

PETROGENESIS

Lack of genetic relationship between alkali and tholeiite magmas has been suggested explicitly or implicitly by several authors (Kuno, 1959; O'Hara, 1965; Green and Ringwood, 1967c; Kushiro, 1968). Kuno (1959) and Dickinson and Haetherton (1967) have suggested, from geologic and chemical relations that alkali basalts originate deeper in the mantle than tholeiite basalts. The experimental work of Green and Ringwood (1967c) and Kushiro (1968) tend to support the earlier suggestion of Kennedy (1966) that partial melting is strongly limited by pressure. Gast (1968), from the study of trace element fractionation of alkali and tholeiite basalts, inferred that tholeiite basalts are produced by extensive (20-30%) partial melting of mantle material whereas silica-undersaturated liquids originate by a much smaller degree of partial melting (3-7%). Griffen and Murthy (1969) have supported the inference of Gast (1968) on the basis of the distribution of K, Rb, Sr, and Ba in basaltic minerals. However, they suggest 5-10% of partial melting for the generation of alkali magmas. Derivation of tholeiite magmas through extensive partial melting of mantle material is generally agreed.

Ultramafic nodules occur sporadically in under-saturated basaltic rocks. Such inclusions do not occur or

are extremely rare in tholeiites (Forbes and Kuno, 1965). Griffen and Murthy (1969) account for the abundance of ultramafic inclusion in undersaturated magmas by the extent of partial melting. In undersaturated magmas, where only a few percent of liquid is present, the remaining solid is more likely to retain enough coherence to form inclusions, especially if melting involves one or two dimensional hydrous phases. On the other hand, at higher degrees of melting, as the pyroxene and olivine begin to melt along grain boundaries, the rock might tend to break up into individual grains whose further assimilation may be easily affected.

Presence of ultramafic inclusions and xenocrysts of various minerals in basaltic rocks have been considered to reflect mantle composition and the stage of magma evolution under polybaric conditions. Where such nodules are entirely lacking, as in the case of Panjal Traps, evidence regarding the genesis of magma may be sought either through experimental approach or by assessing chemical variations of the observed and inferred phenocryst assemblages. In the following discussion, besides field, microscopic, and chemical data, petrogenesis of the Panjal Traps is discussed in the light of known implications of experimental investigations of various workers.

Though a few reported occurrences of very small highly differentiated members of the Panjal Traps, e.g., rhyolites

from Srinagar (Ganju, 1943; Ganju and Rajnath, 1939; Wakhloo, 1969) fit well with the standard model of basaltic magma differentiation where the volume of the more evolved members of the basalt-rhyolite series decreases with the progressive differentiation, lack of ultrabasic and also paucity of basic varieties (the common rock type is basaltic-andesite) in the Panjal Traps need consideration. Further, the absence of ultramafic nodules and olivine appears to have an important bearing on the origin and evolution of these rocks.

The important observation about the chemistry of the Panjal Trap is that these rocks are less basic in average bulk composition. This may indicate that these lavas either represent a lesser degree of partial melting of peridotite mantle material in the source region, or that they have undergone greater degree of fractionation of ferro-magnesian minerals during ascent, or some combination of both. Smaller degree of partial melting is inconsistent with their tholeiitic character since it is accepted on all hands that tholeiite magmas originate by extensive partial melting of mantle material (Gast, 1968; Griffen and Murthy, 1969). Instead, if this is primarily due to greater degree of fractionation, then a slow rate of ascent is implied. This is consistent with the absence of ultramafic inclusions and xenocrysts in the Panjal Traps and also with their olivine free nature. Strong (1972) has suggested that large high-density peridotite

TABLE VII

Chemical composition of the Panjal Traps from different regions of Kashmir compared with the average chemical composition of the Panjal Traps of Mount Kayol, Liddervat (Trace element values given in ppm)

Region	Aru	Mishat	Harwan	Handwara	Erin	Mt. Kayol
SiO ₂	51.85	50.73	50.53	51.70	51.20	51.12
TiO ₂	1.51	1.35	1.77	2.18	1.95	1.75
Al ₂ O ₃	14.27	14.94	14.75	14.50	14.50	14.36
Fe ₂ O ₃	1.92	2.12	1.57	2.23	2.27	1.84
FeO	9.87	9.90	10.10	9.94	10.15	8.95
MgO	5.76	5.38	6.78	5.81	5.55	5.59
CaO	9.74	10.24	9.12	9.72	9.94	9.87
Na ₂ O	2.89	3.25	3.10	3.03	2.15	3.15
K ₂ O	0.52	0.95	1.16	0.50	0.64	1.14
MnO	0.09	0.10	0.10	0.13	0.27	0.11
P ₂ O ₅	0.27	0.15	0.17	0.20	0.35	0.17
H ₂ O	1.22	1.05	0.82	1.10	1.15	2.03
Total	99.91	100.16	99.97	100.08	100.12	100.08
Ni	26	22	30	20	25	32
Co	15	20	25	19	23	15
Cr	55	78	67	60	57	68
Cu	217	175	230	170	210	197
V	310	450	376	265	300	380
Y	55	31	45	28	37	14.8
Zr	110	93	88	67	109	113
Ga	24	22	46	32	30	26
Mb	6	9	10	6	12	10
Rb	59	65	55	3	4	76
Ba	395	418	437	17	29	400
Sr	172	210	115	100	152	173

TABLE VI

Lateral variation in the chemical composition of a single flow of the Panjal Traps on Mount Kayol, Liddervat. (Trace element values given in ppm)

Location No.	1	2	3	4
SiO ₂	51.40	51.35	51.49	51.45
TiO ₂	1.51	1.57	1.43	1.50
Al ₂ O ₃	14.70	14.21	14.32	14.30
Fe ₂ O ₃	1.82	2.13	1.91	1.90
FeO	8.50	8.68	8.47	8.42
MgO	5.95	5.48	5.50	5.65
CaO	9.42	9.66	9.52	9.51
Na ₂ O	3.14	2.94	3.44	3.75
K ₂ O	1.25	1.75	1.69	1.70
MnO	0.09	0.07	0.05	0.10
P ₂ O ₅	0.12	0.11	0.10	0.09
H ₂ O	2.10	1.97	2.07	1.65
Total	100.00	99.92	99.99	100.02
Ni	42	40	46	42
Co	16	20	15	18
Cr	62	65	60	66
Cu	175	190	167	174
V	460	445	450	453
Y	45	49	51	50
Zr	106	110	110	105
Ga	29	20	24	26
Mb	6	8	5	5
Rb	60	112	75	85
Ba	448	573	430	517
Sr	133	128	130	136

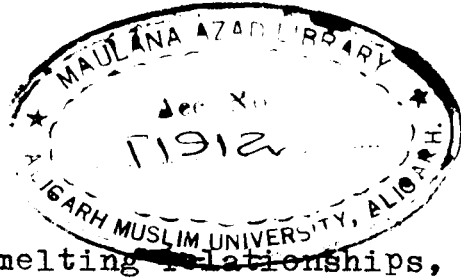
The lateral distances between the adjacent locations is approximately 15 feet.

inclusions in the La Grille lavas, Grande Comore, reflect faster rate of magma ascent.

Many features of the Panjal Traps lead one to suspect that they have evolved by a continuous fractional crystallization of the parental basalt magma. There are, for example, no compositional gaps in the sequence as a whole as is seen by the clustering of points for these rocks within a small region on different variation diagrams. Also, there is no significant lateral variation in the composition of a single flow as is evident from the closely similar values of different oxides (Table VI). Further, the uniformity of chemical composition on regional scale is indicated by the similarity in the composition of these rocks from different regions of Kashmir as shown in Table VII. MgO is less in all the samples. Na₂O, K₂O, Rb and Ba in rocks of Nishat and Harwan are high. Both Nishat and Harwan are near Kangan granite. This again supports the earlier inference that alkali metasomatism by granite liquids have enriched the alkali content of the Panjal Traps in Lidderwat area.

The generally close relationship between phenocryst assemblages and the chemistry of these rocks seems to indicate that crystal-liquid equilibria have controlled the evolution of these rocks. A petrogenetic model for the Panjal Traps may be to envisage the extensive partial melting of mantle to generate basic liquids. As the magma started ascend to crustal reservoirs, it cooled to the crystallization temperature of

olivine, and this mineral started to form. These olivine phenocrysts may have settled faster than the rate of rise of the enclosing magma, which appears usually to be quite slow from the zone of magma generation to the shallow reservoirs (Macdonald, 1968) and in consequence of slow ascent extraction of olivine may have been complete. Along with olivine, some pyroxene may also have crystallized and separated. This probably resulted in the depletion of magnesium and some iron relative to calcium and aluminium in the residual magma that reached the shallow reservoirs. At shallow depths, release in pressure may have caused the escape of volatile constituents that are largely comprised of water. This caused explosive eruption and presumably resulted in the formation of pyroclastic material on the surface. Easy availability of calcium and aluminium, under decreased partial water pressure, may have favoured the precipitation of more calcic plagioclase in preference to pyroxene. These crystals along with the liquid erupted at the initial stages of volcanism and formed the lower porphyritic flows. The eruption of the Panjal lava appears to have occurred with a steady and continuous flow towards the surface. Conditions were probably such that near-perfect fractionation (implying a slow rate of ascend) operated almost throughout and gave rise to uniform lava type almost devoid of phenocrysts.



From laboratory studies of melting relationships, Green and Ringwood (1967c) concluded that liquid derived from a mantle of general peridotite or pyrolite (dunite-basalt) compositions under pressure from 30-40 Kb and high degree of partial melting would be of tholeiitic composition with 20% or more of normative olivine in solution. O'Hara (1965), following a similar approach on Hawaiian basalts, also concluded that the primary magma must be undersaturated olivine tholeiite, and that the silica-saturated tholeiites result from the fractionation of olivine tholeiite magma during its rise to the surface. Macdonald (1968) opined that the majority of the visible tholeiitic lavas of Hawaii may not represent the parent tholeiite magma as originated in the mantle. He further, suggested that the recognised masses of very dense material with high seismic velocities beneath the summit regions of most of the Hawaiian volcanoes (Kinoshita, 1965; Kinoshita and Okamura, 1965; Adams and Furumoto, 1965) and the areas of high gravity along the rift zones of volcanoes (Kinoshita, 1965; Strange, Machesky, and Wollard, 1965) are most likely bodies of olivine cumulates that were formed by the lagging behind of heavy phenocrysts in the rising magma. Macdonald (1968) further suggested that the olivine phenocrysts present in Hawaiian tholeiites represent the excess amount of olivine to its stoichiometric ratio that has failed to react with surrounding liquid and become transformed into pyroxene before consolidation of the

magma. If reaction were carried to completion, most of the visible tholeiitic rocks of Hawaii would be olivine free. Murata and Richter (1966) have considered that most olivine rich lavas of 1959 A.D. eruption of Kilauea resulted from the entrainment of olivine that were eroded by unusually rapid flowing magma from a cumulate mass within the magma chamber of the volcano.

Cox et al. (1967) suggested that olivine-free tholeiites of Nayamandhlovu and Featherstone, South Africa have flowed long distances from the source areas, implying that greater time was available to complete the reaction between olivine and residual liquid. In the process, olivine was reacted off from the mineral assemblage.

The low pressure experimental data on basalt fractionation indicates that any one of olivine, clinopyroxene, or plagioclase may be the first mineral phase to separate out from the magma. Within a small temperature interval all three phases will eventually crystallize from the liquid. However, in tholeiite magmas, because of reaction relationship between olivine and pyroxene, crystallization of olivine finally ceases. The presence of only calcic plagioclase phenocrysts in the lower two porphyritic flows of the Panjal Traps may, thus, indicate that the composition of the magma that reached shallow reservoirs after the separation of olivine, and under low partial water pressure has dictated the precipitation of calcic plagioclase as the first phase to separate out from

the liquid. Clinopyroxene, that occurs as microphenocrysts, has formed later. This is further supported by the results of 'simple basalt system' which shows that fractionating liquids lying within the primary phase volume of forsterite will produce plagioclase as the second phase, if they are relatively rich in normative plagioclase, and will precipitate diopside, if they are relatively poor in anorthite.

Cox et al. (1967) have differentiated between the phenocrysts that separate first and form cumulates and those that do not occur as cumulates, instead they show signs of skeletal crystallization. To the first they named "fractionating phenocrysts"; they represent phases responsible for the fractionation of the magma. The second type, "non-fractionating phenocrysts", may be defined as crystals which are significantly larger than the groundmass crystals but have not separated from the liquid in which they formed. They form during the relatively rapid cooling which accompanies or immediately precedes the eruption of the magma. On the basis of this definition of the two types of phenocrysts, the inferred olivine and little pyroxene cumulates that presumably settled in the magma chamber itself and the plagioclase phenocrysts that occur in clusters at the base of the Panjal lava flow sequence may be called "fractionating phenocrysts" whereas clinopyroxene microphenocrysts that occur throughout the whole sequence of lava beds and also the plagioclase of aphyric flows (Flow nos. 3-32) form "non-fractionating

phenocrysts". Since these rocks are largely constituted of early and lower-middle stage members of basalt-rhyolite series, their evolution appears to be largely controlled by the early separation of olivine. The crystallization of small amount of plagioclase as large phenocrysts did not significantly affect further change in the composition of magma.

The amount of inferred accumulation of olivine implies that the trend of the curve for magnesium for that portion may be steep and solely controlled by the separation of olivine (and may be little pyroxene). The known portion of the curve for MgO, and also CaO (Figures 13 and 14) is controlled by the crystallization of plagioclase and clinopyroxene; this agrees well with the present mineralogy of these rocks. A similar conclusion was reached by Macdonald and Katsura (1964) for the Hawaiian tholeiite series, and by Kuno (1968) for the Karroo, Palisades and Dillsberg Sills where the steep portion of the variation curve for MgO was attributed to olivine accumulation and other part to the separation of olivine and pyroxene. In the case of the Panjal Traps the nature of the variation curve for the early part is based purely on inference drawn from the existing type of mineral phases and the bulk chemistry of these rocks. Such an inference is favoured by the low contents of Ni, Co and Cr in these rocks since these elements are incorporated in the structure of olivine and early pyroxene.