

A REVIEW OF EXPERIMENTAL EVIDENCE ON THE ORIGIN OF BASALTIC AND NEPHELINITIC MAGMAS

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Geological and petrological arguments are used to select those basaltic compositions which have been directly derived from the upper mantle with minimum opportunity for crystal fractionation or for contamination within the crust. The experimental study of the crystallization of these magmas at high pressures, under both anhydrous and hydrous conditions provides evidence of genetic links between magma types. These studies also provide data necessary to evaluate a major constraint on "primary" magmas, i.e. that magmas derived by direct partial melting of the upper mantle must have olivine and enstatite among their liquidus phases at the P, T conditions of magma segregation. The characteristic magma derived from either direct partial melting (~20–25%) of pyrolite or fractional crystallization of olivine-rich tholeiite at depths of 15–35 km is high alumina olivine tho-

leite. At 35–70 km partial melting of anhydrous pyrolite or fractional crystallization of olivine-rich tholeiite or tholeiitic picrite produces a series of liquids from olivine-rich tholeiite through olivine basalt and alkali olivine basalt to basanite (~25% Ol, ~5% Ne). With availability of water in the pyrolite source or during crystal fractionation, the pyrolite solidus is depressed. This produces changes in the subsolidus mineralogy and in the nature of liquids formed by low degrees of partial melting or by extensive crystal fractionation of less undersaturated magmas. Olivine nephelinites and basanites may be generated by small degrees of melting of water-bearing (0.1–0.2% H₂O) pyrolite at ~50–70 km and olivine melilite nephelinites, olivine-rich nephelinites and olivine-rich basanites form in a similar way, as hydrous magmas at 70–100 km depth.

1. Introduction

The processes of generation of basaltic magmas within the earth's mantle involve crystal-liquid equilibria in chemically complex systems at pressures at least up to 30 kb. The availability of solid media high pressure apparatus (BOYD and ENGLAND, 1960) and the application of the electron probe microanalyser to the chemical analysis of complex phases synthesized at high pressure, have resulted in important advances in the study of basalt genesis in recent years. With the ability to quantitatively study the behaviour of natural, complex basalt compositions at high pressures, the need to attempt extrapolations from simple 3 and 4 component systems to the behaviour of natural basalts has largely disappeared, although the intrinsic value of studies of simple systems has not diminished. However, working with natural basalts involves a large element of choice and a dependence on geological and petrological arguments to select those basaltic compositions which are of direct mantle derivation and thus readily justify, on petrogenetic grounds, the study of their crystallization behaviour at high pressures.

In studies of basalts where the chemical composition of a magma is the principal concern, it is convenient to adopt a normative (i.e. indirect chemical) classification rather than a modal (mineralogical) classification. The nomenclature used is as follows:

Tholeiite: basalt with normative hypersthene;

Quartz tholeiite: basalt with normative hypersthene and quartz;

Olivine tholeiite: basalt with normative hypersthene and olivine, hypersthene > 3%;

Olivine basalt: with normative olivine and with 0–3% normative hypersthene; no normative nepheline;

Alkali olivine basalt: with normative olivine and nepheline; nepheline < 5%;

Basanite: basalt with normative olivine, nepheline and albite and with nepheline > 5%, albite > 2%;

Olivine nephelinite: basalt-like composition with major normative olivine and nepheline; albite < 2%, normative orthoclase and/or leucite but no normative larnite;

Olivine melilite nephelinite: basalt-like composition with normative olivine, nepheline, leucite and larnite. The principal variation between the above magma

types is the degree of silica saturation. Most workers recognize continuity and transition in chemical composition between the various basalts. Silica content decreases from 47–49% in the olivine tholeiites to <38% in olivine melilite nephelinite, whereas alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) increase and CaO also increases, particularly in the nephelinitic compositions. A further variation in basalt compositions is apparent in the recognition of distinctive high-alumina basalts (TILLEY, 1950; KUNO, 1960). These are aphyric basalts with normative olivine and either normative hypersthene or low normative nepheline contents but with Al_2O_3 contents distinctly higher (at 16–20% Al_2O_3) than “normal” olivine tholeiites or alkali olivine basalts of similar SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ contents (KUNO, 1960).

The following review does not attempt to be comprehensive and in particular, recent papers by KUSHIRO (1968), ITO and KENNEDY (1968), O'HARA and YODER (1967) contain relevant experimental data, and illustrate other approaches to the problems of basalt genesis. The paper is mainly concerned with summarizing data and presenting inferences from those experimental studies with which the author has been associated and also with rebuttal of recent criticism of earlier papers.

2. Constraints on magma composition in the upper mantle

The geophysical and petrological arguments for a peridotitic composition for the upper mantle are considered to be compelling. It is assumed that the average mantle composition, in regions unaffected by earlier extraction of basaltic or other liquids, is that of a peridotite capable of providing 20–30% of basaltic liquids, or 40% of picritic liquids, by partial melting leaving residual olivine and enstatite. This is the rationale of the “pyrolite” model (RINGWOOD, 1962; GREEN and RINGWOOD, 1963; and RINGWOOD, 1966). It is emphasized that the concept of pyrolite is a general one but the actual calculation of a specific “pyrolite” composition will change with improved knowledge of liquid-residue relationships in the upper mantle. Thus the “pyrolite” composition calculated by GREEN and RINGWOOD (1963) utilized NOCKOLDS' (1954) average basalt and highly refractory dunite, whereas RINGWOOD's (1966) calculation taking into account the studies in basalt crystallization at high pressures, utilized

a Hawaiian tholeiite as the basaltic liquid and an enstatite-peridotite as the residue. The particular proportions of basalt and residual peridotite were chosen to yield compositions similar in major elements to a class of peridotites (high temperature peridotites, lherzolite nodules in basalts and in kimberlites) which are of mantle derivation and cannot be less refractory than the parental material for basalts. The deduced pyrolite composition was also compared with the mantle composition inferred from the chondritic earth model.

The acceptance of a pyrolite composition for the upper mantle imposes a major constraint on basalt compositions in that liquids derived by partial melting of the mantle must be in equilibrium, at their depth of magma segregation, with residual minerals of pyrolite. The choice of an eclogite composition for the upper mantle would impose very different constraints on partial melting but these can be shown to be inconsistent with natural basalts and their high pressure crystallization products. The subsolidus mineralogy of pyrolite has been investigated experimentally (GREEN and RINGWOOD, 1967b, and this volume) and some data also obtained on partial melting of pyrolite. From these data we can infer that at very low degrees (1–3%) of melting, magmas would be in equilibrium with olivine, enstatite, clinopyroxene and plagioclase at low pressures; olivine, aluminous enstatite, aluminous clinopyroxene \pm spinel* at intermediate pressures; and olivine, enstatite, clinopyroxene and garnet at high pressures. With increasing degree of melting, minerals enter the melt in proportions and sequence dependent on the P, T conditions, until at high degrees (>15–20%) of melting, only olivine and enstatite remain as residual phases. A self-consistent model for basalt genesis from a pyrolite mantle thus requires that basaltic liquids which are unfractionated products of direct partial melting should include olivine and enstatite as liquidus phases at pressures and temperatures matching those of their origin. Magmas which segregate from residual peridotite and begin to fractionate by removal of liquidus crystals at the depth of magma segregation may yield liquids which do not have olivine and orthopyroxene as liquidus phases, provided that there are reac-

* The presence or absence of spinel at the solidus depends sensitively upon the bulk composition and on the solidus temperature, i.e. whether the solidus is depressed by the presence of water or not.