Mantle source characterization of Sylhet Traps, northeastern India: A petrological and geochemical study

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In this study, mineralogical, geochemical, and isotopic data are presented for the Sylhet Trap at the southern flank of the eastern Shillong Plateau, northeastern India, to determine the magma genesis in relation to the Kerguelen plume mantle source. Sylhet Trap rocks are porphyritic tholeiite and have diverse chemical compositions from picro-basalt, basalt, andesite to dacite, but mostly are within the subalkaline field. Major and trace element data were used to identify two distinct magma fractionation trends, a low and medium K series, characterized by relatively flat MORB-like (analogous to Rajmahal Traps (II)) and enriched OIB chondrite-normalized Rare Earth Element (REE) patterns. Initial $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ isotope compositions were widely varied, ranging from 0.70435–0.71357, 0.51196–0.51266, and 17.92–19.72, respectively, when compared with basalts from the West Bengal, the Rajmahal Traps and the Kerguelen plume. Correlations among isotopic and trace element ratios of the Sylhet Traps provide evidence for the involvement of (1) HIMU-like mantle component, (2) the Kerguelen plume-like component, and (3) EMII-like crustal component. Magma from the Sylhet Traps was originated from a melting that derived directly from the heterogeneous Kerguelen mantle plume (components 1 and 2), which strongly suggests the presence of the Kerguelen plume-head in the Bengal basin.

1. Introduction

The volcanic outpouring of the southern Indian Ocean covers an enormous region consisting of the Kerguelen Plateau, the Broken Ridge, the Bunbury (southwestern Australia), and northeastern India (Rajmahal–Sylhet traps). This area's original formation derived from the breakup of the Indian and the Australian plate and is usually thought to be associated with the Kerguelen hotspot–mantle plume system that occurred ca. 132 Ma (Kent *et al.* 1997, 2002; Frey *et al.* 2000a, b; Coffin *et al.*

2002; Ray *et al.* 2005; Srivastava and Sinha 2007). Moreover, Srivastava and Sinha (2007) proposed that the Kerguelen hotspot was located near the eastern Indian margin between 100 and 120 Ma and was responsible for the Rajmahal basalts that are exposed over the Gondwana Supergroup and the Sylhet Traps rocks of the Shillong Plateau.

The Shillong Plateau is part of northeastern India (figure 1) and is characterized by Proterozoic ultramafic (Rao *et al.* 2009) to Late Cretaceous ultramafic–mafic alkaline magmatic activity (e.g., Srivastava and Sinha 2004; Saha

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(a)

(b)

Figure 1. (a) Map of part of the Indian Ocean and surrounding continents, after Ghatak and Basu (2011), Ingle *et al.* (2002) and Frey *et al.* (2000a, b), showing locations of the Sylhet and Rajmahal Traps in northeastern India. Also shown in gray is the extended Eastern Ghats-Shillong orogenic belt (Yin *et al.* 2010) along the east coast of India. Basalt provinces attributed to the Kerguelen plume (Frey *et al.* 2002) include the Kerguelen Plateau, Broken Ridge, Ninety-East Ridge, Bunbury basalts and Rajmahal Traps. Abbreviations used: BB – Bunbury basalt drill core sites; NKP – North Kerguelen Plateau; CKP – Central Kerguelen Plateau; SKP – South Kerguelen Plateau; CG – Chalka Granulites (Chakrabarti *et al.* 2011). Black crosses are ODP sites. Sites 253, 254, 756, 757, 214, 216, and 758 are from the Ninety-East Ridge and are grouped as NER in subsequent Nd–Sr–Pb isotopic plots, and (b) regional geology and tectonic framework of the Shillong Plateau (modified after Saha *et al.* 2010). MB and CH sections are shown by a filled square and the study location is shown by a filled star.

et al. 2010). Many previous studies (e.g., Storey *et al.* 1992; Kent *et al.* 1997, 2002; Ray *et al.* 1999; Srivastava and Sinha 2004, 2007) have suggested that the spatial and temporal distribution of Shillong Plateau magmatism are related to a plume that is presently beneath Kerguelen. It has also been suggested that the nature of the Shillong Plateau volcanism is plume-related N-MORB (Rao *et al.* 2009) or OIB (Veena *et al.* 1998; Srivastava and Sinha 2007). A recent geochemical and Nd–Sr–Pb isotopic study on the Sylhet Traps (STGB) from the Cherrapunji–Shella bazaar (CH) and Mawsynram–Balot (MB) sections in the Shillong Plateau (Ghatak and Basu 2011) suggested that the Sylhet Traps basalt of the CH section is associated with E-MORB; whereas, basalts from the MB section involve lower crustal contamination. Rare earth elements (REEs) in the Sylhet Trap basalts are characterized by high La abundance and experience less contamination, similar to the Rajmahal basalt (Storey *et al.* 1992; Kent *et al.* 1997) and the ODP sites on the Kerguelen Plateau (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003).

However, since a report on the Sylhet Trap basalts by Palmer (1923), and subsequent geologic, petrochemistry and tectonic studies (Talukdar 1966; Talukdar and Murthy 1971) were performed, there has been limited research in this area. Recently, Ghatak and Basu (2011, 2013) reported on the heterogeneity of the Kerguelen Plateau of tholeiitic series (with high Mg# of ~60–61) from the Shillong Plateau, and there have been a few dyke samples taken from Bihar–West Bengal. Therefore, there is a need to perform additional detailed studies on the petrography, geochemistry, and isotopic characteristics of other sections in the region to fully understand the origin and nature of the Sylhet Trap basalts. In this study, we present petrographic, geochemical, mineralogical, isotopic data for samples collected in the eastern portion of the Shillong Plateau, including a K–Ar dating result from one relatively primitive basalt. Our dataset will be used to discuss: (i) the temperature–pressure conditions for mineral accumulation of the Sylhet Traps, and (ii) the nature of the mantle source with respect to the Kerguelen plume.

2. Geology of the area

The Shillong Plateau has a ‘pop-up’ structure between the Brahmaputra Valley in the north and the Surma Valley in the south. The Shillong Plateau is dissected by major E–W, N–S, and NW–SE oriented faults (Nongchram Fault, Um Ngot lineaments, Barapani–Tyradsad shear zone, Chedrang Fault, Dudhnoi Fault, Kopili lineaments) related

to tectonic forces from both the Himalayan collision zone and the Indo-Burma subduction zone (Kayal 2001; Islam *et al.* 2011). This type of plateau is usually observed in a convergent tectonic setting with major plateau bounding strike-slip faults (Schellart and Nieuwlan 2003; Islam *et al.* 2011). Although substantial research has been performed in this area, there remain debates about the Shillong Plateau bounding faults, its origin and major earthquake producing deformation (Oldham 1899; Evan 1964; Verma and Mukhopadhyay 1977; Hiller and Elahi 1984; Chen and Molnar 1990; Johnson and Alam 1991; Bilham and England 2001; Rajendran *et al.* 2004; Mitra *et al.* 2005; Srinivasan 2005; Rajasekhar and Mishra 2008; Islam *et al.* 2011). The Sylhet Trap (figure 1) is exposed in a narrow east–west strip, 60–80 km long and 4 km wide (Talukdar and Murthy 1971; Saha *et al.* 2010) along the southern edge of the Shillong Plateau with maximum thickness of ~500–650 m (Mazumder 1986; Baksi *et al.* 1987). It is a part of the Sylhet–Rajmahal flood basalt province at the southern margin of the Shillong Plateau at ~117–115 Ma (Ray and Pande 2001) and is associated with the Kerguelen mantle plume activity (Storey *et al.* 1992; Kent *et al.* 1997, 2002; Srivastava and Sinha 2004). The Traps appear to overlie the eroded Pre-Cambrian basement and are inconsistently overlain by Upper Cretaceous–Eocene sediments (figure 1b). The sediments and the lavas outline a monocline that becomes a flexure southward, and the sediments at the top of the flexure have subsequently been eroded in places (Biswas and Grasemann 2005; Islam *et al.* 2010). This flood basaltic volcanism is generally associated with the breakup of the Gondwana supercontinent and the northward movement of the Indian plate and its ultimate collision with the Eurasian plate (Rao 2002). However, Talukdar and Murthy (1971) suggested that the Sylhet Traps were not extruded outside the present northern limit of the Raibah Fault and the southern limit of the Dauki Fault. For example, the Dauki was initiated and sustained activity through the Tertiary to Recent times. There is no evidence supporting volcanism with an association of vertical movement on the Dauki Fault. However, Talukdar and Murthy (1971) also proposed that the Dauki Fault may be another zone of fissure where eruptions may have occurred. Gupta and Sen (1988) observed, using Landsat images and aerial photographs that a N–S trending Um Ngot lineament cuts across the general NE–SW trend of the Shillong Plateau (figure 1b). This lineament developed during the late Jurassic–Early Cretaceous period and contains several alkaline intrusive bodies, including the Sung Valley complex (ultramafic-alkaline-carbonatite complex) and is geologically related to the Ninety-East

Ridge in the Indian Ocean (Gupta and Sen 1988; Srivastava and Sinha 2004; Srivastava *et al.* 2005). Several granite plutons (700–450 Ma) also intrude the gneissic basement and the Shillong Group envelops sequence. The Archaean gneissic basement of the Shillong Plateau is traversed by a number of mafic dyke swarms (Rao *et al.* 2009). Two suites of dykes have been reported by Rao *et al.* (2009) in the Garo Hills that represent Proterozoic Khasi greenstone related dolerites and younger Cretaceous dolerite dykes. In places, bodies of metamorphosed mafic igneous rocks have also been reported (Mazumder 1976; Ghosh *et al.* 1994).

3. Petrography

The Sylhet Traps are predominantly comprised of basalts. The Sylhet Traps volcanic rocks are predominantly porphyritic (figure 2), containing ~4% to 19% phenocrysts. The major phenocrysts phases are plagioclase and pyroxene, but only sample 7 contains 16% olivine. Sample 1 is highly weathered, with phenocrysts of orthopyroxene, quartz, albite, and calcite (all these minerals are alteration products). In this sample, groundmasses are comprised of albite, ilmenite, orthopyroxene, and biotite. Sample 4 is dacite with a predominant phenocryst of amphibole; whereas, the minor phenocrysts consist of albite, ilmenite, and magnetite. Samples 5 and 6 are composed of similar types of phenocrysts and groundmasses. The phenocrysts are plagioclase (labradorite, andesine) and clinopyroxene (augite) and the groundmasses consist of plagioclase (labradorite, andesine), clinopyroxene (augite, pigeonite), and ilmenite. The olivine-rich (>16%) sample (sample 7) is predominantly composed of olivine (forsterite) with some clinopyroxene (augite) as phenocrysts. Spinel inclusions were identified within a few olivine phenocrysts. In the groundmasses, olivine (forsterite), plagioclase (albite, labradorite), ulvospinel, and ilmenite were found. Sample 10 contains phenocrysts of plagioclase (bytonite) and clinopyroxene (augite) within a groundmass of clinopyroxene (augite), plagioclase (andesine, labradorite), and ilmenite.

4. K–Ar dating

Sample 7 is a very distinct sample that contains fresh olivine phenocrysts and similar samples have never been reported in previous studies. Therefore, to place constraints on volcanic activity, we conducted K–Ar dating on this sample, which revealed an age of 84.0 ± 1.9 Ma (table 1). Groundmass separates (mesh size, #100–200), concentrated by means of magnetic separation, were analyzed for K

and Ar at the Okayama University of Science, Japan and the calculation of age and errors were determined using the methods described by Nagao *et al.* (1984) and Itaya *et al.* (1991). Decay constants for ^{40}Ar and ^{40}Ca and the ^{40}K content in potassium used in the age calculation are derived from Steiger and Jäger (1977): $0.581 \times 10^{-10}/\text{y}$, $4.962 \times 10^{-10}/\text{y}$ and 1.167×10^{-4} , respectively. Our K–Ar dating results, along with previous studies (Ray *et al.* 2005), indicate that plume-related Sylhet basalt emplaced during 120–84 Ma, which is similar to the ~118–84 Ma age of the Rajmahal Traps (Baksi *et al.* 1987). These data contrast with the ^{40}Ar – ^{39}Ar dating results of 118–105 Ma for basalts from the Rajmahal–Bengal–Sylhet Traps (Cherrapunji–Shella bazaar section) (Baksi 1995; Coffin *et al.* 2002; Kent *et al.* 2002).

5. Analytical methods

Six volcanic rock samples were collected from the Dauki river bed at the Jafiong point (25.11°N, 92.01°E) of Sylhet. Mineral chemical analyses were conducted using energy-dispersive X-ray spectroscopy (EDX; EDAXTM Genesis 4000) attached to a scanning electron microscope (SEM; Hitachi 300N) at the Department of Physics and Earth Sciences, University of the Ryukyus. The SEM-EDX operating conditions were 20 kV and 0.5 nA. The whole-rock major and selected trace elements (Ba, Co, Nb, Ni, Rb, Sr, V, Y, and Zr) were determined (table 2) on fused glass beads by X-ray fluorescence spectrometry (Shimadzu XRF-1800) at the Department of Physics and Earth Sciences, University of the Ryukyus. Reproducibility and accuracy of the XRF analyses were verified using international rock standards (JA-1 and BHVO-2).

Additional whole-rock trace element concentrations (including rare earth elements (REE)) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS; Yokogawa Analytical System (now Agilent Technologies) HP 4500) at the University of the Ryukyus (table 3). The detailed analytical procedure is described in Shinjo *et al.* (2000). The precision and reproducibility of the ICP-MS measurements were verified using international rock standards: BIR-1, JA-1, JP-1, JB-1, JB-2, and DST-2. The accuracy of the majority of trace element analyses was $\pm 5\%$ relative to the recommended values.

Sr, Nd, and Pb isotope analyses were performed on a Finnigan MAT262 mass spectrometer at the University of the Ryukyus, using the procedures outlined in Shinjo *et al.* (2000) and Wang *et al.* (2004) (table 4). The isotopic ratios were corrected for mass fractionation by normalizing to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$. In this

Figure 2. Photomicrographs of samples 1 (a), 4 (b), 5 (c), 6 (d), 7 (e) and 10 (f). Opx=orthopyroxene, Qtz=Quartz, Cal=calcite, Amp=amphibole, Ab=albite, Lb=labradorite, Cpx=clinopyroxene, Ad=andesine, Ol=olivine, Byt= Bytownite.

Table 1. *K–Ar dating result of sample 7.*

Sample no.	Specimen type (mesh size)	K content (wt%)	radiogenic ^{40}Ar (10^{-8}cc STP/g)	K–Ar age (Ma)	Nonradiogenic ^{40}Ar (%)	Reproducibility (%)
BGD-7	Concentrated groundmass (#100–200)	0.684 $\pm$ 0.014	228.2 $\pm$ 2.5	84.0 $\pm$ 1.9	12.3	0.28

Table 2. *Major element compositions.*

Sample	1	4	5	6	7	10
SiO ₂ (wt%)	47.77	64.81	52.04	50.58	44.53	49.83
TiO ₂	2.00	1.09	1.998	1.98	2.02	2.85
Al ₂ O ₃	15.27	12.41	13.43	13.46	8.17	14.61
Fe ₂ O ₃ ^T	12.74	11.59	12.69	12.88	12.44	12.21
MnO	0.19	0.17	0.288	0.27	0.19	0.16
MgO	6.47	0.46	5.44	5.73	12.29	4.04
CaO	6.10	3.16	10.11	10.07	14.42	8.41
Na ₂ O	3.82	5.13	2.48	2.29	1.97	2.82
K ₂ O	0.38	0.80	0.49	0.43	0.80	1.55
P ₂ O ₅	0.17	0.18	0.21	0.20	0.32	0.29
Total	94.91	99.81	99.18	97.90	97.15	96.78
Trace element						
Ba (ppm)	139	422	140	129	331	462
Co	50	10	42	44	64	41
Cr	242	5	124	134	728	24
Nb	11.8	23.7	11.7	11.2	28.3	26.1
Ni	60	3	50	52	402	29
Rb	13.7	20.3	9	7.3	28.9	36
Sr	335	209	199	196	620	552
V	309	1	308	300	291	330
Y	31.4	92.7	34	31.4	19.6	27.7
Zr	150	416	141	137	132	243
CIPW norm						
Q	–	24.25	8.48	7.57	–	5.88
Or	2.388	4.77	2.94	2.62	4.91	9.54
Ab	34.36	43.78	21.34	19.97	6.51	24.86
An	24.87	8.54	24.48	25.96	11.52	23.58
Ne	–	–	–	–	5.85	–
Di	4.95	5.28	20.46	19.67	48.36	14.51
Hy	21.58	3.32	11.78	13.72	–	8.81
Ol	0.74	–	–	–	12.55	–
Mt	6.66	7.57	6.18	6.14	5.54	6.47
Il	4.04	2.08	3.86	3.89	3.99	5.64
Ap	0.42	0.41	0.49	0.48	0.78	0.70
Mg#	60.35	12.44	55.91	56.41	73.53	50.25

study, the NIST SRM-987 Sr standard had a mean of $^{87}\text{Sr}/^{86}\text{Sr}=0.710251\pm 42$ (2SD, $n=5$) and the La Jolla Nd standard had a mean of $^{143}\text{Nd}/^{144}\text{Nd}=0.511824\pm 10$ (2SD, $n=2$). All data for the samples were normalized to a value of SRM-987 $^{87}\text{Sr}/^{86}\text{Sr}=0.71025$ and La Jolla $^{143}\text{Nd}/^{144}\text{Nd}=0.51186$.

The ^{207}Pb – ^{204}Pb double spike method was applied to the Pb isotope analyses. The compositions of fractionation-corrected values of the NIST SRM-981 Pb standard ($n=2$) during this study have $^{206}\text{Pb}/^{204}\text{Pb}=16.939$ (± 6 ; 2SD), $^{207}\text{Pb}/^{204}\text{Pb}=15.496$ (± 8), and $^{208}\text{Pb}/^{204}\text{Pb}=36.713$ (± 26).

Table 3. Trace and REEs data by ICP-MS analysis.

Sample	1	4	5	6	7	10
Li (ppm)	32.54	7.04	9.11	10.18	36.94	24.84
Be	0.71	4.21	0.74	0.68	1.64	1.60
Sc	40.95	16.50	40.43	39.61	31.85	22.83
V	299.90	1.39	324.30	317.70	317.50	353.70
Cr	188.60	3.19	99.75	132.20	517.20	22.34
Co	45.03	6.23	41.71	43.98	68.56	40.22
Ni	48.54	0.32	51.8	49.82	310.20	26.87
Rb	8.60	20.31	8.44	5.42	31.70	37.56
Sr	314.60	228.80	209.00	198.40	648.70	563.20
Y	34.88	110.60	39.25	35.08	21.40	32.19
Zr	138.30	259.20	143.70	134.60	132.10	251.70
Nb	8.15	22.61	7.98	7.47	29.75	26.83
Cs	0.41	0.81	0.01	0.10	4.93	3.04
Ba	122.30	389.90	127.50	114.60	331.90	443.10
La	14.09	53.05	9.97	9.35	26.53	33.37
Ce	26.63	117.40	23.32	22.34	53.20	68.96
Pr	3.594	14.81	3.33	3.14	6.40	8.36
Nd	16.85	63.64	16.47	15.33	26.32	34.39
Sm	4.73	15.30	5.08	4.72	5.450	7.327
Eu	1.65	3.76	1.73	1.66	1.69	2.27
Gd	5.63	16.31	6.22	5.78	5.18	6.83
Tb	0.95	2.86	1.08	1.01	0.76	1.05
Dy	5.85	18.09	6.70	6.13	4.19	5.90
Ho	1.17	3.78	1.36	1.24	0.78	1.13
Er	3.30	11.28	3.84	3.44	2.07	3.11
Tm	0.48	1.68	0.55	0.50	0.28	0.45
Yb	2.90	10.14	3.35	3.10	1.70	2.75
Lu	0.41	1.36	0.48	0.45	0.24	0.39
Hf	3.57	6.74	3.67	3.48	3.38	6.06
Ta	0.59	1.74	0.59	0.55	2.06	1.94
Pb	3.55	10.52	1.93	1.83	4.88	7.37
Th	1.41	12.22	1.28	1.20	3.46	4.51
U	0.20	2.63	0.27	0.24	0.72	0.76

6. Mineral chemistry

Microprobe analyses of phenocryst and groundmass minerals were performed on all samples. Representative average mineral compositions are discussed below.

All samples of the Sylhet Traps contained a wide range of plagioclase compositions (An_{20-72}) as listed in table 3. Sample 5 consists of a higher orthoclase percentage (Or_{66}), indicating the alkali nature of the magma. However, the matrix of the picrite sample (sample 7) contains higher levels of An_{77} . Samples 1 and 4 have higher albite (Ab_{92}) levels in both the phenocryst and groundmass. Pyroxenes from the Sylhet Trap basalts are mostly augites ($\text{Wo}_{36-50}\text{En}_{39-50}\text{Fs}_{6-25}$) (figure 3a). Pyroxene in sample 7 is diopside with higher $\text{Mg}\#$ 92.5. Moreover, groundmass of sample 6 indicates pigeonite. Most of the samples are rich in FeO ($\sim 7-18\%$) and their $\text{Mg}\#$ ranges from 76 to 82.

The phenocrysts and groundmasses in samples 5, 6, and 10 contain 1.85–2.80% of Al_2O_3 and less than 1.6% of TiO_2 , a range that corresponds to tholeiitic clinopyroxene (Leterrier *et al.* 1982). In contrast, pyroxenes in sample 7 have higher Al_2O_3 , Na_2O , and CaO content in the pyroxenes that range from 0.23–0.54% and 9–24%, respectively. The $\text{Ca}+\text{Na}$ vs. Ti diagram (figure 3b) shows that most of the clinopyroxenes represent tholeiitic basalt affinity, excluding sample 7, which displays an alkali basalt. Olivine and spinel were found in the picrite sample (sample 7) as phenocrysts and groundmasses. The phenocrysts are mainly forsterite (Fo_{89}) with 48% MgO . However, the groundmass composition has lower Fo content (Fo_{46}). Spinel was identified within olivine phenocrysts as an inclusion, which indicates the primitive nature of the rock. Similar picrite samples are found in places in the Reunion hotspot, which is related to the Deccan Traps of western India

Table 4. Measured and initial_(I) (assumed as 117 Ma) Sr, Nd and Pb isotopic ratios of Sylhet Traps Basalts.

Sample	1	4	5	6	7	10
Rb (ppm)	8.600	20.310	8.440	5.420	31.700	37.560
Sr (ppm)	314.600	228.800	209.000	198.400	648.700	563.200
⁸⁷ Rb/ ⁸⁶ Sr	0.079	0.257	0.117	0.079	0.141	0.193
⁸⁷ Sr/ ⁸⁶ Sr ₍₀₎	0.707	0.714	0.705	0.704	0.707	0.710
⁸⁷ Sr/ ⁸⁶ Sr _(I)	0.707	0.714	0.704	0.704	0.706	0.710
ε _{Sr(I)}	37.300	130.700	−0.100	−0.200	30.200	81.100
Sm (ppm)	4.730	15.300	5.080	4.720	5.450	7.330
Nd (ppm)	16.850	63.640	16.470	15.330	26.320	34.390
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.170	0.145	0.186	0.186	0.125	0.129
¹⁴³ Nd/ ¹⁴⁴ Nd ₍₀₎	0.513	0.512	0.513	0.513	0.513	0.512
¹⁴³ Nd/ ¹⁴⁴ Nd _(I)	0.512	0.512	0.513	0.513	0.513	0.512
ε _{Nd(I)}	−0.600	−10.300	3.300	3.100	2.000	−6.000
U (ppm)	0.200	2.630	0.270	0.240	0.720	0.760
Th (ppm)	1.410	12.220	1.280	1.200	3.460	4.510
Pb (ppm)	3.550	10.520	1.930	1.830	4.880	7.370
²⁰⁶ Pb/ ²⁰⁴ Pb ₍₀₎		19.035	18.081	18.079	19.884	18.363
²⁰⁷ Pb/ ²⁰⁴ Pb ₍₀₎		15.650	15.571	15.573	15.719	15.760
²⁰⁸ Pb/ ²⁰⁴ Pb ₍₀₎		39.129	38.369	38.370	39.979	40.204
²³⁸ U/ ²⁰⁴ Pb		15.431	8.635	8.095	9.107	6.365
²³⁵ U/ ²⁰⁴ Pb		0.112	0.063	0.059	0.066	0.046
²³² Th/ ²⁰⁴ Pb		74.089	42.301	41.824	45.223	39.031
²⁰⁶ Pb/ ²⁰⁴ Pb _(I)		18.752	17.923	17.931	19.717	18.246
²⁰⁷ Pb/ ²⁰⁴ Pb _(I)		15.636	15.563	15.566	15.711	15.754
²⁰⁸ Pb/ ²⁰⁴ Pb _(I)		38.699	38.123	38.127	39.716	39.977

(Krishnamurthy *et al.* 2000). The spinel contains significant amounts of Cr (45.99%) and FeO (29.68%). Amphiboles were observed in samples 4 and 10. Sample 4 contains a large amount of amphiboles megaphenocrysts with >29% of FeO; whereas, a very small amount of amphibole is present as groundmass in sample 10. Ilmenite is common in most samples, excluding sample 7, as groundmass. However, sample 4 contains ilmenite and magnetite as phenocrysts with higher TiO₂ (~50%) and FeO (~93%). Ilmenites within samples 1 and 5 have a very high FeO (>68%) content.

7. Geochemistry

7.1 Whole-rock geochemistry

Major and trace element data for six samples are presented in table 2. In the total alkali *vs.* silica (TAS) classification diagram (figure 4a) of Le Maitre *et al.* (2002), Sylhet Trap rocks display diverse chemical composition from picro-basalt (sample 7), basalt (samples 1 and 10), basaltic andesite (samples 5 and 6) to dacite (sample 4), and they mostly fall in the subalkaline field. The subalkaline nature of the investigated rocks is also

indicated by their CIPW-normative composition (table 2). Furthermore, the SiO₂–K₂O diagram has two distinct trends: samples 1–6 plot near the boundary between the low K and medium K series; samples 7 and 10 plot near the boundary between the medium K and high K series (figure 4b). Only sample 7 contains nepheline, indicative of an alkaline nature. All samples have an average 10% of magnetite and ilmenite in their normative composition. Sample 7 has a higher Mg number (73.53) and MgO (12.29), indicating that this sample has a primitive nature (Green 1971; Luhr 1997; Velasco-Tapia and Verma 2001; Srivastava and Sinha 2007). The other samples have a lower Mg number (~50–60), suggesting that they are a differentiated product of primary magma that may have experienced some degree of olivine and Cpx fractionation.

The variation diagrams (figure 5a–b) between MgO and other oxides indicate two different trends. For example, TiO₂ has a negative correlation with MgO content whereas CaO has a positive correlation in samples 7 and 10. Samples 1, 5, and 6 have a negative correlation between MgO and CaO and a positive correlation between MgO and TiO₂. The diagram (figure 5c–d) between Mg number (Mg#) and selected trace elements (Zr and Nb) also has two distinct trends. Samples 7 and 10 have

Figure 3. **(a)** Wollastonite–enstatite–ferrosilite classification diagram for pyroxenes (after Morimoto *et al.* 1988). **(b)** Ca+Na vs. Ti diagram (Leterrier *et al.* 1982) for basalt classification using Cpx.

negative correlations between Zr and Mg#, but no correlation between Nb and Mg#.

Chondrite-normalized REE plots are shown in figure 6(a). The LREE/HREE is generally higher in samples 7 and 10 compared with samples 1, 5, and 6. A negative Eu anomaly ($\text{Eu}/\text{Eu}^*=0.73$) is observed in sample 4, suggesting possible plagioclase fractionation and/or crustal contamination. Our results are consistent with the field of the Rajmahal (Kent *et al.* 1997) and STGB (Ghatak and Basu 2011, 2013), with the exception of sample 4.

The two distinct groups of basalts are illustrated in the primitive mantle-normalized incompatible element pattern (figure 6b). The patterns broadly resemble OIB pattern and correspond to the field of the Rajmahal Traps (Storey *et al.* 1992; Kent *et al.* 1997), the Kerguelen Plateau (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003) and the STGB (Ghatak and Basu 2011). Samples 7 and 10 display marked enrichments in trace elements compared with samples 1, 5, and 6. The patterns are characterized by pronounced positive Pb anomalies, but do not display significant enrichment in HFSE (Nb and Ta) relative to LREE and LILE.

Sample 4 shows marked negative anomalies of K, Sr, P and Ti.

7.2 Sr–Nd–Pb isotope geochemistry

Sr–Nd–Pb isotopic analyses are presented in table 4 and plotted in figure 7 in comparison with the STGB (Ghatak and Basu 2011, 2013), the Rajmahal Traps (Storey *et al.* 1992; Kent *et al.* 1997), the Kerguelen Plateau (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003), and the Ninety-East Ridge (Mahoney *et al.* 2002). $^{87}\text{Sr}/^{86}\text{Sr}_{(I)}$ and $^{143}\text{Nd}/^{144}\text{Nd}_{(I)}$ range from 0.70435 to 0.71357 and 0.51196 to 0.51266, respectively. As shown in figure 7(c), the data define a linear trend between HIMU and EM-II mantle end member (Zindler and Hart 1986). Most of the data show a similar trend with the STGB and the Kerguelen Plateau basalt, but display higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than the Ninety-East Ridge basalts.

The plot of $^{206}\text{Pb}/^{204}\text{Pb}_{(I)}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}_{(I)}$ (figure 7a) shows that samples 5 and 6 have lower values and fall within the field of the Kerguelen

Figure 4. (a) TAS diagram for igneous rock classification (Le Maitre *et al.* 2002). (b) Plot of SiO_2 vs. K_2O .

Plateau, the Rajmahal Traps and the STGB. In contrast, sample 10 has higher $^{207}Pb/^{204}Pb_{(I)}$ and plots close to the field of the Ninety-East Ridge of the Indian Ocean (Mahoney *et al.* 2002) and upper crustal field (Chakrabarti *et al.* 2011) and is close to ancient non-volcanic continental clasts from ODP site 1137 (Ingle *et al.* 2002). Samples 4 and 7 show EM-II and HIMU-type characteristics with higher $^{206}Pb/^{204}Pb_{(I)}$. The $^{206}Pb/^{204}Pb_{(I)}$ vs. $^{208}Pb/^{204}Pb_{(I)}$ plot has a similar pattern as figure 7(b). Samples 5 and 6 fall within the field of the STGB, the Rajmahal Traps and the Kerguelen Plateau with lower $^{208}Pb/^{204}Pb_{(I)}$. Samples 4, 7, and 10 have higher $^{208}Pb/^{204}Pb_{(I)}$ and are distinct from any compared fields. Sample 10 has a resemblance to ODP site 1137 samples.

8. Discussion

The Sylhet Trap basalts can be correlated with basalts at the Rajmahal Traps (Storey *et al.* 1992; Kent *et al.* 1997) and the Kerguelen Plateau (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003), having similar age and geochemical compositions (Ghatak and Basu 2011, 2013). Here we will discuss the petrography and mineralogy, geochemistry, Nd–Sr–Pb isotope geochemistry, and K–Ar dating for a primitive sample (sample 7) as presented in the results section. We explore some salient features of the geodynamic setting and mantle source characterization of the Sylhet Trap rocks and compare our data with the STGB, the Rajmahal Traps, and the Kerguelen Plateau basalts.

Figure 5. Variation diagrams between MgO and other oxides and Mg# and other incompatible trace elements.

8.1 Mantle source characterization

Trace elements and isotopic data from our analyses suggest at least two mantle components were involved in magma generation for the Sylhet Traps: (i) the Kerguelen plume-like component and (ii) HIMU-type component. Moreover, an upper continental contamination is evident in the generation of the Sylhet Trap magmas. These issues are further described in the following sections.

8.1.1 Kerguelen plume-like component

The Kerguelen plume is represented mostly by basalts from ODP sites 1138, 1141, and 1142. These samples are characterized by relatively uncontaminated lava and less enrichment of incompatible trace elements (Neal *et al.* 2002). The Rajmahal Group I and samples from the CH section of Sylhet Traps (Ghatak and Basu 2011) also exhibit similar characteristics, indicating the same plume component as these areas. Ghatak and Basu (2011)

Figure 6. (a) Chondrite-normalized REE patterns. (b) Primitive mantle-normalized incompatible elements pattern of basalts of the Sylhet Traps (normalized values are from Sun and McDonoug 1989). Filled areas indicate the field of the Rajmahal (Storey et al. 1992; Kent et al. 1997) and the STGB (Ghatak and Basu 2011). (c) and (d) average REE and incompatible trace element pattern from various Kerguelen Plateau ODP sites (Frey et al. 2000a, b, 2002; Ingle et al. 2002; Neal et al. 2002), and continental clasts from Site 1137 (Ingle et al. 2002) are shown for comparison.

Figure 7. (a) $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$, (b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and (c) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ plots for Sylhet Traps. Data fields for the Kerguelen (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003), Rajmahal (Storey *et al.* 1992; Kent *et al.* 1997), STGB (Ghatak and Basu 2011), Chilka granulites (Chakrabarti *et al.* 2011) and ODP-1137 (Frey *et al.* 2002) are also shown for comparison. NHRL: Northern Hemispheric Reference Line (Hart 1984). Location of lower crust and upper crust are from Hart (1984) and Zindler and Hart (1986).

proposed that the Kerguelen plume-head composition in Nd–Sr–isotopic space has $\varepsilon\text{Nd}_{(t)} = +2.0$ and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} = 0.7046$, which is in excellent agreement with the average value for site 1138 basalts ($\varepsilon\text{Nd}_{(t)} = +0.6$ and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} = 0.7048$) and was suggested to be representative of the Kerguelen starting plume-head by Neal *et al.* (2002). Sr–Nd isotopic compositions (figure 7c) and the incompatible trace element pattern and the rare-earth element pattern of samples 5 and 6 closely resemble those of the Rajmahal Group I and most of the CH section of the STGB (figure 2 of Ghatak and Basu 2011) (figure 6). In addition, $^{208}\text{Pb}/^{204}\text{Pb}_{(t)}$, $^{207}\text{Pb}/^{204}\text{Pb}_{(t)}$, and $^{206}\text{Pb}/^{204}\text{Pb}_{(t)}$ of these two samples fall within the field of Kerguelen (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003) and the Rajmahal Group I (Storey *et al.* 1992; Kent *et al.* 1997), and the STGB (Ghatak and Basu 2011) (figure 7b–c). The plot of $\varepsilon\text{Nd}_{(t)}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ also demonstrates the similar properties of samples 5 and 6 and these three fields (figure 7c). Therefore, we propose that in samples 5 and 6, the basalt magma was derived from the primitive Kerguelen plume source.

8.1.2 HIMU-type component

Picritic sample (sample 7) has higher values of $^{208}\text{Pb}/^{204}\text{Pb}_{(t)}$, $^{207}\text{Pb}/^{204}\text{Pb}_{(t)}$, and $^{206}\text{Pb}/^{204}\text{Pb}_{(t)}$ (39.716, 15.711 and 19.717), which fall between the EMII and HIMU mantle components of Zindler and Hart (1986). High $^{206}\text{Pb}/^{204}\text{Pb}_{(t)}$ and $^{208}\text{Pb}/^{204}\text{Pb}_{(t)}$ suggest either HIMU (of OIB) components in their source (e.g., St. Helena (Chaffey *et al.* 1989), Mangaia (Saunders *et al.* 1988) or crust contamination (e.g., Hercinian granite, Vitrac *et al.* 1981)). Sample 7 is characterized by the content of fresh Mg-rich olivine (Fo₈₉) with Cr-spinel inclusion (figure 2e) and high bulk Mg#, which indicate its primitive nature. Therefore, a model for HIMU character caused by upper crustal contamination (or sediment involvement) can be rejected; instead, we propose that there are HIMU characteristics in the mantle source. This HIMU component in primitive rock has not been reported from the STGB (Ghatak and Basu 2011, 2013), the Rajmahal Traps (Storey *et al.* 1992; Kent *et al.* 1997) and the Kerguelen (Weis *et al.* 2001; Ingle *et al.* 2002; Kurnosov *et al.* 2003). The plot of Ba/Nb vs. Zr/Nb (figure 8b) also indicates that picritic sample 7 has a HIMU affinity and its Zr/Nb is similar to those of the St. Helena basalts (Weaver 1991).

Whether this HIMU component was inherited from the Kerguelen plume heterogeneity requires further data collection from the region affected by the Kerguelen plume. Sample 7 was dated at

Figure 8. (a) La/Nb vs. $^{206}\text{Pb}/^{204}\text{Pb}_{(t)}$ and (b) Zr/Nb vs. Ba/Nb, illustrating the mantle components for Sylhet Traps compared with samples from Borako dyke (Ghatak and Basu 2013). Locations of MORB, EM, HIMU and continental crust are from Hart (1984) and Zindler and Hart (1986).

~84 Ma, which also supports further study of the adjoining location where our sample was collected.

8.1.3 Upper continental source

The upper continental crust is characterized by enrichment of LREE and high $^{87}\text{Sr}/^{86}\text{Sr}$, $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{206}\text{Pb}/^{204}\text{Pb}$, and low $^{143}\text{Nd}/^{144}\text{Nd}$ values (Weaver 1991). Ghatak and Basu (2011) reported that Sylhet Traps from the MB section are contaminated by lower continental crust (granulite metamorphism) and are comparable to the Chilka granulite (Chakrabarti *et al.* 2011) or the Eastern Ghat granulites

(Rickers *et al.* 2001). Our analyses demonstrated that sample 10 exhibits an enrichment of REE (figure 5), which is comparable with an ancient continental fragment from ODP site 1137 (Ingle *et al.* 2002) in the Kerguelen Plateau. Few samples from the STGB (Ghatak and Basu 2011, 2013) have similar characteristics. In figure 8(b), sample 10 has an association with continental crust (Weaver 1991) and is consistent with a few dyke samples reported in Ghatak and Basu (2013) from the Bokaro coal field of Bihar–West Bengal. The high $^{87}\text{Sr}/^{86}\text{Sr}_{(1)}$ (0.71008) and low $^{143}\text{Nd}/^{144}\text{Nd}_{(1)}$ (0.51218) values of sample 10 (figure 7c) suggest involvement of the upper continental crust component and are comparable with the STGB (Ghatak and Basu 2011, 2013) and ODP 1137 (Ingle *et al.* 2002). Moreover, high $^{208}\text{Pb}/^{204}\text{Pb}_{(1)}$, and $^{207}\text{Pb}/^{204}\text{Pb}_{(1)}$ (figure 7b) values fully support upper crustal source involvement in sample 10. Therefore, it may be concluded that the Sylhet Trap rocks experienced both lower crustal (Ghatak and Basu 2011) and upper crustal contamination (Ghatak and Basu 2013).

9. Conclusion

Petrographic, geochemical, and isotopic analyses of the Sylhet Traps from the eastern Shillong Plateau indicate two suites of magma, MORB-like tholeiitic basalt for samples 1, 5 and 6 and OIB-like medium to high K basalts. Sample 4 (dacite) is an EMII type with negative anomalies of K, Sr, P, and Ti, and low $^{143}\text{Nd}/^{144}\text{Nd}_{(1)}$ (0.51196), suggesting a major involvement of crustal components. The olivine-rich, primitive sample (sample 7) has a HIMU-type mantle component. This sample was dated to 84.0 ± 1.9 Ma by the K–Ar method, indicating that the Sylhet basalt was not emplaced at ~ 117 Ma in the Shillong Plateau and that its activity continued for ~ 30 m.y. Samples 5 and 6 indicate that the Kerguelen plume-like component is analogous to Rajmahal Traps Group I. Sample 10 indicated that it had upper continental crust involvement supported by an enrichment of light rare earth elements and high $^{87}\text{Sr}/^{86}\text{Sr}_{(1)}$ (0.71008), $^{208}\text{Pb}/^{204}\text{Pb}_{(1)}$ (39.977), $^{207}\text{Pb}/^{204}\text{Pb}_{(1)}$ (15.754), and $^{206}\text{Pb}/^{204}\text{Pb}_{(1)}$ (18.246), and low $^{143}\text{Nd}/^{144}\text{Nd}_{(1)}$ (0.51218).

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