THE UPPER MANTLE AND ALKALIC MAGMAS

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Abstract. The inhomogeneity of the upper mantle is consistent with the expression of magma types on the global surface. The possible relation between the spatial variations in the mantle pyrolites and the distribution of alkalic magmas has been discussed, and it is emphasized that a mantle phase having bulk composition equivalent to amphibole is the potential source for alkalic magmas. Petrological and geochemical data indicate that alkalic salic magmas may be derived directly from the mantle under a suitable physical environment.

Introduction

Though the areal investigation of the earth's surface was launched by geoscientists a few centuries ago, our attempt to view the earth in its third dimension is a relatively new venture. Available data at hand now strongly affirm that the growth and evolution of the relatively young crust are influenced to a great extent by the mantle — to be more precise the 'upper mantle'. Accordingly, in our efforts to reach a 'deeper' understanding of the planet, adequate emphasis is being put on exploration of the subcrustal earth.

The inhomogeneous upper mantle

Geophysical and petrological observations clearly indicate a layered inhomogeneity in the upper part of the mantle. Petrogenetic and geotectonic discussions in which the upper mantle is involved should particularly focus attention on a significant physical inhomogeneity in the shallow mantle manifested through the 'low velocity layer', whose potentialities should be explored more fully. In this narrow 'plastic' zone in the upper mantle, temperature takes an upper hand

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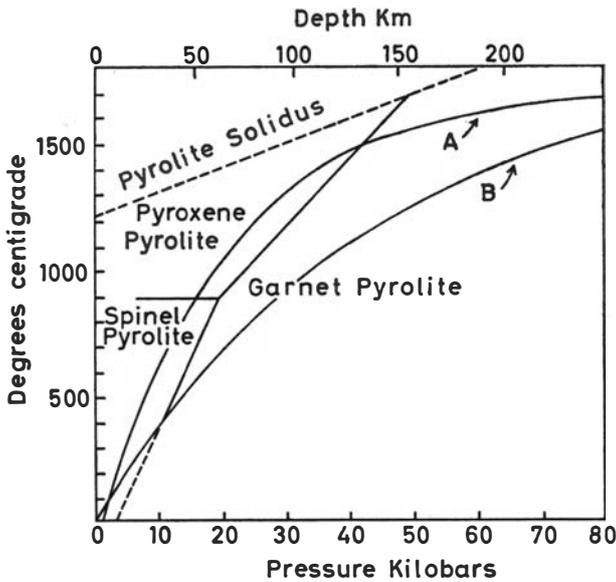
Depth Km

Fig. 1. Possible stability fields of different types of ultramafic assemblages in relation to geotherms for oceanic areas (A) and Precambrian shields (B). Modified diagram after RINGWOOD *et al.* (1964).

over pressure; in other words, in this level, the melting point of the mantle material comes close to the thermal gradient within the earth (Fig. 1). However, along with the temperature effect, some phase effect like development of plagioclase (RINGWOOD 1962a, b), complex pyroxene (RINGWOOD 1962b), or amphibole (OXBURGH 1964) may be involved in lowering the seismic velocity in the zone. In any case, the outer part of the mantle (extending to about 300 km beneath the Moho) provides the potential source of the magmas and is thus responsible to a great extent for the geochemical (and tectonic) evolution of the crust.

Some petrological aspects of the upper mantle

There have been considerable discussions on the possible composition of the subcrustal earth—particularly from the point of view of genesis of basaltic magmas. However, it should be emphasized that the subcontinental Moho, if imposed by phase transformation (YODER

& TILLEY 1962), cannot be continuous with that below the oceanic crust. Thus, there must be a phase diversity in the upper mantle immediately below the subcontinental and suboceanic crust. It may be mentioned here that the largely restricted occurrence of eclogite inclusion in *continental* basalts suggests that eclogite layers (rather lenses) are possibly localized immediately below the continental platforms. Such eclogite pockets may have genetic relation with a parent garnet peridotite (YODER & TILLEY 1962) developed extensively at a greater depth (see also Fig. 1).

The basaltic fraction in the mantle material (the 'pyrolite' after RINGWOOD 1962a, b) may develop an eclogitic assemblage (which would only increase the proportion of pyroxene in the mantle), or it may be contained *in a single phase* comparable to amphibole in bulk composition. The development of this phase may also account for the physical inhomogeneity manifested through the low velocity channel as thought to be caused by plagioclase or complex pyroxene (RINGWOOD 1962a, b). It is not unlikely that under the conditions prevailing in the mantle, both pyroxene and amphibole may co-exist when they loose the reaction behaviour at high pressure (YODER & TILLEY 1962). Further, some experimental data (SCHREYER & YODER 1960) seem to indicate that water may be accommodated in silicate minerals, particularly in double-chain silicate structure with open channels. Such a (hydrous) mantle phase may serve as a potential source of alkali basaltic magma or even of salic alkalic magmas as discussed below.

The upper mantle as a source of alkalic magmas

It is now convincingly proved by experimental petrologists that the process of generation of the major magma types, namely the basalts, takes place in a region where basalt itself is unstable (YODER & TILLEY 1962). The magma composition arising from the partial melting of the mantle source is affected by pressure conditions, that is by the depth factor. The tholeiitic character of the derived magma is induced by garnet-rich composition, while the alkalic nature is related to the clinopyroxene (O'HARA & YODER 1964) or similar chain-silicate structure as discussed earlier.

With reference to Fig. 1, it could be observed that in the zone of magma generation (at about 60 km, occasionally exceeding 100 km

in depth) garnet is an essential constituent in the subcontinental mantle, while in the suboceanic sector it is not a significant phase where a chain-silicate phase is encountered along this level. Such diversity in phase assemblage in the mantle pyrolite has significant bearing on the expression of magma types on the global surface. As oceanic basalts are in general influenced by the chain-silicate mantle phase, they are normally characterized by alkali metals and *titanium*. On the other hand, subcontinental mantle sources may produce *both* hypersthene normative (tholeiitic) and nepheline normative (alkalic) liquids, depending on whether the garnet or the chain-structure is involved in the process of melting. The 'mixed provinces' are more likely to be developed in continental borders because of the unique disposition of the mantle along the transition zone.

In view of the chemical equivalence of hornblende with basalt and particularly of the nepheline normative character of common calciferous amphibole (YODER & TILLEY 1962), it seems likely that the alkalic character is empressed on a basic magma by the mantle phase having bulk composition comparable to that of sodi-calcic amphibole. This chain-silicate phase can account for the relative enrichment of water and titanium (besides the alkalies) in alkalic basaltic magma, which could be discriminated from the circum-oceanic basalts on the basis of distribution of the minor element, titanium (CHAYES & VELDE 1965). Further, as the partition of elements between the chain-silicate and co-existing phase(s) is likely to be influenced by the prevailing physical conditions in the mantle, it may also be possible to *discriminate* alkali basaltic magmas in the oceanic and continental sectors on the basis of distribution of some of the elements.

A process comparable to incongruent melting behaviour of sodi-calcic amphibole (BOYD 1959) may be invoked to account for the generation of salic alkalic fluids in a regional scale, apparently un-related to any parent intracrustal alkali basaltic magma (e.g. in the eastern African and southern Norwegian alkalic petrographic prov-inces). Abundant evidence of super heat in some such syenitic mag-mas (McCULLOH 1952) would distinguish them from normal late differentiates and hint at a derivation directly from the mantle. Some of the experiments conducted in the Geophysical Laboratory indicate that there are invariant points at very high pressure which are rich in nepheline and plagioclase normative components. Liquids generated

at or near such invariant points by complete fusion when brought into the crust could then crystallize as nepheline-syenitic rocks provided the olivine and clino-pyroxene were removed either by reaction or by settling (Yoder 1965, personal communication). In this respect, it would be interesting to study the nodules in large alkali-syenitic bodies or similar rocks (PECORA & HEARN 1965) for their possible derivation from depth. Attention may be drawn to the 'ultrabasic facies' (BRÖGGER 1933) of rocks somewhat 'floating' in the voluminous syenitic members in the alkalic province of Oslo, South Norway. Though the exact genetic relation of this restricted rock type with salic members has yet to be critically examined, it may not be out of place to mention some significant characters of the rock: namely, 1) it is nepheline normative; 2) it does not contain modal hypersthene and lacks in the reaction relation between olivine and pyroxene; 3) it contains appreciable amounts of titanium, and the discriminant factor based on titanium (CHAYES & METAIS 1964) would indicate its affinity with those rocks which have been influenced by the chain-silicate phase in the mantle.

The geochemical riddles associated with the alkalic-salic rocks must be tackled properly to gain insight into their mechanism for genesis. An abnormal feature of many such rocks is their relatively low concentrations of Rb, Cs, U, Th (compared to K), which again indicate that at least in such cases the normal fractionation processes were not involved in the generation of the alkalic liquids. On the other hand, it is significant that distribution of certain trace elements in the salic-alkalic rocks, e.g. in the nepheline syenites, is comparable to that in the ultramafic rocks (HEIER 1964), and, thus, it seems possible that many of the geochemical characters in such rocks might have been imposed by the ultramafic mantle material. Two other possible factors which may impress this abnormal geochemistry on the alkalic syenites are 1) selective escape of some elements with the vapour phase during partial melting of mantle, e.g. the incongruent melting of the mantle amphibole, and 2) changes in the geochemical behaviour of some minor elements like Rb, Cs, etc. at high pressure (as indicated for K), and, accordingly, these elements may not be concentrated in the late liquid and thus also not in the early formed liquid fraction 'distilled' from the mantle.

It is observed that even among the salic-alkalic rocks themselves
there are distinctive chemical and petrographic characters which are
impressed by the different physicochemical conditions on the crystal-
lizing alkalic liquids. Thus, the characteristic geochemistry and mineral-
ogy of the agpaitic rocks apparently indicate their derivation from
liquids enriched in volatiles, which again may cause selective enrich-
ment of certain elements in the system (BARTH 1954). However, it
may be useful to study the distribution of the minor elements in salic-
alkalic rocks with possible derivation from the mantle in an attempt
to discriminate them from late liquids developed through differenti-
ation of intracrustal emplacement of alkali basaltic magma.

Potash enrichment in magmas derived from the mantle is a prob-
lem which demands adequate attention both in the field and in the
laboratory. However, the average potash content of basaltic magmas
could reasonably be attributed to primary amphibole in the mantle
(OXBURGH 1964). There is also some possibility that $KAlSi_2O_6$ molecules
in the pyroxene, which forms extensive solid solutions in jadeite, may
play some role in contributing potash to the basic magma (Yoder 1965,
personal communication).

Tectonic setting for emplacement of alkalic magmas

The classical concept that alkalic rocks are characteristic of 'nonoro-
genic' areas very likely developed because of their prolific development
in oceanic sectors (the low cratonic areas). Subsequently, this tectonic
setting was considered to be requisite for emplacement of alkalic
magmas in continental (high cratonic) areas too. No critical test has
yet been undertaken to prove the validity of this contention. On the
other hand, increasing data are exposing the fact that alkalic magmas
may develop in diverse tectonic setting (SHACKLETON 1954). It is
remarkable that in many areas the salic-alkalic members (the so-
called late derivatives) overwhelmingly dominate over basic fraction.
A well-known region is the rift areas of East Africa where the age-old
concept of crystallization differentiation of basic magma does not
seem to be effective. A parallel case, exposing the deeper part of
graben, is manifested through the Permian alkalic petrographic
province of southern Norway, where the salic-alkalic magmas are out

of all proportion to the basic members. More than twenty years ago, BARTH (1945) pointed out that the relative abundance of the igneous rock types in the Oslo province does not fit with the normal expectation from the fractionation of a parent basic magma.

Though the rift areas seem to be the most favourable sites for the development of such salic-alkalic rocks, all rifts are not representative of the same tectonic environment. This raises difficulties in correlating alkalic igneous activity with tectonism. Critical studies on the deformation plan in such rift areas are needed, and it is particularly interesting that in such areas there are indications of transcurrent or rotational movement in the crust rather than only a down-dip subsidence of the faulted blocks. A somewhat ill-defined mechanism of crustal buckling (BAILEY 1964) cannot be applicable to all alkalic petrographic provinces. This idea of crustal warping as the possible mechanism for the origin of alkalic magmas was originally offered by SHACKLETON (1954) in an attempt to correlate the sequence of crustal deformation (with particular reference to East Africa) with phases of igneous activity. It should be kept in view, however, that salic-alkalic magmas may develop in close association with the orogenic belts and may also be related to the revolutionary phases of deformation of the earth's crust. The crystallization history of the salic magma and the consequent petrographic characters of the rocks are likely to be much influenced by the nature of deformation and its time relation with emplacement.

Magmas of different chemical characteristics are likely to be derived from the mantle, which suffers differential melting under different physical conditions. Thus, the dominant alkalic-salic magmas of the rift zones, the extensive flood basalts of the cratons, and the stupendous volume of andesitic lavas of the island arcs are all manifestations of the fusion of the mantle under diverse physical (tectonic) environments. The requisite conditions for the generation of alkalic magmas directly from the mantle have yet to be established, but, from the available data, it seems likely to be induced by high heat flow from the deeper earth accompanied by torsional stress (as may be caused by intersecting convection currents in the mantle). Undoubtedly, such conditions of melting may be attained both in subcontinental and suboceanic mantle, though the crustal expression of this deep mechanism may appear in different patterns in the two sectors.

ACKNOWLEDGEMENT

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