Geochemistry and petrogenesis of Neoproterozoic Mylliem granitoids, Meghalaya Plateau, northeastern India

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The Mylliem granitoids of the Meghalaya Plateau, northeastern India, represent one of the disharmonic Neoproterozoic igneous plutons, which are intrusive into low-grade Shillong Group of metasediments. Field studies indicate that the Mylliem granitoids cover an area of about 40 km^2 and is characterized by development of variable attitude of primary foliations mostly marked along the margin of the pluton. Xenoliths of both Shillong Group of metasediments and mafic rocks have been found to occur within Mylliem granitoids. Structural study of the primary foliation is suggestive of funnel-shaped intrusion of Mylliem granitoids with no appreciable evidence of shearing. Petrographically, Mylliem granitoids are characterized by pink to white phenocrysts of prismatic microcline/perthite and lath-shaped plagioclase (An_{20}–An_{29}). Groundmass material is characterized by quartz, microcline, plagioclase, muscovite and biotite. Sphene and apatite occur as accessory minerals. Petrographically Mylliem granitoids have been discriminated as granite and granodiorite according to IUGS system of classification.

Critical evaluation of geochemical data and variation trends of major oxides/trace elements suggests a significant role of fractional crystallization in the evolution of Mylliem pluton. Th/U ratios (3.22–6.77) indicate a relatively higher abundance of Th over U. Chondrite-normalized REE diagram characteristically shows an enriched LREE pattern and prominent negative Eu anomaly (Eu/Eu* = 0.16–0.42) indicating the significant role of plagioclase fractionation from the parent magma. An overall strong REE fractionation pattern has been envisaged for Mylliem granitoids. The strong REE fractionation of the Mylliem granitoids is depicted by $(Ce/Yb)_N$ values, which show a range of 1.39 to 1.65. The aluminium saturation index (ASI) (ranging from 1.0 to 1.3), A/CNK ratios (ranging from 1.4 to 2.11) and A/NK ratios (ranging from 1.75 to 2.43) provide evidences for the peraluminous, S-type nature of the Mylliem granitoids. The peraluminous, S-type character is further supported by geochemical parameters such as Fe* and MALI (modified alkali lime index). Normative corundum >1.0 wt.% is suggestive of the S-type nature of Mylliem granitoids. This is indicative of parent melt-extraction from metasedimentary source rocks by partial melting. Distinct geochemical parameters suggest a post-orogenic tectonic environment for the Mylliem granitoids. The peraluminous, calc-alkalic to alkali-calcic, post-orogenic Mylliem granitoids are geochemically correlatable with the post-orogenic Caledonian granitoids of Ireland and Britain.

Keywords. Mylliem granitoids; northeastern India; peraluminous; post-orogenic; Caledonian.

1. Introduction

The Archaean basement gneisses and Mesoproterozoic granulites (Chatterjee *et al* 2007) and the Shillong Group of metasediments of the Meghalaya Plateau have been impregnated with disharmonic emplacements of several granitoid plutons (Mazumdar 1976; Acharyya *et al* 1986; Ghosh *et al* 1994). These syn- to late-tectonic granitoids straddle the entire Precambrian regime of the Meghalaya Plateau and Mikir Hills in north-eastern India and range in age from 479 to 881 Ma (Nandy 2001; Ghosh *et al* 2005). South Khasi batholith (690±26 Ma), Mylliem pluton (607±13 Ma), Kyrdem pluton (479±26 Ma) and the Nongpoh batholith (550±15 Ma) represent a few significant porphyritic granitoids of the east-central Meghalaya Plateau, broadly becoming younger in age from south–west to north–east (Ghosh *et al* 2005) (figure 1). The emplacement of different granitoid plutons was controlled by pre-existing fractures and lineaments (Evans 1964; Nandy 1980). The occurrences of discordant mafic xenoliths within these plutons suggest their undoubted magmatic origin. But in some cases, the presence of sedimentary/metasedimentary xenoliths within the granitoid plutons is truly significant, recording a strong sedimentary influence in the course of their evolution. The current investigation at and around Mylliem (25°26′N to 25°32′N and 91°49′E to 91°52′E), East Khasi Hills district, Meghalaya brings out the occurrence of granitoid pluton intrusive into the Shillong Group of rocks. Currently, only a rudimentary idea on the petrochemistry of the Mylliem granitoids is available (Rahman 1985). This paper, for the first time, highlights the field occurrence, petrography and geochemistry of granitoid pluton at and around Mylliem (25°26′N to 25°32′N and 91°49′E to 91°52′E), East Khasi Hills, Meghalaya in order to build up a cogent petrogenetic model and to place constraints on tectonic evolution of the Mylliem pluton.

2. Geological setting

The Meghalaya Plateau forms a part of the north-eastern extension of the Indian Peninsular Shield (Gupta and Sen 1988). It is an E–W trending, oblong, uplifted horst-block elevated about 600–1800 m above the Bangladesh Plains in the south. The uparching of the landmass forming a horst has been facilitated by extensive faulting (Srivastava

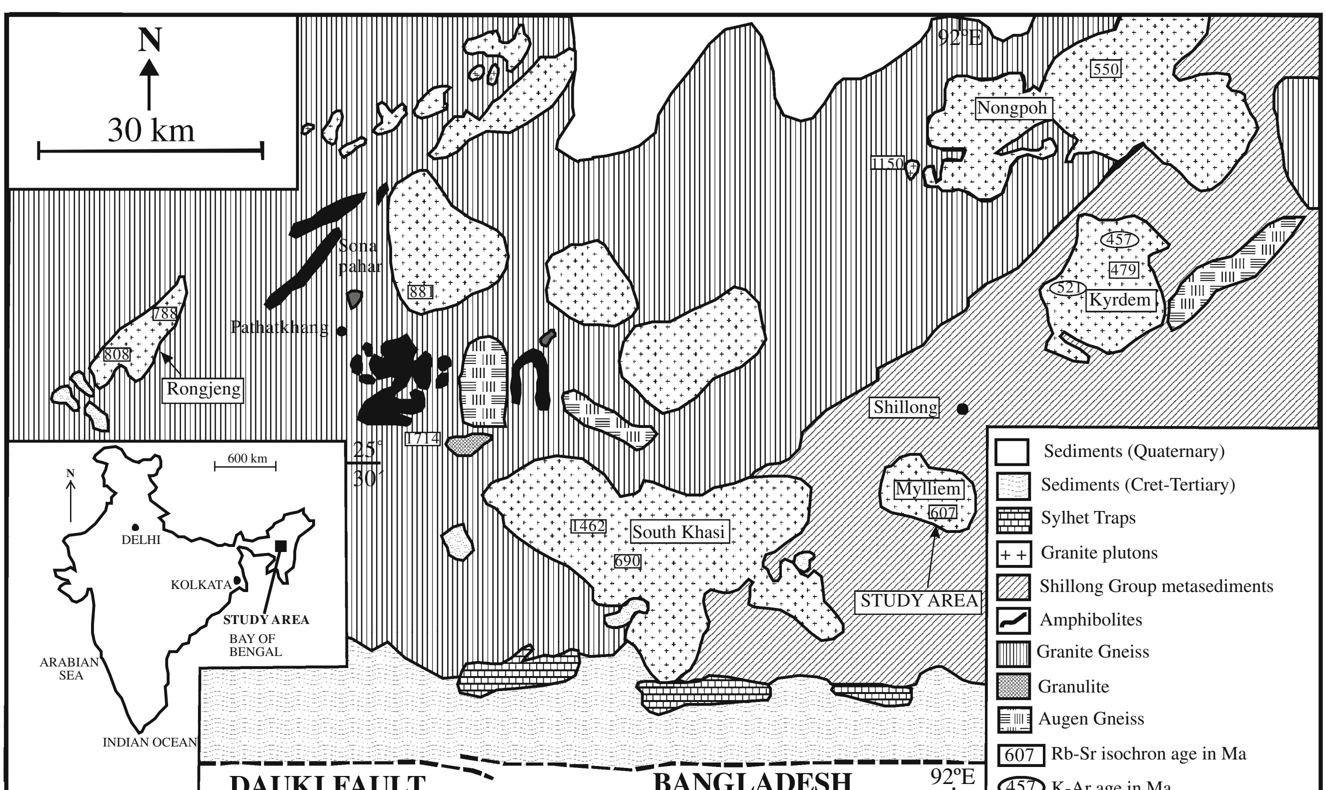

Figure 1. Geological map of Meghalaya showing the granitoid plutons with isotopic ages (after Ghosh *et al* 2005). Inset map shows the position of study area in the map of India.

and Sinha 2004). The Meghalaya Plateau covers an area of about 4×10^4 km^2 and is bounded by the E–W trending Brahmaputra fault systems in the north and the Dauki fault systems in the south (Nandy 2001). The western and the eastern sides are bordered by the N–S trending Jamuna fault system and the NW–SE trending Kopili fracture zone, the latter separating the Meghalaya Plateau from the Mikir Hills (Evans 1964; Desikachar 1974; Acharyya *et al* 1986; Nandy 1986; Gupta and Sen 1988; Nandy 2001).

The geology of the Meghalaya Plateau has been dealt with by several workers (Desikachar 1974; Mazumdar 1976; Das Gupta and Biswas 2000). The lithostratigraphic succession of the Meghalaya Plateau suggested by Mazumdar (1976) is presented below:

Mesozoic–Tertiary sedimentary rocks
——————Unconformity——————
Sylhet Traps of pre-Upper Cretaceous age
——————Fault contact——————
Porphyritic granite
——————Intrusive contact——————
Khasi Greenstone Belt
Shillong Group
——————Unconformity——————
Non-porphyritic migmatitic granitoid
——————Diffused contact——————
Archaean basement gneissic complex

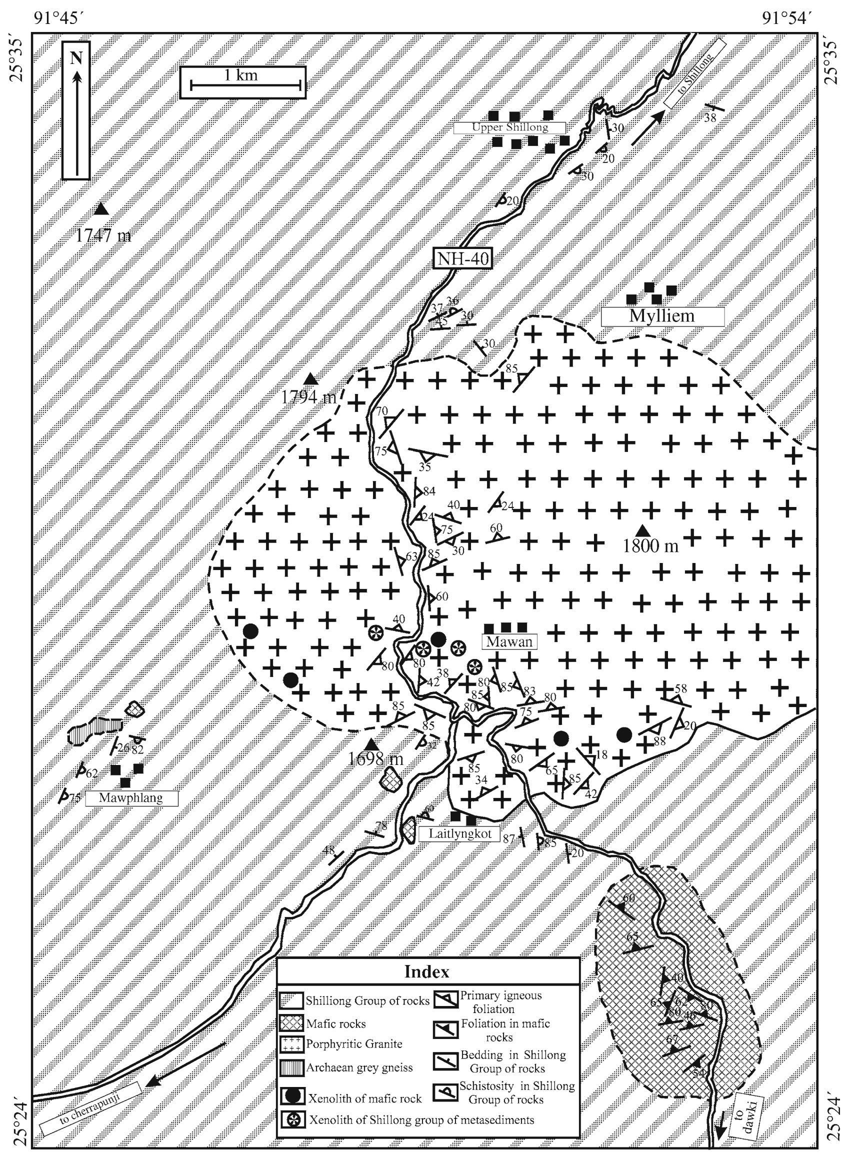

Figure 2. Geological map of the study area prepared by the first and second authors. For granitoid, only representative attitudes of primary igneous foliation have been shown.

The Archaean basement gneissic complex consists of two different units viz., gneissic complex proper and the non-porphyritic migmatitic granitoid rocks (Mazumdar 1976; Nandy 2001). The gneissic complex proper is made up of an assortment of rock types including sillimanite-bearing gneisses, amphibolite, granulites, granite gneisses, etc. The Shillong Group of rocks were deposited in a 240-km long, NE–SW trending intracratonic basin resting unconformably, as indicated by a basal conglomerate, over the basement gneissic complex (Nandy 2001). The Shillong Group of rocks was later metamorphosed to Greenschist facies (Nandy 2001). These have been later intruded by concordant and discordant bodies of mafic igneous rocks referred to as Khasi Greenstones (Mazumdar 1976). Porphyritic granitoids occur as discordant plutons cutting across the Shillong Group of metasediments (e.g., Kyrdem, Mylliem plutons) and basement gneisses (Rongjeng, Sindhuli plutons). In some cases, as for example in Nongpoh and South Khasi areas, the granitoid plutons intrude both the Shillong Group and the gneissic complex (Ghosh *et al* 2005). The Cretaceous Sylhet Trap basalts and Tertiary shelf sediments occupy the southern fringe of the plateau (figure 1).

3. Mode of occurrence

The currently investigated Mylliem pluton has been the earliest described pluton from the Meghalaya Plateau and is named after a village of the same name located near Shillong (Nandy 2001). The Mylliem pluton covers an area of about 40 km^2 and is intrusive into the metasedimentary and quartzitic rocks of the Shillong Group (figure 2). Current field studies indicate that the pluton is exposed in a roughly elliptical outcrop, the longer axis being approximately E–W and 8.4 km in length, the E–W elongation is oblique to the prevailing NE–SW strike of the enclosing Shillong Group of rocks. Mylliem granitoids are structurally characterized by primary foliations developed mainly along the margin of the pluton. The primary foliation is defined by the preferential parallel alignment of lath-shaped prismatic megacrysts of feldspar (around 4 cm in length) embedded in a more or less equigranular groundmass mainly composed of quartz, biotite, muscovite and feldspar. In some exposures, the primary foliation exhibits a swerving attitude due to variation in the orientation of lath-shaped feldspar megacrysts. The intrusive nature of the magma giving rise to Mylliem granitoids can be conjectured from field evidences such as (a) local apophyses and tongues of Mylliem granitoid extending into the Shillong Group of rocks and (b) occurrence of discrete xenoliths

Table 1. *Modal data (vol%) of Mylliem granitoid.*

Sp. no.	PG/2	PG/7	PG/9	PG/13	PG/23	PG/32	PG/76	PG/79	PG/85	PG/87	PG/90	PG/93	PG/99	PG/100	PG/109	PG/136
Quartz	34.1	18.5	24.7	23.9	20.5	37.8	22.9	22.9	28.7	21.1	19.5	23.3	20.1	29.4	20.6	20.8
K-feldspar	13.8	60.9	25.2	52.8	20.2	11.0	49.5	43.4	30.8	38.3	61.5	38.84	52.0	32.8	53.6	39.4
Plagioclase	47.1	13.1	34.7	18.8	26.3	38.3	19.3	21.0	30.1	25.9	12.6	29.5	22.1	27.7	18.1	27.8
Biotite	4.6	7.1	14.3	4.00	31.3	11.1	7.7	10.5	9.5	12.8	4.7	8.0	2.2	9.3	6.8	10.7
Muscovite	–	–	–	0.4	–	–	–	–	–	–	0.1	–	–	–	0.1	0.6
Chlorite	–	0.1	–	–	1.2	–	–	–	–	–	1.0	–	2.9	–	–	–
Sphene	–	–	0.3	–	0.4	–	0.5	1.7	0.2	1.0	0.1	0.1	–	–	–	–
Apatite	–	–	–	–	–	1.5	–	–	–	–	–	–	–	–	–	–
Opaque	0.5	0.4	0.8	0.2	0.2	0.4	0.2	0.5	0.9	0.9	0.5	0.3	0.8	0.8	0.9	0.6

of Shillong Group of metasediments and metabasic rocks within Mylliem granitoids. Detailed structural studies in the study area reveal that the dip of primary foliation is towards the central portion of the pluton and roughly parallel to the trend of the margin indicating a funnel-shaped intrusion. The attitudes of primary foliation planes of Mylliem granitoids have been projected in a stereo pole diagram where the poles to the primary foliation are found to be distributed along a small circle girdle with a sub-vertical girdle axis (∼ 70°). Such a distribution pattern of primary foliation is suggestive of forceful injection from the parent magma. Field-relations clearly indicate that the Mylliem pluton forms a domal up-arch (figure 2) within the surrounding Shillong Group of rocks. This would imply a domal intrusion of Mylliem granitoid into the Shillong Group of rocks. There is no evidence of shearing in Mylliem granitoids and reduction of grain size of the megacrysts at the place of contact.

4. Petrography

Mylliem granitoids are distinctly characterized by the development of pink to white coloured phenocrysts (length ranging up to 4 cm) of feldspar. Microscopic studies reveal that the phenocrysts are mainly composed of prismatic grains of microcline and lath-shaped plagioclase. Perthite occurs in both flame and string varieties showing well-developed exsolution lamellae. Anorthite content of plagioclase varies from An_{20} to An_{29} (determined by X′ˆ 010 symmetric extinction angle) corresponding to oligoclase. Groundmass composition is characterized by the presence of quartz, microcline, plagioclase, muscovite and biotite. Muscovite occurs in two forms. One type is flaky muscovite with idiomorphic outlines closely associated with biotite, while another type occurs as irregular tiny flakes within altered plagioclase. Accessory minerals include opaque grains formed at the expense of biotite and sphene, lozenge-shaped grains of apatite and sphene. Large phenocrysts of microcline and plagioclase are embedded in a groundmass of quartz, feldspar and mica representing porphyritic texture. In some places, vermicular intergrowth of quartz within plagioclase is observed depicting myrmekitic texture. Graphic texture is also present. Saussuritization of plagioclase is a common feature. Modal analyses of representative samples from Mylliem pluton has been presented in table 1. According to the IUGS system of classification, the Mylliem granitoids, on the basis of their modal mineralogy, occupy the fields of granite and granodiorite in the Q–A–P diagram of Streckeisen (1976) (figure 3).

5. Geochemistry

5.1 *Sampling and analytical techniques*

Systematic samplings were carried out in the study area at and around Mylliem (25°26′N to 25°32′N and 91°49′E to 91°52′E) and over 65 samples were collected in order to represent the rock types from the Mylliem pluton. In all cases, efforts had been made to collect fresh samples free from alterations and any secondary minerals. Major and trace element (including REE) analyses of nine representative samples of Mylliem granitoid were carried out at the National Geophysical Research Institute, Hyderabad. The major oxides were analysed

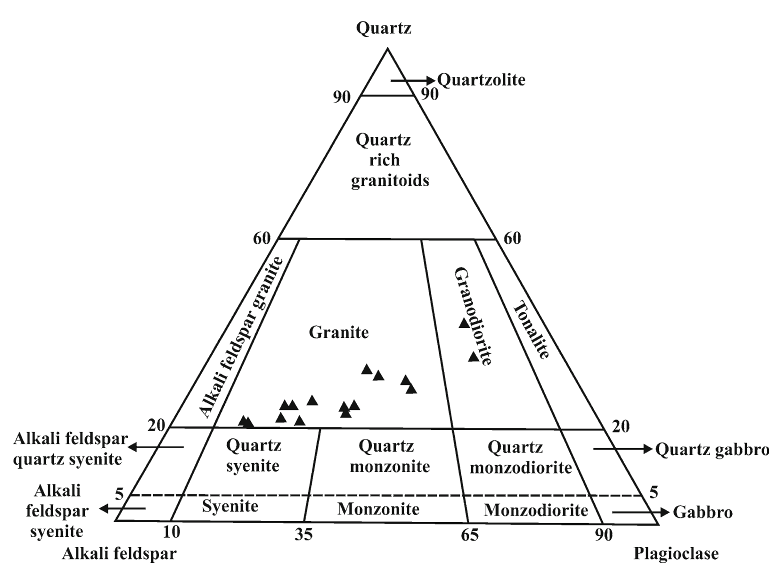

Figure 3. Modal plots of Mylliem granitoid in IUGS-recommended Q–A–P diagram (Streckeisen 1976).

Table 2. *Major oxide data (wt.%) of Mylliem granitoid.*

Sp. no.	PG/2	PG/23	PG/79	PG/85	PG/87	PG/93	PG/99	PG/100	PG/136
SiO_2	68.86	62.13	68.11	72.12	68.85	69.41	71.9	71.37	72.08
TiO_2	0.56	1.25	0.52	0.62	0.46	0.53	0.49	0.47	0.56
Al_2O_3	16.11	16.16	14.28	13.5	14.48	14.07	12.58	14.7	13.76
Fe_2O_3	3.65	6.42	3.43	3.82	3.02	3.4	3.31	3.22	3.97
MnO	0.08	0.09	0.06	0.08	0.06	0.07	0.07	0.07	0.09
MgO	1.12	2.15	1.2	1.11	1.07	1.05	1	0.82	1.05
CaO	1	2.36	2.06	1.45	2	2.51	1.91	0.45	0.84
Na_2O	2.16	1.73	2.5	2.13	2.83	3.04	2.59	3.11	1.77
K_2O	4.48	5.17	5.65	3.78	5.19	4.11	4.01	4.57	4.54
P_2O_5	0.28	0.66	0.24	0.25	0.19	0.22	0.21	0.19	0.16
LOI	1.13	0.98	0.18	1.18	0.22	0.84	1.22	0.46	1.42
Total	99.43	99.1	98.23	100.04	98.37	99.25	99.29	99.43	100.24
Na_2O+K_2O	6.64	6.9	8.15	5.91	8.02	7.15	6.6	7.68	6.31
A/CNK	2.11	1.75	1.4	1.83	1.45	1.46	1.48	1.81	1.92
A/NK	2.43	2.34	1.75	2.28	1.81	1.97	1.91	1.91	2.18
K_2O/Na_2O	2.07	2.99	2.26	1.77	1.83	1.35	1.55	1.47	2.56
Ti/P	2.75	2.6	2.97	3.41	3.32	3.31	3.2	3.4	4.81
*A.S.I.	1.5	1.3	1	1.3	1	1	1	1.2	1.3
#Fe*	0.74	0.73	0.72	0.75	0.72	0.74	0.75	0.78	0.77
##MALI	5.64	4.54	6.09	4.46	6.02	4.64	4.69	7.23	5.47
CIPW norm									
Quartz	36.75	26.37	26.94	41.68	27.69	30.15	37.21	34.49	41.99
Corundum	6.67	5.09	0.89	3.91	1.04	0.59	1.02	4.31	4.84
Orthoclase	26.93	31.14	34.05	22.59	31.25	24.68	24.16	27.29	27.15
Albite	18.59	14.92	21.57	18.23	24.4	26.14	22.35	26.59	15.16
Anorthite	3.19	7.54	8.83	5.63	8.85	11.19	8.26	1	3.16
Hypersthene	2.83	5.43	3.04	2.78	2.7	2.65	2.53	2.05	2.64
Magnetite	0.26	0.3	0.2	0.26	0.2	0.23	0.23	0.23	0.29
Haematite	3.53	6.34	3.36	3.68	2.94	3.3	3.22	3.1	3.81
Rutile	0.47	1.15	0.45	0.53	0.39	0.45	0.41	0.39	0.46
Apatite	0.62	1.47	0.53	0.55	0.42	0.49	0.47	0.42	0.35
**D.I.	82.27	72.43	82.57	82.5	83.33	80.97	83.72	88.37	84.29

*A.S.I: Alumina saturation index; **D.I.: Diffentiation index; #Fe*: $FeO^{(t)}/(FeO^{(t)}+MgO)$; ##MALI: Modified alkali lime index.

by XRF while the trace elements (including REE) were analysed by ICP-MS. The procedures and accuracy and precision of XRF method adopted during this study have been proposed by Acharyya *et al* (2006), while the analytical details and precision involved in ICP-MS have been given by Satyanarayanan *et al* (2006). The whole rock major (wt.% oxides) and trace element (including REE) (ppm) data for the Mylliem granitoids have been furnished in tables 2 and 3.

5.2 *Major and trace element characteristics*

Major oxide data (table 2) reveal that the Mylliem granitoids have a variable composition with moderate-to-high silica (SiO_2 ranging from 62.13 to 72.12 wt.%) and low content of CaO (0.45 to 2.51 wt.%), MgO (0.82 to 2.15 wt.%), TiO_2 (0.46 to 1.25 wt.%), MnO (0.06 to 0.09 wt.%) and P_2O_5 (0.16 to 0.66 wt.%). Total alkali content ranges from 5.19 to 8.15 wt.%, while Al_2O_3 ranges from 12.58 to 16.16 wt.%. K_2O varies between 3.78 and 5.65 wt.% and is higher than Na_2O, which ranges from 1.73 to 3.11 wt.%. K_2O/Na_2O ratio ranges from 1.35 to 2.99 depicting the potash-rich character of Mylliem granitoids. CIPW normative compositions have been calculated on an anhydrous basis for the analysed Mylliem granitoid samples (table 2). The Mylliem granitoid samples fall within the field of 'Granite' in the normative An–Ab–Or diagram (after O'Connor 1965). Compositional plots of Mylliem granitoids in the CaO–Na_2O–K_2O ternary diagram (after Barker and Arth 1976) indicate that the data-points occupy the field of 'Granite' with a minor spill to the field of 'Quartz Monzonite'.

Table 3. *Trace element (including rare earth element) data (in ppm) of Mylliem granitoid.*

Sp. no.	PG/2	PG/23	PG/79	PG/85	PG/87	PG/93	PG/99	PG/100	PG/136
Sc	5.77	7.63	7.88	7.8	6.18	6.44	6.89	8.07	7.74
V	1.27	1.6	1.64	1.17	1.04	1.1	1.64	0.96	1.53
Cr	10.31	7.63	6.46	8.14	7.71	7.6	10.12	7.9	7.58
Co	54.6	36.1	141.04	143.77	110.31	152.06	86.35	106.24	66.61
Ni	3.71	2.5	2.58	2.9	2.66	2.62	2.35	2.46	2.84
Cu	0.65	0.74	0.78	0.74	0.68	0.81	0.61	0.99	0.69
Zn	18.65	27.78	28.81	23.01	22.78	29.83	25.32	25.85	27.26
Ga	14.48	12.24	19.92	16.8	16.81	16.96	16.53	20.35	13.59
Rb	226.61	140.76	300.08	284.98	294.61	237.31	233.63	365.12	236.83
Sr	74.91	141.62	245.3	139.86	182.86	189.7	155.15	87.04	73.9
Y	34.43	35.41	83.76	45.85	52.38	55.87	42.65	56.16	43.54
Zr	156.24	284.47	236.35	296.97	243.06	243.36	262.15	225.67	193.63
Nb	27.69	24.01	39.2	35.21	28.23	25.44	33.27	41.05	29.3
Cs	8.58	4.7	8.86	13.19	8.91	5.55	5.12	9.76	9.95
Ba	153.81	257.43	336.83	200.28	280.41	223.59	144.67	221.59	120.24
Hf	5.32	7.1	7.37	9.39	7.37	7.5	8.48	7.64	6.43
Ta	1.54	1.8	5.32	4.38	2.51	1.89	2.44	4.25	3.41
Pb	43.42	32.91	47.73	46.45	50.35	68.43	65.67	43.89	39.05
Th	49.9	32.52	70.41	74.79	58.21	57.17	66.64	85.39	51.1
U	15.38	4.8	11.92	21.33	14.98	11.55	20.71	15.98	14.11
Rb/Sr	3.02	0.99	1.22	2.04	1.61	1.25	1.51	4.19	3.2
Ba/Rb	0.68	1.83	1.12	0.7	0.95	0.94	0.62	0.61	0.51
Ba/Sr	2.05	1.82	1.37	1.43	1.53	1.18	0.93	2.55	1.63
Th/U	3.24	6.77	5.91	3.51	3.89	4.95	3.22	5.34	3.62
K/Rb	164.09	304.86	156.27	110.09	146.22	143.75	142.46	103.89	159.11
K/Ba	241.76	166.69	139.22	156.65	153.62	152.57	230.06	171.17	313.4
La	40.17	92.98	40.62	83.7	65.66	76.94	66.32	89.75	28.5
Ce	96.79	130.17	80.68	130.29	129.06	152.15	131.26	192.08	101.5
Pr	8.5	19.47	8.14	19.54	13.52	15.58	13.66	17.61	6.02
Nd	32.25	73.6	30.36	73.27	50.96	58.39	50.78	63.07	23.95
Sm	6.33	11.53	5.5	12.74	9.41	10.77	9.01	10.87	5.63
Eu	0.55	1.16	0.6	1	0.95	0.92	0.68	0.83	0.52
Gd	6.45	11.76	5.85	12.57	9.85	10.96	9.62	12.06	6.16
Tb	0.94	1.34	0.77	1.5	1.37	1.51	1.23	1.49	1.03
Dy	6.1	6.81	4.66	8.36	8.53	9.41	7.07	8.65	7.54
Ho	0.7	0.73	0.52	0.93	0.94	1.06	0.8	0.95	0.85
Er	2.5	2.56	1.86	3.37	3.44	3.72	2.73	3.53	2.86
Tm	0.35	0.28	0.25	0.43	0.45	0.48	0.32	0.42	0.39
Yb	3.88	2.94	2.95	4.99	4.87	5.06	3.54	4.36	4.16
Lu	0.65	0.46	0.47	0.82	0.8	0.81	0.61	0.72	0.63
ΣREE	206.14	355.79	183.21	353.5	299.81	347.76	297.63	406.37	189.73
$(Ce/Yb)_N$	1.4	1.65	1.44	1.42	1.42	1.48	1.57	1.64	1.39
$(Ho/Yb)_N$	0.54	0.75	0.53	0.56	0.58	0.63	0.68	0.66	0.61
$(La/Yb)_N$	1.02	1.5	1.14	1.22	1.13	1.18	1.27	1.31	0.84
Eu/Eu*	0.16	0.3	0.32	0.24	0.3	0.42	0.22	0.21	0.25

In the Harker variation diagrams (figure 4), Al_2O_3, TiO_2, MgO and P_2O_5 show a systematic decrease with increasing SiO_2, while FeO^t/MgO and Ti/P show a systematic increase with rising SiO_2. Among trace elements, Rb, Nb, K/Ba and Rb/Sr depict significant positive correlation with SiO_2, while K/Rb shows a negative trend. Ba and Sr show a prominent decreasing trend with increasing SiO_2.

Trace element data (table 3) for the Mylliem granitoids depicts variable concentrations of trace elements including REE. Figure 4 indicates that Sr shows a gradual increase with increasing Ba while Zr depicts a positive correlation with Y.

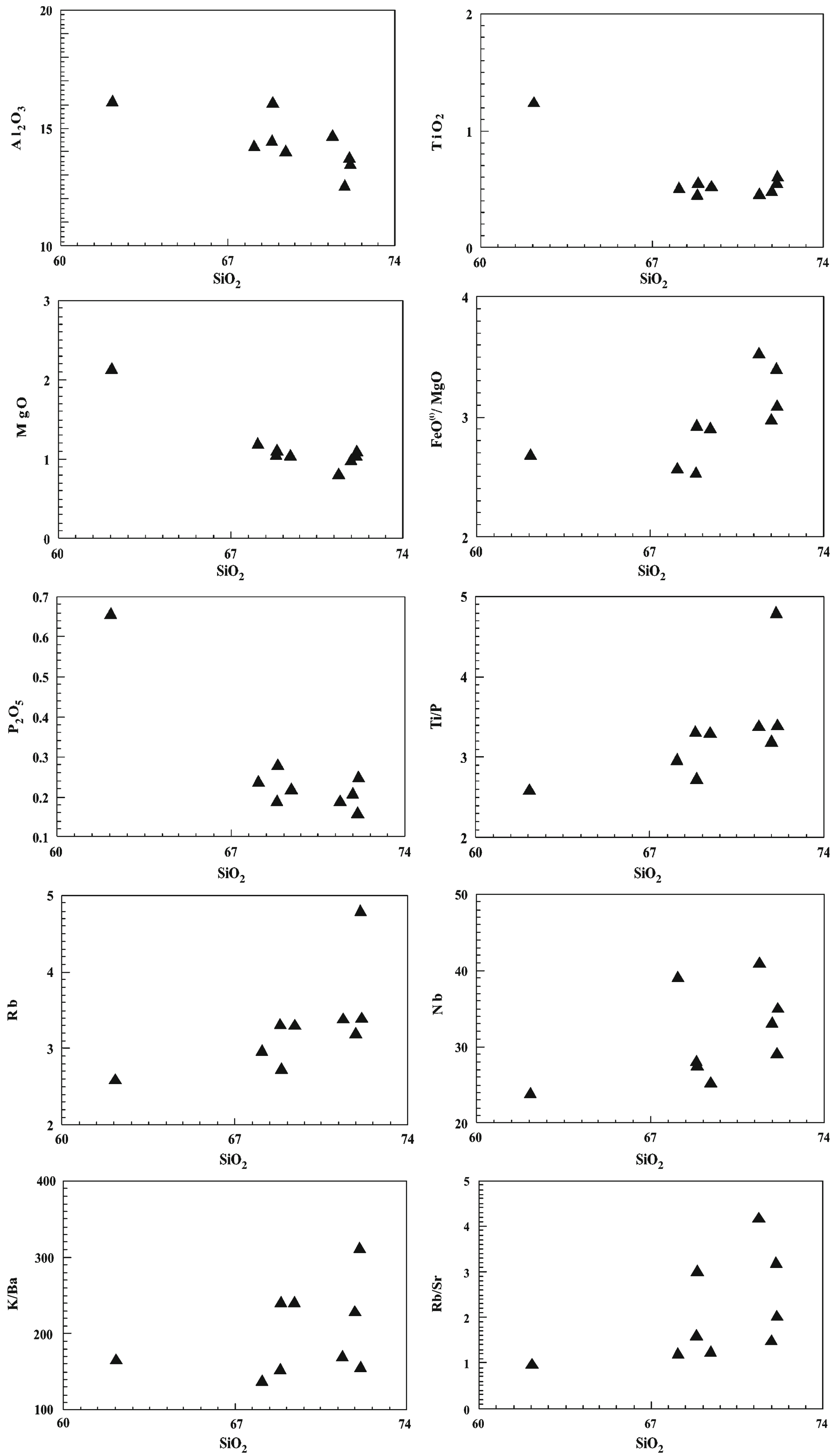

Figure 4. Harker variation diagrams for Mylliem granitoid.

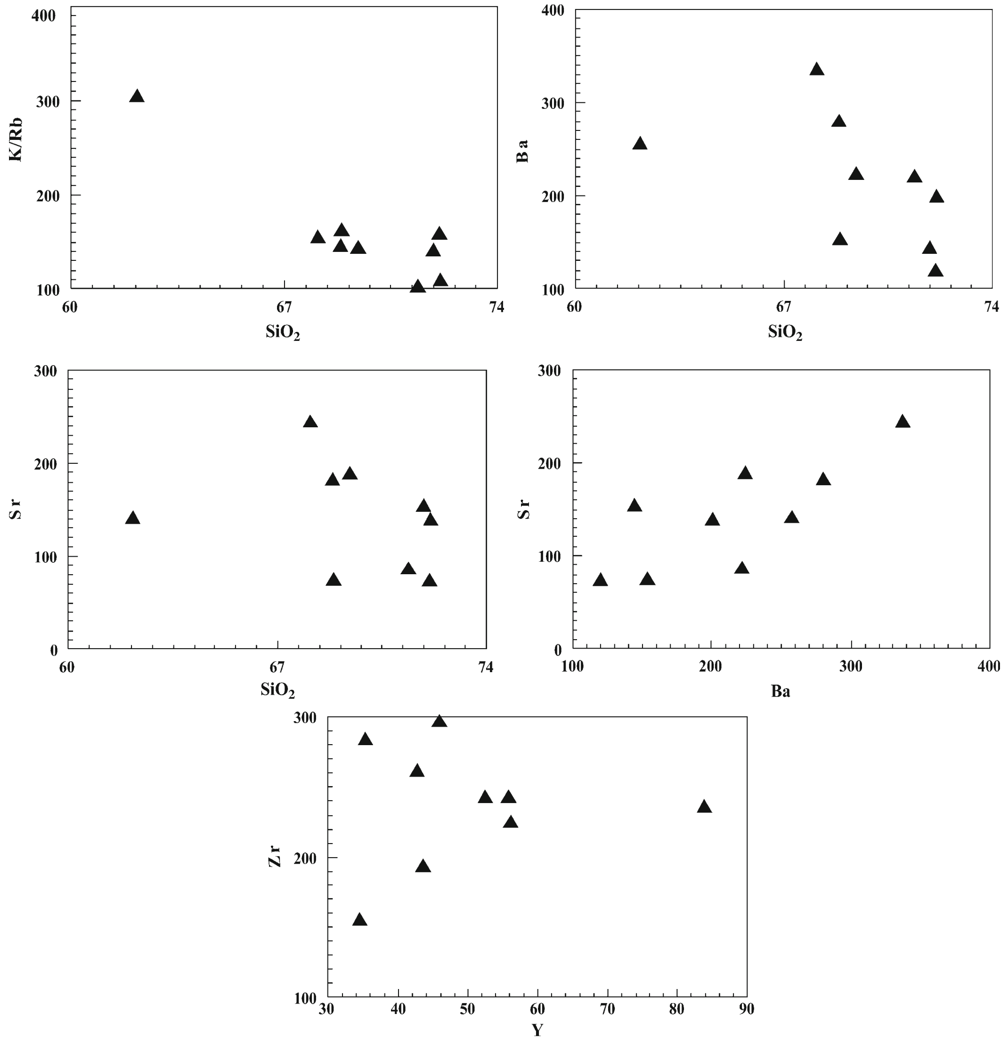

Figure 4. (*Continued*).

Chondrite-normalized multi-element diagram for incompatible trace element patterns of Mylliem granitoids depicts negative Nb and Sr anomalies (figure 5a). The Mylliem granitoids are characterized by high concentrations of U and Th (figure 5a), while high field strength elements such as Zr and Y show moderate abundances. The U content ranges from 4.8 to 21.3 ppm which is much higher than the value of 3.5–5 ppm usually present in normal granites (Krauskopf 1982; Singh 2007). Thorium content ranges from 32.52 to 85.39 ppm. Thus, the currently investigated granitoids are characterized by distinct uranium and thorium enrichment (Sen *et al* 2009). Critical examination of Th/U ratios (ranging from 3.22 to 6.77) indicates a relatively higher abundance of thorium over uranium and thereby suggests significant thorium mineralization in the Mylliem pluton. The chondrite-normalized REE patterns (Sun and Mc Donough 1989) of the Mylliem granitoids are depicted in figure 5(b). The granitoids are enriched in LREE and show prominent negative Eu anomaly (Eu/Eu* ranging 0.16–0.42) indicating a significant role of plagioclase fractionation from the parent magma. $(Ce/Yb)_N$ values show a range of 1.39 to 1.65 (table 3) which indicates a strong REE fractionation. $(La/Yb)_N$ values also suggest similar fractionation trends. Ho/Yb ratios show a moderate range of variation (0.53 to 0.75) which is suggestive of mild HREE fractionation.

6. Characterization of Mylliem granitoids

Geochemical parameters supplemented with distinctive petrographic criteria and field observations provide suitable attributes for characterization of granitoids and inferring the nature of source rocks. The geochemical characterization of granitoids is primarily based on three variables and these are Fe* $[FeO^{(t)}/(FeO^{(t)}+MgO)]$, modified alkali-lime index (MALI) $(Na_2O+K_2O–CaO)$ and the aluminium saturation index (ASI) [Al/(Ca–1.67P+Na+K)] (Shand 1943). The Mylliem granitoids

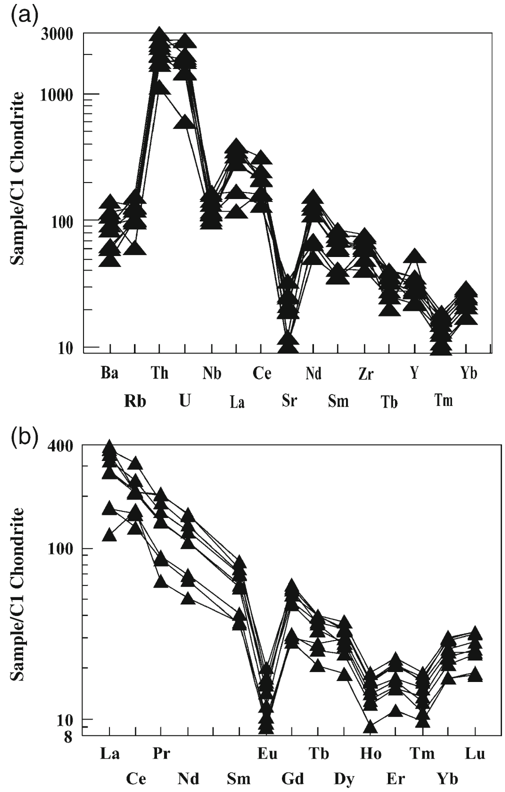

Figure 5. (**a**) Chondrite-normalized plot for incompatible trace elements of Mylliem granitoid. Normalization factors after Sun and McDonough (1989). (**b**) Chondrite-normalized rare earth element patterns of Mylliem granitoids. Normalization factors after Sun and McDonough (1989).

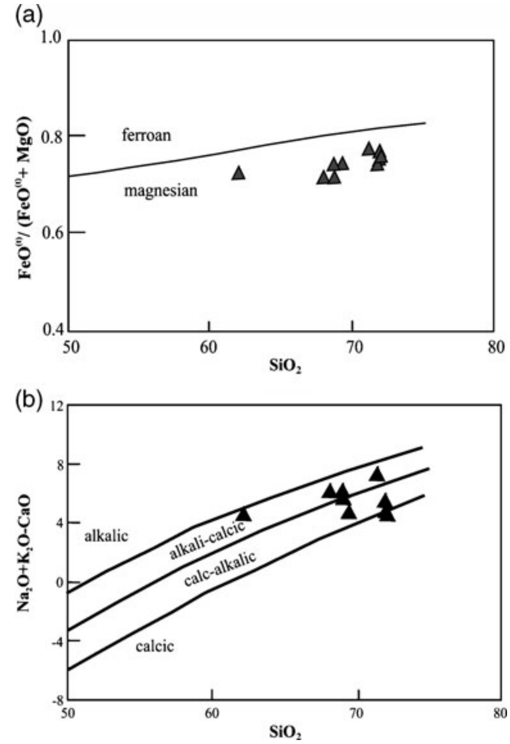

Figure 6. (**a**) $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 diagram showing the magnesian character of Mylliem granitoids (Frost *et al* 2001). (**b**) $Na_2O+K_2O–CaO$ *vs.* SiO_2 diagram depicting the calc-alkalic to alkali-calcic character of Mylliem granitoids (Frost *et al* 2001).

are characterized as magnesian granitoids with Fe* ranging from 0.72 to 0.78 and they cluster in the 'magnesian field' of $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 diagram (Frost *et al* 2001) (figure 6a). MALI of Mylliem granitoids ranges from 4.46 to 7.23 and plots of Mylliem granitoids in $Na_2O+K_2O–CaO$ *vs.* SiO_2 diagram (Frost *et al* 2001) (figure 6b) depict a calc-alkalic to alkali-calcic trend thereby indicating a transitional character of Mylliem granitoids and gradual potash enrichment during the course of differentiation. The Mylliem granitoids have ASI ranging from 1.0 to 1.3 and are thus designated as peraluminous granitoids. Normative corundum (ranging between 0.59 and 6.67 wt.%), A/CNK ratios ranging from 1.4 to 2.11 and A/NK ratios varying from 1.75 to 2.43 (Shand 1943; Chappell and White 1974) of the currently investigated Mylliem granitoid support its characterization as strongly peraluminous, relatively potassic, S-type granite. A/CNK *vs.* A/NK plots of Mylliem granitoids (figure 7) occupy the peraluminous field. A set of petrographic and chemical parameters for typical S-type granite, as compiled from Johannes and Holtz (1996), have been used to draw a comparison with the S-type signatures of the currently studied Mylliem granitoids.

	S-type	Mylliem porphyritic granoid
SiO_2	65–76%	62.13–72.12%
Na_2O	Low	Low (1.73–3.11 wt.%)
Na_2O/K_2O	Low	Low
CIPW norm	> 1% corundum	> 1% corundum
CaO	< 3.7%	0.45–2.51%
Cr	> 45 ppm	6.5–10.3 ppm
Co	> 16 ppm	36.1–152.1 ppm
Zr	> 150 ppm	156.2–297 ppm
A/CNK	> 1.1	1.4–2.1
Minerals	Al-silicates, cordierite, muscovite, apatite	Muscovite, apatite

Petrographic studies of Mylliem granitoids record the presence of muscovite and individual apatite crystals which illustrate their S-type nature. Occurrence of metasedimentary xenoliths of Shillong Group within the Mylliem granitoids

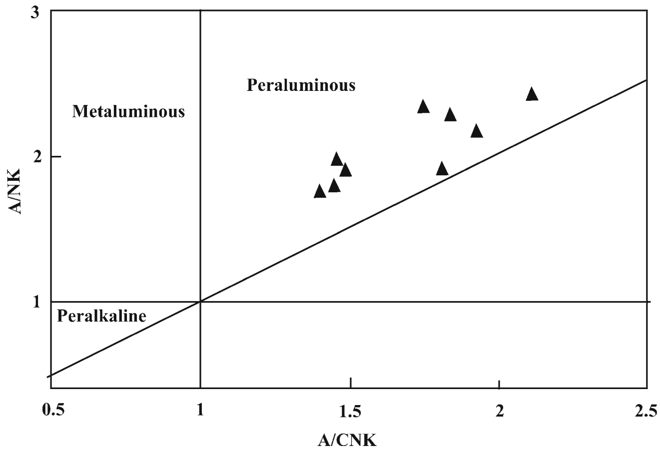

Figure 7. A/NK *vs.* A/CNK plots for Mylliem granitoid (after Shand 1943).

provides a distinctive field evidence for designating these granitoids as S-type granites and suggesting a sedimentary source for them (Barbarin

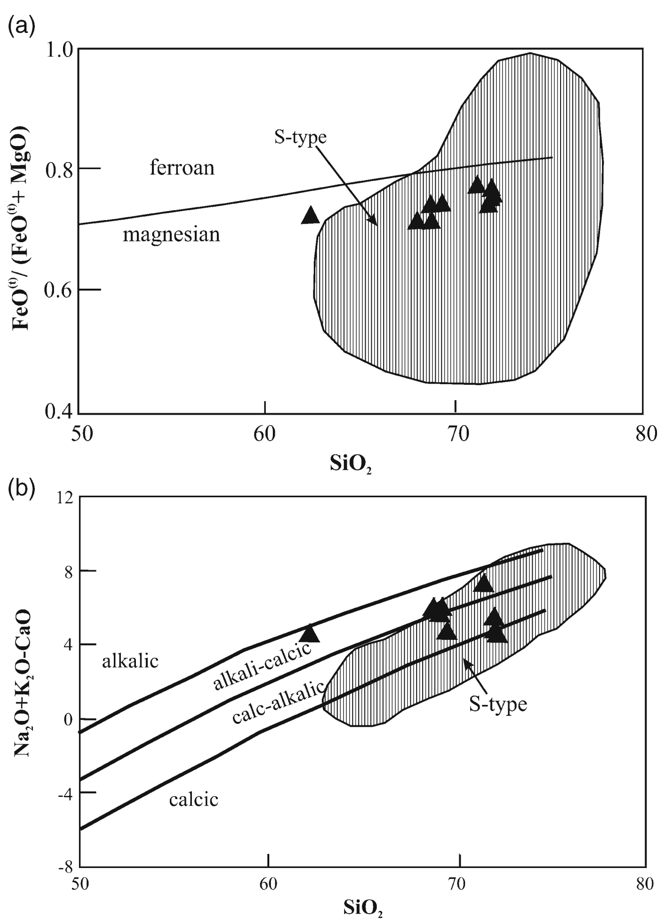

Figure 8. (**a**) $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 diagram showing the plots of Mylliem granitoids in the field of S-type granoids from Lachlan Fold Belt (Frost *et al* 2001). (**b**) $Na_2O+K_2O–CaO$ *vs.* SiO_2 diagram showing the plots of Mylliem granitoids in the field of S-type granoids from Lachlan Fold Belt (Frost *et al* 2001).

1999). $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 (figure 8a) and $Na_2O+K_2O–CaO$ *vs.* SiO_2 (figure 8b) plots of Mylliem granitoids fall in the field of S-type granitoids from the Lachlan Fold Belt. This compositional affinity suggests that the peraluminous, S-type Mylliem granitoids are chemically correlatable with the peraluminous, S-type Lachlan Fold Belt granitoids.

7. Discussion

Granitoids are often derived by the melting of preexisting sedimentary or meta-igneous rocks and the melt-products often give rise to generation of large- or moderate-sized batholithic intrusion in the country rock, in syn- to post-collisional tectonic environments (MacDonald 1966; Nagudi *et al* 2003 and references therein, Kochhar and Dhar 1993; Dhar *et al* 1996). In the Meghalaya Plateau (the study area), occurrences of several granite plutons have been described by Ghosh *et al* (2005) and significant discordant granitoid plutons have been marked as Kyrdem, Mylliem, Rongjeng, Nongpoh, South Khasi, Kyllang, etc. (figure 1). An overall syn- to late-tectonic condition was envisaged for those discordant granite plutons (Ghosh *et al* 2005). However, much remains unknown about the source rock characters, petrogenesis and tectonic environments of the granitoid plutons which have to be found out through sustained field investigations, petrography and geochemical studies. We now try to integrate the lithological and petrological attributes of the currently investigated Mylliem pluton on the basis of available geochemical data.

7.1 *Implications on source rock characters*

Field evidences record the occurrence of xenoliths of both Shillong Group metasediments and metabasic rocks within Mylliem granitoids. These xenolith-lithologies offer suitable clues to ascertain the source-characters of Mylliem granitoids. A question thus arises whether mafic rocks or Shillong Group of rocks should be taken as the potential source that could have given rise to Mylliem granitoids on different degrees of melting. Geochemical compositions of granitic magmas reflect the compositions of their source rocks. Certain geochemical parameters such as Fe^* $[FeO^{(t)}/(FeO^{(t)}+MgO)]$, aluminium saturation index (ASI), etc., are sensitive indicators of the source regions of granitic magmas and provide reliable means for better understanding of their origin and evolution (Frost *et al* 2001). The differentiation paths followed by granitic magmas strongly affect the Fe^* and in this case, the magnesian character of the Mylliem granitoids suggest their derivation from a melt which has followed a relatively oxidizing differentiation trend. Geochemical aspects including high values of Zr (156–297 ppm), Co (36–152 ppm), lesser CaO wt.% (0.45–2.51) and moderate SiO_2 (∼62–72 wt.%), aided by distinct petrographic characters corroborate the peraluminous, S-type nature of the Mylliem granitoids. The ASI of granitic rocks is predominantly a function of the composition of the source rock and the nature of the melting process with peraluminous magmas formed from hydrous melting of pelitic or semi-pelitic rocks (Frost *et al* 2001). Johannes and Holtz (1996) have noted that the presence of certain minerals is decisive to ascertain the source characters of granitoid plutons and this holds true for Mylliem granitoids as the presence of modal muscovite and apatite with >1 wt.% normative corundum is indicative of the S-type character and points to a sedimentary origin. Thus, in terms of both petrography and chemistry, the Mylliem granitoids differ significantly from tonalite–trondjhemite–granodiorite suite (Tarney 1976; Arth 1979; Collerson and Bridgwater 1979; Tarney *et al* 1979) and it is clear that the currently studied granitoids have a source character which is quite distinct from amphibolites/basaltic materials. According to Chappell and White (1974) and Hine *et al* (1978), the peraluminous, S-type granitoids are most commonly produced by parent melt extraction from metasedimentary source rocks by partial melting. Thus, from the foregoing discussion, it is evident that partial melting of Shillong Group of metasediments (rather than mafic rocks) provides the most viable source material for the Mylliem granitoids.

7.2 *Implications on petrogenesis*

The trends of variation depicted by major element oxides with respect to SiO_2 suggest a significant role of fractional crystallization during the course of magmatic evolution. The fall of Al_2O_3 with increasing SiO_2 clearly indicates the fractionation of feldspar. The decreasing trend of MgO with increasing SiO_2 represents the fractionating behaviour of the parent magma. The variation patterns of trace elements such as Ba, Sr have been effectively used for evaluating fractional crystallization processes in granites (Mittlefehldt and Miller 1983; Mackenzie *et al* 1988). In this study, negative correlations depicted by Ba and Sr with SiO_2 strongly suggest fractionation of plagioclase and K-feldspar in Mylliem porphyritic granites. Zr *vs.* Y shows a positive trend as expected in fractional crystallization processes. The negative Eu and Sr anomalies support the contention of early fractionation of plagioclase from the magma by fractional crystallization (Rollinson 1993). The geochemical variations observed for the Mylliem porphyritic granites are in consonance with the idea of fractional crystallization playing a dominant role in the petrogenetic evolution of the Mylliem pluton. Inferences drawn on the basis of geochemical criteria aided by field and petrographic evidences suggest the separation of plagioclase and alkali feldspar as constituent phenocrystal phases due to fractional crystallization. Some critical element ratios can be successfully employed for evaluating the source characteristics and evolutionary trend (Whalen *et al* 1987). High Rb/Sr, Ba/Sr ratios, high K% and relative enrichment of HFSE suggest that the Mylliem porphyritic granites are primarily derived from a felsic source (Rogers and Greenberg 1990) characterized by high K content and relatively low Ca.

7.3 *Implications on tectonic setting*

The mineralogy and chemistry of granitoids serve as effective tools for fingerprinting their tectonic environment (Brown *et al* 1984; Pearce *et al* 1984). Mylliem granitoids with characteristic mineralogical and geochemical features can be tectonically discriminated as post-orogenic granites (POG) (Maniar and Piccoli 1989). The tectonic discrimination diagram of Maniar and Piccoli (1989), using Al_2O_3 *vs.* SiO_2 as suitable parameters, depicts a post-orogenic setting for the Mylliem granitoids, where all the relevant data-points cluster in the field of POG (figure 9a). Thus, a post-orogenic setting for the Mylliem granitoids is envisaged. It has been widely observed that POG are emplaced during the last phase of an orogeny, generally after the cessation of deformation in the region. These granitoids represent the transitional phase of the continental crust undergoing stabilization following the orogenic episode (Maniar and Piccoli 1989). These well-documented observations on POG are in accord with the conclusions derived from the field evidences in the study area at and around Mylliem which reveal that the Mylliem granitoids have not been affected by regional deformational and metamorphic events. Thus, it is evident that the emplacement of Mylliem pluton is marked by a post-orogenic tectonic environment. In $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 (figure 9b) and Na_2O+K_2O-CaO *vs.* SiO_2 (figure 9c) diagrams, the Mylliem granitoids occupy the field of Caledonian post-collisional plutons of Ireland and Britain. These Caledonian post-collisional plutons are typified by peraluminous, alkali-calcic, magnesian, post-orogenic granitoids with high potassium content and lack of iron enrichment. Thus, it is inferred that the Mylliem pluton of Shillong Plateau, Northeastern India,

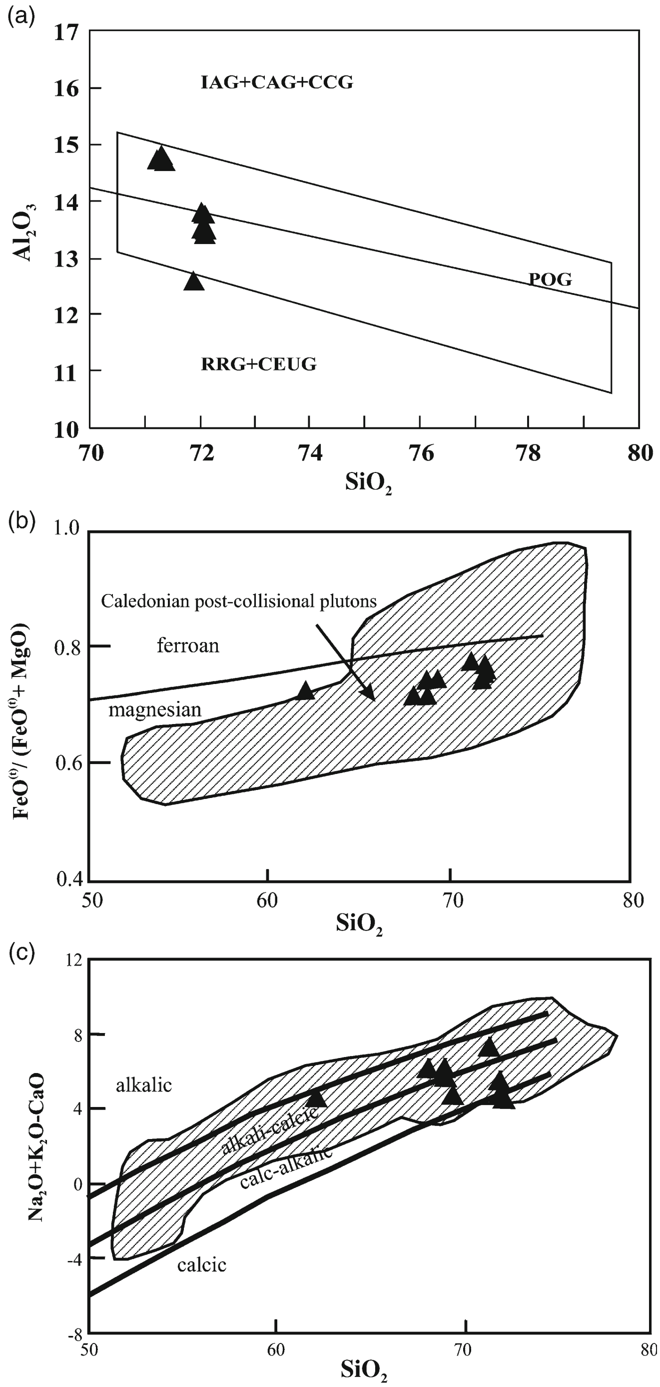

Figure 9. (**a**) Al_2O_3 *vs.* SiO_2 diagram depicting a post-orogenic setting (POG) for Mylliem granitoids (Maniar and Piccoli 1989). (**b**) $FeO^{(t)}/(FeO^{(t)}+MgO)$ *vs.* SiO_2 diagram showing the plots of Mylliem granitoids in the field of Caledonian post-collisional pluton (Frost *et al* 2001). (**c**) $Na_2O+K_2O–CaO$ *vs.* SiO_2 diagram showing the plots of Mylliem granitoids in the field of Caledonian post-collisional pluton (Frost *et al* 2001).

with peraluminous, magnesian, calc-alkalic to alkali-calcic, S-type characters and post-orogenic tectonic setting are correlatable with the Caledonian post-collosional plutons of Ireland and Britain.

8. Conclusions

The Meghalaya Plateau of northeastern India forms the northeastern margin of Neoproterozoic segments signifying the evolving plate boundary at that time. A number of cross-cutting syn- to late-tectonic granite plutons have been described in the Meghalaya Plateau. This study brings out for the first time detailed field relations, petrography and geochemical characters of Mylliem pluton which marks one of the important granitoid plutons in the plateau (Ghosh *et al* 2005). Field studies indicate that the Mylliem granitoids bear evidences of forceful injection of granitic melt into the neighbouring country rock (Shillong Group of rocks). The Mylliem granitoids contain xenoliths of Shillong Group of metasediments and mafic rocks which serve as further evidence of their intrusive origin. Petrographically the Mylliem granitoids show a compositional spread from granite to granodiorite in the Q–A–P diagram (Streckeisen 1976). Normative An–Or–Ab diagram (O'Connor 1965) discriminates the granitoids to be 'granitic' with a limited compositional range. Critical consideration of their mineralogical, petrological and geochemical characters suggests that the Mylliem granitoids have a distinct peraluminous, S-type affinity. The Shillong Group of rocks has been deduced to be the precursor of the Mylliem granitoids and it has been suggested that partial melting of the Shillong Group of rocks gave rise to melt parental to the Mylliem granitoids. Geochemical signatures characterize the Mylliem Granitoids as POG and they are chemically similar to the Caledonian post-collisional granitoid plutons.

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