

$\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}} \sim 90$ , whereas the more iron-rich alkali olivine basalt had liquidus olivine (9 kb) and orthopyroxene (13.5 kb) with  $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}} = 83$ . In general terms, liquids which could be in equilibrium with the pyrolite ( $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}} = 89$ ) or residual assemblages from the pyrolite

must be relatively magnesian basalts i.e.  $\frac{100 \text{ Mg}}{\text{Mg} + \text{Fe}} \sim 68 - 73$ . In this respect the alkali olivine basalt composition of Table 1 is unsuitable for direct derivation from a pyrolite source, but a more magnesian composition of similar normative mineralogy is predicted to show similar crystallization behaviour with a slightly higher liquidus temperature and possibly slightly enhanced role of orthopyroxene crystallization at  $> 13$  kb.

Referring to fig. 1, it is apparent that the phases which were invoked in the postulated crystal fractionation of olivine tholeiite to alkali olivine basalt are the same as the phases at the anhydrous pyrolite solidus within the pressure range 10 - 13 kb. This applies to a more detailed comparison of

$\frac{\text{Mg}}{\text{Mg} + \text{Fe}}$  ratios and of alumina contents of the pyroxenes (Green and Ringwood 1969). Furthermore, the limited partial melting data on the pyrolite (Green and Ringwood, 1967a) shows that clinopyroxene rapidly enters the liquid and disappears from the residue leaving olivine and enstatite only. The studies on basalt crystallization and mineralogy of pyrolite at high pressure may be integrated to suggest a model of partial melting at depths of 13 - 18 kb. At these depths, if the pyrolite source rock is anhydrous, then the first liquid at the solidus will be in equilibrium with olivine, aluminous orthopyroxene, and aluminous clinopyroxene — a liquid saturated with these phases will be nepheline-normative, i.e. an alkali olivine basalt or, at low degrees of melting at about 18 kb, an olivine-rich basanite (Bultitude and Green 1970). Up to 15 - 20% melting, clinopyroxene will remain among the residual phases and the liquids will remain nepheline-normative, though decreasingly so with increasing temperature. Since all the phases existing in the source rock are Fe-Mg solid solutions, it is considered that melting with increasing temperature will be nearer to a linear process (as illustrated in fig. 3) than a eutectic and 'stepped' process (O'Hara 1968) although different 'gradients' of the various solid-solution cotectics may produce some non-linearity in the % melting *vs.* temperature curve. For degrees of melting greater than 15 - 20%, clinopyroxene will be absent from the residual phases and the liquid, saturated only with olivine and aluminous enstatite, will become increasingly hypersthene normative changing through olivine basalt to olivine-rich tholeiite ( $\sim 22\%$  olivine, 15% hypersthene, at 13 kb;  $\sim 27\%$  olivine, 13% hypersthene at 18 kb).

At lower pressures ( $\sim 9$  kb) the experimental studies permit a similar deduction that liquids developed at 15-20% melting will be in equilibrium with olivine, enstatite (lower  $\text{Al}_2\text{O}_3$  content), and minor clinopyroxene and such liquids will be high-alumina olivine tholeiites (10-15% normative olivine). With higher degrees of melting, clinopyroxene, orthopyroxene and minor olivine enter the melt changing it to olivine tholeiite of low  $\text{Al}_2\text{O}_3$  type with high normative olivine and hypersthene contents. At higher pressures,

~ 22 kb, initial melts may be olivine-rich or picritic basanite, and change through alkali picrites to tholeiitic picrites with increasing melting.

The preceding discussion has considered partial melting in a source pyrolite composition which is anhydrous. However, it has been inferred in previous sections that some mantle derived magmas, such as olivine nephelinite or olivine melilitite, are hydrous magmas at their depth of origin implying that the mantle source region is itself water bearing. The effects on the near-solidus mineralogy and solidus temperature of water contents of 0.1 - 0.2% have been discussed in earlier sections, and now must be integrated with the basalt melting data under both wet and dry conditions.

(b) *Partial melting of a hydrous pyrolite mantle: andesitic or nephelinitic magmas?* Turning to the nature of liquids derived by partial melting of a hydrous peridotite source, there are two hypotheses in the current literature which could hardly be more diametrically opposed or mutually exclusive. Each is based on experimental data which are probably correct. Kushiro *et al.* (1968) and Kushiro (1969) have studied melting relations in the systems enstatite + water, and forsterite + diopside + silica + water, and inferred that enstatite melts incongruently to forsterite + quartz normative liquid under high water pressures (up to 30 kb water pressure). A similar incongruent melting relationship for enstatite is inferred for water undersaturated conditions i.e.  $P_{\text{H}_2\text{O}} < P_{\text{total}}$ . These results are

extrapolated to the melting of more complex olivine + enstatite + clinopyroxene-bearing assemblages in the presence of a minor water-rich fluid phase in the upper mantle, and lead to the hypothesis that liquids developed from such a source will be silica-oversaturated, specifically, quartz tholeiites or andesites. Such silica-rich magmas ( $\text{SiO}_2 > 50\%$ ) might also form from parental olivine tholeiite by crystal fractionation at high water pressures (Kushiro *et al.* 1968).

In contrast, Bultitude and Green (1968) had experimented on the role of water in depressing the liquidus of very undersaturated natural magmas (olivine nephelinites, Table 1), and reported a major role for orthopyroxene as a near-liquidus phase at 20 - 30 kb,  $P_{\text{H}_2\text{O}} < P_{\text{total}}$ , temperature 150 - 250° C below the anhydrous solidus. From these studies it was inferred that highly undersaturated olivine melilitite nephelinite, olivine nephelinite, and olivine-rich basanite magmas could form by partial melting of a pyrolite source (i.e. be in equilibrium with residual olivine, orthopyroxene, ± clinopyroxene, ± garnet) at pressures of 20 - 30 kb. It was inferred that parental olivine tholeiite could fractionate to these silica-poor magmas ( $\text{SiO}_2 \sim 42\%$ ) by crystal fractionation in the presence of small but essential water contents.

Kushiro (1969) considered that Bultitude and Green's data were in error due to the experiments being carried out in crimped (rather than welded) Pt capsules with the result that the sample composition had altered during the run. Precautions against this had been taken by Bultitude and Green, and the use of the microprobe to analyze charges after runs effectively restricted any such sample leaching or contamination to very selective migration of alkali elements. Confirmation of the effect, using sealed platinum capsules and known quantities of water, was obtained for olivine-rich basanite composition (Table 1, column 5, reported in Green 1969a (footnote) and 1969b). In anhydrous runs on this composition, clinopyr-