

closed system except for depletion by fractional crystallization. There are great uncertainties in use of trace element and isotopic data obtained from basaltic rocks rich in incompatible elements to deduce element abundances and geochemical pre-histories for the mantle source region and such attempts should be viewed with caution.

### The Significance of Cognate Xenoliths in Basalt Petrogenesis

#### *a) Peridotite Nodules*

Coarse-grained inclusions of peridotite have a sporadic but world-wide occurrence as inclusions in alkali olivine basalts, basanites, nephelinites and melilite nephelinites. The most abundant type of nodule may be classed as lherzolite and has the mineral assemblage olivine ( $\text{Fo}_{85-92}$ ), aluminous enstatite, aluminous chrome-diopside (also with appreciable  $\text{Na}_2\text{O}$  content) and minor spinel ( $\text{MgAl}_2\text{O}_4$ -rich). Other types, less common and of more restricted occurrence, ranging from dunite through wehrlite to clinopyroxene (FRECHEN, 1948, 1963), are probably genetically distinct (de ROEVER, 1963; WHITE, 1966).

The lherzolite inclusions commonly have the character of xenoliths of previously consolidated rocks showing internal effects of deformation, cataclasis, grain-boundary recrystallization and dimensional or crystallographic orientation of minerals (DEN TEX, 1963). There may be internal evidence of disequilibrium and reaction between phases and the minerals of the inclusion are clearly not in equilibrium with the enclosing basaltic liquid — orthopyroxene, spinel and clinopyroxene all showing clear evidence of partial reaction. The lherzolite nodules apparently do not occur in olivine tholeiitic magmas or their derivatives (WHITE, 1966). The proportions of olivine, pyroxenes and spinel are variable amongst individual nodules but the order of abundance is almost invariably olivine  $\gg$  enstatite  $>$  chrome-diopside  $>$  spinel. Compilations of modal analyses by VILMINOT (1965) from Rocher du Lion, Velay, France and WHITE (1966) from Hawaii indicate a greater frequency of nodules with modes containing olivine from 90—65% and pyroxenes from 10—35%. The ratio of orthopyroxene to clinopyroxene is usually between 2:1 and 3:1. Both authors plot modal data obtained from the literature giving a wider scatter and including types with clinopyroxene in excess of olivine (cf. BROTHERS, 1960). Spinel is almost ubiquitous as a minor phase (1—4%) and accessory minerals noted in the literature on nodules and in a study (GREEN — in preparation) of Eastern Australian examples, include phlogopite, hornblende, sulphides, melilite, plagioclase ( $\text{An}_{90}$  and  $\text{An}_{65}$ ; WHITE, 1966) and garnet.

Nodules show evidence of internal disequilibrium — thus some Australian examples show reaction between clinopyroxene and spinel at mutual grain boundaries to yield fine grained plagioclase, olivine and chromite aggregates. WHITE (1966, p. 289—293) notes that enstatites in some inclusions are of variable  $\text{Al}_2\text{O}_3$  content and may be zoned in  $\text{Al}_2\text{O}_3$  content. Comparison of the mineralogy and bulk chemical composition of lherzolite nodules with the chemical compositions of high temperature peridotite intrusions (GREEN, 1963, 1964) and with other peridotites (GREEN and RINGWOOD, 1963), coupled with the internal evidence of disequilibrium in the peridotites themselves, demonstrates that the mineral assemblage of the lherzolite inclusions is unstable at high temperatures at upper

crustal levels. Preliminary experimental work indicates that the olivine + aluminous pyroxenes + spinel assemblage is stable at pressures  $> 8$  kb approx. at  $1100^{\circ}\text{C}$  in compositions close to those of the lherzolite nodules. The temperature at which the mineral assemblages of individual nodules reached equilibrium is probably variable but the degree of solid solution of the two pyroxenes is very much less than the experimentally crystallized pyroxene pairs at  $1300\text{--}1400^{\circ}\text{C}$  (p. 138, Fig. 3). The CaO content of most orthopyroxenes is  $< 1.0\%$  CaO and commonly around  $0.5\%$  CaO (ROSS, FOSTER and MYERS, 1954; WHITE, 1966; GREEN and EASTON, unpublished data) and the orthopyroxene very commonly has exsolution lamellae of clinopyroxene indicating a history involving cooling from an earlier, higher temperature environment. The low CaO content of olivine ( $< 0.1\%$  CaO; WHITE, 1966) also suggests temperatures rather less than volcanic temperatures or the temperatures of the experimental high pressure runs previously reported. These features suggest that the lherzolite nodules were at temperatures of less than  $1000^{\circ}\text{C}$  before inclusion in their host basalts. The partition of Mg and  $\text{Fe}^{++}$  between co-existing pyroxenes in lherzolite nodules has been discussed by several authors (KRETZ, 1961; BARTHOLOME, 1961; DEN TEX, 1963; GREEN, 1964; WHITE, 1966) and, in some cases, used to suggest temperatures of equilibrium crystallization of the nodules similar to or greater than those of igneous, basaltic rocks. The distribution coefficients ( $K_D$ ) for the analyzed orthopyroxene and clinopyroxene pairs (Tables 9, 11) obtained experimentally range from 1.14 to 1.27 and are thus distinctly higher than the values for igneous rocks (0.7 approx.) and somewhat higher than those of lherzolite nodules (around 1.0), cf. DEN TEX, 1963; WHITE, 1966. A considerable uncertainty in the use of mineralogical criteria for estimation of crystallization temperature is that different indicators may be "frozen in" at different stages of cooling.

Hypotheses of origin of the lherzolite nodules must be consistent with the above observations and may be broadly grouped into four possibilities:

1. Lherzolite nodules are accumulates of crystals precipitated from olivine-rich picritic or basaltic magmas at moderate to high pressures.
2. Lherzolite nodules are xenoliths of "parental mantle" from which a basaltic magma can still be derived under appropriate melting conditions.
3. Lherzolite nodules are xenoliths of residual, refractory mantle peridotite after basaltic magma has been removed.
4. Lherzolite nodules are xenoliths of mantle peridotite which have been selectively depleted in those "incompatible elements" which do not readily substitute in the major minerals of the peridotite.

In the simplest statement of the first hypothesis, a crystal accumulate relationship to the magmas *in which they occur* fails to account for the evidence of cataclasis, deformation and recrystallization in the lherzolite nodules. The estimated equilibration temperature of  $< 1000^{\circ}\text{C}$  and the compositions of pyroxenes and spinel are inconsistent with liquidus temperature equilibrium with a basaltic magma. It would be necessary to postulate an earlier precipitation from another magmatic event, cooling of the accumulates with variable cataclastic effects and accidental incorporation in a later magmatic event. The chemistry and mineralogy of the lherzolite inclusions would require that the initial precipitating