Chapter- 5

PETROGENESIS
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5.1 PETROGENESIS

5.1.1 Granite Gneisses

To understand the petrogenesis of the granite gneisses per say the precursor melts for the granite gneisses of Shillong Plateau, it becomes imperative to analyse the role of fractional crystallization, assimilation fractional crystallization (AFC), crustal contamination and partial melting processes, as these are the potential processes for magmatic differentiation of acidic rocks. Almost all the elements of granite gneisses of Shillong Plateau show negative correlation with SiO$_2$ except for K$_2$O, CaO, Rb, Th and U which show no discernible trends (Figs.4.1.1, 4.1.8) in the Harker’s variation diagram. The trace elements of the granite gneisses of Shillong Plateau show slight scattering compared to the major elements on the Harker’s variation diagram (Fig. 4.1.8). The observed trends for the rock suites indicate fractional crystallization of K-feldspars, plagioclase, biotite, ilmanite, apatite, rutile and other Fe-Ti oxides from the precursor melts of granite gneisses. The depletionary trends at Ba, Sr, P, Ti and Nb in the multielemental spider diagram (Fig. 4.1.9) also bear the evidence. The role of fractional crystallization of a mafic magma during Archaean, in producing trondhjemitic, calcalkaline and granodioritic magmas is considered to be minor due to paucity of intermediate crystallization products such as diorites and andesites (Glikson, 1968; Arth et al., 1978; Arth, 1979). Spulber and Rutherford (1983) further observed that a 90% fractional crystallization of tholeiitic magma is required to produce silica enriched residual melts. In Shillong plateau, no such large bodies of cumulate phases are observed by us nor reported by any other workers. Thus fractional crystallization of a basaltic source in alone seems to be a quite inefficient mechanism to characterize the petrogenesis of the Archaean volumetric calc-alkaline felsic rocks (Green and Ringwood, 1978) including the basement granite gneisses of Shillong plateau. However a combination of fractional crystallization and crustal contamination processes may explain generation of the precursor magmas for the granite gneisses of Shillong plateau. The relative enrichment trends of the most of incompatible elements e.g. Rb, Ba, Th and U in the multielement spider diagram points to some influence of assimilation fractional crystallization mechanism. Moreover such enrichments can also be ascribed due to
addition from subduction zone components (Saunders et al., 1980) and possible sediment incorporation into the mantle (see e.g. Tatsumi et al., 1986).

The primordial mantle normalized multi-elemental patterns for the gneisses show marked enrichment in the LILE with enriched abundance in Rb, Ba, K, Th and U (Fig. 4.1.9). The patterns simultaneously display lesser abundance of HFSE with strong negative anomalies at Ba, Nb, P and Ti, Zr. Such elemental pattern may be explained by magmatism in a subduction zone environment (Tatsumi et al., 1986; Peacock, 1990; Saunders et al., 1991; Hawkesworth, 1994). Fractionation of LILE from HFSE in the melts generated in a subduction environment can be due to dehydration of the subducting slab (Tatsumi et al., 1986; Saunders et al., 1991), whereas the melting of the subducting slab will not fractionate the LILE from the HFSE unless minor phases like rutile, titanite, alanite, phlogopite, hornblende etc. are present in the residual phases (Tatsumi et al., 1986; Saunders et al., 1991). The selective depletion of P and Ti in the granite gneisses of shillong plateau indicates that one or more mineral phases removed Ti and P selectively without causing larger depletion in other HFSE. Although Ti and P are the principal constituents of rutile and apatite, but at high pressures both Ti and P may have enhanced solubility in garnet (Saunders et al., 1991). The garnet retained at the site of partial melting can also act as a repository for Ti and P and can explain the depleted nature of the elements.

The REE patterns of the gneisses are characterized by moderately fractionated (LaN/YbN = 4.47–78.6) trends, HREE depletion and concave upward shape with curvature of the HREE ends along with prominent negative Eu anomalies (Fig. 4.1.10). Such REE patterns are similar to those of various Archaean silicic gneisses from around the world, which were explained by various workers (e.g. Martin, 1986, 1993, 1994) in terms of subduction zone magmatism. Partial melting of an Archaean mafic source (amphibolite and/or eclogite) with hornblende and/or garnet in the residuum can result in depletion of the heavy rare earth elements. Fractional crystallization of hornblende and plagioclase can account for the negative Eu anomaly.

5.1.2 Cordierite bearing Granulitic Gneisses (Metapelites) and Quartz Sillimanite Schists

The petrological and geochemical signatures indicate that the Cordierite bearing granulitic gneisses (metapelites) and the quartz sillimanite schists are
metasedimentary rocks. On the $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ versus $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ diagram of Garrels and McKenzie (1971), most of metapelitic samples plot within the sedimentary/metasedimentary field (Fig. 4.2.2a). On $\text{Al}_2\text{O}_3$ versus $\text{MgO}$ diagram of Marc (1992) the metapelites also plot within the paragneiss field (Fig. 4.2.2b). On the Niggli 100mg-c-(al-alk) triangular diagram of Leake (1964), all the samples lie within the boundary field of typical shales.

$\text{Al}_2\text{O}_3$, $\text{MgO}$ and $\text{TiO}_2$ show negative correlation against $\text{SiO}_2$ in the Harker’s variation diagram (Fig. 4.2.1). A strong positive correlation between $\text{SiO}_2$ and $\text{Fe}_2\text{O}_3$, a weak positive correlation between $\text{SiO}_2$ and $\text{Na}_2\text{O}$ are observed while $\text{CaO}$, $\text{K}_2\text{O}$ and $\text{MgO}$ display no discernible trend against $\text{SiO}_2$ (Fig. 4.2.1). Most of the trace elements e.g. $\text{Rb}$, $\text{Ni}$, $\text{Cr}$, $\text{Y}$, $\text{Nb}$ and $\text{Pb}$ show strong negative correlation against $\text{SiO}_2$ (Fig. 4.2.4) except $\text{Sr}$, $\text{Ba}$, $\text{U}$, $\text{Th}$ which show scattered plotting. The major and trace element in particular the LILEs composition of metapelites and their behavior in the Harker’s variation diagram thus indicate probable weathering of the protoliths of the metapelites.

As Aluminum increases, calcium and the alkalis decrease with progressive weathering, a good measure of the degree of weathering may be obtained from the major element chemistry by their so-called chemical index of alteration (CIA) (Nesbitt and Young 1982). The CIA is obtained from the following formula using molecular proportions:

$$\text{CIA} = \left[ \frac{\text{Al}_2\text{O}_3}{(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})} \right] \times 100$$

The $\text{CaO}$ is the amount of this oxide in the silicate fraction and should be corrected for any carbonate or apatite content. As carbonates are absent and the amount of apatite is negligible in our samples, such a correction was inappropriate in this particular case. As pointed out by Nesbitt and Young (1982), CIA values for average shales range from about 70 to 75 due to a large proportion of hydrous aluminum silicates and related minerals. CIA values of the metapelite samples range between 62 and 84 (average 81). Omitting S08-22 (CIA = 50) and S08-33 (CIA = 93), the eight remaining samples vary between 81 and 86 (average 75), indicating a highly weathered precursor that formed in a warm, humid climate. The quartz-sillimanite schists have an average CIA index of 99 and thus, the schists probably had a highly weathered precursor (see e.g. Nesbitt and Young, 1982).
Thorium correlate strongly with the LREE in many sedimentary rocks (McLennan et al., 1980). In the metapelites of Shillong plateau, Th correlate well with La (LREE) (Fig. 5.1) and the La/Th ratio range from 2.06 – 2.91. In La vs. Th (McLennan, 1989) diagram, all the metapelite samples plot within the field of post-Archean cratonic deposits (Fig. 5.1). In addition, REE fractionated pattern and a pronounced negative Eu anomaly (Eu/Eu*: 0.17-0.68), are well within the compositional range of various post-Archaean shale estimates (Taylor and McLennan, 1985). It follows therefore that the Sonapahar metapelites are metamorphosed post-Archean sediments. The erosion of acidic rocks is evident from the elevated values of Th/Sc = 2.6 – 3.4 and Th/U = 6.06 – 15.37 relative to those PAAS which strongly supports the presumed parent rocks for metapelites.

**Figure 5.1**: La vs. Th diagrams for the metapelites from the Sonapahar area (after McLennan, 1989).

### 5.1.2.1 Sedimentary processes

The previous discussions and plots support the cordierite bearing granulitic gneisses (metapelites) and the Quartz-sillimanite schists as metasedimentary rocks which were formed of weathered precursor sediments derived in a warm, humid climate. But it is important to emphasize the compositional complexity of sedimentary rocks as there are at least four main factors which have to be considered. Chemical weathering in situ or during transport may cause profound alteration of the
provenance rock(s) and judging from the previous plots this has obviously been an important factor. The source rock in the provenance area is also important; if there are several source rocks, a mixing of the debris or weathered material may cause different chemical trends. Other processes during sediment transport and deposition, such as grain-size sorting, adsorption and other syn- or post-depositional alterations may change the geochemical signature of the provenance rocks profoundly. Moreover, diagenesis and metamorphism may also cause element mobility. Unfortunately, the nature of the source rock is unknown. Since granite gneiss is the only basement rock older to the metapelites the sediments are most likely to be derived from the granite gneisses. Rare earth elements are not much affected during sedimentation (very short residence period in water), diagenesis and metamorphism, the REE plot of the metapelites shows a very conformable trend (Fig. 4.2.5) indicating a singular source for the precursor sediments and REE patterns of the metapelites conforms to the trend defined by the granite gneisses of Shillong plateau (Fig. 4.1.10). For the quartz sillimanite schists, both the granite gneisses and metapelites are the older rocks and were possible sources for precursor sediments of the Schists. The high CIA and CIW values indicate that the sillimanite schists might have been derived from both metapelites with larger proportions and granite gneisses in smaller proportions. The quartz fractions might have been derived from more granite gneisses and clay fraction most likely derived from the metapelites.

5.1.2.2 Trace element distribution

In a relatively wet climate, hydrous solutions are expected to play an important role in dissolving minerals and controlling the behaviour of elements during transportation and precipitation. Important in this connection is the Ionic Potential (IP) or Field Strength (FS) which is defined as $Z/r$, where ‘$Z$’ is the ionic charge and ‘$r$’ is the ionic radius. This factor will, to some extent, control the solution/precipitation behavior of the different elements. Elements with an ionic potential or field strength less than 2 (denoted LFSE or Low Field Strength Elements) will be easily dissolved. Thus, Sr, Ba, K and Rb will be removed in hydrous fluids as soluble cations during weathering and remain in solution during transportation. Elements with higher Field Strength (or HFSE with FS between 2.5 and 9.5) (Krauskopf and Bird 1995) become fixed to hydroxyl groups and are precipitated by hydrolysis. Elements with FS higher than approximately 10 or 11 will normally form
soluble anionic complexes. In the present investigation this includes phosphorus (P) and the spider diagrams in the present study are constructed with P (highest FS) on the left followed by elements with gradually decreasing FS values (Figs. 5.2, 3). The pH and redox potential also influence the element distribution during sedimentary processes. Colloidal processes, where sols and gels influence precipitation, may be an important factor, such as the adsorption of K, Rb and Ba to montmorillonite-rich clay. Some heavy metals, such as V, may also be adsorbed under certain conditions and thus be removed from solution by natural colloids. Despite these complications, which may influence the element distribution, an attempt to identify the nature of the protolith has been made by normalising all the analysed trace elements to Post Archaean Australian Shale (PAAS) (McLennan, 1989).

In the PAAS normalized spider diagrams, all the metapelite samples, with just one exception (S08-14), have pronounced negative P anomalies in the spider diagrams (Fig. 5.2). The metapelites have large negative anomalies for Zr, and Sr and small negative anomalies for Y, and K. The metapelite possess positive anomalies for Nb, Ti, Th, Ce, La, Ba and Rb. Th, Ce and La are enriched relative to PAAS. The quartz sillimanite schists exhibits a very fractionated trend with P, Nb, Ti, Y, Sr, Ba, K and Rb are highly depleted and Zr, Th, Ce and La are enriched relative to PAAS. The spider diagram exhibits pronounced negative anomalies for Y and K and positive anomalies for Zr (Fig. 5.3). The strong negative anomalies at P for almost all the metapelites and quartz-sillimanite schists may indicate that it stayed in solution in the form of soluble anion complexes during formation of the precursors to the sillimanite rocks. Alternatively, phosphorus may have been dissolved and removed during diagenesis or, less likely, during metamorphism. Niobium in the metapelite is in the range of 8 -17 (average 12.5); which is slightly lower than the PAAS (19 ppm). The Nb content of the schists is extremely low compared to PAAS in the range of 1.3 ppm to 6 ppm (average 2.5 ppm). Since Nb substitutes for Zr in zircon, the elevated concentration of Zr in the schists can therefore account for the substitution of Nb for Zr. Both the rock suites have higher Thorium (Th) Cerium and (Ce) values than the PAAS. Ce is the main element in monazite, a highly resistant mineral that is chiefly derived from the weathering of granites and granite pegmatites and there suggests the precursor sediments are possibly derived from felsic rocks and probably not mafic rocks.
Figure 5.2: Spider diagram for the elements of the cordierite bearing granulitic gneisses (metapelites) normalised to PAAS (Post-Archaean Australian Shale; McLennan 1989). The elements are in succession with decreasing ionic potential towards the right.
Figure 5.3: Spider diagram for the elements of the quartz-sillimanite schists normalised to PAAS (Post-Archaean Australian Shale; McLennan 1989). The elements are in succession with decreasing ionic potential towards the right.

The large-ion lithophile elements Sr, Ba, K and Rb should ideally form dissolvable ions in aqueous solutions owing to their low ionic potential or field strength, unless other processes, such as adsorption, have led to their precipitation in the clay fraction. In a sedimentary context, Sr is known from deposits formed in a dry climate. The negative Sr anomalies for both the rocks types may be taken as an indication that Sr was brought into solution during weathering in a humid climate and stayed in solution during formation of the precursor sediments. Barium is recovered from residual clay deposits where Ba is trapped because of its higher tendency for adsorption to clay minerals than Sr. The metapelites and quartz sillimanite schists have positive Ba anomalies. Relatively high Ba in the metapelites may be ascribed to the adsorption model. Potassium is commonly adsorbed to clay minerals under suitable conditions. Pettijohn (1975) estimated that Precambrian and Palaeozoic shales contained on average 3.2% $\text{K}_2\text{O}$ and 1.1% $\text{Na}_2\text{O}$, close to Condie’s (1993) calculated averages for Proterozoic shales of 3.62% $\text{K}_2\text{O}$ and 1.06% $\text{Na}_2\text{O}$ compared to 3.7% $\text{K}_2\text{O}$ and 1.2% $\text{Na}_2\text{O}$ in PAAS. In primitive Precambrian paleosoil, K was mainly derived from the weathering of K-feldspar and/or muscovite and fixed in illite, whereas Ca and Mg were dissolved and removed from the sediments. The relatively
high K$_2$O values in the metapelitic samples may be explained by either diagenetic processes may give rise to some K-metasomatism (Nesbitt and Young 1989) or adsorption of K to clay minerals leads to higher K contents or K may also have been added at a later stage during metasomatism and/or magmatic injections. A variety of different processes may therefore have contributed to an increase in the K contents of the metapelites. Rubidium occurs in small concentrations in most K-bearing minerals. The metapelites have enriched Rb contents while the quartz sillimanite have depleted Rb content. During sedimentation dominated by clay precipitation, Rb will have a greater tendency to become adsorbed in clay minerals than K. The present distribution of Rb i.e. high Rb in the metapelites thus indicates that the precursor sediments to the metapelites were relatively clay rich than those for the schists.

The positive enrichment ratios for almost all trace elements, apart from P and Sr, Zr and Y in the metapelites suggest clay rich sediment from continental source rocks. However, high values for Zr, Th, Ce and La suggest that the precursors to the quartz-sillimanite Schists were probably sand-clay mixtures with zircon enrichment in the sand fraction. The major element geochemistry rules out some other possible models of origin for the sillimanite schists. Immature sediments, such as glacial clay or loess, can be excluded because the high CIA index suggests rather highly weathered sediments derived in a warm, humid climate. The quartz-sillimanite schists and cordierite bearing granulitic gneisses cannot be simple metamorphic derivatives of bauxite deposits, as bauxites normally contain more than 40% Al$_2$O$_3$, which is well above the level for the sillimanite schists. Pelagic red clays can also be excluded since they have different element distributions than the sillimanite rocks (McLennan et al., 1990; Li 1991, 2000). Even if the protolith and paleoenvironmental condition for the precursor sediments of the cordierite bearing granulitic gneisses and sillimanite-bearing schists remains somewhat elusive, there seems to be ample support for the notion that clay-rich sedimentary precursors for the gneisses and sandy-clay mixture for the schists developed during weathering in a warm, humid environment.

Chondrite normalize REE concentrations for the metapelites show variable LREE/HREE ratios $[(\text{La/Yb})_N = 16.67 – 68.98]$. The normalized patterns are steeply inclined with highly enriched LREEs and fractionated HREEs along with prominent Eu anomaly ($\text{Eu/Eu}^* = 0.17 – 0.68$) (Fig. 4.2.5). When compared with the patterns of the granite gneisses, the rare earth elemental patterns of the metapelites show a
remarkable similarity. From the field relationships with the granite gneisses hosting the metapelites and their ages [granite gneisses: ca. 1600 Ma (Yin et al., 2010); metapelites: ca. 520 Ma (Chatterjee et al., 2007)] it is reasonable to assume that the metapelites were derived from granite gneisses.

5.1.3 Basic Granulites

Both major and trace elements vary significantly in basic granulite samples. Some distinct trends have been noted in the variation diagrams, ratio-ratio plots, multi-elemental spider diagram and also in the REE patterns (Figs. 4.3.1- 4.3.8). These trends were either likely to be results of the individual processes like fractional crystallisation, crustal contamination, mantle metasomatism of the primary precursor basaltic magma for the granulites or a combined effect of these processes. In the primitive mantle-normalized multi-element plot (Fig. 4.3.7), the trace element data show typical island arc basalt trace element patterns, with enriched LILEs such as Rb, Ba, Pb and K relative to HFSEs such as Hf, Zr and Ti. Typical island arc lavas are enriched in LILE and LREE but depleted in HFSE, particularly in Nb, Ta, and Ti on normalized trace element diagrams (Saunders et al., 1991; Hawkesworth et al., 1993; Hawkins, 2003; Murphy, 2007). However, primitive mantle normalized multi-element plot displaying prominent positive Ta suggests OIB like trace element patterns and which might have originated in a subduction zone geodynamic setting.

5.1.3 a. Crustal Contamination

Negative Nb anomaly in the multi-element patterns (Fig. 4.3.7) along with enriched LREE patterns (Fig. 4.3.8) for the basic granulites indicate possibility of crustal contamination for its precursor magma. Further, high La/Nb ratios (0.86 – 1.78) with an average value of 1.5 for the basic granulites also indicate crustal involvement (see e.g. Hasse et al., 2000). But the high Ce/Pb values (18.94 – 31.63) and low Ba/Nb values (9.14 – 23.87) do not reflect any such contamination signature. Incompatible elements such as La or Ba should increase relative to Nb if basaltic magma is contaminated by crustal material, which usually has high La/Nb, Ba/Nb and low La/Ba (Weaver and Tarney, 1984; Wedepohl, 1995). The studied samples show increase in La with increase in Nb, but the correlation of Ba/Nb and La/Ba is not very clearly established which can also be due to limited number of samples. It follows therefore that contributions of crustal material is very limited. The observed LREE
enrichment may be either due to subduction of crustal material into the mantle or due to metasomatism of mantle.

The basement rocks of shillong plateau consist of granite gneisses, which are exposed quite ubiquitous throughout the plateau. For comparison and to check for the possibility of any contamination at crustal level, the mantle normalized data of the host granite gneisses are plotted in the multi-elemental spider diagram (Fig. 5.4). The host granite gneisses share similar patterns and similar level of enrichment for individual element in the spider diagram. These are enriched in both large ion lithophile elements (LILE) and high field strength elements (HFSE) compared to primordial mantle (PM) except for Ti, P, Y, Yb and Lu of only one sample. The patterns have distinct Nb, Sr, P, Zr and Ti negative anomalies. Moreover, the level of enrichment of Nb, Sr, P, Zr and Ti contents of the basic granulites are higher than those in the host granite gneisses. Thus considering the whole set of data it becomes apparent that the geochemical signatures of the granulites are not much affected by crustal contamination. Their geochemical characteristics represent source characteristics or contamination of crustal material at mantle level.
Figure 5.4: Primordial mantle normalized multi-element patterns for the Basic granulites and the basement granite gneisses of Shillong Plateau. Normalizing values are from Sun and McDonough, (1989).
5.1.3 b. Fractional crystallization

Both major and trace element data are sensitive to the effects of fractional crystallization (Cox et al., 1979). Basic granulites are characterized by high SiO$_2$, Al$_2$O$_3$ and CaO moderate high Fe$_2$O$_3$ medium to low MgO and low to moderate TiO$_2$ and low Na$_2$O and K$_2$O. These geochemical features point towards fractional crystallization of some of the mineral phases. Both CaO and Al$_2$O$_3$ for the basic granulites show a decreasing trend against Mg # plot (Figure not shown). CaO/Al$_2$O$_3$ of basic granulites is always lower than that of chondrite (0.9). These features account for clinopyroxene, olivine ± plagioclase fractionation for the basic granulites. Ni and Cr show positive relationship with Mg # (Figure not shown). Negative anomalies of Sr in the multi elemental spider diagram for the dykes (Fig. 4.3.7) and negative anomalies at Eu in the REE plot (Fig. 4.3.8) of the granulites also indicate plagioclase fractionation.

Alle`gre et al., 1976 deduced that Ni concentrations between 130 and 200 ppm can be derived by 15% fractional crystallisation of olivine from a mantle derived primitive magma with 300–450 ppm Ni. The low Ni content of the basic granulites (13 – 67 ppm) thus indicates that the precursor basaltic magma was derived from a olivine-poor source material or this may be derived from a less primitive magma. Nb and Y show increases with decreasing MgO as predicted by the fractionation of plagioclase, olivine and pyroxene. The low Ni/V (0.04 – 0.34) and Zr (~56.49) contents also suggest olivine fractionation.

5.2 TECTONIC IMPLICATIONS

5.2.1 Granite gneisses

Several attempts have been made to discriminate granitoids of different tectonic settings based mainly on some critical trace element abundances; because the major element concentration of granitoids from different tectonic environments are observed to exhibit gross similarities. Besides, the major elements being mobile, any inferences on the mode of emplacement of magma based on their concentrations may not be reliable. However, anorogenic, orogenic, syn-collisional and post-collisional granitoids probably cannot be distinguished in any straight forward basis based on their trace element chemistry either, because they share a common range of trace element concentrations. Since trace element discrimination diagrams more accurately
reflect distinct chemical source reservoirs than tectonic setting characteristics (Pearce et al., 1984), therefore it is not surprising that the same source region might have been tapped during the evolving tectonic setting scenario. For instance, present arc or syn-collisional sources might have been tapped as “within plate” sources and may have become source for collision magmatism. However the compositional diversity of the magma of different tectonic settings is also not unexpected and as a result, a lot of empirical tectonic discrimination diagrams are drawn based on the study of the geochemical characteristics of rocks of known tectonic settings and later, these diagrams are extrapolated to understand the geodynamic environment for other suites (Pearce et al., 1984; Harris et al., 1986) and construct paleo-tectonic environment. Pearson et al. (1984) have empirically drawn tectonic discrimination diagrams using some trace elements into four main groups: (i) Ocean ridge granite (ORG) - associated with ophiolite or belongs to oceanic crust (ii) Volcanic arc granite (VAG) – formed due to subduction of oceanic crust (iii) Within plate granite (WPG) – anorogenic granite and (iv) Syn-collisional granite (syn-COLG) – evolved as a consequence of continent-continent, arc-continent or arc-arc collisions. The granite gneisses of Shillong plateau are plotted on a number of tectonic discrimination diagrams (Figs. 5.5) of Pearce et al. (1984) and Pearce (1996) based on Rb vs. Y+Nb; Nb vs. Y; Rb vs. Yb+Ta and Ta vs. Yb. In the Nb vs Y discrimination diagram the gneissic suites plot within the common field for VAG and syn-COLG. In the Rb vs. Yb +Ta diagram the granite gneisses are plotting within the Volcanic Arc Granite (VAG) field. In the Ta vs. Yb granite gneisses are plotting confined within VAG. In the Rb vs. Y+Nb granite gneisses are mostly plotting within VAG filed except two samples plot within WPG and one within Syn-COLG. Thus with a view to reconstruct the paleo-tectonic settings of the emplacements of the protoliths for the Granite gneisses of Shillong plateau it appears that these rock suites were emplaced in an arc related magmatic setting.
Figure 5.5: (a) Rb vs. Y + Nb (b) Rb vs. Yb + Ta, and (c) Nb vs. Y (d) Ta vs. Yb discriminant diagrams for the granite gneisses of the Sonapahar area allowing reproducing the tectonic environments in which the granitoids were produced. Compositional fields of the granitoids: post-COLG—postcollision, syn-COLG—collision, VAG— tongue-arc, WPG—within-plate, ORG—oceanic ridges. The dashed lines in the Nb vs. Y and Ta vs. Yb diagrams mark the ORG boundary for normal rifts.
5.2.2 Basic granulites

Based on major and trace element abundance and ratios of modern basaltic rocks many tectonomagmatic geochemical discriminant diagrams have been proposed (e.g. Pearce, 1982, 1983; Pearce and Norry, 1979; Pearce and Cann, 1973; Mullen 1983, Pearce et al., 1984). These discriminant diagrams are now being widely used in paleo-tectonic reconstruction. But it has been observed that many of these discrimination diagrams always overlap some portion of the fields of other tectonic setting and as a result, interpretation becomes more misleading and ambiguous. Most of the diagrams are not very useful to discriminate continental basalt, from oceanic basalt; the majority of the data on continental basalts plot in every fields except within plate basalt field. Because the data on continental basalt do plot in other fields such as MORB and arc basalts, the discriminating ability of these diagrams is impaired. Nevertheless these diagrams are widely used by geologists since these were propounded.

Four discrimination diagrams based on Ti, Mn, P, Sr, Zr and Y contents (Mullen, 1983; Pearce and Cann, 1973; Pearce and Gale, 1977 and Pearce and Norry, 1979) were chosen to constrain the tectonic setting of the protolith of basic granulites of Shillong plateau. On Zr – TiO$_2$ discrimination diagram (after Pearce and Cann, 1973), all the samples plot within the field of arc basalt overlapping MORB (Fig. 5.6a). In the TiO$_2$ - MnO- P$_2$O$_5$ tectonomagmatic discrimination diagram (Mullen, 1983) (Fig. 5.6d), all the basic granulites fall in the field of island arc tholeiites (IAT). Other diagrams such as Zr - Ti/100 - Sr/2 and Ti/Y vs. Zr/Y are also applied to the discrimination of the tectonic environment. In all these diagrams, the basic granulite samples fall within the field of island arc tholeiite or Plate Margin basalts (Figs. 5.6b, c). These results indicate that the protolith of basic granulites of Shillong plateau probably formed in a volcanic island arc tectonic setting.

Condie (1989) proposed basalt classification schemes using the ratios of immobile elements (e.g, Ti/V, Ti/Y, Zr/Y and Ti/Zr) for Archean and Proterozoic basic rocks. According to Condie (1989), Ti/V =30 is the boundary between the arc basalt (ARCB) [or N-type mid oceanic ridge basalt (NMORB)] and the MORB [or within plate basalt (WPB)]. Ti/V values of the basic granulites of Shillong plateau ranges between 33.08 and 41.14 minus two samples with Ti/V values less than 30. The basaltic rocks of tholeiitic to calc-alkaline composition are found almost
**Figure 5.6a:** Zr vs. Ti discrimination diagram for basic granulites of the Sonapahar area, Shillong Plateau (after Pearce and Cann 1973).

**Figure 5.6b:** Zr - Ti/100 - Sr/2 tectonic discrimination diagram for basic granulites of the Sonapahar area, Shillong Plateau (after Pearce and Cann, 1973).
Figure 5.6c: Ti/Y vs. Zr/Y chemical discrimination diagram for tectonic environments of basic granulites from the Sonapahar area, Meghalaya (after Pearce and Galle, 1977)

Figure 5.6d: TiO$_2$-MnO-P$_2$O$_5$ tectonomagmatic discrimination diagram (after Mullen, 1983) for basic granulites of the Sonapahar area. OIT: Oceanic island Tholeiite, OIA: Oceanic island alkali; MORB: Mid ocean ridge basalt, IAT: Island arc tholeiite, CAB: Island arc calc alkali basalt.
exclusively in subduction related tectonic environment (Pearce, 1983). The LILE enrichment and low HFSE abundances of the basic granulites of Shillong Plateau also attest to subduction related magmatism for their precursor magma.

5.3 PETROGENETIC EVOLUTION

Reliable geochemical as well as geochronological data on the basement rocks of Shillong Plateau consisting of granite gneisses, metapelites, sillimanite schists and basic granulites are very scarce. Thus in absence of quality geochronological data and geochemical data on the basement rocks, it seems difficult to constraints the evolution of Shillong Plateau. An approach is made to constraint the evolution of the Shillong Plateau using the few available geochronological data on the basement rocks and geochemical data synthesized for this present work.

As observed in the field, granite gneisses constitute the host rock for other rock units in the basement rocks of the Sonapahar area. Metapelites are intimately associated with the host rocks. Basic granulites occur as concordant and discordant intrusive within metapelites.

Ghosh et al., (2005) assigned ages for the basement gneisses to vary between 1714 and 1150 Ma. Mitra (1988) obtained Pb–Pb detrital zircon ages of 1530–1550 Ma for the Shillong Group of supracrustals. The detrital zircons are probably derived from the basement gneisses. There is periodic granite plutonism within the basement gneisses. Different works (e.g. Ghosh et al., 1991; 1994; Chimote et al., 1988; Selvan et al., 1995) are assigning ages of emplacement for the undeformed granite pluton ranging between ca. 890 – 480 Ma.

Maibam and Deomurari (2007) carried out $^{207}$Pb–$^{206}$Pb zircon age data of basement gneisses in different parts of the Shillong Plateau and obtained an Archaean age of about 2600 Ma. However they have yielded ages of about 1500 Ma for the gneisses from Riangdo which is very close to the present study area. A very recent geochronological work done by Yin et al., (2010), suggests an age of about ca. 1600 Ma for the basement gneisses.

The timing of metamorphism in the basement rocks has been determined by chemical ages of metamorphic monazites from the metapelites of Shillong Plateau by Chatterjee et al., (2007) with ages clustering at 1600 – 1400 Ma, 1000 – 1300 Ma, and
ca. 500 Ma respectively. Similarly, the timing of tectonothermal activity within the basement rocks has been determined by Yin et al., (2010) conducting U-Pb datings on zircons from undeformed granitoids and basement gneisses and on detrital zircons from Shillong Group of Sedimentary rocks. Their works reveals three distinct episodes of tectonothermal events at ca. 1600 Ma, ca. 1100 Ma and ca. 500 Ma and three ductile deformation events at ca. 1100 Ma, ca. 520 – 500 Ma and during the Cretaceous. Thus looking from the geochronological data, it appears that the Shillong Plateau experienced episodic rather than semi-continuous tectonothermal events.

Yin et al., (2010) described the first two tectonomagmatic events (i.e ca. 1600 Ma and ca. 1100 Ma) within Shillong Plateau as contractional and suggested these are possibly induced by assembly of Rodinia and Eastern Gondwana. The tectonomagmatic events have been related to magmatic arc developments and subsequent terminal continental collision that form the proto-continent (Shillong Plateau) (Yin et al., 2010) (Fig. 5.7). The geochemical signatures of the basement gneisses with multi-element spider diagrams, REE patterns and tectonic discrimination diagrams (Figs. 4.1.9, 10; 5.5) accord well with volcanic magmatism signatures.

The 1100 Ma event in Northeastern India correlates well with the development of the Eastern Ghats orogenic belt during collision between India and Antarctica (Kelly et al., 2002). They further suggested that the first separation from Antarctica did not occur until the late Proterozoic during the deposition of the Shillong Group. It was likely that the depositions of metapelites are coeval with deposition of Shillong Group of sediments. After deposition of these sediments, the westward oceanic subduction started below the eastern Indian margin and produced arc magmatism between 520 - 480 Ma and the closure of the ocean between India and Antarctica led to the formation of Eastern Gondwana (Meert, 2003; Collins and Psarevsky, 2005; Collins et al., 2007). Intense regional contraction occurred between 520 Ma and 500 Ma, which was expressed by the development of the central Shillong thrust and isoclinals folding in the Shillong Group of metasediments and the post kinematic plutons with ages ranging from ca. 500 Ma – 480 Ma or even younger, might have generated after the collision between Antarctica and India (Yin et al., 2010).

The tectonomagmatic events at ca. 1600 Ma of Yin et al., (2010) could therefore be correlated with the emplacement of the precursors for basement gneisses
of Shillong Plateau which subsequently might have suffered the ductile-deformation at ca.1100 Ma possibly due to collision of Eastern Gondwana and Rodinia.

Despite gap in ages, granite gneisses and metapelites of the Shillong plateau shows a remarkable similarity in their geochemical characteristics in various aspects. It is therefore reasonable to assume that metapelites were derived from granite gneisses. The exhumation of granite gneisses possibly started subsequent to assemblage of Rodinia and Eastern Gondwana. As soon as these rocks were exposed to the surface, the deposition of sedimentary materials, mainly derived from these granite gneisses took place. This assumption was strongly supported by the fact that all analysed samples of metapelites display Post Archean nature of sediments.

For the basic granulites, no geochronological data are available so far. Therefore it is difficult to make assumption regarding the time of emplacement of the precursor magma to the basic granulites. However, on the basis of field relationship it can be ascertained that basic granulites are younger than metapelites as it occurs as intrusive within metapelites.

Chatterjee et al., (2007) interpreted four metamorphic episodes based on the textural relations in metapelites in which the last episode represent post-tectonic. In the present study, a spectacular example of synkinematic prophyroblast growth is provided by the so-called snowball garnets, which have spiral trails of biotite inclusions (Plate 7A). Keeping this in mind, ca. 520-500 Ma deformation events of Yin et al., (2010) seems responsible for the prograde metamorphism in metapelites and basic granulites of Shillong plateau.

Lal et al. (1978) suggested that the metamorphic equilibrium pressure–temperature ($P$–$T$) conditions of the Sonapahar granulites including the corundum–spinel–sapphirine metapelites are 750°C and 5 kbar. Keeping the average geothermal gradient (35°C/Km) in mind, such a high temperature could be expected only deep inside the crust, specifically middle to lower continental crust. However, it is not very likely for metapelites to be buried at such depth. Therefore, it is possible to assume that the last igneous activity proposed by Yin et al., 2010 could be also responsible for high temperature conditions of metamorphism within Shillong plateau.
Figure 5.7: Schematic diagrams showing possible evolutionary history of basement rocks Shillong plateau. (A) 1750–1600 Ma: magmatism and amalgamation of two proto-Indian continental blocks. (B) 1150–950 Ma: arc magmatism and collision of India-Antarctica and Australia belt. (C) 900 Ma(?)-560 Ma: deposition of the Shillong Group in a passive-margin setting. (D) 500–480 Ma: Contractional deformation related to final closure of the Mawson Sea and collision of India and Australia (E) Exhumed basement rocks of Shillong plateau