CHAPTER IV

PETROGENESIS

In recent years geochemical data are being advantageous for
identifying the original tectonic situation of basic volcanic rocks.
Forbes and Kuno (1967) used the $K_2O/(Na_2O + K_2O) - SiO_2$ variation
diagram to mark the differences among the peridotite inclusion-bearing
basalts from intraoceanic, mediterranean and continental localities.
Six magma types can be defined on the basis of plate tectonic processes
(Pearce and Cann, 1973; and Pearce, 1976). They are (1) ocean- floor
basalt, (2) island are tholeiites, (3) calc- alkali basalts,
(4) shoshonites, (5) ocean- island basalts, and (6) continental basalts.
Discriminant functions based on major element oxides; SiO_2, TiO_2, Al_2O_3,
FeO, MgO, CaO, Na_2O and K_2O are used to distinguish these magma types.

Classification of volcanic rocks which is based on the tectonic
environment associated with their eruption can be made up by four major
groups, (Pearce and Cann, 1973) and the six magma types mentioned above
are included. Four major groups of magmas are as follows :

    (1) Ocean-floor basalts (diverging plate margin)

    (2) Volcanic are basalts (converging plate margins)

    (3) Ocean-island basalts (within plate-oceanic crust)

    (4) Continental basalts (within plate-continental crust)

As cited in Forbes and Kuno (1965 and 1967) "In circum Pacific regions, inclusion-bearing basalts occur on the continental side of currently active orogenic volcanic belts or in the hinterlands of the circum-Pacific arces. These are the Cenozoic alkalic basalt provinces as previously noted by Tomkeiff (1949); Barth (1956); Sugimura (1960) and Kuno (1969b). These provinces occur in tectonic setting characterized by epeirogenic uplift and high angle faulting during Tertiary and/or Quaternary time".

The association of alkalic basalts with continental regions of Cenozoic uplift, extensional tectonism and high heat flow of the southeast Asia region are being compared with those of the southwestern United States and southeastern Australia (Barr and Macdonald, 1981). These late Cenozoic basalts of southeast Asia are similar in age to those occur in Malaysia and China (Barr and Macdonald, 1981).

The Bo Phloi Basalt is a peridotite inclusion-bearing basalt and being dated by K-Ar method, having the age of 3.14 ± 0.17 m.y. (Barr and Macdonald, 1981). Its geological and geographical distributions are undoubtedly suggestive for continental origin basalt. The $K_2O/(Na_2O + K_2O)$ vs. SiO_2 diagram (Figure 33) following Forbes and Kuno (1967) and also the plot of discriminant functions F_1 and F_2 (Figure 34) after Pearce (1976) of the Bo Phloi Basalt support a within-plate basalt and has a continental environment during eruption.

The eruptive Bo Phloi Basalt carries numbers of xenoliths of upper mantle lherzolite nodules and gneissic country rock. The presence
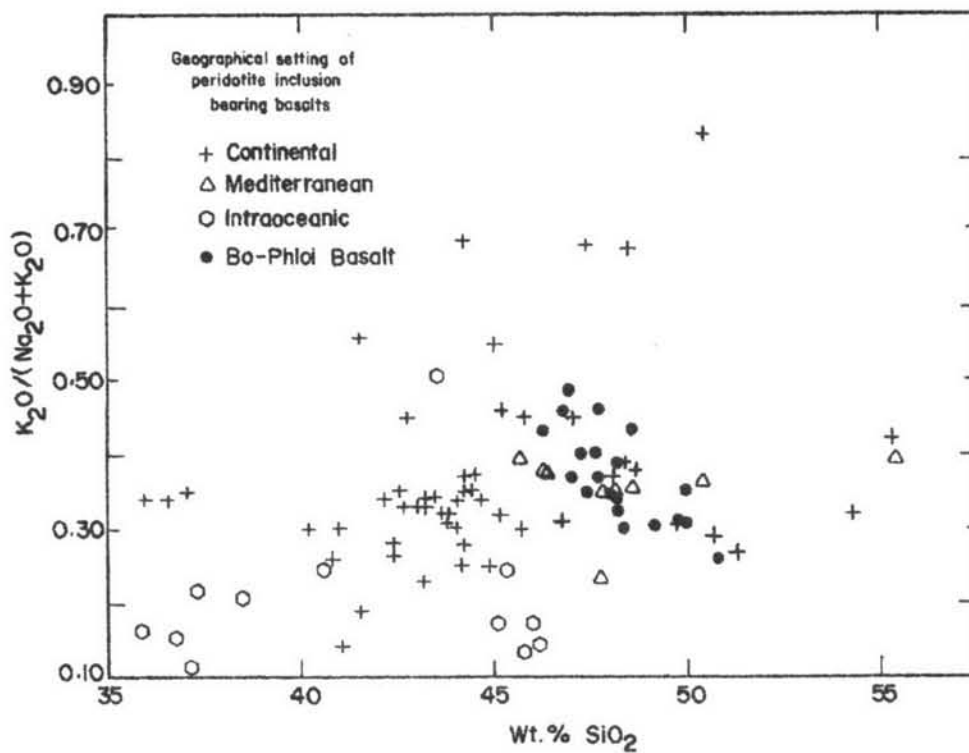
Figure 33 $K_2O/(Na_2O+K_2O)-SiO_2$ diagram of peridotite inclusion bearing basalts from continental, mediterranean and intraoceanic (after Forbes and Kuno, 1967) and the Bo-Phloi Basalt.
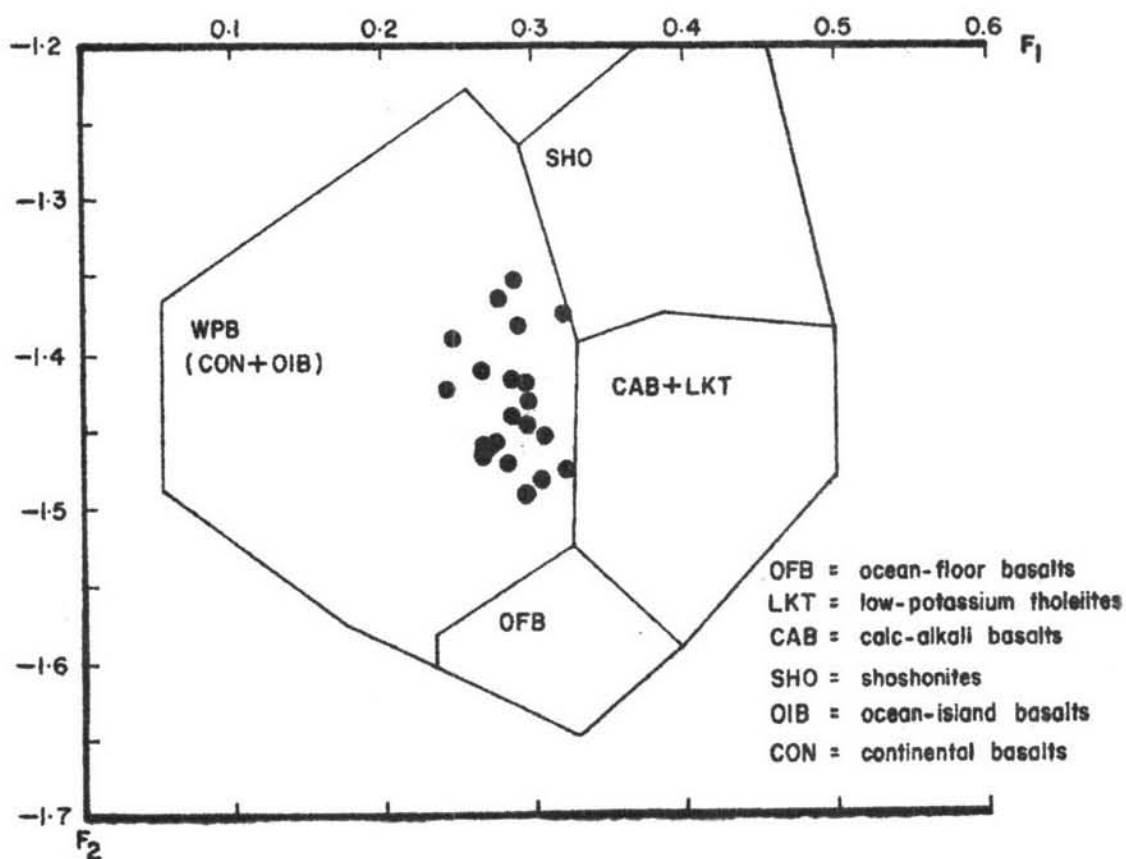
Figure 34   Plot of discriminant functions, F_1 against F_2, for samples from the Bo-Phloi Basalt. Magma type boundaries are after Pearce, 1976.

Remark : Discriminant functions (Pearce, 1976) are :

$$F_1 = +0.0088\,SiO_2 - 0.0774\,TiO_2 + 0.0102\,Al_2O_3 + 0.0066\,FeO$$
$$- 0.0017\,MgO - 0.0143\,CaO - 0.0155\,Na_2O - 0.0007\,K_2O$$

$$F_2 = -0.0130\,SiO_2 - 0.0185\,TiO_2 - 0.0129\,Al_2O_3 - 0.0134\,FeO$$
$$- 0.0300\,MgO - 0.0204\,CaO - 0.0481\,Na_2O + 0.0715\,K_2O$$

of the crustal material may suggest the possibility of contamination
in the basalt. However, the existence of high-pressure origin in
inclusions such as lherzolite in the basalt in the contrary, may
establish that the magma has ascended directly and rapidly from depths
greater than 30-35 km without crystal fractionation above the level at
which the lherzolite inclusions were collected (Green, 1969, 1970;
Maaløe, 1973; Irving and Green, 1976) and with meagre opportunity for
chemical interaction with wall rock or crustal contamination even if
crustal xenoliths were incorporated en route to the surface (Irving
and Green, 1976; Frey, Green and Roy, 1978). For example, the Newer
Basalts of Australia which are enriched in xenoliths of peridotite
and crustal material show normal range of Sr^{87}/Sr^{86} ratio for
uncontaminated modern basalts (Stueber, 1969, Dasch and Green, 1975;
Stuckless and Irving, 1976). But, for more definite evidence of the
extent of contamination process that might possibly happen and hence
have an effect on the chemistry and evolution of the Bo Phloi Basalt,
an additional study on isotopic Sr^{87}/Sr^{86} ratio is needed.

The peridotite nodules have been interpreted either as
representative of primary mantle material from which basaltic magmas
can be produced by partial melting; as residual mantle material left
after extraction of basalt; as accumulated from primary basaltic magma
formed as bottom cumulates in temporary reservoirs (Wyllie, 1967; Kuno,
1969 a ; Kuno and Aoki, 1970). Among the ultramafic nodules of the
world, lherzolite is the most common type, wehrlite and pyroxenite are

the next, and eclogite occurs only at some localities, being invariably associated with lherzolite and garnet lherzolite (Kuno and Aoki, 1970). Kuno (1959) and Kushiro and Kuno (1963) and other workers had previously noted that peridotite inclusions occur preferably in alkali-olivine basalts rather than tholeiites. Thus, the origin of these nodules or inclusions appears to be related to the genesis of basaltic magma that containing them within the mantle, especially when high aluminous pyroxene megacrysts are incorporated in the magma in additional to the peridotite nodules (Irving, 1974 a, 1974 b; Frey and Green, 1974; Irving and Green, 1976). Thus an erupted basalt liquid containing any of these high-pressure inclusions must be either (a) a primary partial melt of the mantle or (b) a derivative of such a primary melt produced by crystal fractionation process at high pressure (Irving and Green, 1976).

It has long been accepted that the basaltic rock, either formed from primary or secondary derivative magma, is ultimately a product of partial melting of the upper mantle source material, pyrolite (Ringwood, 1966; Green and Ringwood, 1967; Green, 1970 a; 1970 b; 1971, 1973 a; 1973 b) or peridotite (Ito and Kennedy, 1967; O'Hara, 1968; Kushiro, 1968, 1969 and 1973; Kushiro et al., 1972 and Mysen and Boettcher, 1975). The origin of the Bo Phloi Basalt is no exception from the general believes. Its Mg-value (average 68.12) indicates that the rock is formed from a primary magma (Irving and Green, 1976; Frey, Green and Roy, 1978) which is in equilibrium with the Mg-value (87.4-89.3) of the lherzolite nodules (Ringwood, 1966; Nicholls, 1967;

Roeder and Emslie, 1970; Carter, 1970; Grove et al., 1973; Irving and
Green, 1976; Frey, Green and Roy, 1978). However the widespread
presence of megacrysts, aluminous clinopyroxene, spinel, sanidine, olivine
and perhaps corundum, in the Bo-Phloi Basalt indicate crystallization
of these minerals at high pressure(Kuno, 1964; Green and Ringwood, 1967;
Aoki and Kushiro, 1968; Binns, 1969), probably at the depth where the
magma was generated. But fractionation crystallization due to separation
of crystals should not be effective in this magma during its ascent
(Kushiro, 1979).

Petrographic and geochemical determinations of the Bo-Phloi Basalt
suggest that the rock is undersaturated and alkalic. It has been
advocated by many experimental petrologists that the alkalic undersaturated
basalts are generated by small degree of partial melting of upper
mantle at great depth (Gast, 1968; O'Hara, 1968; Kushiro, 1968; Green
and Ringwood, 1967; 1969; Green, 1970; Bultitude and Green, 1971;
Kushiro, 1973; Jaques and Green, 1980). The derivation of the Bo-Phloi
Basalt by process of fractional crystallization from primary olivine
tholeiite (Yoder and Tilley, 1962; Green and Ringwood, 1967; 1969) has
been ruled out by the ineffective process of fractional crystallization
as mentioned above.

It had been concluded and accepted that garnet peridotite with
the assemblages of Ol + Opx + Cpx + Gr, is commonly chosen as the parental
material for basaltic liquids (Yoder, 1973). It was indicated that a
garnet peridotite formed at high pressures should change at successively

lower pressure to a spinel peridotite and then to a plagioclase peridotite
(O'Hara, 1969; Yoder 1976). The almost bimineralic compositions, namely
olivine and orthopyroxene, of the nodules of the Bo-Pholi Basalt cannot
be exclusively used to specify one of these upper mantle materials.
However, the plagioclase peridotite is rather unlikely to be the parental
source rock on account of the widespread presence of aluminous
clinopyroxene megacrysts. Furthermore, the existences of small amount
of clinopyroxene and spinel in the nodules and spinel in megacryst
provide strongly informative evidence that the physical environment of
the upper mantle at the time of partial melting should have spinel rather
than garnet as a stable phase. Ito and Kennedy (1967) found that a
garnet peridotite produced the assemblage Ol + Opx + Cpx + Sp at
pressures less than 20 kbar. Similarly, Kushiro, Syono and Akimoto
(1968) found a spinel lherzolite assemblage to persist at pressure less
than 20 kbar, and transformed to garnet bearing assemblages above 20 kbar.
The transformation pressure between garnet and spinel at approximately
20 kbar has been confirmed additionally by many workers (eg. MacGregor,
1965; Cohen et al., 1967; Kushiro et al., I972). Hence, the upper limit
of generation of the Bo-Phloi Basalt should not exceed too far beyond
20 kbar. Forbes and Kuno (1967) concluded by the fact that alkali-
olivine basalts commonly host spinel lherzolite xenoliths but rarely
transport garnet lherzolite xenoliths is consistent with the hypothesis
that they form in the stability region of spinel lherzolite, that is
ranging approximately from 10 to 25 kbar. Takahashi (1979), on his
study on the melting relation of basalt, has suggested that the alkali-

basaltic melt is last equilibrated with the upper mantle lherzolite at about 14 kbar, provided that the effects of H_2O and CO_2 on the melting relations are insignificant. If spinel lherzolite is presumed to be the parental source for magmatic genesis, the solidus temperatures of the spinel lherzolite ranging from 10 to 25 kbar would correspond to 1300 to 1475° c (Kushiro, 1968; Yoder, 1976). Wigh slightly increase (approximately 50° c) above these minimum temperatures required for the beginning of melting, clinopyroxene will be entirely consumed into the liquid. Therefore, the primary basaltic liquid generated by small degree of partial melting will be composed predominantly of clinopyroxene composition and of some certain amounts of spinel and olivine compositions. The residual solid left behind would be enriched with olivine and orthopyroxene with subordinate clinopyroxene and spinel. This would be in consistency with the mineral compositions of the nodules that found in the Bo Phloi Basalt. The chemical composition of the basaltic liquid produced, prior to the crystallization of various megacrysts, must be preferably rich in CaO, MgO and MgO/FeO ratio and low in SiO_2. Crystallization of the sanidine megacrysts from the primary liquid at high pressure has created problem of K_2O content in the primary melt. The ordinary minerals of the mantle contain only small amount of potassium (Erlank and Kushiro, 1970; Shimizu, 1971). Therefore, certain amount of K-bearing mineral, i.e., phlogopite (Kushiro, Syono and Akimoto, 1967; Dawson and Powell, 1969; Jackson and Wright, 1970) and/ or amphibole (Oxburgh, 1964) might have incorporated in the mantle material and participated into the melt during the process of partial melting of the upper mantle. Melting behavior of phlogopite and

pyroxene (especially clinopyroxene) at high pressure would produce melt
of alkalic and undersaturated characteristic (Modreski and Boettcher,
1973).

Crystallization of the sanidine megacryst in the Bo Phloi Basalt
provides also information concerning the physical condition of melt.
Sanidine is likely to crystallize directly from melt at pressure above
19 kbar (Lindsley, 1966). Experimental work in the system $KAlSiO_4$-Mg_2
SiO_4-SiO_2 indicates crystallization of sanidine and olivine from melt
at pressure above 18 kbar (Wendlandt and Eggler, 1980). Thus, the
physical condition of generation of the Bo Phloi Basalt can be limited
further to the pressure range of 18-25 kbar and the temperature range of
1340-1475° c. However, the suggested physical conditions for the
generation of the Bo Phloi Basalt is estimated under the assumption of
dry condition. This would generally be referred to as upper limit of
the condition for this magmatic generation. Lowering of this estimated
physical condition is possible due to introduction of volatile
substances especially H_2O, into the process of partial melting.
Nonetheless, the lowering of the estimated physical condition would
not be drastic on account of a limited amount of water presented. Large
amount of water in the process would produce saturated magma which is
irrelevant to the nature of the Bo Phloi Basalt.