ENVIRONMENT AND TECTONIC SET-UP OF ERUPTION

Bion (1928) observed that the topmost layer of the Agglomeratic slate immediately below the Panjal Traps in Kolahai-Basmai area contains irregular blocks of traps of all sizes with pillow appearance which they suggest to be the result of lava flows and bombs entering a shallow sea. Nakazawa and Kapoor (1973) also reported pillow lava with spilitic composition from Guryul Ravine, Khunumu, Srinagar, where it is seen as a single interflow in the upper part of the Panjal Traps; the outcrop of this flow is very small, 20 m x 4 m, and 3.5 m thick. They concluded that the Panjal Traps in the eastern and southeastern Kashmir were erupted "at very shallow sea-bottom, presumably coastal if not lagoonal conditions". According to Pascoe (1959) the Panjal Traps erupted on coastal land surface subjected to occasional transgressions of sea or on a sub-marine shelf. However, Wadia (1957) concluded that the Panjal Traps of Kashmir represent subaerial eruptions that "bridge the gap which is usually perceived at the base of Permian in all other parts of India". During the present study, carried out mainly in Lidderwat area, pillow structure was not observed in the Panjal Traps. Further, petrographic and geochemical investigation do not favour eruption of these lavas under marine conditions of any nature, or for that matter, even the transgressional conditions at least during the upwelling of the thirty-two flows that were studied.

The characteristic feature of the Panjal Traps of the Lidderwat area is their vesicular nature. Vesicles in a single flow vary in size from small specks to as large as 8 centimeters (longest-axis), generally their diameter is 1 centimeter. Pipe amygdules, mostly confined to basal parts of each flow, are also observed.

Under subaqueous conditions of lava eruption below a certain critical depth, separation and expansion of dissolved gases into bubbles will be inhibited by the pressure of overlying water (Rittman, 1936; Macdonald, 1954a; McBirnery, 1963). Rittman's (1936) theoretical deduction of 2,000 meters as critical depth has recently been confirmed by dredging on submerged portions of the East rift zone of Kilauea volcano, Hawaii. At a depth of 4,000 meters vesicles are rare and average less than 0.1 mm in diameter; lava erupted at 800 meters have only 10% of the vesicles with an average diameter greater than 0.5 mm whereas below 800 meters vesicles decrease both in number and diameter (Moor, 1965). However, the lavas erupted in shallow waters may have the same vesicularity as subaerial flows but in that case lava develops pillow structure which is a distinctive feature of the subaqueous eruptions. Yagi (1969) and Snyder and Frazer (1963a, b) maintain intrusive origin for certain pillow lavas, the magma having intruded into unconsolidated silty or sandy sediment with 70 to 85 volume percent water on sea bottom may result in pillow structures. Whether we assume eruption of lava in subaqueous environment or intrusion of magma into unconsolidated sediments impregnated with water on the sea bottom, under both circumstances the presence of water to the extent of atleast 70 to 85 volume percent is prerequisite for the formation of pillow structures.

The pillow structure, however, was not observed on any of the flows of the Panjal Traps form base to the top in the area under discussion. Thus, this feature in addition to the high vesicularity of these rocks suggest that the Panjal lava eruption took place under subaerial environment.

The composition of the plagioclase crystals in the Panjal Traps is highly calcic (An_{56}- An_{82}). This is also expressed by the high CaO content of these rocks in their bulk chemistry; CaO varies from 13.06 to 6.84%, with an average of 9.88%. Under subaqueous environment of eruption ionic exchange, Ca from lava for Na of ocean water, results in the depletion of Ca in the lava and, as such, plagioclase composition changes from calcic to sodic nature; thus, Ca content in the bulk composition decreases. This type of chemical exchange has been invoked by many investigators (Daly, 1914; Beskow, 1929; Gilluly, 1935; Park, 1946; Szadeky-Kardoos, 1963; Rösler, 1963) to explain the secondary origin of spilites. Nakazawa and Kapoor (1973) also argued that pillow lava reported by them in the Panjal Traps at Guryul Ravine, Srinagar is spilitic in composition and has formed due to the eruption of Panjal lava in coastal or lagoonal conditions during the transgression of the sea water. But in Lidderwat area, as noted earlier, pillow structure was not observed in the Panjal Traps, and also the lavas are tholeiitic with high Ca-content instead of spilitic; the chemical exchange between Ca of Panjal lava and ocean water does not appear to have occurred.

Furthermore, submarine basalts are found to have consistently low concentration of TiO_2, K_2O and P_2O_5 (Manson, 1968; Cann, 1971). Loss of K from lava through exchange with Na of sea water causes depletion of K_2O in the lava erupted under sea water (Aumento, 1969; Cann, 1969). Hart (1970) concluded that TiO_2, K_2O, and P_2O_5 are lost to sea water in the order of $TiO_2 > K_2O > P_2O_5$. Though enriched values of Na_2O are consistent with the assumption that the Panjal Traps erupted under subaqueous conditions, the high percentage of K_2O and TiO_2 goes against this in view of the findings of Hart (1970), Still, supposing the Panjal lava erupted under submarine conditions and later alkali metasomatism increased its potassium concentration above normal, in that condition TiO_2 should also have very less since this element is lost to sea water in preponderance to K_2O and P_2O_5 and there is no evidence to warrant consideration of later enrichment of TiO_2 from some extraneous source. Instead, TiO_2 content of the

Panjal Traps is even slightly above normal for their tholeiitic nature which may be due to their relatively deeper source (Beus, 1976). Moreover, the high P_2O_5 content of the Panjal Traps also suggests that this element in these rocks has not been depleted under oceanic water. Basalts erupted under marine conditions have generally low P_2O_5 values (Clarke, 1970).

Thus, various lines of evidence strongly indicate that the Panjal Traps are the result of volcanic eruption that occurred subaerially. The two isolated occurrences of pillow structures in Kolahai-Basmai and Guryul Ravine, Srinagar, are probably due to local limited subaqueous conditions.

Tectonic Set-up

Based on the major oxide and rare earth composition of spilitic pillow lavas of the Panjal Traps at Guryul Ravine near Srinagar, Nakazawa and Kapoor (1973) noted "strong resemblance" of these rocks with the geosynclinal basic volcanics of late Palaeozoic in Japan which according to Sugisaki et al. (1971) are the result of ocean spreading like that of the Gulf of Aden and Red Sea. Nakazawa and Kapoor (op.cit.) suggested that though the Panjal Traps and the geosynclinal basic volcanic of Palaeozoic in Japan belong to two different types of environment of eruption, the Panjal Traps may offer an interesting problem on the genesis of the basalts with "oceanic affinity".

Ahmad and Ahmad (1976) suggested that the basic volcanic rocks along the Himalayas from the Panjal Traps of Kashmir in the west to the Abor volcanics of Assam in the east with Mandi and Bhowali traps of Himachal Pradesh and Uttar Pradesh respectively in between, and their counterparts in southern and western Siberia, are the result of ocean spreading along this region. However, Ahmad (1977) opined that this volcanic activity occurred much to the north of Kashmir and continued for a long time before the actual ocean spreading, to last for a short span of time, started in the Triassic period. To account for the present position of the Siberian-Cathysian block, Ahmad and Ahmad (1976) suggested that this block was oroclinally rotated in the clock-wise sense around a pivot in the Verkhoyansk mountain area in the Jurassic period. Rotation of Siberia is also indicated by the paleomagnetic studies of Hamilton (1970) and Kropotkin (1971).

Vine (1966) thinks that flood basalts erupt much before the continents split apart. Flood traps may precede the breaking up of a continent and development of a spreading plate margin on the lines suggested by Cox (1970) for the Gondwanaland.

In the present study, "geochemical fingerprints" are used to provide more detailed information about the tectonic environment of the Panjal Trap eruption. For this purpose, the methods proposed by Pearce and Cann (1973), Flyod and Winchester

(1975), and Pearce et al. (1975) are used. Pearce and Cann (1973) showed that trace elements like Ti, Zr, Y, Nb, and Sr can be used to determine the tectonic setting of the basic volcanic rocks. The main problem in this type of study is the chemical mobility of elements during alteration processes. The nature of trace elements composition of the Panjal Traps has already been discussed and it can be inferred that the use of these elements may largely display primary features of these rocks. Moreover, the elements used here have been shown to be insensitive to alteration processes.

Pearce and Cann (1973) distinguished different tectonic environments of lava eruption. Ocean floor basalt series belong to volcanic rocks erupted at accreting plate margins; island arc (low potassium) tholeiite suite (LKT), calc-alkali basalt suite (CAB), and the shoshonitic suite (SHO) are produced at converging plate margins. Within-plate basalts (WPB) include basalts of continental regions and ocean islands which are erupted within plates. This type of vulcanicity is attributed to hot mantle plumes.

Pearce and Cann (1973) proposed a set of diagrams to determine the tectonic set up of lava eruption of unknown basaltic rocks. After characterizing the nature of the magma, tholeiitic or alkalic, by Y/Nb ratio, the three diagrams, Ti-Zr-Y, Ti-Zr (for altered samples), and Ti-Zr-Sr (for fresh rocks), are plotted. On Ti-Zr-Y diagram, within-plate basalts fall in a distinct field D, and ocean floor basalts in field B. Calc-alkali basalts plot in fields C and B, and low potassium tholeiites in fields A and B. Winchester and Floyd (1975) found that a number of "clearly continental tholeiites", such as Tertiary Baffin Bay basalts, plot in ocean floor basalt field of the Ti-Zr-Y diagram and Ti-Zr diagrams, and show a trend similar to ocean floor basalts on Ti-Zr diagram. They also quote the classification of these continental tholeiites as "oceanic" on the TiO_2-K_2O-P_2O_5 discrimination diagram of Pearce et al. (1975). On these basis they suggested that the field B (ocean floor basalt field) of the Ti-Zr-Y diagram of Pearce and Cann (1973) represent not only ocean floor basalts but all tholeiitic basalts erupted in a rifting environment (such as mid-oceanic ridge continental rifts) from relatively primitive magmas.

After within-plate basalts have been identified or screened out on Ti-Zr-Y diagram, the next step is to plot the Ti and Zr values on Ti-Zr diagram to confirm the characterization of other basalt types (ocean floor basalts, island arc basalts, etc.). In this diagram none of the basalt types occupies a single distinct region. Ocean floor basalts plot in fields D and B, calc-alkali basalts within C and B, and low potassium tholeiites in fields A and C. Thus all the basalt types encroach on field B. In cases where majority of the plots lie in field B, Pearce and Cann (1973) suggested that further

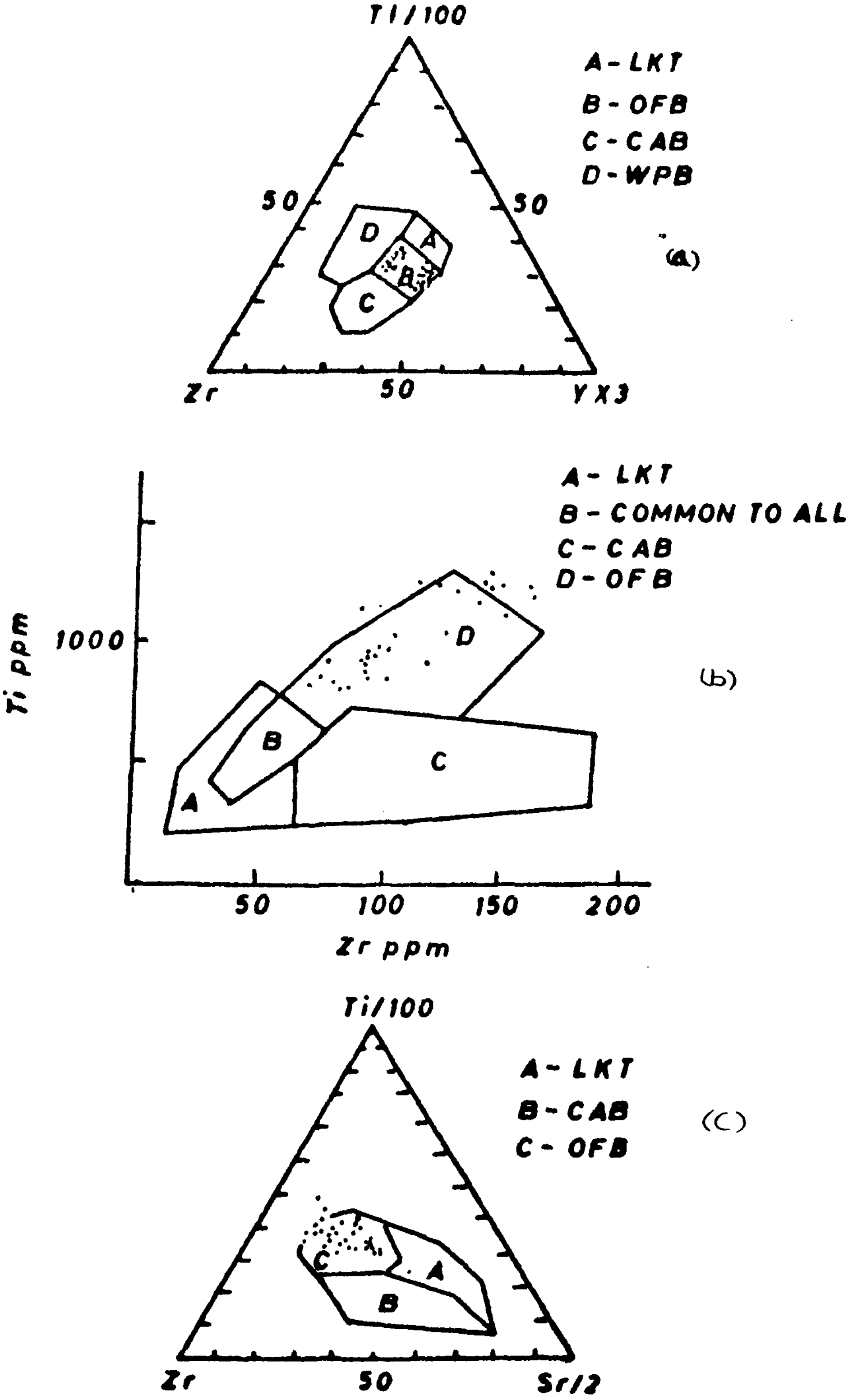

Figure 18. Plots of the Panjal Traps on (a) Ti —Zr —Y, (b) Ti — Zr, and (c) Ti — Zr —Sr of Pearce and Cann (1973).

evidence about the tectonic environment of lava eruptions should be sought.

The third diagram of the proposed discriminant flowchart, Ti-Zr-Sr, is used for fresh samples and for those rocks in which Sr content has been shown unaffected. In this diagram ocean floor basalts are well separated in field C, low potassium tholeiites plot in field A, and calc-alkali basalts in field B.

Figure 18 shows plots of (a) Ti-Zr-Y, (b) Ti-Zr, and (c) Ti-Zr-Sr for the Panjal Traps on Pearce and Cann's (1973) diagrams. On Ti-Zr-Y diagram (Figure 18a), the plots exclusively occupy B field which suggests ocean floor basalt tectonic environment. Since, field B in this diagram is also encroached by calc-alkali basalts and low potassium tholeiites, assignment of the Panjal Traps to an ocean floor basalt environment may need further verification. However, the possibility of within-plate basalt tectonic environment for these rocks may be eliminated.

On Ti-Zr diagram (Figure 18b), the Panjal Traps occupy field D which is distinctive for ocean floor basalts. Thus an ocean floor basalt or spreading plate margin environment may be suggested on this basis. This is also supported by the plots of these rocks on Ti-Zr-Sr diagram (Figure 18c) in which points fall in field C (ocean floor basalt field).

Miyashiro and Shido (1975) have shown that abyssal tholeiites (ocean ridge tholeiites) cluster within a small distinct region on plots of Fe_2O_3+ FeO, V, and TiO_2 against Fe_2O_3+FeO/MgO (Figures 12a, b, and 16b) and V against Cr (Figure 16a). It is seen that majority of the points for the Panjal Traps lie within the abyssal tholeiite region (encircled area) on these diagrams except in Figure 16a in which the points plot outside the abyssal tholeiite field. This is obviously due to low Cr content which has been inferred to be related to the separation of early formed pyroxenes. Although these diagrams do not distinguish between the different tectonic environments of lava eruption, they do, indeed, show affinity of the chemical composition of the Panjal Traps with the ocean ridge basalts. Such a similarity may further lend support to the ocean floor basalt tectonic environment of eruption for the Panjal Traps as is indicated by the plots of these rocks on Pearce and Cann's (1973) diagrams.

Ocean floor basalts are produced at diverging plate boundaries. Such basalts are predominantly and characteristically pillow lavas with associated diabase dikes, gabbros and ultramafics (Pearce, 1975). These rocks characterise mid-ocean ridges and marginal basins (Hart et al., 1972). As noted earlier, the Panjal Traps in the area under investigation do not exhibit pillow structures. Such a character which indicates continental environment of lava eruption appears incompatible with the strong similarity in chemical composition and the inferred tectonic setting of eruption that these rocks show with ridge basalts.

The resolution of this contradictory evidence may be sought in the ternary diagram of Pearce et al. (1975). This diagram used TiO_2, K_2O and P_2O_5 as three end members. With the help of this diagram, Pearce et al. (1975) found that non-alkaline "primitive" oceanic and non-oceanic (continental) basalts can be discriminated. They used a maximum of 20% alkalis in $(Fe_2O_3 + FeO) - MgO - (Na_2O + K_2O)$ diagram as a screen for the analyses of basaltic rocks that can be plotted on this diagram. Of the various basalt suites from different parts of the world plotted on this diagram, Pearce et al. (1975) found that the Tertiary basalts of Scoresby Sund, Greenland and the Deccan traps of India show abnormal plots. Though both these suites are accepted to be eruption in continental environments, they occupy regions of oceanic basalts in the $TiO_2 - K_2O - P_2O_5$ diagram. Pearce et al. (1975) suggested that "continental basalts suite displaying oceanic affinity in the $TiO_2 - K_2O - P_2O_5$ diagram may be a result of abortive attempt to generate new ocean floor".

Out of the 32 analyses representing the thirty-two flows in Lidderwat area that were sampled and analysed for the present study, only 15 analyses were found to contain less than 20% alkalis in total MFA. When these analyses were plotted on the $TiO_2 - K_2O - P_2O_5$ diagram, 60% of the total points fall in

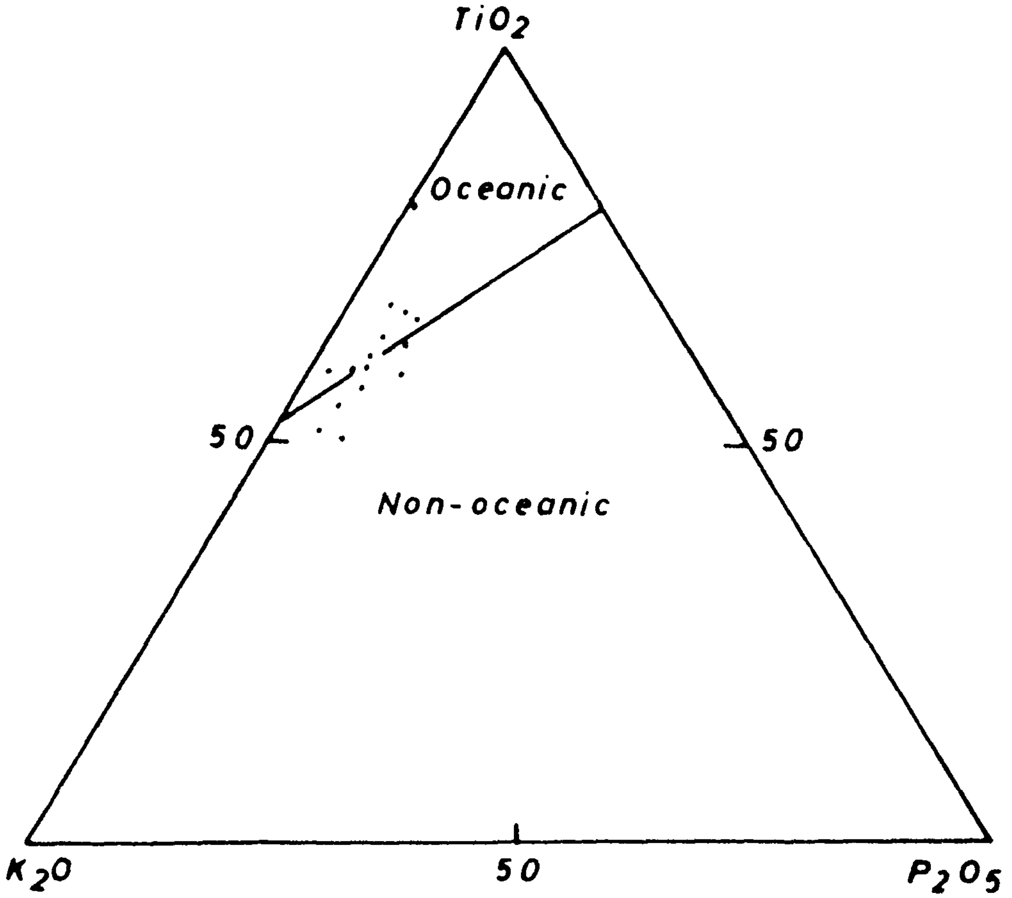

Figure 19. TiO_2 — K_2O — P_2O_5 plots of the Panjal Traps on Pearce et al. (197). The boundary line in the diagram separates oceanic and non-oceanic (continental) environments.

oceanic region whereas the rest plot in non-oceanic region (Figure 19). It is evident from this diagram that those analyses that plot in non-oceanic field are very close to the discriminant boundary and do not extend much away from it. Further, the plots have a linear trend extending from oceanic to non-oceanic field towards K_2O corner of the diagram. Weathering and alteration tend to move oceanic basalts into non-oceanic field; however, altered basalts which plot in oceanic region are unlikely to have a non-oceanic origin (Pearce et al., 1975). It has been mentioned earlier that the Panjal Traps have been enriched in alkalis which may be responsible for the plots of some of these rocks in non-oceanic field.

Also, it was noted that the Panjal Traps have Sr-depleted character similar to submarine tholeiites (ridge basalts). Furthermore, the Panjal Traps bear resemblance in their Sr-depleted nature with Antarctic tholeiites (average Sr = 120 ppm; Gunn, 1966; Compston et al., 1968), Tasmanian Tholeiites (average Sr = 130 ppm, Heier et al., 1965; MacDougall, 1962) and Deccan traps (average Sr = 100 ppm, Karkare, 1965). However, ridge basalts are low in Ba too. In the Panjal Traps both Rb and Ba contents have been suggested to represent enriched amounts. Thus, nothing can be said with reliability about the original amounts of these two elements except that they were probably lower in the magma at the time of its extrusion.

Compston et al. (1968) found that Mesozoic dolerites of Antarctica and Tasmania have significantly close similarity in their geochemistry and age which may not be a simple coincidence. They opined that a common source and history for these two now widely separated basic rocks may be explained by accepting the proposition that Tasmania and Antarctica were joined together in Jurassic period. They suggested a similar approach to explain the chemical and chronological similarity of basaltic rocks of South Africa and South America. Brooks (1973) opined that the Tertiary basalts exposed in East Greenland may be related to the initial rifting of the (super) continent and generation of ocean floor with the formation of Atlantic ocean. Possibly the basalts of West Greenland and Baffin Islands are contemporaneous with the opening of Labrador Sea (Clarke, 1970; Clarke and Upton, 1971; Le Pichon et al., 1971). Similarly, the 50,000 km^2 of basalts forming Deccan traps may be related to a major flexure or tensional feature approximately parallel to the mid-oceanic ridge (Gibson, 1971). Thus, it may be suggested that the Panjal Traps represent volcanic eruptions that occurred in a rifting environment. The plots of these rocks in ocean floor basalt fields in the Pearce and Cann's (1973) diagrams may indicate that ocean floor basalt field in these diagrams includes not only ocean floor basalts but all such basalts that are erupted in a rifting environment.

The present investigation thus, support the view of Nakazawa and Kapoor (1973) that the Panjal Traps bear oceanic affinity. The most plausible suggestion for the origin of these rocks consistent with their oceanic affinity and the inferred tectonic environment of eruption may be the one proposed by Ahmad (1977) that these volcanic rocks are the result of eruptions that preceded the actual fragmentation and separation of Siberian-Cathysian block from Gondwanaland a ? and the formation of mid-ocean ridge and consequent Tethys ocean in this region during Triassic period. The phase of ocean spreading was short lived when in Cretaceous period the southward movement of Siberian-Cathysian block due to the push of the Gakkal ridge in Arctic ocean which started forming during this period, and the northward migration of India due to its oroclinal rotation about a pivot in Baluchistan arc, closed the then emergent Tethys ocean. Such an explanation is in conformity with the geochemical results of the Panjal Traps. TiO_2 - K_2O - P_2O_5 diagram for these rocks also indicates that these lavas were erupted along a rift that was later "aborted". Kamen-Kay (1972), Burrett (1972) and Menzies (1976) agree that the Tethys opened up as an ocean by "rifts".