

comparatively small degree of crystallization of the parental olivine tholeiite within the specified pressure interval. This second basalt had a composition lying close to the critically undersaturated plane (Fig. 1), possessing 1% of normative hypersthene. A detailed study of the crystallization behaviour of this second basalt, called "olivine basalt" for convenience (YODER and TILLEY, 1962) was then carried out. It was found that within the above pressure range, the residual liquids resulting from crystallization of the olivine basalt followed a fractionation trend directly across the critically undersaturated plane and into the alkali olivine basalt field. The fractionation trend was followed further into the critically undersaturated field in an exactly analogous way by the detailed study of a typical alkali olivine basalt with a composition just within the critically undersaturated field.

The objective, in studying the crystallization behaviour of a series of related basaltic compositions linked by a common fractionation trend between 12 and 18 kb, was to establish the nature and limitations of this fractionation trend in the most unambiguous way possible. Assumptions and extrapolations concerning the proportion of phases which crystallize, their compositions, and changes in oxidation states are minimized by this procedure. Some doubts had previously been expressed regarding the implications of GREEN and RINGWOOD'S (1964) preliminary results and interpretation on the fractionation of the parental olivine tholeiite (O'HARA, 1965; TILLEY and YODER, 1964) because of the degree of crystallization which was assumed, and because of possible changes in oxidation state. The present methods of investigation should remove these doubts.

These methods also yield results directly applicable to problems of partial melting and magma segregation in the mantle. If the liquidus phases of the basaltic compositions are also stable in the sub-solidus mineral assemblage of a "parental peridotite" then the partial melting process can be regarded essentially as the reverse of the fractionation process. In this way we are able to apply our results to problems of partial melting deep within the mantle and attempt deductions on the nature and proportions of the basaltic liquids derived by partial melting.

#### *a) "Primary" Basaltic Liquids*

In a project designed to study the fractionation trends of basaltic magmas at high pressure it is obviously desirable to select those compositions which exist as liquids at depth and are not the end result of processes of crystallization and fractionation, or of contamination, at upper crustal levels. The liquids formed by processes of partial melting or complete melting of mantle rock are commonly referred to as "primary magmas" or "primary liquids" and these liquids may be considerably different in chemistry from the major basaltic magma types which we see extruded in bulk at the earth's surface. O'HARA (1965, p. 19—27) has given a thoughtful review and analysis of the arguments on the nature of primary basaltic liquids and concludes that the composition of extrusive basalt magmas is the product of the interplay of two processes (p. 27):

"(i) Partial melting of the mantle, yielding primary magmas which vary in composition according to the pressure, partial pressure of volatiles and degree of overheating which accompany the process.

(ii) Continuous crystallization differentiation during the movement of the liquids to the surface."

These general conclusions indicate that the compositions of liquids or glasses observed in natural rocks may not provide a reliable guide to liquid compositions at depth.

Studies of the currently active Kilauea and Mauna Loa volcanoes of Hawaii demonstrate most convincingly the role of fractionation at shallow levels in producing a series of bulk compositions ranging from picrite with over 30% normative olivine to tholeiites with variable normative quartz (MUIR and TILLEY, 1963; MACDONALD and KATSURA, 1961; MURATA and RICHTER, 1966a, b). The low-pressure fractionation in these Hawaiian tholeiites is dominated by settling of olivine. The most undersaturated basaltic glass from Kilauea Iki (1959 eruption) contains only 6.5% normative olivine (MACDONALD and KATSURA, 1961) but MACDONALD and KATSURA clearly recognize the role of olivine settling in making their estimate of the *average magma* composition for the 1959 Kilauea Iki lava lake. These authors note the tendency for the bulk composition of the erupted magma to become more mafic as the eruption proceeds and their estimated composition for the lava lake contains 18% normative olivine. The olivine tholeiite composition chosen for this study matches very closely with MACDONALD and KATSURA'S estimated 1959 average Kilauea Iki lava lake composition<sup>2</sup>. The chosen olivine tholeiite composition also compares closely with a weighted average composition for the first eruptive phase of Kilauea Iki in 1959 (MURATA and RICHTER, 1966b) although the  $\text{Al}_2\text{O}_3$  content is higher (13.1% compared to 11.4%) in our olivine tholeiite composition. There is, of course, no compelling evidence that these estimates represent the bulk composition of a Kilauean liquid at 30–60 km. However, the relatively rapid ascent of the Kilauea Iki magma (EATON and MURATA, 1960) deduced from seismic evidence suggests that, particularly in the most vigorous extrusive phase or slightly thereafter, the bulk composition of erupted magma may be virtually unmodified from the liquid composition existing at considerable depth (20–60 kms).

The estimation of liquid compositions at depth from the evidence of natural extrusive magmas is thus somewhat subjective and requires detailed investigations of the type which have been undertaken at Hawaii. Limitations may be deduced by restricting attention to extrusive bulk compositions with high  $\text{Mg}/\text{Mg} + \text{Fe}^{++}$  values, as the generalization that the liquidus ferro-magnesian silicates are enriched in Mg relative to Fe, appears well founded. This limitation directs attention towards olivine-rich, picritic rocks but the distinction between possible primary liquids and shallow level accumulative picrites is currently impractical.

An alternative, more direct approach to this problems is to seek the composition of liquids forming at the minimum melting temperatures under high pressure in peridotitic compositions such as are believed to be present in the upper mantle. O'HARA (1963 a, p. 71–77; 1963 b, p. 116–118), DAVIS (1964, p. 165–171) and DAVIS and SCHAIRER (1965) have presented data relevant to this problem. O'HARA (1963 a, 1963 b) made a preliminary study of melting relations in various

<sup>2</sup> MACDONALD and KATSURA (1961) list  $\text{Al}_2\text{O}_3 = 12.9\%$  for the "parent magma" for the 1959 lava lake samples but this is derived from the average of columns 2 and 3, Table 1, and should be 12.1%. This error was followed in our own work with the  $\text{Al}_2\text{O}_3$  content of the prepared olivine tholeiite being 13.1%.