

rather than olivine + aluminous orthopyroxene + aluminous clinopyroxene (Green and Ringwood 1967a, b). However the garnet: pyroxene ratio of many kimberlite xenoliths is such that at temperatures near their solidi (200–600°C above their probable equilibration temperature, depending on the water content of the source rock at the time of melting), the garnet would be taken up in the aluminous pyroxene solid solutions giving olivine + orthopyroxene ± clinopyroxene mineralogy. This would be valid for depths of 80–150 kilometres in the upper mantle. There is no unique composition for peridotite inclusions in kimberlite, they exhibit a small range in  $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$  ratio from ~89 to ~93, and relatively larger variations in CaO, Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O and TiO<sub>2</sub> contents. They are probably residue from basalt magma extraction but represent re-equilibration of the residual phases at temperatures well below the peridotite solidus. Their contents of minor elements such as Ba, Rb, K, etc. are likely to be grossly contaminated by their host 'magma' (kimberlite); this process can be seen in the growth of secondary carbonates, serpentine or phlogopite in some inclusions.

The inclusions of kimberlite thus suggest an upper mantle which is inhomogeneous and at least partially residual in nature and in which magnesian olivine and orthopyroxene are the most abundant phases. Their investigation appears unlikely to lead to the selection of a specific individual xenolith composition as representative of any part of the upper mantle.

(b) *Xenoliths in Alkali Olivine Basalts, Basanites and Nephelinites*

Olivine-rich and nepheline normative magmas quite commonly contain xenoliths of coarse-grained lherzolite with the typical mineral assemblage of olivine > enstatite > clinopyroxene > spinel. Hornblende, phlogopite, and apatite occur as accessory minerals in some examples. There is variation from sample to sample in the relative proportions of the major and minor minerals and in the presence or absence of particular accessory minerals. The pyroxenes are characteristically aluminous (2–5% Al<sub>2</sub>O<sub>3</sub> in orthopyroxene) and the degree of solid solution between the two pyroxenes indicates temperatures below the solidus temperatures for the lherzolites. The spinel is aluminous spinel with variable chromite solid solution and the stability of the olivine + aluminous pyroxenes + spinel assemblage relative to lower or higher pressure alternatives indicates pressures at equilibration of > 8 kb and < 30 kb, probably < 23 kb. The lherzolite inclusions have a limited range of  $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$  values from > 88 to < 92. Detailed geochemical and isotopic studies (see Cooper and Green 1969, for references) demonstrate that the lherzolites (at least the intensively studied examples) are accidental xenoliths with no cogenetic or cognate relationship to their host magmas. It has been inferred that the lherzolite inclusions include residual peridotite after magma extraction, but range from such refractory residue to materials which have not suffered partial melting and complete magma extraction but may have lost a small low temperature melt or fluid phase. Again it is possible to ascertain which lherzolites are not refractory and residual in character, only after detailed geochemical study, and it is not yet possible to select a specific lherzolite composition as appropriate for a mean upper mantle composition. Rather it appears that the mantle

source region for the lherzolite inclusions is appreciably inhomogeneous on the hand-specimen scale.

Other coarse-grained inclusions occur with the dominant lherzolite and include olivine orthopyroxenites, websterites, spinel websterites, and garnet clinopyroxenite. These compositions have lower  $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}^{++}}$  ratios, decreasing approximately in the order listed above, and show clear evidence of exsolution and partial reaction and recrystallization of the assemblages in a high pressure cooling history following initial crystallization. These inclusions are interpreted as random xenoliths of small bodies of *high pressure* ( $> 10 \text{ kb}$ ) accumulates and accumulates + entrapped liquid. Another group of xenoliths, which may occur with or without the lherzolite xenoliths described above, includes dunites ( $\text{Fo}_{87.5} - \text{Fo}_{84}$ ) with minor chromian spinel, clinopyroxene and minor plagioclase, and possibly related wehrlites and olivine clinopyroxenites (Jackson and Wright 1970). This group contains more iron-rich olivine than the lherzolite inclusions and the mineral assemblages lack the clear evidence of a high pressure cooling history which is evident in the garnet pyroxenites. They are interpreted as accumulates or recrystallized accumulates from basaltic magmas at shallower depths ( $< 20$  kilometres approximately). Inclusions of olivine gabbro, gabbro, and anorthosite (approximately  $\text{An}_{80}$ ) are interpreted as accumulates from shallow magma chambers ( $< 10$  kilometres). Ultimately the detailed study of xenolithic inclusions and their host magmas, together with knowledge of the crystallization sequence in various basalt magma types, should provide important evidence on the natural processes of crystallization and fractionation of basaltic magmas at various depths.

(c) *High-temperature peridotite intrusions* There are some peridotite intrusions, usually of dome or plug-like form and emplaced in metamorphic terrains, which have high temperature, dynamothermal, metamorphic aureoles. The peridotites themselves provide evidence of initial crystallization at high pressure and high temperature (to olivine + aluminous pyroxene + spinel) and subsequent movement as high temperature crystalline diapirs to emplacement in the crust at lower pressures. The mineralogy of these peridotites is olivine  $>$  enstatite  $>$  clinopyroxene  $>$  spinel (high pressure assemblage). The major element composition and mineralogy is such that these rocks could potentially yield some proportion of basaltic magma by partial melting but detailed geochemical studies such as that of Frey (1969) show evidence for more complex history and selective depletion in some elements by an earlier melting or volatile-extraction process. Inhomogeneity within the peridotites due to lenses or bands of dunite or pyroxenite and modal variation within the peridotite again pose difficulty in selecting a valid mean composition for these mantle-derived peridotites.

*To summarize*, at least three geological processes sample materials which, because of their high pressure mineralogy, demonstrably crystallized under upper mantle conditions. All three processes indicate the importance of peridotitic composition with major olivine, enstatite as the second most abundant phase, essential clinopyroxene and a minor but essential alumina-rich phase which may be plagioclase, spinel or garnet depending on the final P, T conditions of equilibration. In all three processes, there is a