high-alumina olivine tholeiite type, similar to the "oceanic tholeiites" occurring on the sea floor along the mid-oceanic ridges.

Hypotheses of magma fractionation and generation by partial melting are considered in relation to the abundances and ratios of trace elements and in relation to isotopic abundance data on natural basalts. It is shown that there is a group of elements (including K, Ti, P, U, Th, Ba, Rb, Sr, Cs, Zr, Hf and the rare-earth elements) which show enrichment factors in alkali olivine basalts and in some tholeiites, which are inconsistent with simple crystal fractionation relationships between the magma types. This group of elements has been called "incompatible elements" referring to their inability to substitute to any appreciable extent in the major minerals of the upper mantle (olivine, aluminous pyroxenes). Because of the lack of temperature contrast between magma and wall-rock for a body of magma near to its depth of segregation in the mantle, cooling of the magma involves complementary processes of reaction with the wall-rock, including selective melting and extraction of the lowest melting fraction. The "incompatible elements" are probably highly concentrated in the lowest melting fraction of the pyrolite. The production of large overall enrichments in "incompatible elements" in a magma by reaction with and highly selective sampling of large volumes of mantle wall-rock during slow ascent of a magma is considered to be a normal, complementary process to crystal fractionation in the mantle. This process has been called "wall-rock reaction". Magma generation in the mantle is rarely a simple, closed-system partial melting process and the isotopic abundances and "incompatible element" abundances of a basalt as observed at the earth's surface may be largely determined by the degree of reaction with the mantle or lower crustal wall-rocks and bear little relation to the abundances and ratios of the original parental mantle material (pyrolite).

Occurrences of cognate xenoliths and xenocrysts in basalts are considered in relation to the experimental data on liquid-crystal equilibria at high pressure. It is inferred that the lherzolite nodules largely represent residual material after extraction of alkali olivine basalt from mantle pyrolite or pyrolite which has been selectively depleted in "incompatible elements" by wall-rock reaction processes. Lherzolite nodules included in tholeiitic magmas would melt to a relatively large extent and disintegrate, but would have a largely refractory character if included in alkali olivine basalt magma. Other examples of xenocrystal material in basalts are shown to be probable liquidus crystals or accumulates at high pressure from basaltic magma and provide a useful link between the experimental study and natural processes.

Introduction

Basaltic rocks, by virtue of their widespread occurence in both oceanic and continental regions, occupy a unique position in igneous petrogeny. It is widely believed that basaltic magmas are derived from the earth's mantle. Basalts accordingly contain a vast reservoir of information, the correct interpretation of which should throw a great deal of light on the chemical and mineralogical nature of the mantle. Petrologists have long recognized the existence of a number of different types of basalt characterized by distinctive chemical and mineralogical properties, e.g. alkali basalts, olivine tholeiites, high-alumina basalts and quartz tholeiites. The main theme of this paper is a detailed experimental study of the relationships between the principal magma types, their fractionation trends at various pressures and their derivation by partial melting processes in the peridotitic mantle.

Recent workers have attempted to systematise the classification and nomenclature of basaltic rocks and the reader is referred particularly to the excellent summaries of previous and present views on basalt classification by Yoder and Tilley (1962, p. 346—348, 349—356), Macdonald and Katsura (1964), Coombs (1963), Kuno (1960). We shall adhere to a classification of basaltic rocks similar to that accepted by Yoder and Tilley (1962) and Macdonald and Katsura

(1964). Since our main concern is with chemistry rather than the modal mineralogy of basaltic rocks, it is convenient to accept a classification directly based on CIPW normative mineralogy (i.e. an indirect chemical classification). The "basalt tetrahedron" of YODER and TILLEY (1962; Fig. 1) is a convenient and simple illustration of this method of classification of basaltic rocks. The principal classes of

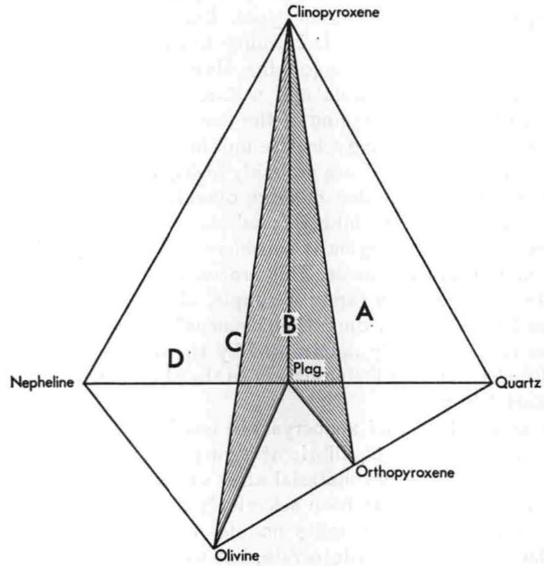

Fig. 1. Diagrammatic representation of the major mineralogy of basalts using the "basalt tetrahedron" (YODER and TILLEY, 1962). The plane olivine—clinopyroxene—plagioclase is referred to as the "critical plane of undersaturation". *A* field of quartz tholeiites; *B* field of olivine tholeiites; *C* field of alkali olivine basalts; *D* field of olivine basanites

basalts are clearly represented as primary phase volumes in this figure. The following terms are used to define these principal magma types:

Tholeiite or tholeiitic suite: basalts characterised by the presence of normative hypersthene.

Quartz Tholeiite: — basalts with normative quartz and hypersthene.

Olivine Tholeiite: — basalts with normative olivine and hypersthene. *Olivine basalt* is used for brevity and convenience in nomenclature for basalts falling within this group but having low (0—3%) normative hypersthene content. This convention is similar to the use of the term by YODER and TILLEY (1962).

Alkali[1] *Olivine Basalt:* — basalts characterised by the presence of normative olivine and nepheline but with normative nepheline less than 5%.

Basanite: — basalts characterized by normative olivine and nepheline and with more than 5% nepheline.

Olivine Nephelinite: — basalt-like rocks without normative albite and typically with olivine, diopside and nepheline as the major normative minerals.

[1] The term alkali olivine basalt is preferred to the more grammatically correct "alkaline olivine basalt" or "alkalic olivine basalt" (MACDONALD and KATSURA, 1964, p. 89) for reasons of common usage and euphony.