General Statement

Although a general consensus has been reached among the geoscientists that the southern part of Delhi fold belt has been evolved through Phanerozoic type plate tectonic processes (Sychanthavong and Desai 1977; Sinha-Roy 1988; Sugden et al. 1990; Volpe and MacDougall 1990; Yedekar et al. 1990; Raza et al. 1993) the tectonic setting of north Delhi fold belt comprising Bayana, Alwar and Khetri basins is poorly understood. In various models, the tectonic setting of these basins has been interpreted in different ways. For example, Singh (1982) and Roy (1990) proposed that these basins opened as a system of ensialic grabens arranged in three NE-SW trending belts following the closure of Aravalli and related rifts. According to these authors the Bayana and Alwar basins tapered out towards south but the Khetri basin extended up to Gujrat covering the entire axial part of Aravalli mountain belt. Sinha-Roy (1988) considered the development of northern and southern parts of Delhi fold belt under different tectonic conditions and postulated that the sedimentary basins of north Delhi fold belt opened up as pull apart basins in a N-S trending rifting system, the southern boundary of which was bounded by E-W trending Sambar-Jaipur-Dausa (SJD) transcurrent fault. This fault behaved as a transform fault for the ocean opening in the
south Delhi fold belt. Sinha-Roy (1988) also suggested that the north Delhi rifting was aborted, but the south Delhi basin developed into an oceanic trough. Sugden et al. (1990) have considered the development of Khetri Copper Belt in a back arc tectonic setting. Yedekar et al. (1990) have also proposed the evolution of Khetri belt over a Proterozoic subduction zone.

Although the tectonic setting of north Delhi fold belt has been interpreted in different ways by different authors, the mafic rocks occurring in different basins have not been taken into consideration probably due to the lack of geochemical data. In the present chapter, the geochemical data corroborated with field evidence are used to interpret a possible geodynamic model which could account for the geological and geochemical characteristics of the magmatic rocks of north Delhi fold belt.

Bayana Volcanics

Geochemical data presented in this study suggest that the Bayana volcanics are essentially tholeiites and that they have remarkably similar characteristics to continental flood basalts (CFB) of Proterozoic and Phanerozoic ages which erupted on the surface as lava flows or emplaced at shallow depths as dyke swarms at the time of continental breakup. The geochemical data in combination with field evidence also suggest that the Bayana volcano-
sedimentary sequence was laid down in a rifted basin.

On the basis of a large body of structural sedimentallogical, geochronological and geochemical data, it has been advocated that northwestern Indian shield comprising Aravalli Craton bears the stamp of nearly ordered Phanerozoic type Wilson cycle events (Sinha-Roy 1988; Deb and Sarkar 1990; Sugden et al. 1990; Raza et al. 1993; Banerjee and Bhattacharya 1994). Rift related continental tholeiites which have been reported from many Proterozoic belts of this region (Ahmad and Rajamani 1991; Raza and Khan 1993; Abu-Hamattteh et al. 1994) appear to be the markers of this type of evolution and their study may provide useful informations about the mechanism of continental breakup in that time and thus may highlight the major features of Proterozoic evolutionary history of north Indian shield.

The rifts are linear depressions which are formed under the influence of extensional regimes. If their development is not stopped by compressive stresses, they are the sites of lithospheric attenuation, continental rupture and eventually the generation of new oceans. The ancient rifts are best indicator of extensional regimes which operated at the time of their origin. The development of continental rift system has been described and discussed in two ways (Sengor and Burke 1978; Bedard 1985) depending upon the mechanism that causes the upward movement of
asthenosphere-lithosphere boundary. In the first type the rifting is directly induced by a plume activity resulting in domal uplift with the formation of radial rift structure or rift-rift-rift triple junctions. In this process the upwelling of deep mantle plume causes melting of the mantle as well as thinning of lithosphere, eventually leading to rifting (White and McKenzie 1989). This mechanism of rift formation, that is termed as "active", produces the volcanism that is usually alkaline and predates the major taphrogenesis. In another type that is described as "passive", the already existing tensional forces, probably along the pre-existing weak zones, cause lithospheric stretching and attenuation and subsequent adiabatic decomposition. The basic magma is produced when the mantle temperature exceeds the solidus temperature of mantle materials (White and McKenzie 1989). In such a case mantle participation is not active, doming is not necessary, magma produced has a uniform composition and the resulting volcanism postdates the taphrogenesis. It is important to determine whether the crustal extension predates, synchronous or postdates the volcanism. It would help to understand whether the mantle was a passive or active participant in rift formation.

The origin and evolution of Bayana rifted basin can be constrained by geochemical characteristics and
field occurrences of mafic lavas and the nature of sedimentary formations associated with them. Sedimentation in this basin started with the deposition of about 200m thick unit comprising predominantly of conglomerate with quartzite (Singh 1982) which immediately lie on pre-Delhi basement (Figure 2A) consisting low to high grade metamorphites, gneisses, migmatites, granites and highly altered mafic rocks. The basement rocks are tightly folded on NE-SW axis (Singh 1982). The basal conglomerate-quartzite formation contains abundant well developed cross stratification and ripple marks. The deposition of this thick conglomerate-quartzite unit directly on the Pre-Delhi basement suggests that sedimentation in Bayana basin started with the development of rift generated fault scarps. The presence of conglomerate-quartzite unit between volcanics and underlying basement lithologies is a clear indication that crustal extension started well before the volcanism (Figure 2B). The crustal extension continued even during the volcanism, is evident from occurrence of sediment beds within the volcanic pile.

The unconformity between the volcanic pile and overlying sediments suggests that the basin was subjected to uplift after the volcanic episode. The continuation of extensional regime even after peak volcanism is apparent not only in Bayana basin but also in Alwar basin.
as indicated by occurrence of faults which cut the entire volcanic sequence and probably the older rocks. Furthermore, the development of fissures along northeasterly trending deep seated structures (Banerjee and Singh 1977), which occur parallel to the Aravalli folding (NE-SW), suggest that stretching and subsequent rifting followed the older structures of the area. This is also evident from the trends of boundary faults of Bayana rift, and most of the other faults in the region which are mostly northeasterly trending and coincide well with pre-Delhi fold trends and other lineaments of Aravalli mountain belt. The Bayana volcanics can be considered to have been erupted in a tensionally induced rifting environment as suggested by geochemical and field evidences, which are summarised below:

1. Relative timing of rifting and volcanism indicate a rifting process initiated in response to tensional forces applied to lithosphere causing its stretching and attenuation.

2. Formation of rifted basins along general strike of Aravalli mountain belt suggests arrangement of igneous activity along pre-existing weak zone.

3. Eruption of only tholeiites throughout the volcanism does not support plume hypothesis.

4. Geochemical characteristics as discussed in previous chapters are not compatible with the eruption of mafic
flows under the influence of a hot spot or plume. Further evidence is provided by their Nb/Zr and Nb/La ratios. Nb/Zr ratios of tholeiites and high-K basalts of Bayana basin average at 0.09 and 0.07 respectively. These values are considerably lower than those of plume related lavas (e.g. Tristan de Cunha Nb/Zr=0.26; Hawkesworth et al. 1992). Similarly Nb/La ratio of Bayana volcanics (average 0.65) are considerably lower than those of plume related basalts (average ~1.2, Hawkesworth et al. 1992). Therefore, low Nb/Zr and Nb/La ratios of Bayana volcanics even those of high-K samples do not suggest any evidence of involvement of typical plume related OIB in their genesis.

In absence of plume activity it would appear that the Bayana volcanism is the consequence of tectonic processes. Although some thermal problems have been pointed out in generating large volumes of magma solely by extension (Latin and White 1990), most calculated geotherms (Gallagher and Hawkesworth 1992; Hawkesworth et al. 1992) indicate that continental basalts may be generated in subcontinental lithosphere by partial melting of hydrous peridotites even without the involvement of mantle plume. In this way the melting within the subcontinental lithosphere may take place in response to extension and relatively small increase in temperature.
In this manner both geochemical and geological evidence are in accordance with a model for eruption of Bayana volcanics in which they were erupted during a period of crustal extension. The magma appears to has been derived from an enriched lithospheric source and evolved tholeiitic in nature similar to those erupted recently as continental flood basalts. The volcanism ceased abruptly after producing a maximum of 1000 m thick lava sequence but followed by the filling of the basin with continentally derived sediments in a fluviatile sedimentary environment. Therefore, the volcanism is analogous to the volcanic activity associated with failed rifts connected with middle Proterozoic continental breakup.

**Khetri Amphibolites**

The geochemical characteristics of Khetri amphibolites as discussed in previous chapters, in terms of major, minor, trace and rare earth element concentrations and their ratios, suggest that they have some characteristics akin to those of subduction generated magmas. Important geochemical characteristics are their tholeiitic-calc alkaline affinity and enrichment of LREE and LILE relative to HFSE. The enrichment of LREE and LILE relative to HFSE in subduction related magmas is attributed to stabilization of HFSE bearing phases such as rutile, ilmenite and sphene under hydrous partial melting and
simultaneous transfer of LILE through fluids and melts released from dehydration of subducting lithosphere (Saunders et al. 1980). The continental basalts also display enrichment of LILE and HREE relative to HFSE, although the level of abundances of these elements may be high and Nb-Ta anomalies less prominent. The high ratio of LILE/HFSE in Khetri amphibolites relative to Bayana volcanics is evident from figure 33, in which MORB-normalised values of these elements are presented in the form of spidergrams. In case of continental tholeiites, as discussed in previous chapter, these characteristics are explained by employing the enrichment of their source region through fluids and/or melts rising either from deeper part of the mantle or under the influence of earlier subducted slab (Brooks et al. 1976; Jordan 1978; Kyle 1980; Mensing et al. 1984; Alibert 1985). In this manner it becomes very difficult to determine whether the source was contaminated at the time of generation and emplacement of magma in a subduction related tectonic setting (Saunders et al. 1980) or the magma was derived from a subcontinental mantle source which had been geochemically modified during earlier subduction episode when sediments are also likely to have been dragged down and mixed with subcontinental lithospheric mantle (Hergt et al. 1991).

To identify the subduction signature in the
chemistry of the Khetri amphibolites or otherwise, we will further explore the geochemical data. When compared with Bayana continental tholeiites the Khetri amphibolites display following significant differences.

1. Lower concentrations of HFSE including Zr, Y, Nb, Ti (Figure 30B) and also low Ti/Y ratios.

2. Lower concentration of transitional elements Ni, Cr, Co, Sc, and V suggesting their more differentiated nature.

3. High concentration of LILE such as K, Th, U and Ba.

4. The La/Nb ratio (representing LREE/HFSE ratio) of these amphibolites are generally > 2 (except 1.58 of the sample 87) and averages at 4.92. On the other hand, the La/Nb ratios of Bayana continental tholeiites are < 2 and averages at 1.39. The average Y content of Bayana volcanics is 23 ppm on the other hand Y content of Khetri amphibolites averages at 17 ppm. It has been observed that subduction related basaltic rocks generally have La/Nb > 2 and Y < 20 ppm and basalt erupted in extensional tectonic setting have a La/Nb < 1.00 and Y < 20 ppm (Thompson et al. 1983; Lees et al. 1987; Winchester et al. 1987).

5. The extremely high Al₂O₃/TiO₂ and CaO/TiO₂ ratios. Such higher ratios can not be produced by variable degree of partial melting of lherzolite source (Sun and Nesbitt 1978; Sun et al. 1979). This suggests that the source of
amphibolites was extremely depleted in Ti probably by previous volcanic episode or Ti behaved as compatible element during evolution of magma.

The differences in the mantle source characteristics of the Bayana volcanics and Khetri amphibolites can be assessed using incompatible element ratios. Th/Yb and Ta/Yb ratios of these rocks are plotted in figure 52. In this diagram processes of mantle enrichment or depletion, which are not related to the subduction zone and include even fractional crystallization and partial melting effects are represented by a vector (W) with slope of unity. Two other vectors S and C, which are subvertical, represent enrichment of the mantle wedge above subduction zone and crustal contamination respectively. In this diagram the Bayana volcanics and Khetri amphibolites clearly separate out from each other. The plots of Bayana volcanics follow vector W and lie in the field of non arc basalt and suggest that these volcanics have been derived from a within plate enriched source. On the other hand, the plots of Khetri amphibolites cluster separately in the field of arc basalt and follow vectors S and C. The plots of Khetri amphibolites above those of Bayana volcanics may be attributed either to crustal contamination or subduction related metasomatism as indicated by vector C and S respectively. However, the former interpretation is unlikely.
Figure 52 Ta/Yb versus Th/Yb plot for Bayana volcanics and Khetri amphibolites (after Pearce 1982, 1983), vectors represent variation expected for 

- $W =$ Within plate enrichment/depletion; 
- $S =$ Subduction related metasomatism; 
- $C =$ Crustal contamination; 
- $f =$ Fractional crystallization. 

$\bigcirc =$ Primordial mantle (Pearce 1983).
because no significant effect of contamination is found on the chemistry of these rocks as discussed in chapter five. The remaining interpretation is that the melts of Khetri amphibolites have been produced from a source which was enriched through subduction related metasomatism.

To understand the tectonic setting of Khetri amphibolites more objectively, the similar rocks of south Delhi fold belt can be considered. The amphibolite bodies, representing mafic sills and larger bodies of mafic igneous rocks are extensively found in calc-schists, cal-gneisses, limestones and pelite schists of Ajabgarh Group occurring to the south of Ajmer. Some amphibolitic sills, large intrusions and metavolcanics of south Delhi fold belt have geochemical signatures that have been called subduction related (Volpe and MacDougall 1990; Raza et al. 1993). Present study suggests that the amphibolites of Khetri belt that appear to be a northward extension of amphibolites bearing Ajabgarh sequence of south Delhi fold belt (Singh 1988; Roy 1990) also have a geochemical signature that can be called transitional calc-alkaline or subduction generated. A close similarity of Khetri amphibolites and equivalent mafic rocks of south Delhi fold belt in terms of trace elements is evident in figure 32. In this diagram the Khetri amphibolites and similar rocks of Delhi fold belt display a close affinity with volcanic arc of continental
The occurrence of Khetri amphibolites as sills with their subduction related chemistry is in accordance with the suggestion of Tarney et al. (1981), that such igneous rocks are common in back arc basins, perhaps because of irregular spreading process or rapid filling. These features are compatible with the model of Sinha – Roy (1988) and Sugden et al. (1990) who postulated the deposition of Delhi rocks of south Delhi fold belt in a back arc basin. The development of Khetri belt in a subduction related setting is also speculated by Sugden et al. (1990), Yedekar et al. (1990) and Ray (1992). If Khetri amphibolites were emplaced in a back arc basin, it appears that this basin was developed on a continental crust and could not evolve up to an advance stage of rifting in which ocean type crust is formed in back arc basins. In such a situation the basaltic rocks would characterize by trace element enrichments which may contain two components (Pearce 1983), i.e. a subduction component and a lithospheric component (Figure 30). High LILE, and LREE and low HFSE with large variation in Nb values (2 ppm – 13 ppm) in Khetri amphibolites suggest the presence of both types of components in their chemistry. The source related enrichment of LILE, LREE (Figures 28 and 53) and development of calc-alkaline tendency in Khetri amphibolites (Figure 23)
are typical of ensialic basins formed over subduction zones (Saunders and Turley 1984).

The occurrence of ophiolitic sequence (Phulad Ophiolite; Gupta et al. 1980), subduction related lavas and intrusions (Volpe and MacDoughall 1990), fragments of higher pressure grospydite (Sychanthavong and Merh 1984) in south Delhi fold belt, all suggest the subduction of oceanic crust and formation of volcanic arc in that part of Delhi fold belt and that the terminal collision occurred with emplacement of ophiolitic sequences. The site of collision is now represented by tectonic contact between Aravalli and Delhi Supergroups (Sinha-Roy 1988; Sugden et al. 1990; Yedekar et al. 1990). Although the Khetri belt appears to be a northward continuation of south Delhi fold belt (Naha et al. 1984; Singh 1988; Sharma 1988; Roy 1990), the lithologies representing ancient arcs and ocean floor are not developed so prominently as in the case of south Delhi fold belt. However, the absence or paucity of ophiolitic and related sequence is not a generally applicable criteria to identify the ancient suture zones (Windley 1992). This is due to the fact that ophiolites are not found all along the length of a suture but occupy only parts of it (e.g. 600 Km along 3000 Km length of Indus suture of Himalaya: Windley 1992). One reason for this may be that the colliding margins are not always parallel and along the parts where they are
parallel the chances of ophiolitic emplacement are less. The same may be applied to the north Delhi fold belt. However, it is clear that the Khetri basin was at a considerable distance from the arc as indicated by paucity of volcanic rocks (Sugden et al. 1990) and signature of subcontinental lithosphere in the chemistry of amphibolites. With all probabilities it appears that the sedimentary accumulation of Khetri belt are rift basin fill, in which tholeitic lavas with a calc-alkaline tendency was emplaced predominantly as sills in a back arc environment (Sugden et al. 1990). The occurrence of sulphide deposits in the sedimentary package of Khetri belt also favours a back arc basin tectonic setting where the necessary conditions i.e. the heat and the extensional regime are available for the accumulation of such deposits (Vance and Condie 1987).

Tectonic Evolution of North Delhi Fold Belt

Interpretation of the tectonic evolution of north Delhi fold belt hinges on the following important observations.

1. The Bayana basin volcanics show major, trace and rare earth element signatures of within plate continental basalts which erupted in an ensialic rifted basin probably produced by extensional regime along pre-Delhi fold trends.

2. The Khetri amphibolites are transitional between
tholeiite and calc-alkaline basalts with subduction signatures in their chemistry and are likely to have been emplaced in a back arc ensialic basin.

3. Metamorphism and deformation in the north Delhi fold belt increase from east to west. Also, the age of granite intrusions increases from east (~1600 m.y.; Bairat, Dadikar, Harsora granites etc.) to west (~1400 m.y.; Saladipura, Udaipur, Seoli granites etc.).

4. The lithologic make-up and depositional history of Khetri basin and Alwar-Bayana basin appear to be significantly different. For example the proportion of volcanic and sedimentary rocks is high in the later and the former is more pelagic in nature.

5. The overall geological features of southern part of Delhi fold belt (south of Ajmer) suggest that it has been evolved through Phanerozoic type plate tectonic processes.

6. Available data on stratigraphy, structure and metamorphism suggest the continuity of Delhi fold belt from Khetri in the north to near Ahmadabad in south.

7. Several regional longitudinal fault zones and shears are found to run all along the length of Delhi fold belt from south to north.

In view of the above considerations it is expected that the sedimentary basins of NE Rajasthan have
been formed in response to the stresses generated by plate boundary forces. The formation of Bayana - Alwar rifts was probably linked to tectonic processes which operated during preceding period and were responsible for the opening and closure of early Proterozoic Aravalli-Bhilwara and related rifts. Therefore, in order to understand the origin and evolution of north Delhi fold belt, it is prerequisite to understand in first place the early Proterozoic tectonic reconstruction in this part of Indian shield. It is possible that the extensional regimes, held responsible for the formation of middle Proterozoic rifted basin of NE Rajasthan, may have been developed in response to tectonic events which were instrumental in closure of early Proterozoic Aravalli-Bhilwara rifts in the south.

It has been suggested that the Archaean basement in Aravalli Craton was subjected to rifting at about 2500 m.y. (Sugden et al. 1990) with the formation of a series of N-S trending ensialic rifts (Raza and Khan 1993). These rifts are now represented by Udaipur-Jharol, Pur-Banera, Dariba-Bhindar, Hindoli-Jahazpur and similar belts occurring to the south of Ajmer. The closure of these early Proterozoic rifts has been interpreted in terms of termination of extensional regime (Sinha-Roy, 1988; Sugden et al, 1990; Banerjee and Bhattacharya 1994) which caused the horizontal shortening resulting in their crushing.
Probably, in response of this compressive tectonics an extensional regime initiated, resulting in the formation of main Delhi basins in the west of Aravalli-Bhilwara belts and in the region north of Ajmer where Aravalli and equivalent rocks are not unequivocally found.

Since Bayana and Alwar basins of north Delhi fold belt do not extend southwards and appear to be tapered just north of Bhilwara belt, it has been suggested (Sinha-Roy 1988) that the southern boundary of N-S trending Bayana, Alwar and Khetri basins is marked by a E-W trending fault referred to as Sambar-Jaipur-Dausa (SJD) transcurrent fault. However, the field evidence for the occurrence of this assumed fault is yet to be confirmed. In this model (Sinha-Roy 1988) Bayana - Alwar basins are considered to have been formed as pull-apart basins in response to lateral movement along SJD fault which generated extensional stresses in the region north of Ajmer. The subduction signatures in the chemistry of Khetri amphibolites, as identified in the present study, suggest the formation of oceanic crust not only in the region south of Ajmer but throughout the Delhi belt. Although, the remnants of this oceanic crust are not preserved in the north Delhi fold belt it may be represented by Phulad ophiolites in the southern part (Gupta et al 1980; Sychanthavong and Merh 1984; Volpe and Mac Dougall 1990).
the process of terminal collision. The younging of granites from about 1600 m.y. in the east (Bairat, Dadrika and Harsora) to about 1400 m.y. in the west (Saladipura, Udaipur and Seoli), increase in the grade of metamorphism and intensity of deformation from east to west, all suggest a possible polarity of subduction towards west.