may partially react with loss of jadeite component to the liquid phase. By this hypothesis, the enrichment in incompatible elements in alkali olivine basalts is a complementary process to the depletion of these elements in any fragments of mantle accidentally incorporated into a body of magma. The third and fourth hypotheses, which differ in degree rather than in kind, probably together provide an adequate explanation of the mineralogy and chemical compositions of lherzolite inclusions.

b) The Restriction of Lherzolite Nodules to Critically Undersaturated Basaltic Magmas

Both of the preferred hypotheses postulate an initially accidental inclusion of peridotitic mantle material into ascending basaltic magma. The mechanical difficulty of upward transport of xenoliths of density 3.3 in magma of density approximately 2.7 may impose some limitation on the nature of host basalts. On the other hand, the present experimental work and discussion offers a direct reason for the restriction of the lherzolite nodules to undersaturated, alkali olivine basalts, basanites etc. and their absence in olivine tholeiites or quartz tholeiites. The data and discussion on basalt fractionation and on partial melting of pyrolite demonstrated that an alkali olivine basalt liquid may be in equilibrium with olivine, aluminous orthopyroxene and aluminous clinopyroxene near its depth of segregation at 35–70 kms (cf. GREEN and RINGWOOD, 1964). If lherzolite nodules have the character suggested in either the third or fourth hypotheses then they will behave essentially as refractory xenoliths in alkali olivine basalt with little internal melting and without disaggregation of the nodule.

In contrast to their behaviour in alkali olivine basalt magma, lherzolite nodules would be unstable if enclosed in an olivine tholeiite magma at 35–70 kms depth. An olivine tholeiite or tholeiitic picrite magma at these depths will be saturated in magnesian olivine and magnesian, aluminous enstatite but will completely dissolve any aluminous clinopyroxene introduced into it.

A lherzolite nodule which is included in an olivine tholeiite magma at 35–70 kms depth will partially melt with spinel, aluminous clinopyroxene and some aluminous enstatite entering the tholeiitic liquid, i.e. probably some 20–30% of the original inclusion would melt. Under these conditions a lherzolite inclusion would disintegrate although residual xenocrysts of magnesian olivine or chromite might remain, cf. MUIR and TILLEY (1964).