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### Research Article

## Petrological and geochemical study of the Sylhet trap basalts, Shillong plateau, N.E. India: Implications for petrogenesis

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### Abstract

Sylhet Traps exposed along the southern margin of Shillong plateau, Northeast India are subalkaline tholeiitic basalts. The basalts are generally massive but occasionally contain large amygdules of zeolites and chalcedony. Microscopically, some basalts show porphyritic texture with olivine phenocrysts. Phenocryst assemblage of plagioclase ± clinopyroxene ± olivine implies crystallization at shallow level. SEM-EDX analysis shows occurrences of spinel with Ni and Cr within the basalts therefore indicating partial melting of the subcontinental lithospheric mantle as the possible source materials for the basalts. The multi-element plot for the basalts shows two distinct trends: one with significant enrichment of LILE and depletion of HFSE and plot similar to OIB (Type 1) while the other trends are characterized by slight enrichment of LILE and negative anomalies at Nb, P and Ti (Type 2). Chondrite-normalized REE patterns for Type 1 basalt shows very high enrichment of LREE and a strong right dip HREE pattern and also plots similar to typical OIB while Type 2 show a slight enrichment of LREE over HREE with small Eu anomaly.

The geochemical signatures suggest crustal contamination by plume-derived magma produced by low degree of partial melting for Type 1 basalt. Type 2 basalt was produced by partial melting of subcontinental lithospheric mantle, which may be triggered by plume upwelling.

**Keywords:** Basalt, Geochemistry, Sylhet Trap, Petrogenesis.

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### 1. Introduction

Several Hypotheses have been proposed regarding the origin of continental flood basalt (CFB). Many workers (e.g., (Campbell & Griffiths 1990; Richards 1989; White & McKengie 1989 and references therein) invoke mantle plumes in their formation, whereas others (e.g., (Anderson 1994; King & Anderson 1995, 1998) and references therein) advocate for lithospherically controlled melting processes. The CFB in the form of Sylhet Trap Basalts (STB) erupted in the southern flank of the eastern margin of Indian continental crust within the Shillong Plateau during the Cretaceous time. These mafic volcanism have outpoured due to the breakup of Indian and Australian plate and opening of the Indian Ocean induced by the Kerguelen mantle plume (Coffin et al., 2002 ; Davies 1989; Kent et al. 2002; Kent et al., 1997; Ray et al., 2005; Weis et al., 1989). The STB along with other Cretaceous volcanic rocks which occurred along the paleo-Eastern

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Gondwana margins of Australia and India were unanimously attributed to the positioning of the Kerguelen plume beneath the lithosphere of Eastern Gondwana. The Kerguelen Plume is presently lying beneath the Kerguelen plateau in the Indian Ocean. But the issues relating to the extent of involvement of the Kerguelen plume in the production of magma for the STB are still matter of further study. Most of the studies thus carried out on STB have suggested direct derivation of the STB magma from Kerguelen Plume (e.g., (Ghatak & Basu 2011; Kent et al., 1997; Neal et al., 2002; Ray et al., 1999; Srivastava & Sinha 2004; Srivastava & Sinha 2007; Storey et al., 1992; Veena et al., 1998; Ghatak & Basu 2011). Only a few workers inferred partial involvement of the plume (only heat derived and not substance) (see, e.g., (Frey et al., 1996; Kent et al., 1997; Mahoney et al., 1983). Recently Ghatak & Basu (2011) has advocated lower crustal contamination for the STB magmas, while Islam et al. (2014) have suggested the involvement of two mantle components viz. (i) the Kerguelen plume-like component and (ii) HIMU-type component in the generation of magma for STB.

In this study, we present i) result of macroscopic and microscopic analysis of the STB collected along the Cherapunjee section ii) SEM-EDX analysis for spinel within the basalts to identify the melt origin and iii) remarks on the origin of the basalts by using major and trace including rare earth element analysis.

## 2. Geology

Shillong plateau, a prominent Archaean gneissic complex occurs in Northeast India. The plateau is bounded on three sides by tectonic features such as Dauki Fault in the south, Brahmaputra Fault in the north and Jamuna Fault in the east (Evans 1964; Nandy 1980). The plateau covers an area of about 40000 km<sup>2</sup> within 25°20' N - 26°30' N latitude and 90° E - 93°50' E longitude (Figure1b). It is an E-W trending oblong horst block elevated about 600 to 1800m above the Bangladesh plains in the south and separated from peninsular India by the Rajmahal-Garo gap. The Proterozoic metasedimentary Shillong Group and the basement Gneissic complex (Sillimanite-bearing gneisses, granulites amphibolites and granite-gneisses) make up most of the plateau. The southern part of the plateau is covered by basalts of Cretaceous Sylhet Trap and Tertiary shelf sediments. Basement of the Plateau is primarily composed of Precambrian metamorphic rocks and intrusive rocks (Bilham & England 2001 ; Biswas & Grasmann 2005 ; Evans 1964; Gupta 1988; Nandy 1980) and Neo-Proterozoic to Early Palaeozoic granitoid intrusives (Selvan 1995; Breeman et al., 1989). Late Cretaceous sediments lying unconformably on the Precambrian bedrock in the southern part of the plateau indicate that the basement was exposed at the end of the Cretaceous. However, during the Tertiary the basement was submerged and buried under shallow marine and deltaic sediments. The thickest preserved sediment layer is 3,000 m in the southwestern part of the plateau (Chakraborty 1972).

Along the southern slope of the Shillong Plateau, Sylhet Trap basalts are exposed, which are considered part of the Rajmahal-Sylhet flood basalts province and ultramafic-alkaline-carbonatite complexes occurring within the Shillong plateau (Srivastava et al., 2005). On the basis of their geochemical signature and their age and location, it is supposed that these are associated with Kerguelen mantle plume, which was active during the opening of the Indian Ocean between India and Australia-Antartica (Acharyya 1980; Alam 1989). The onset of breakup between India and Antartica is estimated to 133 Ma and the initial massive pulse of Kerguelen magmatism and volcanism on the top of continental basement, occurred between 120 Ma to 110 Ma (Coffin et al., 2002 ).

The Sylhet Trap basalts (STB) are well exposed in two narrow, discontinuous (~4 km width) east, west strips of 60-80 Km length in total (Figure 1b). Two different road sections viz. Mawsynram-Balat and Cherrapunji-Shela passes through each of these strips. In the present work, the STB occurring along Cherrapunji-Shela road section has been investigated. The Sylhet Trap basalts display sharp contact with the Tertiary Mahadek Sandstone that unconformably overlie the STB (Figure 2).

## 3. Petrography

The STBs are largely fine-grained and exhibit porphyritic texture with occurrences of olivine as a visible phenocrystic phase in naked eye. Some of the samples contain amygdules while others are massive and non-amygdular.

Thin sections are prepared for the eight samples of Sylhet Trap basalts for petrographic studies under microscope. Care has been taken by avoiding the area containing amugdules while preparing thin sections of the samples containing visible amygdules. Under the microscope the STB contain phenocrysts of plagioclase ± clinopyroxene ± olivine with plagioclase as the main phenocryst phase for all basalt samples (Figure 3). Olivine phenocrysts are mostly fresh and unaltered and also do not exhibit corona texture. This suggests olivine did not equilibrate with the melt. The reason for which could be a rapid eruption of the magma. STB are made up of two populations of pyroxene and plagioclase; Phenocrysts of pyroxene and plagioclase are surrounded by fine grained groundmass consisting of pyroxene,

plagioclase and ilmenite and thus showing porphyritic texture. Ophitic to sub-ophitic textures with plagioclase laths intergrown with clinopyroxene, is observed in few samples which indicates at- or near-eutectic crystallization conditions for the Sylhet Traps. The partial replacement of plagioclase by sericite and of few olivine by iddingsite is also observed.

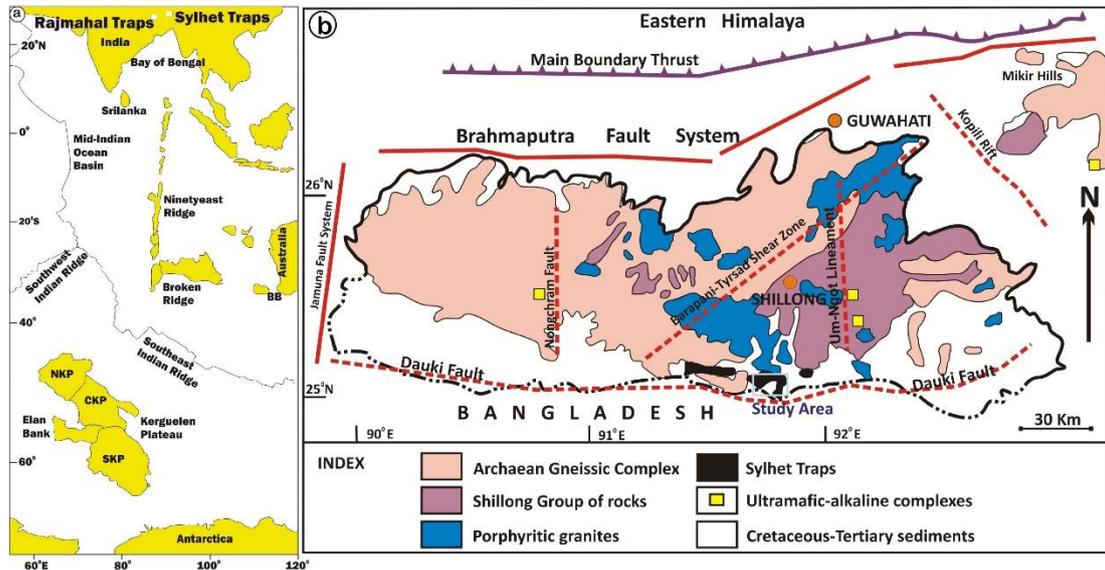


Figure 1: (a) Map of part of the Indian Ocean and surrounding continents, after (Frey & Coffin 2000a; Frey et al., 2002; Ghatak & Basu 2011; Ingle et al., 2003), showing locations of the Sylhet and Rajmahal Traps in northeastern India. Basalt provinces attributed to the Kerguelen plume include the Kerguelen Plateau [North (NKP), Central (CKP), southern (SKP) and Elan bank portions], Broken Ridge, Bunbury basalts (BB), Ninetyeast Ridge, and Rajmahal and Sylhet Traps (Frey et al., 2002). (b) Geological Map of Shillong Plateau (Modified after (Srivastava & Sinha 2004).



Figure 2: Photograph showing the Sylhet Trap Basalts underlying Mahadek sandstone at Cherapunji-Shela road section.

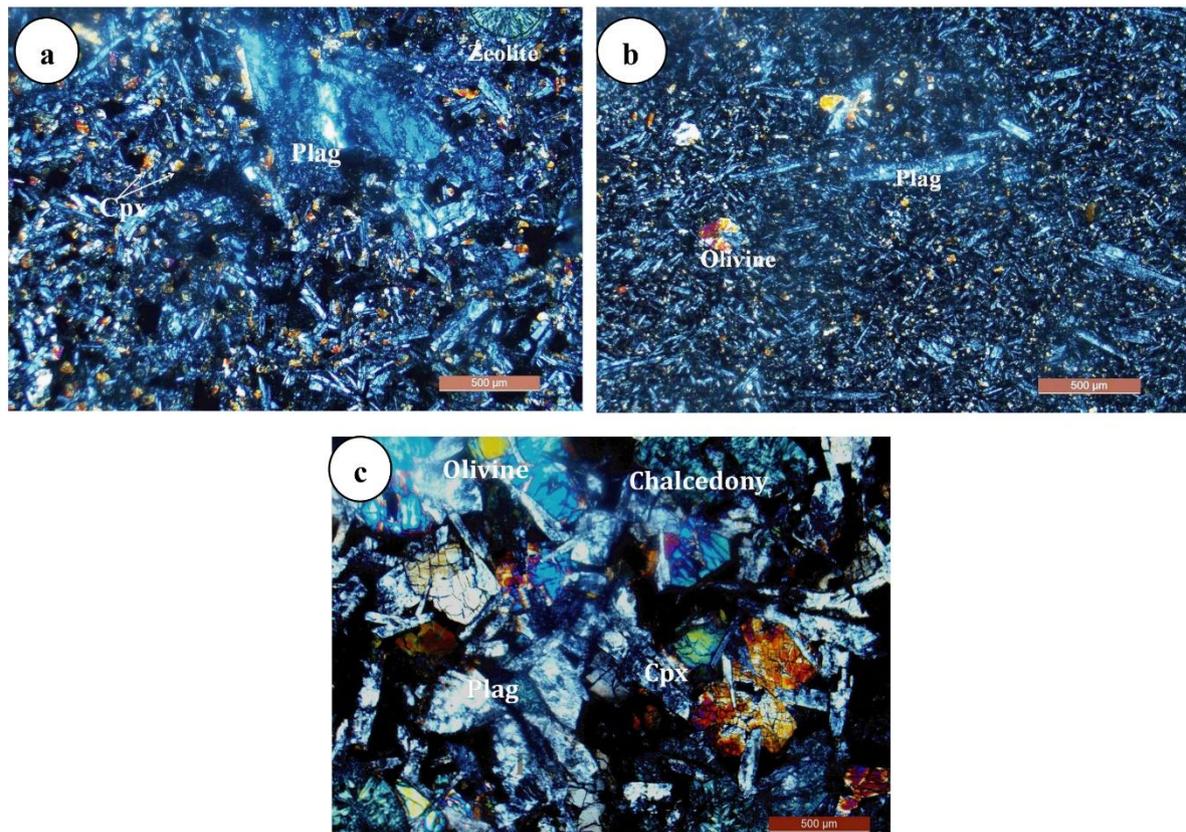


Figure 3: Photomicrographs of STB showing a) abundant phenocrysts of plagioclase (Plag) and pyroxene (Cpx) embedded in intergranular groundmass containing plagioclase and pyroxene and b) phenocrysts of olivine and plagioclase set in an intergranular groundmass of plagioclase and pyroxene; c) cumulus growth of plagioclase, pyroxene and olivine and amygdules of chalcedony.

## 4. Analytical techniques

### 4.1 SEM-EDX analysis

Spinel inclusion chemical analyses were conducted on three fresh rock samples (Figure 4) from Cherrapunji-Shela road section using energy-dispersive X-ray spectroscopy (EDX; EDAX™ Genesis 4000) attached to a scanning electron microscope (SEM; Hitachi 3000N) at the Department of Physics and Earth Sciences, University of the Ryukyus. The SEM-EDX operating conditions were 20 kV and 0.5 nA.

### 4.2 Whole rock geochemical analyses

The STB samples were crushed into smaller chips, washed with cold water and sun dried. Chips with thin traces of veins and containing minor inclusions of zeolite and other secondary minerals were removed. Samples were powdered for analysis by grinding in an agate mill. Major and Trace element data were obtained on pressed powder pellets by XRF (Bruker S-8 Tiger Sequential XRF Spectrometer) at the Wadia Institute of Himalayan Geology (WIHG), Dehradun. Rare earth elements (REE) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS), at WIHG, Dehradun. Calibration was carried out using international geochemical reference samples. Details of analytical procedures are given in (Khanna et al., 2009).

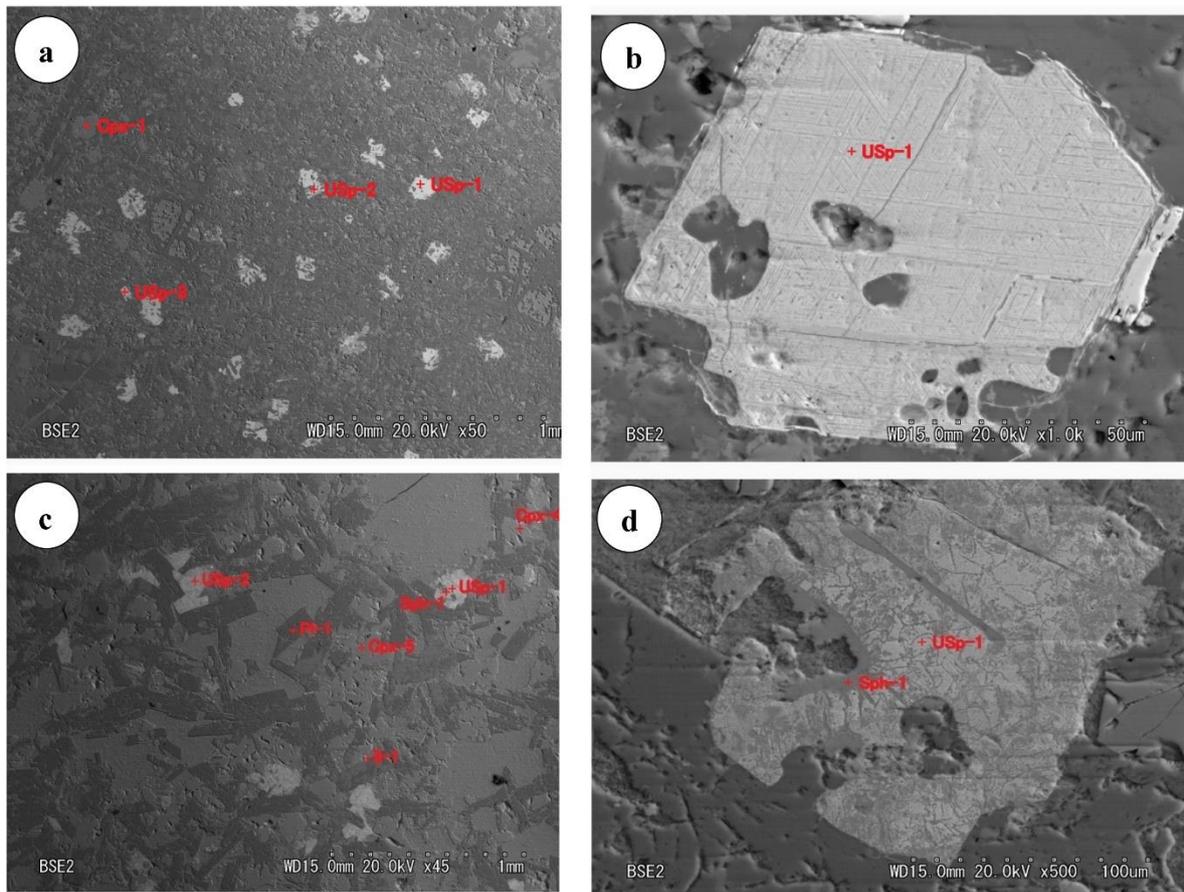


Figure 4: a) SEM and ED X-ray spectroscopy spectra showing the spinel inclusion in the smaller view and b) in the larger view within basalt sample CS-6; c) the spinel inclusion in the smaller view and d) in the larger view within basalt sample CS-8.

## 5. Geochemistry

### 5.1 Spinel within the basalt

Two samples CS 6 and CS 8 have been studied with SEM-EDX to identify the spinel within the samples. In the sample CS 6 several spinels are identified while in the sample CS 8 spinel and ilmanite are identified (Figure 4a, b). The spinels are largely of similar compositions. The SEM-EDX chemical analysis is presented in Table 1(a) and 1(b). The spinels are characterized by an average of 18.82%  $\text{TiO}_2$ , 0.43%  $\text{Cr}_2\text{O}_3$ , 27.29%  $\text{Fe}_2\text{O}_3$  and 46.80 % FeO. Chemically the spinels within the STB are therefore Cr-spinels.

### 5.2 Major elemental characteristics

Major and trace element data for the eight STB samples are presented in Table 2. The MgO content of the Sylhet Trap varies within a range of 6.02-10.40 wt%. The abundance of silica ranges between 42.3 - 47.7 wt% and  $\text{Fe}_2\text{O}_3^{(t)}$  is in the range of 11.76-16.56 wt%. The total alkali content ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) of the rock ranges between 1.8 to 3.5 wt% and averages 2.8 wt%.  $\text{Al}_2\text{O}_3$ , CaO,  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  averages 13.2 wt%, 9.6 wt%, 2.0 wt% and 0.2 wt% respectively. Major oxides for most of the sample plot scattered against MgO (Figure not shown here); indicating the rock has suffered some degree of alteration. The samples CH 45 and CH 53 have high Mg# (60) while other samples have low Mg# (40-55). In the TAS diagram (Figure 5), the majority of the Sylhet Trap basalts plot in a tight cluster in the basalt field while only two samples (CH 45 and CH 50) plot inside the picro-basalt field. The CIPW normative mineralogy of STB is presented in Table 3. Sample CH 45 produces nepheline (ne) in the norm while samples CH 47 and CH 55 produce Quartz (Q) in the norm. Rest of the samples

produce only Olivine (ol) in the norm. Thus based on CIPW normative mineralogy STB can be classified as alkali olivine basalts, olivine tholeiite and quartz-tholeiite.

### 5.3 Trace elemental characteristics

The concentration of Ni is low and averages 98.5 ppm, whereas the abundance of Cr is relatively high and averages 229.5 ppm. The high concentration of Ni and Cr in some samples indicates primitive magma composition. The correlation between Ni, Cr and (fig not shown here) indicates, at least qualitatively, that both olivine and pyroxene fractionation might have occurred. In the plot of trace elements against Zr, the most mobile incompatible elements, including Rb, K and Ba do not correlate well with Zr, but immobile, incompatible elements (e.g., Y, Ti, Nb, Th) shows good correlation with Zr (Figure 6). Primitive mantle-normalized multi-element plot is presented at Figure 7. STBs show enrichment in the most incompatible elements (10 – 30 times PM) relative to the less incompatible elements (4-7 times PM) (Figure8b) except one sample (CH 53) which show high enrichment of incompatible trace element at nearly 60 times that of the Primitive mantle (Figure8a). STBs show significant negative anomalies at Nb ( $Nb/Nb^*$  range = 0.54-1.02) and negative P anomalies ( $P/P^*$  range = 0.59 -0.84) and Ti anomalies ( $Ti/Ti^*$  range = 0.20 – 0.27) (Figure 7). On the Zr/Ti vs. Nb/Y diagram of Pearce, 1996 (Figure 8) Sylhet Trap basalts plot in a cluster in the Sub-alkaline basaltic field except one sample which plots inside the field of alkali basalt.

Table 1(a): Chemical composition of spinel within the sample CS-6.

CS-6				
Sample No Mineral	USp-1 Spinel	USp-2 Spinel	USp-3 Spinel	USp-4 Spinel
SiO <sub>2</sub>	0.44	0.85	1.2	0.98
TiO <sub>2</sub>	24.74	17.4	4.64	19.13
Al <sub>2</sub> O <sub>3</sub>	0.33	0.53	0.33	0.2
Cr <sub>2</sub> O <sub>3</sub>	0.44	0.3	0.35	0.14
Fe <sub>2</sub> O <sub>3</sub>	17.79	28.72	56.23	27.76
FeO	52.65	45.51	35.03	48.19
MnO	0.6	0.27	0.26	0.16
MgO	0	0.06	0.16	0
CaO	0.3	0.59	0.84	0.69
NiO	0.37	0.14	0.28	0.23
Na <sub>2</sub> O	--	---	---	---
Total	97.66	94.37	99.31	97.48
Si	0.135	0.27	0.367	0.301
Ti	5.701	4.158	1.066	4.428
Al	0.119	0.198	0.119	0.073
Cr	0.107	0.075	0.085	0.034
Fe <sup>3+</sup>	4.103	6.868	12.929	6.431
Fe <sup>2+</sup>	13.491	12.093	8.951	12.406
Mn	0.155	0.072	0.067	0.041
Mg	0	0.029	0.073	0
Ca	0.098	0.201	0.275	0.228
Ni	0.091	0.036	0.069	0.058
Na	--	---	---	---
SCat	24.000	24.000	24.001	24.000
OxNum	32	32	32	32

Table 1(b): Chemical composition of spinel and ilmenite within the sample CS-8.

<b>CS-8</b>				
Sample No	USp-1	USp-2	Sample No	Il-1
Mineral	Spinel	Spinel	Mineral	Ilmenite
SiO <sub>2</sub>	0.57	1.8	SiO <sub>2</sub>	0.52
TiO <sub>2</sub>	24.43	25.39	TiO <sub>2</sub>	47.9
Al <sub>2</sub> O <sub>3</sub>	2.27	2.34	Al <sub>2</sub> O <sub>3</sub>	0.32
Cr <sub>2</sub> O <sub>3</sub>	0.1	2.34	Cr <sub>2</sub> O <sub>3</sub>	0
Fe <sub>2</sub> O <sub>3</sub>	16.71	11.95	Fe <sub>2</sub> O <sub>3</sub>	6.56
FeO	48.38	50.62	FeO	34.36
MnO	0.78	0.81	MnO	7.76
MgO	0.08	0.14	MgO	0.12
CaO	0.94	2.17	CaO	0.63
NiO	0.14	0.4	NiO	0
Na <sub>2</sub> O	0.66	0.59	Na <sub>2</sub> O	0.09
Total	95.05	98.87	Total	98.27
Si	0.176	0.528	Si	0.013
Ti	5.659	5.605	Ti	0.921
Al	0.824	0.809	Al	0.01
Cr	0.024	0.544	Cr	0
Fe <sup>3+</sup>	3.873	2.639	Fe <sup>3+</sup>	0.126
Fe <sup>2+</sup>	12.465	12.426	Fe <sup>2+</sup>	0.735
Mn	0.204	0.201	Mn	0.168
Mg	0.037	0.06	Mg	0.005
Ca	0.31	0.683	Ca	0.017
Ni	0.034	0.094	Ni	0
Na	0.395	0.335	Na	0.004
SCat	24.001	23.999	SCat	1.999
OxNum	32	32	OxNum	3

Table 2: Whole rock major and trace and rare earth element analysis of Sylhet Trap Basalt of the Shillong Plateau.

<b>Major Oxides (Values in Wt%)</b>								
Sample	CH 45	CH 47	CH 50	CH 51	CH 52	CH 53	CH 54	CH 55
SiO <sub>2</sub>	43.00	47.65	42.26	46.99	47.24	45.32	45.63	45.93
TiO <sub>2</sub>	2.07	3.14	2.62	1.71	2.34	2.33	2.31	1.47
Al <sub>2</sub> O <sub>3</sub>	12.46	12.25	13.11	13.60	13.83	12.36	12.76	15.23
Fe <sub>2</sub> O <sub>3</sub>	13.76	16.56	13.11	12.72	13.86	11.76	15.45	12.14
MnO	0.25	0.27	0.31	0.16	0.20	0.22	0.26	0.17
MgO	10.40	6.02	7.75	8.23	6.43	10.31	7.74	7.36
CaO	8.56	9.73	10.29	8.75	10.35	10.90	7.36	10.17
Na <sub>2</sub> O	2.66	2.02	2.18	3.48	2.49	1.73	2.94	1.62
K <sub>2</sub> O	0.25	0.23	0.09	0.08	0.36	1.31	0.29	0.21
P <sub>2</sub> O <sub>5</sub>	0.15	0.30	0.24	0.17	0.20	0.36	0.22	0.14
SUM	93.56	98.17	91.96	95.89	97.30	96.60	94.96	94.44
LOI	7.12	2.47	8.54	4.56	2.49	3.86	5.01	6.78
<b>Normative Mineralogy</b>								
Q	-	2.94	-	-	-	-	-	0.25
An	23.09	24.48	28.33	22.43	26.54	23.12	22.18	36.06
Di	17.78	19.47	21.42	18.18	21.10	25.09	12.61	13.95
Hy	-	24.16	5.98	3.76	16.31	2.17	16.27	28.14
Ab	23.20	17.67	20.32	31.07	21.93	15.32	26.58	14.68
Or	1.60	1.41	0.59	0.50	2.21	8.10	1.83	1.33
OI	26.48	-	14.77	17.89	4.29	18.57	12.42	-
Ne	0.63	-	-	-	-	-	-	-
Ap	0.38	0.72	0.61	0.42	0.48	0.87	0.55	0.35
Il	4.26	6.17	5.48	3.43	4.63	4.63	4.69	2.99
Mt	2.59	2.98	2.51	2.34	2.51	2.14	2.87	2.26
<b>Trace Elements (Values in ppm)</b>								
Sample	CH 45	CH 47	CH 50	CH 51	CH 52	CH 53	CH 54	CH 55
Ba	95	149	91	74	148	409	125	56
Co	57	51	50	46	46	53	57	51
Cr	329	71	238	244	159	471	95	229
Cu	241	300	120	103	153	153	49	116
Ga	22.9	26.5	26.4	21.5	21.2	19.4	21.5	17.7
Nb	9.2	16.0	11.5	8.6	7.2	30.5	11.9	5.9
Ni	126	53	64	67	69	212	70	106
Pb	2.3	1.6	1.9	1.8	2.2	4.3	2.1	BDL
Rb	15	5	2	2	8	29	6	7
Sc	48	44	44	38	41	21	37	32
Sr	281	235	227	179	341	643	307	216
Th	2.62	2.73	1.99	1.87	1.07	5.14	1.53	1.73
V	460	490	364	308	348	299	452	341
Y	39	52	38	32	34	29	36	26
Zn	133	179	145	128	131	107	139	89
Zr	144	205	162	131	120	173	142	98
<b>Rare Earth Elements (values in ppm)</b>								
La	10.9	14.6	12.8	9.8	10.7	35.1	10.9	8.1
Ce	26.7	36.8	32.2	23.3	25.9	72.8	26.8	18
Pr	3.8	5.4	4.7	3.4	3.9	9.2	4	3.2
Nd	17	24	21.1	15.3	18.1	35.5	18.2	13.9
Sm	4.68	6.57	6.35	4.6	5.1	6.99	4.89	4
Eu	1.47	2.2	2.21	1.5	1.7	2.12	1.68	1.36
Gd	5.29	7.35	7.29	5.4	5.9	7.14	5.7	4.57
Tb	0.89	1.24	1.23	0.9	0.9	1	0.96	0.8
Dy	5.43	7.37	7.37	5.4	6.1	5.4	5.9	4.75
Ho	1.14	1.58	1.51	1.1	1.2	1.04	1.24	1
Er	3.06	4.16	3.97	2.9	3.3	2.66	3.3	2.63
Tm	0.45	0.62	0.58	0.4	0.5	0.37	0.49	0.4
Yb	2.94	4.04	3.78	2.8	3.2	2.36	3.22	2.54
Lu	0.44	0.62	0.56	0.4	0.5	0.34	0.49	0.38

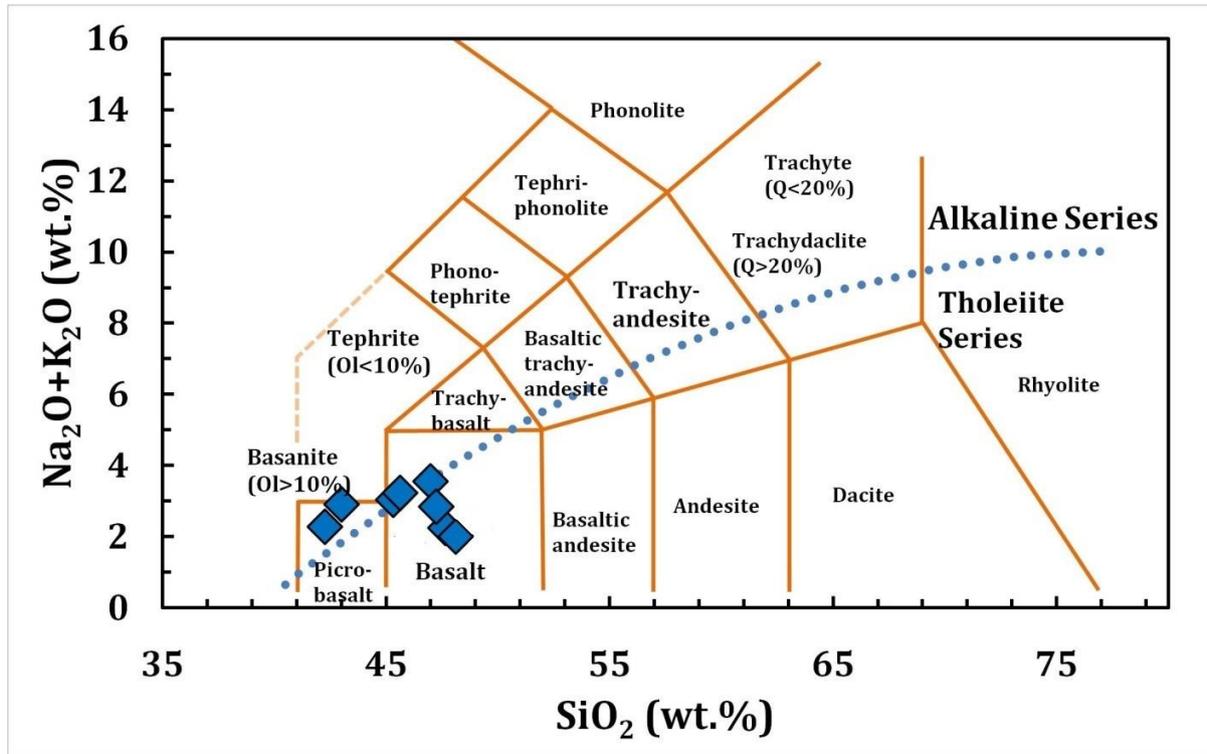


Figure 5: Total alkali vs.  $\text{SiO}_2$  (TAS) diagram for the Sylhet Trap samples. Field boundaries are after (LeBas et al, 1986). The boundary line of alkaline and tholeiite series is from (Irvine & Baragar 1971).

Chondrite-normalized REE patterns for the STBs (Figure 9) show sub-parallel trends with REE concentrations 30 – 110 times chondritic values except CH 53; which show high LREE enrichment along with a right dipping pattern. The STB are enriched in LREEs relative to the HREEs which in turn have relatively flat patterns. The STBs have variably negative Eu anomalies. In the Nb/Y vs. Zr/Y diagram, most of the STB plot on the boundary line of the plume and non-plume sources and plot clustered within oceanic plateau basalt (OPB) field except one sample (CH 53) which plot within oceanic island basalt (OIB) field and clearly within plume source side of the diagram (Figure 10).

On the Zr/Nb vs. Nb/Th diagram (Figure 11), most of the ST basalts form a moderately tight cluster within the field area overlapped between volcanic arc basalt and OPB fields except CH53 which plot within OIB.

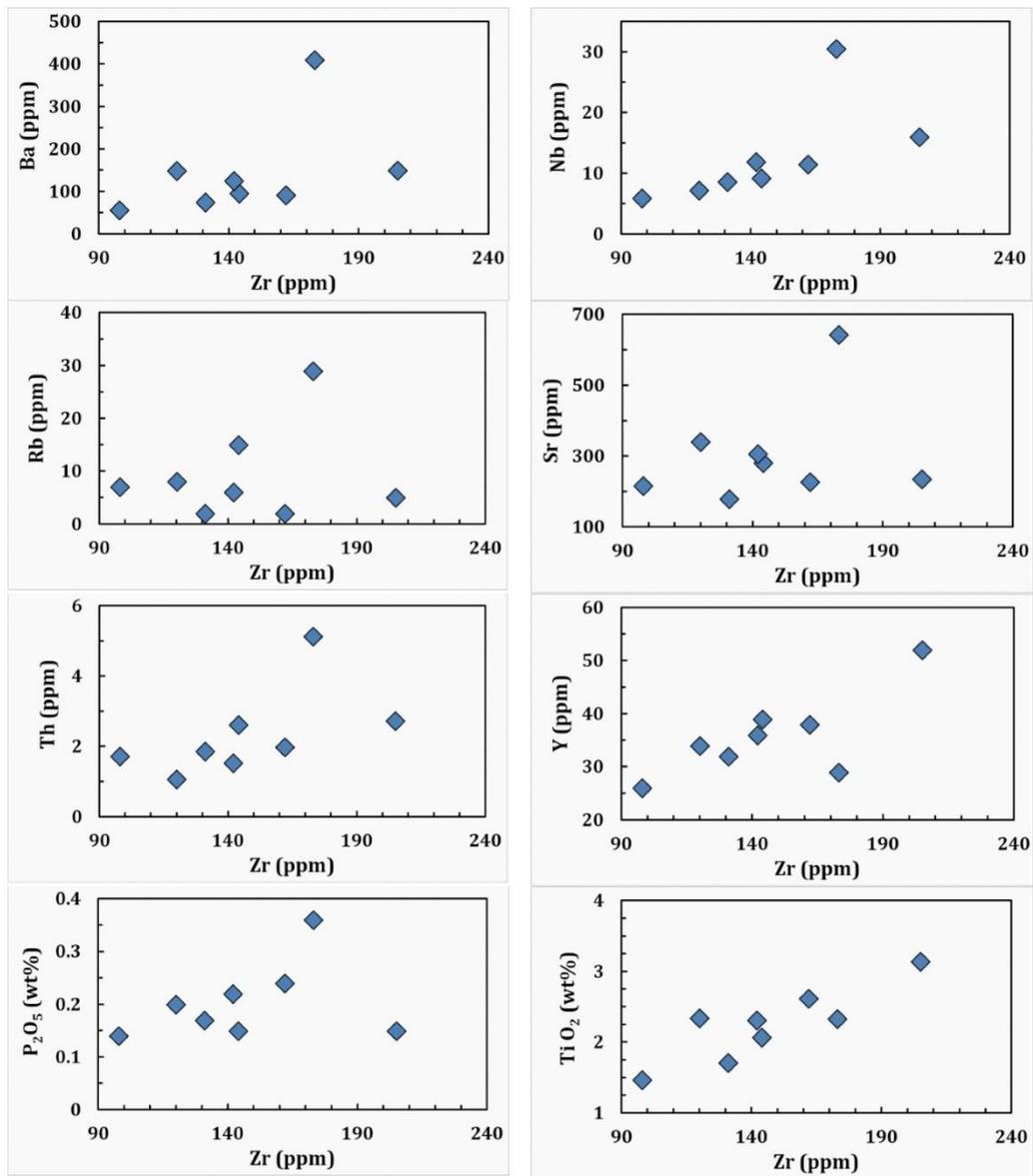


Figure 6: Bivariate diagrams of selected elements vs. Zr for the STB.

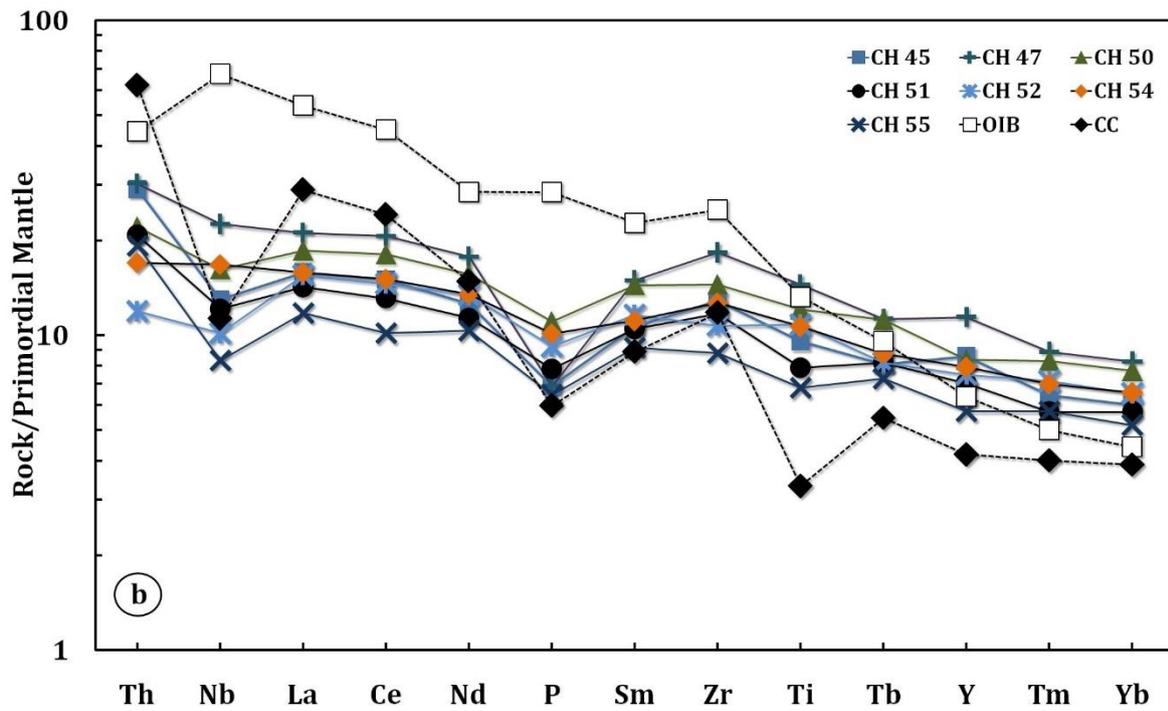


Figure 7: Primordial mantle-normalized multi-element diagrams for the STB. Normalizing values are from (McDonough & Sun 1995). Average OIB of (Sun & McDonough 1989) and modal bulk continental crust (CC) of (Rudnick & Gao 2003) St. Paul island basalts of (Doucet et al 2004) and Kerguelen plateau basalts (KPB) of (Frey et al., 2002) are also plotted with the STB data for comparison.

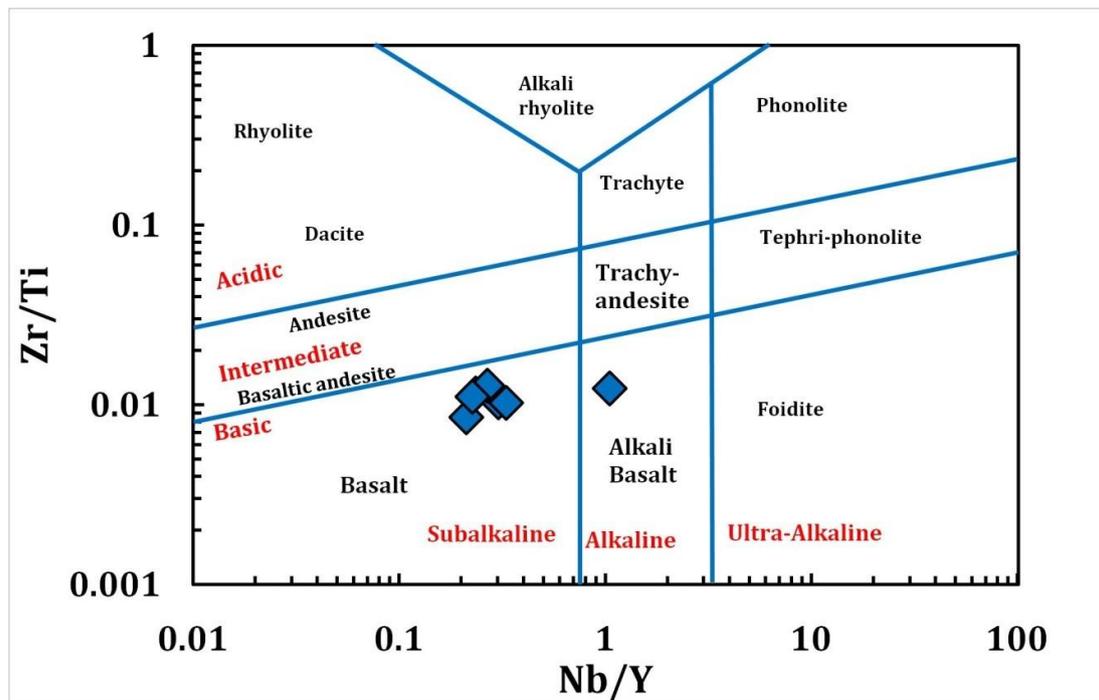


Figure 8: Zr/Ti vs. Nb/Y diagram for the Sylhet Trap samples. Fields are after (Pearce 1996).

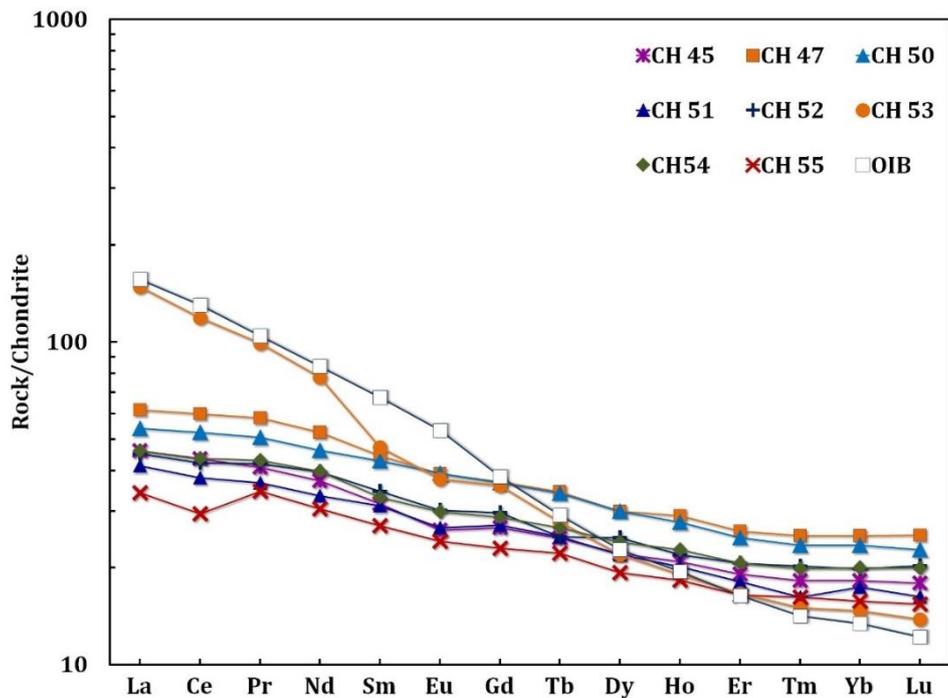


Figure 9: Chondrite-normalized REE diagrams for the STB. Normalizing values are from (McDonough & Sun 1995). Average of REE data of OIB of (Sun & McDonough 1989) is also plotted with the STB for comparison.

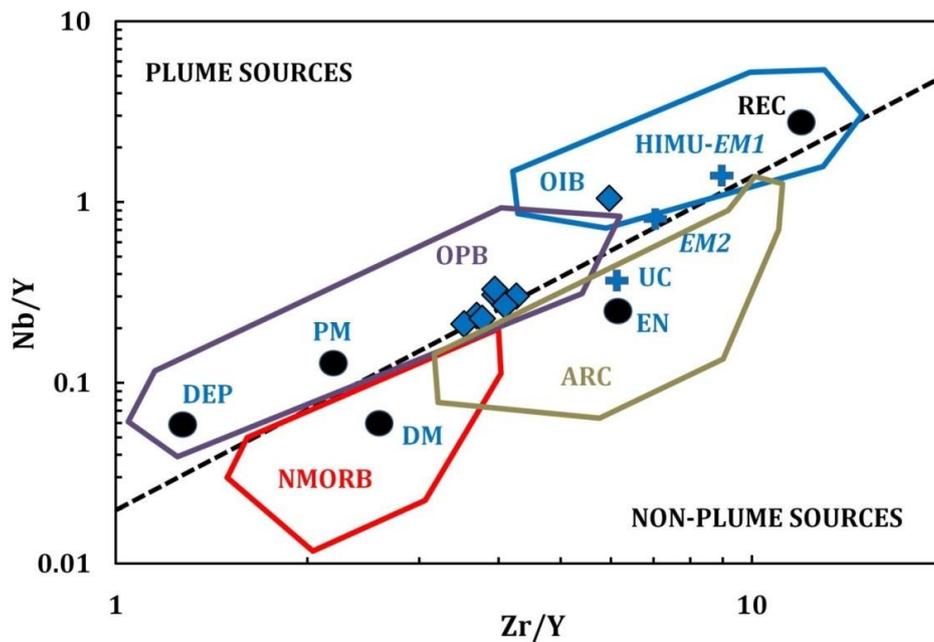


Figure 10: Nb/Y vs. Zr/Y diagram for the STB samples. Field boundaries and end-member compositions are from (Condie 2005). Abbreviations: UC = upper continental crust, PM = Primitive Mantle, DM = depleted mantle, HIMU = high mu (U/Pb) source, EM1 and EM2 = enriched mantle sources, ARC = arc related basalts, NMORB = normal mid-ocean ridge basalt, OPB=oceanic plateau basalt, OIB = oceanic island basalt, DEP = deep depleted mantle, EN = enriched component, REC = recycled component.

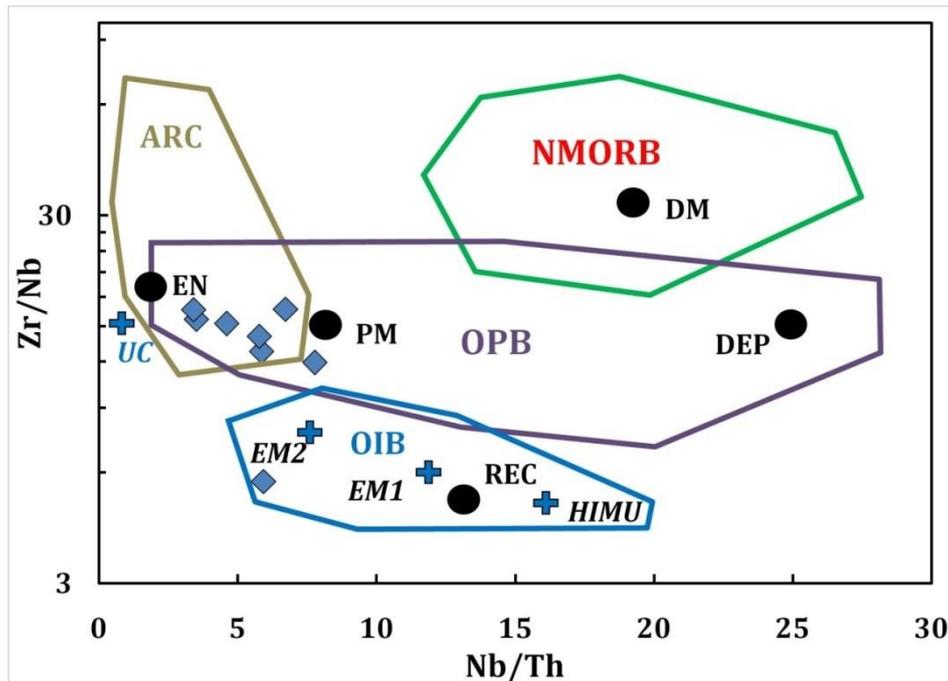


Figure 11: Zr/Nb vs. Nb/Th diagram for the STB samples. Field boundaries and end-member compositions are after (Condie 2005). Abbreviations as in Figure10.

## 6. Discussion and Conclusion

Cr-rich spinel within basaltic lavas is an established tool for interpreting petrogenetic history. It is a particularly sensitive indicator of melt disequilibria, characteristically showing ranges in composition an order of magnitude larger than the silicate melts from which it crystallizes (Allan et al., 1988; Tamaki et al., 1992). Interpretations regarding magma mixing, initiation of precipitation of coexisting phases, (Tamaki et al., 1992) from variations in basalt Cr-spinel composition. Spinel chemistry has also been used to deduce information about oxygen fugacity and temperature during crystallization. Furthermore, Cr-spinel as a petrogenetic indicator for basaltic liquids by directly solving for melt-spinel Mg-Fe<sup>2+</sup> exchange equilibrium, making it possible to determine whether a given spinel was in equilibrium with a given silicate liquid. In this paper, two samples CS 6 and CS 8 have been studied with SEM-EDX (Fig. 4a-b) to identify the spinels characterized by an average of 18.82% TiO<sub>2</sub>, 0.43% Cr<sub>2</sub>O<sub>3</sub>, 27.29% Fe<sub>2</sub>O<sub>3</sub> and 46.80 % FeO. Presence of Cr-spinel in the basalts is considered as a good indicator of a primitive nature (Hekinian 2004) and its enrichment in chrome content is probably from the upper mantle (Hamad, 1982). Cr-spinels inclusions therefore suggest the magma for the STB might have been derived from partial melting of the subcontinental lithospheric mantle. Such basalts with Cr-rich spinel have also been found in the rifting basins and western edge of the Pacific Ocean, usually is understood to have formed by the rifting of a continental volcanic arc in the mid-Tertiary (Celaya & McCabe 1987; Hilde & Wageman 1973; Karig 1971, 1974; Lallemand & Jolivet 1986; Tamaki 1985; Tamaki et al., 1990,1992).

Petrographic and geochemical analyses of the Sylhet Trap of the Shillong plateau indicate these are medium to low-K basalts. Because of a certain degree of post-magmatic alteration the ST basalts suffered, certain trace and major elements of the rock samples are checked for their mobility due to alteration. The more mobile incompatible elements, including Rb, K and Ba do not correlate well with Zr. However immobile, incompatible elements (e.g., Y, Ti, Nb, Th) show good correlation with Zr (Figure 6) and also against each other. For this reason, only data on immobile trace elements are discussed as being relevant to petrogenetic interpretations. Since the alkalis are highly susceptible to weathering and alteration and the ST basalts have also shown the effects of mobility of the alkalis. Therefore the Zr/Ti vs. Nb/Y diagram of (Pearce 1996) (Figure 8) is also used for classifying the Sylhet Trap basalts in addition to the classification of STB based on Total Alkali vs. Silica (TAS) diagram (Figure 5). In Zr/Ti vs. Nb/Y diagram (Figure 8), the Sylhet Trap basalts plot within the Subalkaline basaltic field except one sample which is of alkali basalt. In the multi-element diagram most of the STB shows high

concentrations of incompatible elements, e.g. Th, Nb, La and Ce etc. relative to compatible elements (e.g., Zr, Ti, Y, Tm and Yb) with pronounced negative anomalies at Nb, P and Ti (Figure 7). Such trace elemental characteristics are also observed as distinctive features of many continental flood basalt provinces (e.g., low-Ti basalts of Ferrar, (Hergt et al., 1991; Parana et al., 1996). On the other hand the sample CH 53 of STB shows high enrichment of LILE and no negative anomalies at Nb, P and Ti (Figure 7). Average OIB of (Sun & McDonough, 1989) and modal bulk continental crust (CC) of (Rudnick & Gao, 2003) are also plotted in the multi-elemental pattern with the STB data for comparison. OIBs have characteristic enriched in incompatible elements relative to PM with a positive anomaly at Nb. The continental crust has a characteristic depletion pattern at Nb, P and Ti. Sample CH53 shows similarities with OIB (Figure 7), while all the other samples show a coherent behavior and plot identical to the bulk continental crust of (Rudnick & Gao 2003) (Figure 7). Chondrite normalized REE patterns are relatively flat and their  $La_N/Yb_N$  ratios vary between 2.17 and 2.52 (Figure 9). The sample CH53 shows distinctive right sloping pattern (Figure9). The flat REE pattern can be explained due to the higher degree of partial melting; while CH 53 can be due to low degree of partial melting or involvement of garnet in the melting process.

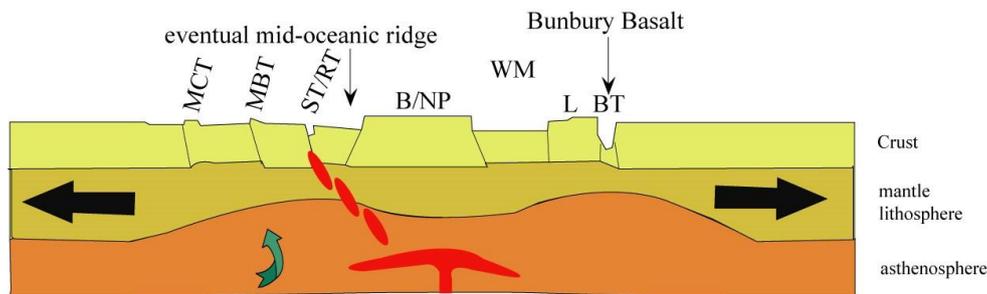
Based on geochemical signatures Sylhet Trap can be thus be grouped as Type 1 basalt: (CH 53) and Type 2 basalts (other samples of the study). Type 1 basalt has chemical (trace element) composition closely similar to OIB and therefore appears originate from plume source. The characteristics trace element signature further invokes crustal contamination by plume-derived magma produced by low degree of partial melting within the garnet stability field.

Another plume-related basalts in the region e.g. Kerguelen basalt, and St. Paul basalts are also plotted in the multi-elemental pattern for comparison. Data for Kerguelen plateau basalt and St. Paul island basalts are after (Doucet et al., 2004; Frey et al., 2002) respectively. These basalts were erupted under the oceanic setting on the Indian Ocean without continental crust or lithospheric mantle. The multi-element patterns of these Indian Ocean Islands basalts plot similar to the type 1 basalt of Sylhet Trap and also to the typical OIB. However the level of enrichment of typical OIB and Type 1 basalts over the entire spectrum of elements is 10 to 100 times higher than Kerguelen and St Paul island basalts. The Type 2 basalt has chemical signatures similar to the bulk Continental Crust of (Rudnick & Gao 2003) and thus appears probably not originated from plume source. However, on the basis of the field relationship with Type 1 basalt, age and area of occurrence, it therefore seems apparent that the magma for the Type 2 basalts were produced by partial melting of subcontinental lithospheric mantle, which may be triggered by plume upwelling associated with lithospheric thinning by continental breakup.

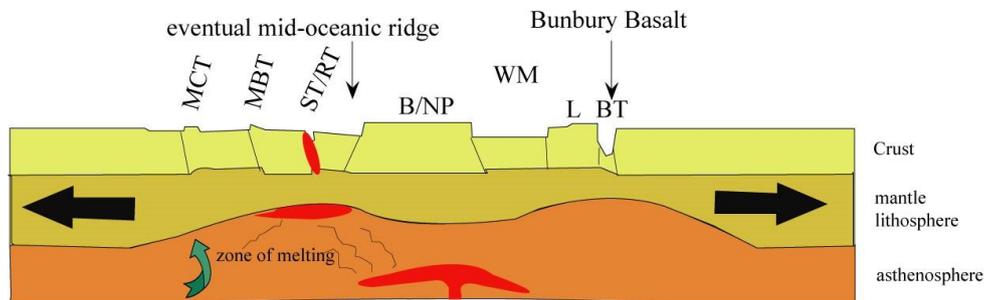
A classic model is proposed on the petrogenesis of ST basalt (Figure 12) which hypothesized that the Type 1 basalt is primarily associated the Kerguelen plume-related volcanism beneath the Shillong Plateau in the Cretaceous time. The following mechanism of ST basalt might involve melting an enriched patch of shallow mantle directly underneath the southern Shillong Plateau. Type 1 basalt may be originated by the partial continental lithospheric mantle due to extra heat from previous plume head and further decompression melting of enriched mantle which have the similar phenomenon described for Bunbury basalt (Olierook et al., 2016) of northern Australia. The decompression melting, which enriched patch may be produced due to break up of India from Australia as well continuous thinning of continental crust during Cretaceous time. ST basalt is exposed only southern flank of the Shillong Plateau along the E-W Dauki Fault because of thinning of the continental crust of this region. The decompression melting further supported by the young magmatic event of ~84 ma (Islam et al., 2014). Emplacement of the ST basalt along the Dauki fault inferred that structural discontinuities, viz., the Dauki Fault was active simultaneously during Gondwana break up which have acted as conduit for magma ascent (Olierook et al., 2016).

All the previous geochemical studies on STB such as Ghatak & Basu (2011; 2013), Islam et al. (2014), Kent et al. (1997; 2002), Ray et al. (1999), Srivastava & Sinha (2004; 2007) and Storey et al. (1992) have advocated for the Plume related origin of the rock type. Many other geochemical studies on Indian Ocean plateau basalts (e.g Doucet et al., 2004, 2005;; Escrig et al., 2004; Frey & Coffin 2000a; Frey et al., 2002; Graham et al., 2006; Hanan et al., 2004; Ingle et al., 2003; Mahoney et al., 2002; Weis et al., 2002; Nauret et al., 2006; Neal et al., 2002; Rehkämper & Hofmann, 1997; Storey et al., 1991; Weis & Frey, 1991; 2002) and on basalts occurring at the paleo-Gondwana margins (Courtillot & Cisowski 1987; Jordan et al. 2004; Saunders et al., 1992; 2002; White & McKengie, 1989) have also implicated for a plume hypothesis for the basalts on the Eastern margin of the Paleo-Gondwana that includes the STBs. The present study identifies occurrences of the basalts of both plume and non-plume origin within shilling plateau.

### a. Melt from the Kerguelen mantle Plume



### b. Extra heat from the Kerguelen mantle Plume



### c. Decompression melting of enriched mantle

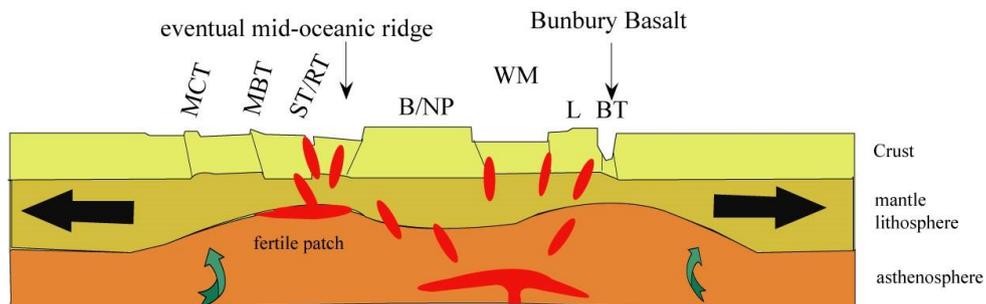


Figure 12. Different cross-sectional models for the petrogenesis of the Rajmahal- Sylhet Trap basalt and associated breakup of Greater India and Australia–Antarctica (modified after Olierook et al., 2016). (a) Melt generated from the Kerguelen mantle plume channeled to the Shillong Plateau. (b) Distal thermal perturbations from the Kerguelen mantle interacting with an already thinned and stretched lithosphere. The mantle plume provided an extra heat source necessary for the initiation of melting. (c) Decompression melting of an enriched, metasomatised shallow mantle. MCT= Main Central Thrust; MBT=Main Boundary Thrust; ST= Sylhet Trap; RT= Rajmahal Trap; B = Batavia Knoll; NP = Naturaliste Plateau; WM = Western Mentelle Basin; L = Leeuwin Complex; BT = Bunbury Trough.

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