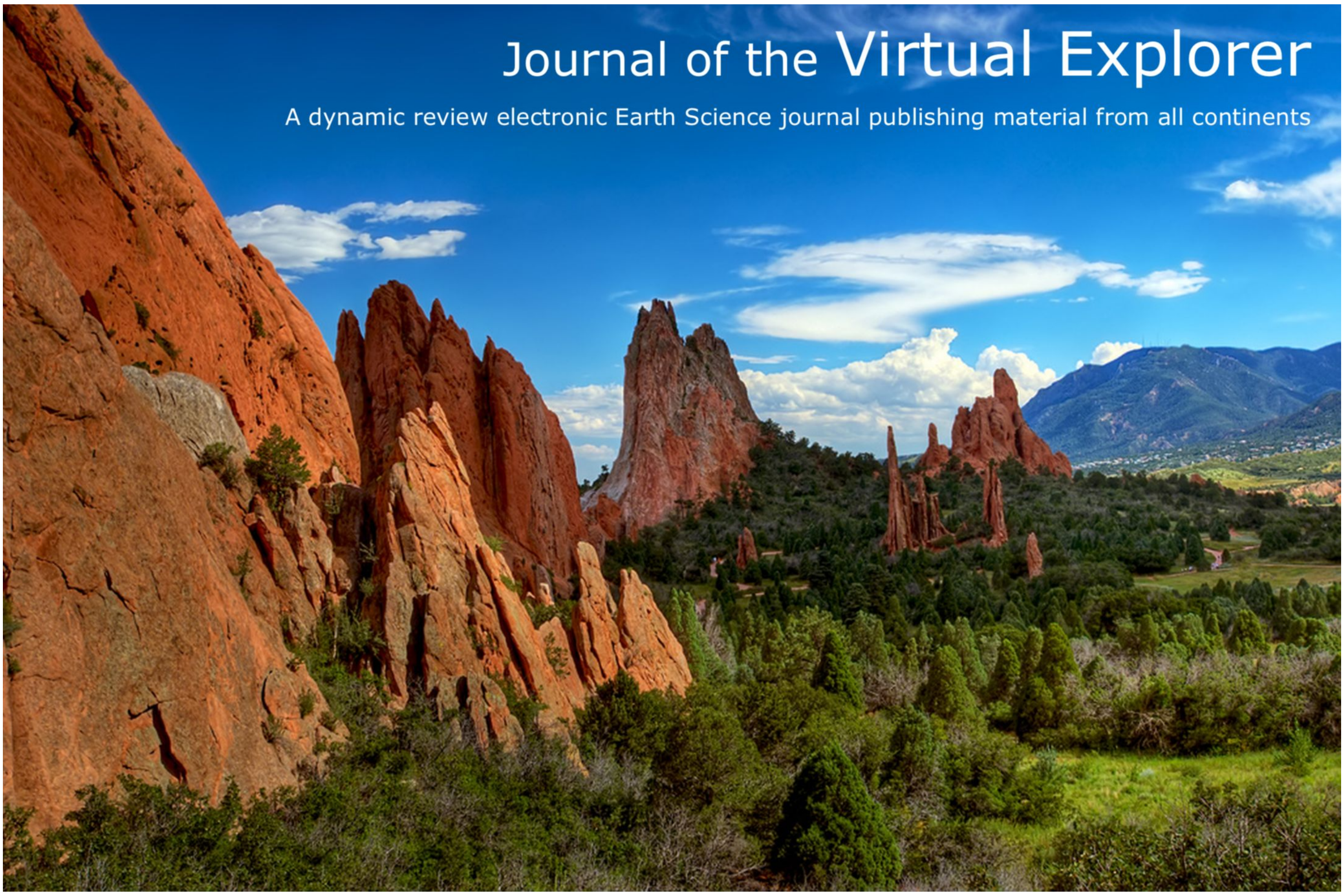

Geochemical characteristics of the Granitoids of Mikir Hills Massif of Shillong Plateau, Northeast India: Implication for Pan-African Magmatic Activity

M. Faruque Hussain, Talat Ahmad

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Abstract: Mikir Hills massif (MHM) of the Shillong plateau, in northeastern India extends over an area of about 7000 km^2. MHM vis-à-vis Shillong plateau record granite magmatism from 881 to 479 Ma related to Pan-African magmatic event.

The analysed MHM granitoids have SiO_2 ranging from 64.5 wt.% to 75.8 wt.%; Al_2O_3 content ranges from 13 to 14 wt.%; CaO content ranges from 1.3 to 3.3 wt.% and the total alkalies range from 7.2 wt.% to 8 wt.%. The granitoids show steeply fractionated chondrite normalized rare earth element (REE) patterns with $(La/Yb)_N$ varying between 18 and 28, strong negative Eu anomaly, and flat heavy REE patterns. They have enriched large ion lithophile element (LILE) abundances relative to high field strength elements (HFSE) with negative Nb, Sr, P and Ti anomalies in the Primitive Mantle normalized multi-elemental patterns. In the tectonic discrimination diagrams, the granitoids plot within volcanic arc granite filed. These geochemical signatures point towards a subduction related magmatism in the Shillong plateau.

The Neoproterozoic granitoids of Shillong plateau with arc geochemical signature and with the plateau at the leading margin of Neoproterozoic Indian plate, place constraints on the evolution of these rocks and their significance in dispersal of Rodinia and subsequent assembly of the Gondwana supercontinent.

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Introduction

Shillong plateau in northeast India is a small but conspicuous gneissic complex. The Plateau has been described as a detached part of the Indian shield (Evans, 1964) or an extension of the Chtanagpur Gneissic Complex (CGC) (Desikachar, 1974) or the Eastern Ghat Granulite Belt (EGB) (Crawford, 1974). The available chronological data from the high grade rocks of CGC (Ray Barman *et al.*, 1994; Harris, 1993) and the granulites of the EGB (Shaw *et al.*, 1997; Dobmeier and Raith, 2003) suggest that the domains are largely Proterozoic in age with relict or reworked Archean components (Rickers *et al.*, 2001; Ramachandra and Roy, 2001) and interspersed Grenvillian domains (Chattterjee *et al.*, 2007).

Neoproterozoic felsic magmatism in Shillong plateau is represented by voluminous granitoid plutons around the plateau. Rb-Sr whole-rock isochron ages of the granite plutons range from 881 to 479 Ma (Ghosh *et al.*, 1994) and contrast with the 1714-1150 Ma ages of the basement gneisses (Ghosh *et al.*, 1994; Selvan *et al.*, 1995, Chatterjee *et al.*, 2007). Smilar granite plutons and felsic volcanic rocks of Neoproterozoic ages are widely recorded in other parts of India e.g. the granite plutons of Kerala (740-550 Ma, Santosh and Drury, 1988); Tamil Nadu (637 to 395 Ma, Santosh *et al.*, 2005) and acid volcanic activity in Rajasthan (780 to 680 Ma, Rathore *et al.*, 1999) and these are believed to be related to Pan-African Orogeny. Ghosh *et al.*, (2005) have suggested that the granitoids belonging to Shillong plateau were formed due to tensional stress and thermal upwell related to the collisional and extensional episodes of the Gondwana supercontinent. Others working on the geochronology of the granitoids and the position of Shillong plateau in a reconstructed assembly of landmasses during Neoproterozoic period (see e.g. Rogers and Santosh, 2002; Collins, 2003; Chatterjee *et al.*, 2007) suggested that the felsic magmatism within Shillong plateau was associated with the disintegration and dispersal of the supercontinent Rodinia that might have begun with the rising of a mantle plume.

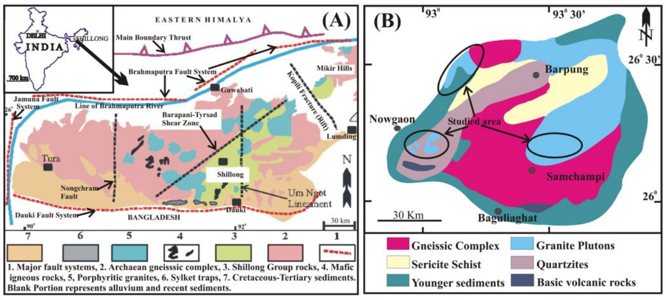
Formation of the Rodinia supercontinent during the 1300-1000 Ma Grenvillian event is believed to have been followed by disintegration and dispersal of the crustal fragments around 750 Ma ago (Kröner and Cordani, 2003). Most of these dispersed terranes reassembled around 550 Ma ago in the Gondwana supercontinent (Meert and Van der Voo, 1997). These events left signatures in the rocks of the dispersed continental blocks (Windley, 1995). In this context the isotopic ages of basement gneisses and high-grade metamorphic rocks of Meghalaya suggest involvement of the Meghalaya region in an accretion event. Various attempts to reconstruct the Precambrian crustal blocks in the Neoproterozoic period place southwestern Australia with northeast India in the eastern Gondwana assembly (Fitzsimons, 2000; Rogers and Santosh, 2002; Ghosh *et al.*, 2005 and references therein). Chattterjee *et al.*, (2007) propose that the Pan-African suture passing through Prydz Bay in Antarctica possibly continued northward into India through the Shillong plateau.

The granitoids dealt in this study belong to the Mikir Hill Massif which is the eastern extension of the Shillong plateau. Petrological and geochemical characteristics of these granitoids are used here to constrain the crustal evolution of Shillong plateau during Neoproterozoic and their significance for dispersal of Rodinia and subsequent amalgamation of India in the supercontinent Gondwana.

Regional Geology

Shillong plateau is separated from the peninsular India by Tertiary Ganges-Brahmaputra alluvium and Cretaceous Rajmahal Volcanics (Nandy, 1980). The plateau covers an area of about 40000 km^2 within 25°20'N - 26°30'N latitude and 90°E - 93°50'E longitude (Fig. 1a). It is an E-W trending oblong horst block uplifted about 600 to 1800m above the Bangladesh plains in the south which is related to collision of the Indian and Tibetian plates during the Cenozoic (Bilham and England, 2001). The plateau is bounded and dissected by several E-W and N-S trending faults such as Dauki Fault in the south, Brahmaputra Fault in the north and Jamuna Fault in the east (Evans, 1964; Nandy, 1980). Many of these faults and lineaments were formed by the Kerguelen plume related doming during the Mesozoic (Gupta and Sen, 1988).

Figure 1. Regional geology of Shillong plateau

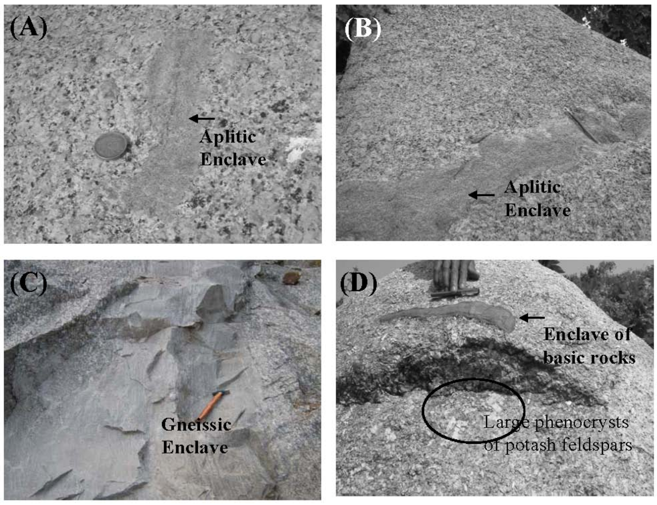


A. Regional geological and tectonic set-up of the Shillong Plateau (modified after Srivastava and Sinha, 2004). B. Simplified Geological map of Mikir Hills massif, Shillong plateau.

The plateau comprises of amphibolite–granulite facies basement gneisses unconformably overlain by the Shillong Group of greenschist facies intra-cratonic sandy and clayey rocks (Nandy, 2001). Granitoids occur as discordant plutons, cross-cut the Shillong Group of metasediments and basement gneisses. Granitoid plutons are more expansive in the east-central parts of the plateau (Ghosh *et al.*, 2005). The mafic dykes and Sylhet Traps represent the youngest igneous activity within the plateau and cut across all the previous magmatic and metamorphic rock suites viz. gneisses and granitoids.

The same geological relationship and stratigraphy is present in the Mikir Hills massif (MHM) which has been described as an eastern extension of the Shillong plateau, extensive over an area of about 7000 km^2 within 25.5° – 27° N latitude and 92.5° – 94° E longitude (Fig. 1b). A major N-S fracture zone viz. Kopili rift separates the Mikir Hills massif from the Shillong plateau proper. The granitoids of the Mikir Hills massif are un-deformed and occur as intrusives into the basement gneisses and contain enclaves of gneisses, aplites and basic rocks (Fig. 2). The un-deformed nature of the granitoids indicates that the plateau might have attained stability after the emplacements of the granitoids and no further orogenic movements have taken place.

Figure 2. Field photographs of granitoids



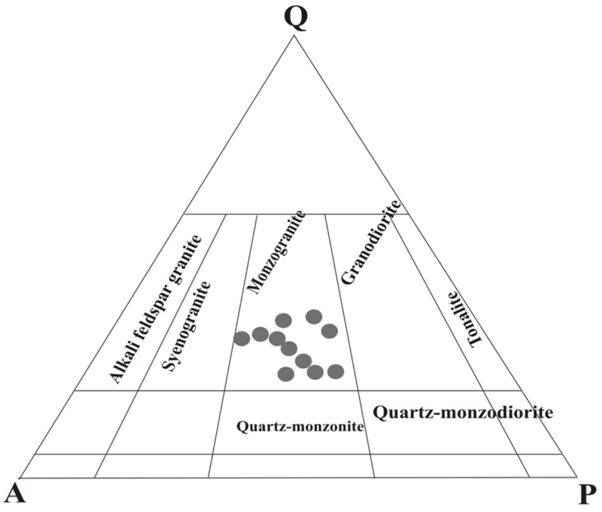
Field photographs of granitoids containing enclaves of gneisses, aplites and basic rocks.

Petrography

Our field and petrographic studies show that the granitoids are less deformed and are invariably porphyritic. The granitoids contain large phenocrysts of potash feldspars and at places the potash feldspars are zoned (Fig. 2.D). Isolated, irregularly shaped enclaves of mafic rocks and quartzo-feldpathic gneisses and long tabular enclaves of aplites are common (Fig. 2). The granitoids show varying degrees of alteration, including chloritisation of biotite and replacement of plagioclase by sericite.

The granitoids are composed of quartz, microcline, orthoclase and plagioclase in varying amounts along with biotite, apatite, sphene, zircon and opaques as accessories. K-feldspars of the granitoids are mostly microclines, although orthoclase is present but constitutes only 5-10% of the total mode. Quartz grains show deformation bands that exhibit undulatory extinction. Orthoclase is commonly associated with exsolved plagioclase in the form of perthite. Perthites of different varieties such as string, rod and flame type are seen. Micrographic intergrowths between quartz and feldspars sometimes occur.

Figure 3. IUGS (modal) classification scheme



IUGS (modal) classification scheme (after LeMaitre et al., 1989) for the granitoids of Mikir Hill massif, Shillong plateau.

Geochemistry

Sampling and analytical techniques

Eight representative samples were selected for geochemical analysis and the whole rock major element analyses for three samples (AG-2, AG-4, AG-6) were carried out at National Geophysical Research Institute (NGRI), Hyderabad, India on XRF and whole rock major and trace element analyses for five other samples (AG-8, AG-10, NK-12, NK-13, NK-18) were carried out at Regional Sophisticated Instrumentation Centre, IIT Bombay, Mumbai, India on XRF (Philips PW 2404). The rare earth elements (REE) for the samples (AG-2, AG-4, and AG-6) were carried out on ICP-MS (Perkin Elmer Sciex ELAN DRC II) at NGRI, Hyderabad. Two representative granulite samples S08-27 and S08-42 were analysed at (NGRI), Hyderabad, India for major trace and REE. The accuracy (% RSD) for major oxides and trace elements is 1% and the precision is 0.5% for the data generated from IIT Bombay. The detection limit is 1ppm for most of the elements. The precision of ICP-MS data are <5% RSD for all the trace elements including the REE. Whole rock major and trace element data of the granitoids and the granulites are presented in Table 1.

Table 1. Whole rock geochemical analyses for the MHM Granitoids and the Shillong plateau basement granulites

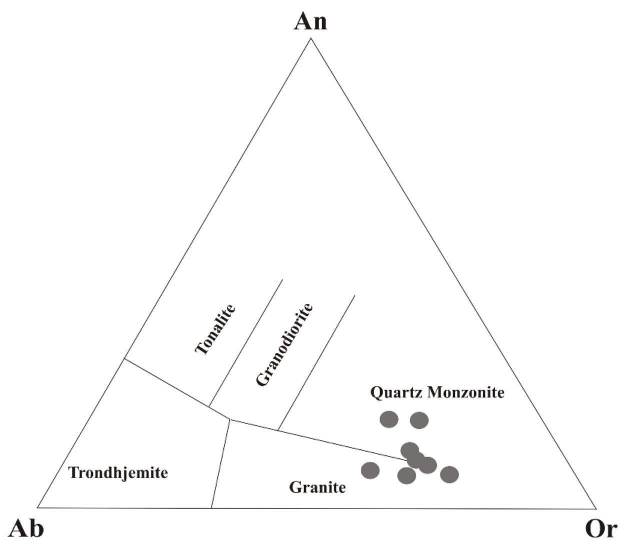
	Granitoids								Granulites	
Sample No	**AG-2$^+$**	**AG-4$^+$**	**AG-6$^+$**	**AG-8$^+$**	**AG-10$^+$**	**NK-12$^+$**	**NK-13$^+$**	**NK-18$^+$**	**S08-27***	**S08-42***
SiO_2	72.36	70.65	73.3	64.54	64.67	73.8	75.79	73.38	76.7	74.73
TiO_2	0.39	0.52	0.47	1.14	1.23	0.35	0.15	0.34	0.19	0.25
Al_2O_3	13.04	13.32	12.58	13.66	13.95	13.52	13	13.44	12.99	13.25
Fe_2O_3*	2.64	3.53	2.48	5.87	5.8	1.97	0.65	2.24	0.84	1
MnO	0.04	0.01	0.08	0.12	0.12	0.1	0.05	0.1	0.01	0.01
MgO	0.95	1.21	1.09	2.99	2.82	1.09	0.62	1.06	0.08	0.44
CaO	1.62	1.93	1.86	3.3	3.09	1.32	1.26	1.38	0.7	0.36
Na_2O	2.17	2.17	2.04	1.85	2.12	2.33	2	2.24	3.83	2.89
K_2O	5.92	5.79	5.2	5.65	5.38	5.1	5.52	4.93	3.4	5.37
P_2O_5	0.08	0.13	0.12	0.42	0.39	0.12	0.08	0.09	0.01	0.02
Total	**98.21**	**99.26**	**99.22**	**99.54**	**99.57**	**99.7**	**99.12**	**99.2**	**98.74**	**98.34**
Rb	41	37	38	17	18	51	34	43	69	157
Th	44	39	46	5	5	27	13	33	35	18
U	42	35	35	30	34	35	29	34	4	1
Nb	7	13	16	8	4	12	3	11	3	2
Sr	55	66	68	125	115	51	28	59	55	59
Zr	93	120	114	173	154	82	41	79	102	66
Y	22	24	26	13	9	25	13	28	15	5
La	139.58	233.26	219.99	nd	nd	nd	nd	nd	90.85	30.15
Ce	267.7	440.6	416.2	nd	nd	nd	nd	nd	242.7	50.45

Geochemical Characteristics

Major elements

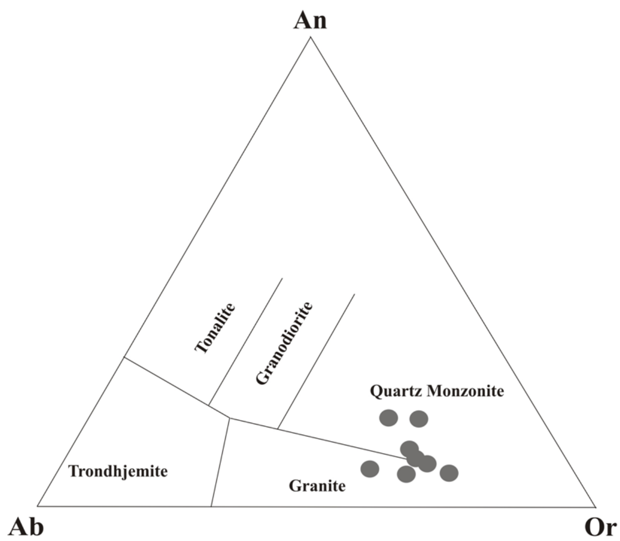
Two samples AG-8 and AG-10 have SiO_2 values 64.54 wt.% and 64.67 wt.% respectively; while the rest of the samples have SiO_2 values clustered between 70.65 wt.% and 75.79 wt.%. AG-8 and AG-10 contain relatively high Fe_2O_3* (5.87 wt.% and 5.8 wt.%), MgO (2.99 wt.% and 2.82 wt.%) and CaO (3.3 wt.% and 3.09 wt.%), while all the other samples have Fe_2O_3* range from 0.65 wt.% to 3.53 wt.%; MgO range from 0.62 wt.% to 1.21 wt.% and CaO range from 1.26 wt.% t 1.93 wt.%. The Al_2O_3, Na_2O and K_2O contents of all the granitoids are more or less similar. Al_2O_3 of the granitoids range from 12.58 wt.% to 13.95 wt.%. MHM granitoids are highly potassic; the K_2O contents of all the samples range between 4.93 wt.% to 5.92 wt.%. The granitoids contain relatively lesser Na_2O and it varies between 2.00 wt.% to 2.33 wt.%. The molar alumina saturation index Al_2O_3/($CaO + Na_2O + K_2O$) values for the granitoids range from 0.9 to 1.2. Thus the granitoids are peraluminous. In the CIPW ternary normative classification diagram using the abundance of albite, anorthite and orthoclase the granitoids plot within the granite and quartz monzogranite fields (Fig. 4). On the K_2O–SiO_2 plot all the samples show both calc-alkaline and shosonitic affinity, while AG-8 and AG-10 show distinct shosonitic affinity suggesting chemical heterogeneity in the source (Fig. 5). The granitoids of Mikir Hills massif plot on the top right side of the CA reference curve in the K-Na-Ca diagram (Fig. 6). All the samples of the granitoids plot towards the potassic side of the reference curve CA (Fig. 6) and show I-type geochemical characteristics in the SiO_2 vs. Y, Zr, Nb diagram (Fig. 7). All the major elements of the granitoids are plotted against SiO_2 on the Harker's diagramand they exhibit overall negative trends against SiO_2 except for K_2O, which shows positive trend (Fig. 8a).

Figure 4. Normative An - Ab - Or classification scheme for the Mikir Hills massif granitoids.



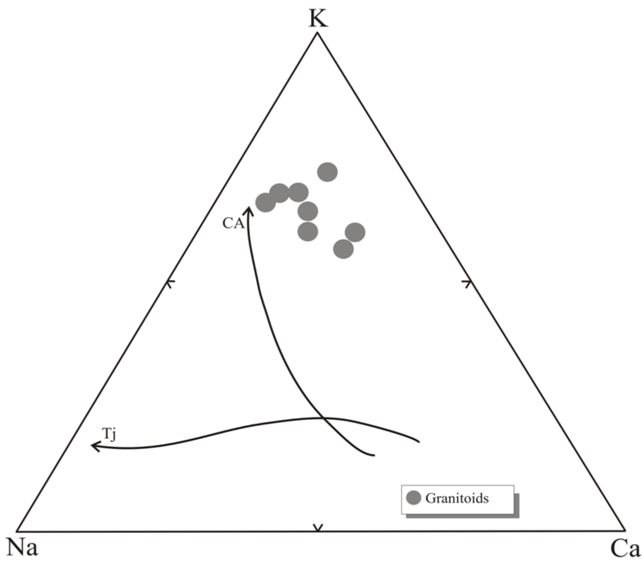
Fields are after O'Connor, 1965 and Barker 1979.

Figure 5. K_2O vs. SiO_2 plot for the Mikir Hills massif granitoids.



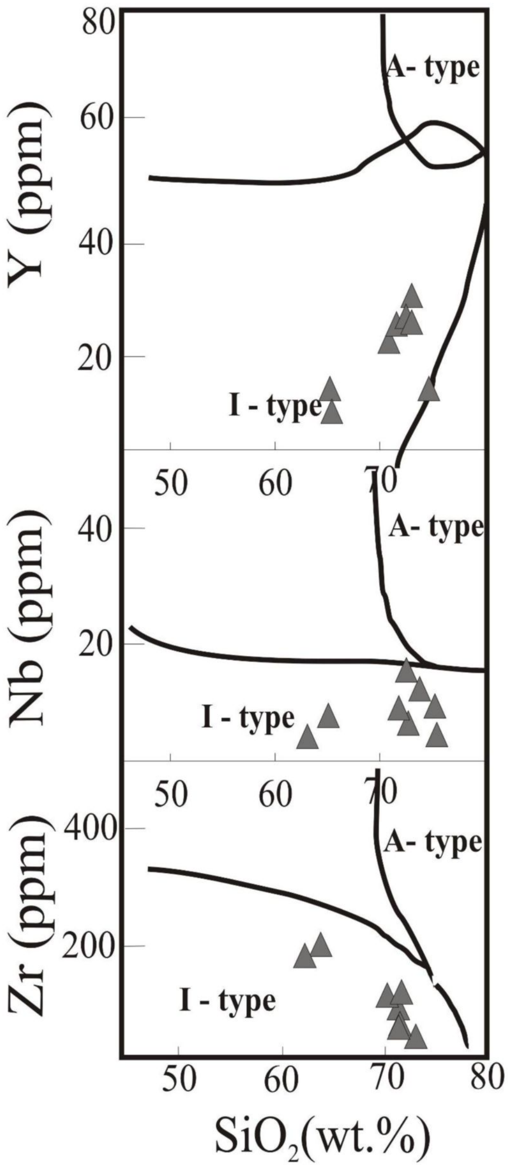
Subdivisions of igneous suites are based on K_2O contents (fields are after Peccerillo and Taylor, 1976).

Figure 6. K- Na-Ca diagram of granitoids of Mikir Hills massif.



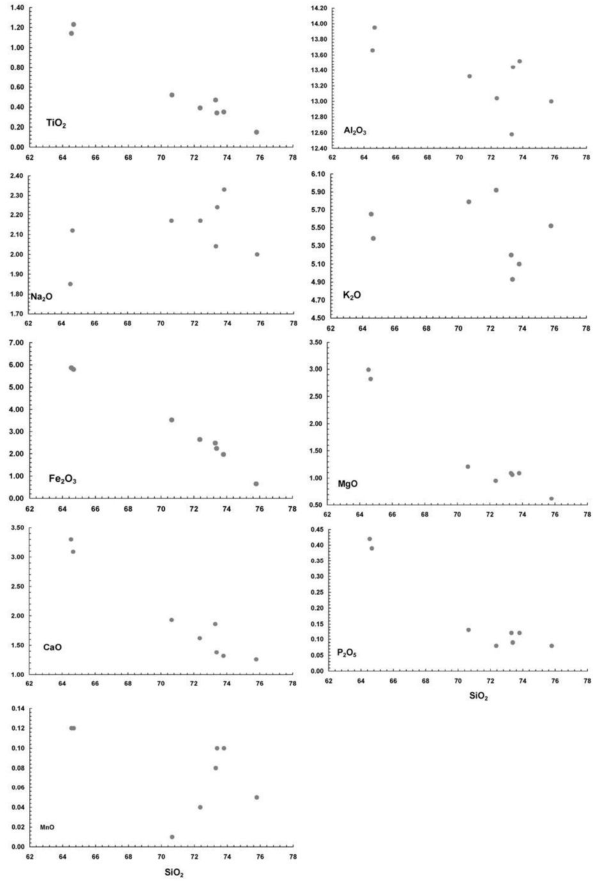
Calc-alkaline (CA) and Trondhjemite (Tj) trends are after Barker and Arth (1976).

Figure 7. Plots of Zr, Nb and Y against SiO_2 of Mikir Hills Massif granitoids.



Fields are after Collins et al., (1982).

Figure 8a. Major elements.

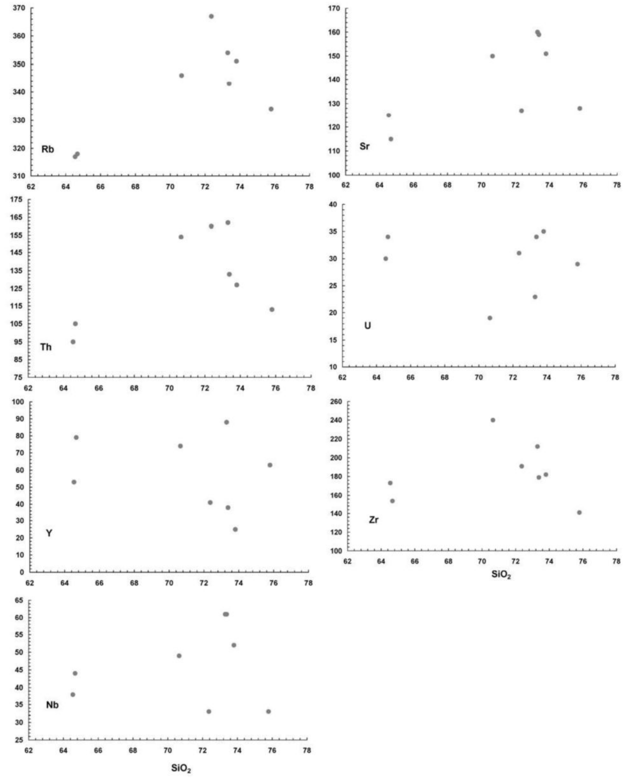


Harker's variation diagram for major elements of the granitoids of Mikir Hills Massif.

Trace elements

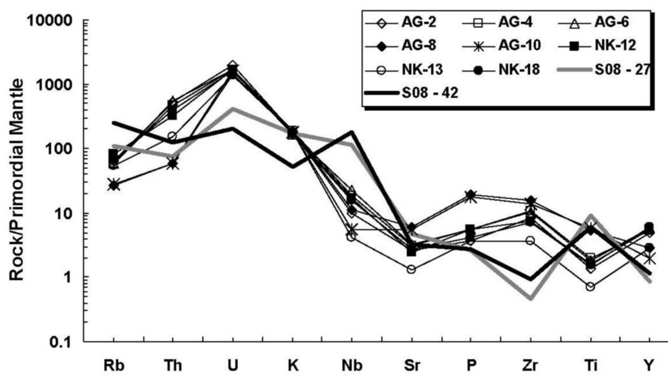
Harker's diagram for all the trace elements of the granitoids defines negative trends except U, which shows positive trend (Fig. 8b). The elemental patterns in the primitive mantle normalized multi-elemental spidergram for the granitoids (Fig. 9) show overall enrichment characteristics with respect to the primitive mantle (PM). The spidergram shows fractionated patterns with Large Ion Lithophile Elements (LILE) such as Rb, Th, U and K of the granitoids 10 – 100 folds enriched compared to High Field Strength Elements (HFSE) (Fig. 9). Negative anomalies are observed at Sr and Ti which may indicate retention of these elements by the refractory phases such as apatite, rutile and ilmanite at the site of partial melting and/or fractional crystallization. In contrast, the spidergram (Fig. 9) in respect of the granulites shows marginal enrichment of Rb, positive anomaly at Nb and Ti and negative anomaly at Zr relative to the granitoids.

Figure 8b. Trace elements.



Harker's variation diagram for trace elements of the granitoids of Mikir Hills Massif.

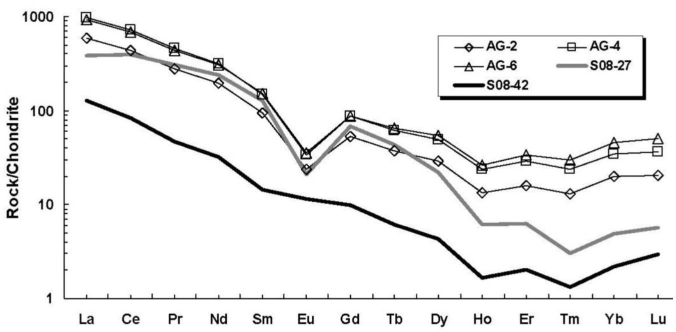
Figure 9. Primordial mantle normalized multi-element patterns for the granitoids of Mikir Hills massif of Shillong plateau.



Normalizing values are from Sun and McDonough, (1989). Data of 2 basement granulite samples are also shown for comparison.

Chondrite-normalized REE patterns for the granitoids are presented in Fig. 10 which show strongly fractionated patterns ((La_N/ Yb_N = 8–28) and negative Eu anomaly. the REE patterns in respect of the granulite sample No. S08-42 (Fig. 10) shows fractionated trends between LREE and HREE with no negative anomaly and the enrichment level of the elements over the entire spectrum is 30 - 40 folds lesser compared to the granitoids. the other granulite sample (No. S08-27) (Fig. 10) shows strongly fractionated trends between LREE and HREE with negative anomaly and the LREE enrichment level is similar to the granitoids but the HREE is significantly less (20 – 30 folds). The comparative trace and rare earth elemental signatures (Fig. 9, 10) between the basement granulite and the Granitoids therefore do not attest to the link between them via dehydration melting in the granulite and producing a granitic melt and generation of the melts for the granitoids is explicable by partial melting of metasomatized mantle and /or overlying crust and subsequent mingling of both the magma.

Figure 10. Chondrite normalised REE patterns for the granitoids of Mikir Hills massif of Shillong plateau.

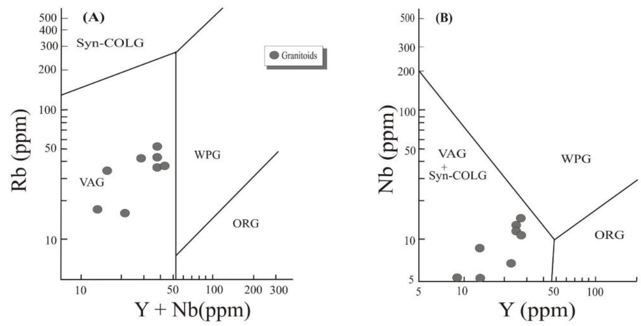


Normalizing values are from Sun and McDonough, (1989). Data of two basement granulite samples are also shown for comparison.

Tectonic Setting

Shillong plateau in northeast India is very significant with regard to its tectonic evolution. Rb vs. (Y+ Nb) and Nb vs. Y relationships show that the Mikir Hills Massif granitoids have geochemical characteristics similar to those of continental arc as the granitoids plot in the Volcanic Arc Granite (VAG) field (Fig. 11). Further high-K calc-alkaline-shosonite, perluminous and I-type characteristics of the granitoids indicate that these rocks were emplaced in a convergent-margin setting or derived from a source previously affected by subduction. Mikir Hills Granitoids exhibit fractioned LILE/HFSE as well as fractionated LREE/HREE patterns (Fig. 9, 10). The fractionated LILE/HFSE pattern is generally recognized as a distinct feature of convergent margin magmatism (Winter, 2001; and references therein). These geochemical characteristics of the granitoids thus favour magmatism in a convergent margin tectonic setting within Shillong plateau.

Figure 11. Tectonic discriminant diagrams.



(A) Rb vs. Y+Nb and (B) Nb vs. Y tectonic discriminant diagram for the granitoids of Mikir Hill massif of Shillong plateau. VAG, volcanic arc granite, Syn-COLG syn-collisional granite, WPG within plate granite, ORG ocean ridge granite fields are after Pearce *et al.*, (1984).

Discussion and Conclusion

The Neoproterozoic MHM granitoids (881 - 479 Ma) are peraluminous and show high-K calc-alkaline and I-type characteristics. They exhibit fractionated LILE/HFSE and LREE/HREE patterns and plot within the volcanic arc granite (VAG) filed in the Rb vs. Y+Nb diagram (Fig. 11A) and common syn-collision granite (Syn-COLG) and VAG field in the Nb vs. Y tectonic discrimination diagram (Fig. 11B).

Shillong plateau experienced Pan-African tectono-metamorphic events during Neoproterozoic resulting in granulite-facies rocks in the basement. It is observed that several Pan-African terrains experienced granulite-facies metamorphism and granitoid magmatism during Neoproterozoic and the later is formed from anatectic melts produced during granulite-facies metamorphism. For example in the southern Granulite Terrain of India the Madurai Block and Kerala Khondalite belt experienced a Pan-African tectono-metamorphic evolution in Neoproterozoic times that culminated in granulite-facies metamorphism at 650–550 Ma and extensive granitoids magmatism at

590–525 Ma (Braun and Kriegsmann, 2003). In the Prydz Bay region of East Antarctica the emplacement of syntectonic granites and prograde amphibolite-granulites facies metamorphism is found coeval during 500–540 Ma (Mikhalsky *et al.*, 2001; Liu *et al.*, 2006). It has been observed that the in general the granulites of lower continental crust are characterized by low concentration of LILE (Rb, Th, U and K) and a number of different mechanisms have been proposed to explain the observed LILE depletion in granulites. An adequate mechanism to explain the observed LILE depletion is partitioning of LILE into an anatectic melt fraction that took place during granulite-facies metamorphism within the lower crust (Fyfe, 1973; Tarney and Weaver, 1987; Cartwright, 1995). A cross-check was thus initiated whether the granitoids under consideration are anatectic magmas produced during granulite-facies metamorphism comparing the trace and rare earth elemental signatures of the granitoids and the granulites in Fig.s 9, 10. The granitoids show contrasting geochemical characteristics with the basement granulites. The granitoids show negative Nb and Ti and positive Zr anomalies in the spidergram, whereas the granulites show positive Nb, Ti and negative Zr. Moreover, the LILE abundances of both the granulites and the granitoids are almost similar suggesting that the granitoids are not anatectic melts produced during the granulite-facies metamorphism. In the event of an anatectic melt the granulites should have been depleted in the LILEs. The granulite S08-42 shows moderately fractionated REE patterns with no negative anomaly and the enrichment level of the elements over the entire spectrum is 30 - 40 folds lesser compared to the granitoids while the other granulite S08-27 shows strongly fractionated patterns with LREE enrichment level similar to the granitoids and HREE is significantly less (20 – 30 folds) (Fig. 10) compared to the granitoids along with a strong negative Eu anomaly. Based on the geochemical observation, it can be inferred that the granitoids are not anatectic magmas derived from partial melting of the basement granulitic rocks. The geochemical signatures of the granitoids point towards magmatism in a convergent margin tectonic setting within Shillong plateau and the emplacement of these granitoids during Neoproterozoic times, thus have significant implications for the construction of the Gondwana supercontinent.

The supercontinent Rodinia formed around a core of Precambrian North America (Laurentia) during the Grenvillian event (~1300–1000 Ma ago) and is supposed to have occurred by accretion of all existing continental fragments of that time, including those that now make up the cratonic components of the Gondwana continents. The process of accretion and amalgamation of continental fragments was followed by a period of supercontinent disintegration and dispersal, considered to have started around 750–800 Ma ago (Hoffman, 1991, 1999; Pisarevsky *et al.*, 2003) and by 550 Ma, most of the dispersed terranes had reassembled, probably in a different configuration, in the supercontinent Gondwana (Meert and Van der Voo, 1997). This occurred after closure of several oceans of different sizes. For instance, the Mozambique Ocean between East and West Gondwana, conventionally interpreted to have been subducted and resulted in collision of these two large continental masses (Burke and Dewey, 1972; Kröner, 2002). Likewise, the South American and African continental blocks amalgamated into West Gondwana in several stages of ocean closure and collision between 900 and ~550 Ma (see, e.g., Campos-Neto, 2000; Alkmim *et al.*, 2001, Cordani *et al.*, 2003).

The high-grade metamorphic basement of Sri Lanka consists of ~895–1100 Ma old calc-alkaline granitoids rocks that are exposed in the Wanni (western Sri Lanka) and Vijayan (eastern Sri Lanka) Complexes (Kehelpannala, 1997; Kröner, 1991; Kröner *et al.*, 2003), which are interpreted to have been produced due to subduction/accretion event at around 1000 Ma. Similarly, the Goia´s Magmatic Arc of Brazil includes a series of 900–600 Ma granitoids rocks, formed during successive episodes of intraoceanic subduction. This large amount of juvenile crustal material, located close to the Neoproterozoic megasuture of the Trans-Brasiliano lineament in central Brazil, is the main evidence for the existence of the Goia ´s Ocean, which must have had a considerable size (Cordani and Sato, 1999; Pimentel *et al.*, 2000).

The geochemical signatures, the age of the granitoids and the position of Shillong plateau at the leading margin of India during Neo-proterozoic the geochemical signatures thus point to the generation of the melts for the granitoids by partial melting of metasomatized mantle and /or overlying crust and subsequent mingling of both the magma and their emplacement in a convergent tectonic setting during re-assembling of the continents in Gondwana subsequent to disintegration and dispersal of Rodinia. Similar explanations are drawn for the 895–1100 Ma old calc-alkaline granitoids of Srilanka; 900–

600 Ma granitoids rocks of the Goia´s Magmatic Arc of Brazil. However, the full extent and knowledge of these rocks within Shillong plateau requires integrated geological, geochemical, isotopic, geochronological and palaeomagnetic studies.

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