

along the tholeiite → alkali olivine basalt trend at 35–70 km; tholeiite → high Al basalt trend at 20–30 km or tholeiite → quartz tholeiite trend at < 10 km.

With lower degrees of partial melting, liquids must be in equilibrium not only with residual olivine and enstatite, but also with clinopyroxene and, at the beginning of melting, with plagioclase (low pressure), possibly spinel (intermediate pressures) or with garnet (high pressures, > 100 km depth). At depths ~35 km, low degrees of partial melting (< 20%) would produce liquids of high alumina character, with ~47–50% SiO₂, and probably with small normative hypersthene or small normative nepheline contents, and with normative olivine (10–15%) and high normative plagioclase. Some magmas classed as hawaiites but containing xenoliths and xenocrysts of high pressure origin may originate in this manner (KUNO, 1964). At depths of 35–70 km under dry conditions, liquids coexisting with olivine, aluminous enstatite and sub-calcic, aluminous clinopyroxene range from basanite with ~5% nepheline to alkali olivine basalts and these magma types would be produced by up to 20% melting of the pyrolite source. Melting to 20–25% of the source pyrolite would eliminate sub-calcic clinopyroxene from the residue and produce olivine basalts. At depths of 70–100 km, lower degrees of partial melting (< 30%) of anhydrous pyrolite would probably produce alkali picrites in equilibrium with olivine, aluminous enstatite and aluminous, sub-calcic clinopyroxene.

If small quantities of water (0.1–0.2%) are present in the source pyrolite then the subsolidus mineralogy will differ from that in fig. 2 in containing 5–15% hornblende or ~3% phlogopite. The stability of amphibole is limited to relatively shallow depths in the mantle < 100–120 km (GREEN and RINGWOOD, 1967c, p. 806; LAMBERT and WYLLIE, 1968) and at deeper levels, amphibole may be replaced by phlogopite and/or a fluid phase. The presence of water in hydrous minerals or in a fluid phase (which may contain a large CO₂ content, ROEDDER, 1965) will cause lowering of the pyrolite solidus and important changes in the mineralogy undergoing partial melting. Amphibole and phlogopite are inferred to melt incongruently to olivine, pyroxenes ± garnet and a liquid phase because of the high (≥ 10%) solubility of water in basalt melts at these pressures and temperatures. Lowering of the pyrolite solidus to ~1200 °C means that garnet may occur on

the solidus at depths > 80 km and also the composition of clinopyroxene at the solidus will be much more Ca-rich (16–18% CaO) and lower in alumina than the clinopyroxene at the anhydrous solidus (~10% CaO) (GREEN and RINGWOOD, 1967a, 1967b; GREEN and HIBBERSON, 1970). Because of the temperature-sensitive nature of the pyroxene solid solution, the proportions of enstatite and clinopyroxene on the solidus will also differ for wet melting.

The experimental confirmation of the role of enstatite on the olivine basanite liquidus and the reconnaissance studies showing a similar role for enstatite and for garnet in the olivine nephelinite and picritic nephelinite compositions suggest that these highly undersaturated liquids may also be partial melting products of pyrolite under wet melting conditions. It is inferred that small percentages (< 10%) of liquid formed at 200–300 °C below the anhydrous solidus at 80–120 km will be in equilibrium with olivine, orthopyroxene, garnet and minor clinopyroxene. Such liquids will be of olivine melilite nephelinite character. With increasing degree of melting, all clinopyroxene, much garnet and orthopyroxene and minor olivine enter the melt changing it to olivine nephelinite composition with residual olivine, enstatite ± minor garnet. It is emphasized that the melting process involves a continuous re-equilibration process between changing basaltic liquid and changing solid solutions and may also involve discontinuous melting relations such as m clinopyroxene₁ + liquid_A → n orthopyroxene + p clinopyroxene₂ + liquid_B; or garnet + liquid_A → orthopyroxene + liquid_B.

At depths < 80 km, garnet is probably not involved in the wet melting of pyrolite and liquids produced with low degrees of partial melting (< 10%) at 200 °C below the anhydrous pyrolite solidus will be olivine nephelinites, ranging with increasing degrees of partial melting, through olivine-rich basanites to alkali olivine basalts (fig. 2). The sequence of magmas derived by wet melting at 35–70 km will be lower in olivine than the sequence from olivine melilite nephelinite to alkali picrite at > 80 km. In the movement of such liquids towards the surface, any crystallization which occurs at shallower depths will involve separation of olivine. Clinopyroxene or amphibole may either join or replace olivine as the liquidus phase as such crystallization proceeds; replacement of olivine will occur if, as is likely, reaction relationships exist between these phases and oliv-

ine + liquid in these particular undersaturated compositions.

Fractional crystallization and the movement of the hydrous undersaturated magmas towards the surface are two processes which will tend to develop supersaturation of the liquid in the volatile components (possibly $H_2O + CO_2$ mainly). A condition will commonly be reached at which separation of a fluid phase occurs – this will have important implications to the transport properties of the magma, the nature of its interaction with the wall-rock environment, the possibility of concentration of elements in the fluid phase and of precipitation of solid phases from the separated fluid phase. At very shallow depths, rapid expansion of a separated fluid phase may initiate explosive eruption. It is suggested that the correlation of magma type with type of xenolithic inclusion [i.e. low P assemblage or high P assemblage (WHITE, 1966; MACGREGOR, 1968; JACKSON and WRIGHT, 1970)] is not indicative of cognate relationship between magma and xenolith nor directly indicative of the depth at which magma segregates from its source material, but is a direct consequence of the water or water + CO_2 (“volatile”) content of the magma and the depth at which vesiculation occurs in a magma. Thus it is inferred that olivine nephelinite or alnoitic magmas containing mineral assemblages indicative of 15–18 kb pressure, contained higher water contents and vesiculated at deeper levels than alkali olivine basalts or hawaiites containing xenoliths or xenocrysts indicative of pressures < 10 kb.

6. Wall-rock reaction and selective element enrichment

Trace element concentration and ratios, while not appreciably affecting the modal or normative mineralogy nor the petrographic classification of a basalt, nevertheless provide important information and constraints on possible inter-relationships between various basalt magma types. In their application of hypotheses of olivine tholeiite and alkali olivine basalt inter-relationships, which were based on major element contents, GREEN and RINGWOOD (1967a, 167–169) considered that the known eruptive sequence and petrology of Hawaiian volcanoes could be interpreted in terms of crystal fractionation of parental olivine tholeiite magmas. The degree of crystallization (dominantly of aluminous enstatite) of the olivine tholeiite was calculated to be ~30%. However examination of the abundances

of some minor elements (K, Ti, P) and trace elements (Rb, Sr, Cs, Ba, U, Th, Zr, Hf and lighter rare earths) in the Hawaiian alkali olivine basalt and tholeiitic series showed enrichment factors in the alkali olivine basalt which were much greater than those predicted from the inferred crystal fractionation. A similar conclusion applies to basalts in general, i.e. these elements (“incompatible elements” of GREEN and RINGWOOD, 1967a) are frequently much more abundant in the undersaturated magmas than predicted by the simple crystal fractionation relationships or differences in degree of partial melting outlined in the previous sections. It was suggested that this group of elements may be highly enriched in a fractionating magma by a process of “wall rock reaction” in which cooling and crystallization of a magma involved complementary processes of reaction and extraction of the lowest melting fraction from the wall-rock. Wall-rock reaction was envisaged as a highly selective contamination of a magma by its wall-rock environment. The incompatible elements were considered to be present in the pyrolite source mainly in accessory minerals such as phlogopite, apatite, ilmenite and, by incongruent melting of these phases or by their entry into the lowest melting liquids, the incompatible elements could be highly enriched in such liquids.

GAST (1968) has given a detailed analysis of the behaviour of trace elements during partial melting with particular reference to two subclasses of basaltic magmas – the oceanic-ridge or abyssal tholeiites and, the alkaline basalts of central volcanoes of oceanic regions. Hawaiian tholeiitic rocks are not adequately considered in GAST's paper but are treated in more detail by HUBBARD (1969) and the latter paper brings out more clearly the inter-relationships of trace-element and major element geochemistry and geographic features. GAST (1968) concurs with GREEN and RINGWOOD (1967a) that fractional crystallization is inadequate to explain the differences in trace element abundances but presents arguments against the wall-rock reaction process on the grounds of inadequacy of the mechanism. GREEN and RINGWOOD (1967a) attempted to work within the framework of a single parental mantle composition and did not pursue the incompatibility between their pyrolite composition (0.71% TiO_2 , 0.13% K_2O) based on Hawaiian tholeiite (RINGWOOD, 1966) and the parental mantle (0.3–0.4% TiO_2 , 0.03–0.05% K_2O) in-