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Vestiges of the Kerguelen plume in the Sylhet Traps, northeastern India

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ABSTRACT

The 117 Ma Sylhet Traps, exposed on the southern edge of the Shillong Plateau in northeastern India, are separated from the Rajmahal Traps ~550 km to the west by the Gangetic-Brahmaputra alluvium of the Bengal basin. On the basis of their similar age, Sylhet and Rajmahal Traps are correlated. We report Nd–Sr–Pb-isotopic and multiple trace element data for 18 discrete and consecutive lava flows from two sections of the Sylhet Traps. Thirteen of the analyzed lavas are from the Cherrapunji-Shella (CH) Bazaar section and five from the Mawsynram-Balot (MB) section. In major, trace elements and Nd–Sr–Pb isotopes, most of these lavas show similarity with Rajmahal Traps, Bunbury basalts and lavas from Naturaliste and parts of the Kerguelen Plateaus, allowing reconstruction of a ~800 km Kerguelen plume-head in the Bengal basin aligned with the Ninetyeast Ridge.

The combined geochemical data and their correlation with the Rajmahal Traps, Bunbury basalts, and some Kerguelen Plateau lavas, imply a relatively less depleted plume source for CH basalts. We assess the average composition of this source at 117 Ma to be: $\varepsilon_{Nd}(I) = 2$, $^{87}Sr/^{86}Sr(I) = 0.7046$, with relatively flat rare earth element patterns, similar to the basalts from the Ocean Drilling Sites 1138, 1141 and 1142 on the Kerguelen Plateau. The Nd–Sr-isotopic data for the Sylhet basalts are modeled with two end members, an 18% partial melt from a chondritic garnet peridotite source, and a granulitic contaminant of the Eastern Ghats Belt. Most of the Sylhet lavas are close to the proposed plume end-member. The contaminated Sylhet basalts reflect as much as 20% of the granulite component caused by the incorporation of lower-continental crust in the Kerguelen plume-derived melt.

Combined Nd–Sr–Pb-isotopic evidence, and, in particular, Ce/Pb vs. $\varepsilon_{Nd}(I)$ mixing-models among different reservoirs indicate more primitive CH lavas to be mixture of bulk-chondritic Earth and E-MORB, without apparent mixing with N-MORB, continental crust, or non-chondritic bulk Earth. However, Sr–Pb-isotopic ratios of these lavas fall in the estimated ranges of non-chondritic bulk Earth. The least contaminated Kerguelen plume component may be common to other large igneous provinces.

1. Introduction

The Gondwana supercontinent was fragmented by heating of the lithosphere from below (Segev, 2002) into constituent continents, Africa, Antarctica, Australia and India, which were separated by the newly created Indian Ocean floor (Fig. 1a). The heat was initially supplied by three plumes whose remnants are now the Marion, Kerguelen and Reunion hotspots in the Indian Ocean. Large volumes of basalt that erupted in the Early Cretaceous on the eastern Indian continental margin, southwestern Australia, and Antarctica are now attributed to the melting of the Kerguelen plume, which also created the Ninetyeast Ridge (NER), Broken Ridge, Bunbury basalts, Naturaliste Plateau, and Kerguelen Plateau in the southern Indian Ocean (Fig. 1a) (e.g. Frey et al., 1996; Frey et al., 2000a; Weis and Frey, 1991). The Kerguelen hotspot, with high $^{3}He/^{4}He$ ratios (18 R/R_A), belongs to the same group of hotspots/plumes as Hawaii and Iceland (Doucet et al., 2006; Ingle et al., 2004). Based on geochronological–geochemical data and plate reconstructions, the early episode of Kerguelen volcanism is believed to be related to a flood basalt province in eastern India comprising the Rajmahal–Sylhet–Bengal Traps of 116 ± 3.5 Ma (Fig. 1b) (e.g. Baksi, 1995; Basu et al., 2001; Ghatak and Basu, 2006; Pantulu et al., 1992).

Initially it was suggested that the Rajmahal volcanism (Fig. 1b) was related to the Crozet hotspot via the eighty-five East Ridge (Curray and Munasinghe, 1991). Using geochemical arguments Mahoney et al. (1983) suggested that the Kerguelen hotspot was probably the source for the NER lavas and postulated that the Kerguelen plume furnished heat but not material for the Rajmahal volcanism. Previous isotopic data of Rajmahal basalts (Baksi et al., 1987; Mahoney et al., 1983; Storey et al., 1992), led Kent et al. (1997) to the inference "…that the Rajmahal basalts are examples of lavas which, though associated spatially and temporally with the magmatic

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products of hot spot activity, were derived from compositionally 'normal' asthenosphere".

In this study we present major, trace elements and radiogenic isotope data for the Sylhet Trap basalts for 18 continuous lava flows from two sections (Fig. 1b). We attempt to correlate the Sylhet Traps with the Rajmahal basalts of similar early Cretaceous age, ~550 km to the west, by their geochemical signatures (Fig. 1b). With available geochemical database, we will explore possible similarity of the Sylhet lavas with other Early Cretaceous Kerguelen plume-related basalts (e.g. Baksi, 1995). Specifically, we investigate geochemical similarity of the Sylhet Traps with the Rajmahal lavas (Kent et al., 1997), Bunbury–Casuarina basalts (Frey et al., 1996) and the basalts from several Ocean Drilling Program (ODP) sites (e.g. Ingle et al., 2002b; Neal et al., 2002).

The Rajmahal basalts are divided into Groups I and II on the basis of Ti/Zr and Zr/Y ratios for a given value of MgO (Storey et al., 1992). If this division is tenable by geochemical results of the Sylhet basalts, are there Rajmahal Group I basalts in Sylhet that can be correlated with the least contaminated Kerguelen plume component? We will also evaluate the presence of an Indian Ocean E-MORB component in the plume. Are there Sylhet lavas indicating contamination by lower crustal source granulites of the Eastern Ghats Belt (Fig. 1a) at the Indian continental margin that was fragmented by flood basalt eruptions?

Drill-core data for the Bengal basin lowlands indicate a continuity of the Bengal traps below the Gangetic alluvium of the basin (Fig. 1b, Sengupta, 1966). It is interesting that the oldest 81 Ma part of the Ninetyeast Ridge (NER) at 10°N is much younger than the Rajmahal–Sylhet Traps or the Southern Kerguelen lavas (Duncan, 1978). By northward extrapolation along the NER beneath the Bengal fan in the Bay of Bengal (Fig. 1a) we will explore geochemically if the Bengal–Sylhet Traps can be linked with the Kerguelen hotspot activity. These observations may point to an extensive flood basalt eruption in the Bengal basin related to the Kerguelen plume. Such a wide geochemical correlation may allow characterization of the 117 Ma Kerguelen plume-head component, allowing comparison of geochemical signatures in other flood basalt provinces.

2. The Sylhet Traps, Rajmahal Traps, and the Kerguelen Plateau

The Shillong Plateau (Fig. 1a–b) in northeast India underwent a major Early Cretaceous mafic and alkaline carbonatitic activity (Sarkar et al., 1996). The mafic volcanic rocks of the Shillong Plateau are represented by the Sylhet Traps (Fig. 1a) (Baksi, 1995), exposed ~500 km east of the Rajmahal Traps in a narrow 240 km^2 east–west band on the southern edge of the Plateau (Talukdar, 1966) (Fig. 1b). The maximum exposed thickness of the lavas is 550–600 m (Sarkar et al., 1996).

The Sylhet lavas were first documented by Palmer (1923), and subsequently their geological setup, petrochemistry and tectonic history were reported (Talukdar, 1966; Talukdar and Murthy, 1972) that indicated quartz–tholeiitic and alkali–basalt lavas, overlying a Precambriam basement (Talukdar and Murthy, 1972). Our major element analyses of 10 Sylhet basalts (Supplementary material Table T1) indicate them to belong to the olivine tholeiite–tholeiitic series. ^{40}Ar–^{39}Ar ages of 116.0 ± 3.5 Ma for the Sylhet Traps documented these lavas to be contemporaneous with the Southern Kerguelen Plateau and Rajmahal Traps (Ray et al., 2005). These lavas received less attention compared to the Rajmahal Traps because of difficult access to the few exposures.

The "Rajmahal–Sylhet volcanic province" is also characterized by widely-spaced contemporaneous alkaline volcanism, including lamproite and kimberlite intrusions in the Bokaro coal fields (Kumar et al., 2003) to the west, lamprophyre sills in Gondwana sediments in Sikkim to the north, and alkaline–carbonatite complexes such as the 115 Ma old Sung in the Shillong Plateau (Srivastava et al., 2005) and Samchampi in the Mikir Hills (Fig. 1b). This alkali igneous activity, based on available geochronologic information, around the Rajmahal–Sylhet basaltic province extends the area of Kerguelen hotspot activity around the Bengal basin considerably. The present paper, however, is concerned with the volumetrically more significant tholeiitic Sylhet basalts.

Basalts of the Sylhet Traps are grouped into (1) massive basalts, with/without amygdules and (2) amygdaloidal, with abundant amygdules, passing into scoriaceous lavas (Talukdar, 1966). In thin sections, the massive basalts are composed of labradorite, augite, opaques, glass, as well as rare olivine pseudomorphs, sparse apatite needles and secondary minerals (Talukdar, 1966). These lavas unconformably overlie a granitic Archean basement and in turn are overlain by Upper Cretaceous sedimentary rocks. The best-exposed flows are found at two roadside exposures along the Cherrapunji-Shella Bazaar (CH, 25°18′7″N and 91°41′51″E) and Mawsynram–Ballot (MB, 25°18′25″N and 91°34′55″E) sections (Fig. 1b), the former is ~259 m thick and has 20 continuous flows and three tuff horizons whereas the latter is ~50 m thick with five flows. For this study, a total of 18 samples were analyzed from the two sections of the Sylhet Traps; thirteen from the CH section and five from the MB section (Fig. 1b), representing approximately 150 m and 50 m of lava thickness, respectively. All eighteen samples of this study are fresh massive basalts without amygdules (Supplementary Figs. A3–A4). These rocks were collected under the direction of Dr. S. Sengupta of the Geological Survey of India, Calcutta, and given to us for this study.

3. Analytical methods

Whole rock samples were powdered using a spex alumina ball mill in our laboratory at the University of Rochester. Starting with one-kg size rock sample, we broke them into chips which was rinsed with cold 1.5 M HCl, washed in de-ionized water and dried, and finally selected 20 g of these chips to be powdered for each sample to ensure that the powder was representative of the whole rock. A commercial laboratory was used for major element analysis (Activation Laboratories Ltd., Ontario). All the trace element and isotopic analyses were carried out at the University of Rochester.

Major element concentrations of the samples were determined by ICP-OES (Inductively coupled plasma optical emission spectrometry) and are reported in Table T1 (Supplementary material). The samples underwent lithium metaborate/tetraborate fusion prior to measurements. Repeated measurements of known rock standards indicate that the concentrations of the major elements are within 2% of several known rock standard values, as certified by Activation Laboratories Ltd. Trace elements and Nd–Sr–Pb isotopic ratios were measured at the University of Rochester using established procedures as described in Supplementary Section S1. These data are reported in Tables 1–2.

4. Analytical results

In this section we present the geochemical results for the 18 basalts of this study. The data are presented in Tables 1–2 and Figs. 2–7 and are compared with similar data obtained from literature on volcanic rocks related to the Kerguelen plume activity, including the Rajmahal Traps, Broken Ridge which was part of the Central Kerguelen Plateau before the plateau rifted, NER, Naturaliste Plateau, Bunbury basalts, Kerguelen Archipelago, and the central and southern parts of the Kerguelen Plateau. Literatures references for the various geochemical fields as indicated in Figs. 2–7 are given in the respective figure captions.

4.1. Trace element geochemistry

Trace element analyses for the CH and MB basalts are presented in Table 1. The chondrite-normalized (Evensen et al., 1978) rare earth element (REE) patterns are shown in Fig. 2a and b and compared to Rajmahal Group I and II lavas respectively; Group I lavas are considered least contaminated, in contrast to Group II, most contaminated (Storey et al., 1992). The REE patterns for the CH rocks are relatively flat and subparallel ($La_N/Yb_N = 1.2–2.4$; $La_N/Sm_N = 1.1–1.3$), with the exception of sample CH-4 that is light rare earth element (LREE) enriched. Except CH-4, all other CH samples show ~10–30 times chondritic La abundance. It is noteworthy that four of the CH lavas (5, 8, 8A, and 9) showing flatter REE patterns also have the highest Mg# of 60–61 (Supplementary Table T1). In contrast, the MB section basalts show ~25–100 times chondritic La and general LREE enrichment, and ~10–20 times chondritic heavy rare earth element (HREE) abundances. The MB-1 pattern is relatively flat compared to the rest of the MB basalts ($La_N/Yb_N = 3.8–7.5$; $La_N/Sm_N = 2.1–2.6$) and is similar to most of the CH section lavas with subparallel patterns. Partial melting estimates using the batch-melting equation for a garnet lherzolite have been modeled in Fig. 2c. The CH lavas, except CH-4, showing subparallel REE patterns are similar to a modeled 18% partial melt of a garnet lherzolite (Fig. 2c) using the batch melting equation (Supplementary material S2); note the correspondence of this modeled melt with sample CH-5 in Fig. 2c. For comparison, average REE patterns of various analyzed rocks (references in figure caption) from the ODP sites on the Kerguelen Plateau are shown in Fig. 2d.

Compatible and incompatible trace element concentration patterns normalized to primitive mantle for the Sylhet lavas are shown for 22 elements (Sun and McDonough, 1989) in Supplementary Fig. A1. Primitive-mantle-normalized patterns for the CH basalts are compared to Rajmahal Group I basalts (Fig. 2a) and show low relative Rb, Pb, and U, high Ba and Sr, and flat HREE ($Gd_N/Yb_N = 0.9–1.7$). In general, rocks of the CH section are similar to and ~10 times more enriched than primitive-mantle in the elements of Fig. A1. Sample CH-4 has the greatest enrichment (~60 times primitive mantle), especially in the LREEs, as already shown. Tholeiites from the MB section are compared to Rajmahal Group II basalts (Fig. A1-b) and are more enriched than the CH section lavas, with the more incompatible elements being ~20–100 times primitive-mantle. Two samples from the MB section (MB-1 and MB-4) have trace element patterns similar to those of the CH section suck as lack of negative Nb–Ta anomaly. These two rocks also have different Nd–Sr–Pb-isotopic ratios compared to the other three MB section tholeiites, as discussed in Sections 5.2–5.3. The remaining three MB basalts have negative Nb–Ta anomalies, high concentrations of Rb, Pb and La, low Ba and Sr concentrations, higher values of Gd_N/Yb_N (1.6–2.5), that are similar to Rajmahal Group II basalts.

Primitive mantle normalized trace element ratios of Hf, Zr, Nb, Th, and La in the CH and MB lavas are compared with some ODP site rocks, Bunbury basalts, Rajmahal Traps, average continental crust estimates, and various mantle reservoirs in Fig. 3a–c. Most of the CH basalts cluster around the primitive mantle whereas the MB basalts trend towards the field of continental crust, specifically lower continental crust (Fig. 3c) in these plots. The proximity of E-MORB field to most of the CH basalts is noteworthy in the plots Fig. 3. This aspect will be further explored with Fig. 6.

4.2. Pb–Pb isotopic geochemistry

Initial $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ of the Sylhet Trap basalts at 117 Ma have ranges of 17.57–18.18, 15.49–15.70, and 37.73–38.92, respectively, as reported in Table 2. It is interesting that these initial Pb-isotopic ratios are within close ranges recently estimated for chondritic bulk silicate Earth based on ^{142}Nd evidence (Boyet and Carlson, 2006). Pb–Pb isotopic ratios of these rocks are plotted in Fig. 4a–b along with the fields of Rajmahal Traps Groups I and II, NER, Bunbury basalts (BB), Naturaliste Plateau, Kerguelen Archipelago, some Kerguelen Plateau lavas, Chilka granulites (CG) of the Eastern Ghats Belt and ancient non-volcanic continental clasts from ODP site 1137. Average values of various continental crustal and mantle reservoirs, as well as the Northern Hemisphere Reference Line (NHRL), are also plotted in Fig. 4a–b for reference. Most of the CH and MB section data are clustered broadly around Rajmahal Group I, ODP sites 749, 1136, 1138, 1141, 1142, parts of the Naturaliste Plateau, and Bunbury–Casuarina data (Fig. 4a–b).

Correlation between $^{207}Pb/^{206}Pb_{(I)}$ and $^{208}Pb/^{206}Pb_{(I)}$ at 117 Ma for all the Sylhet Trap basalts are shown in Fig. 4c, for comparison with the various relevant fields as indicated in this diagram. All the Sylhet

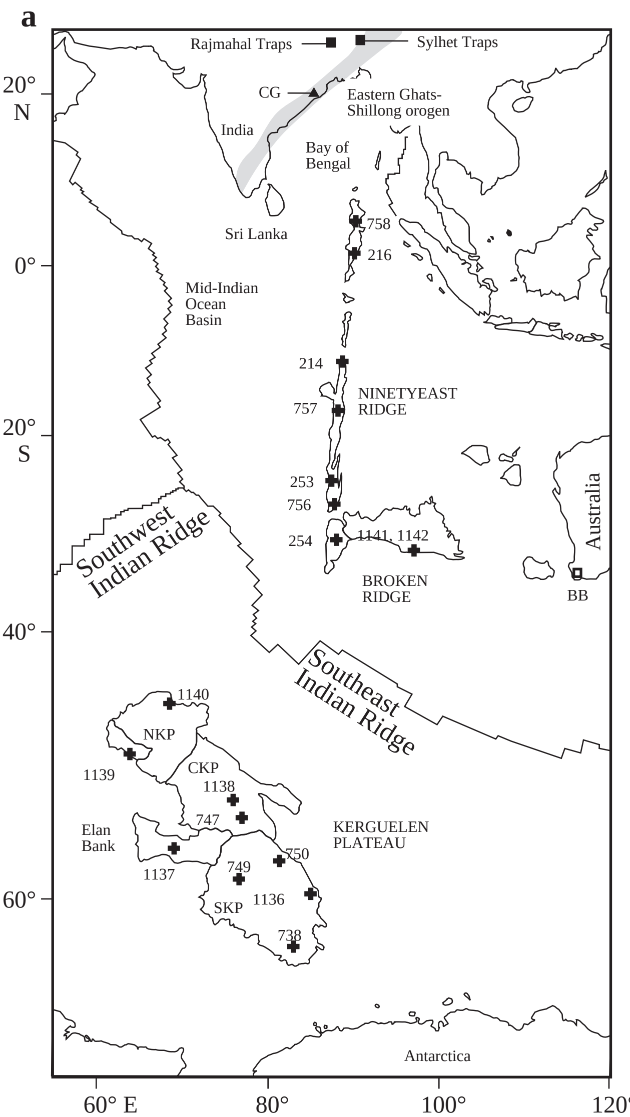

Fig. 1. a. Map of part of the Indian Ocean and surrounding continents with physiographic features, after Ingle et al. (2002b) and Frey et al. (2000a, b), showing locations of the Sylhet and Rajmahal Traps in northeastern India. Also shown in gray is the extended Eastern Ghats — Shillong orogenic belt (Yin et al., 2010) along the east coast of India. Basalt provinces attributed to the Kerguelen plume (Frey et al., 2002) include Kerguelen Plateau, Broken Ridge, Ninetyeast 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 — Chilka Granulites (Chakrabarti et al., 2011). Black crosses are ODP sites. Sites 253, 254, 756, 757, 214, 216, and 758 are from the Ninetyeast Ridge and are grouped as NER in subsequent Nd–Sr–Pb isotopic plots. b. Geological map showing structural features and locations of the Rajmahal and Sylhet Traps in and around the Bengal Basin including bore hole sites, some of which encountered Rajmahal-age basalts (Sengupta, 1966), and the alkalic-ultrabasic rocks of Samchampi, Sung, Sikkim, and Bokaro also thought to be related to the Rajmahal–Sylhet Traps. Legend for map is in the lower right hand column. Volcanic stratigraphy of lava samples with corresponding flow and sample numbers from the CH and MB sections of the Sylhet Traps analyzed in the present study is in the lower left column.

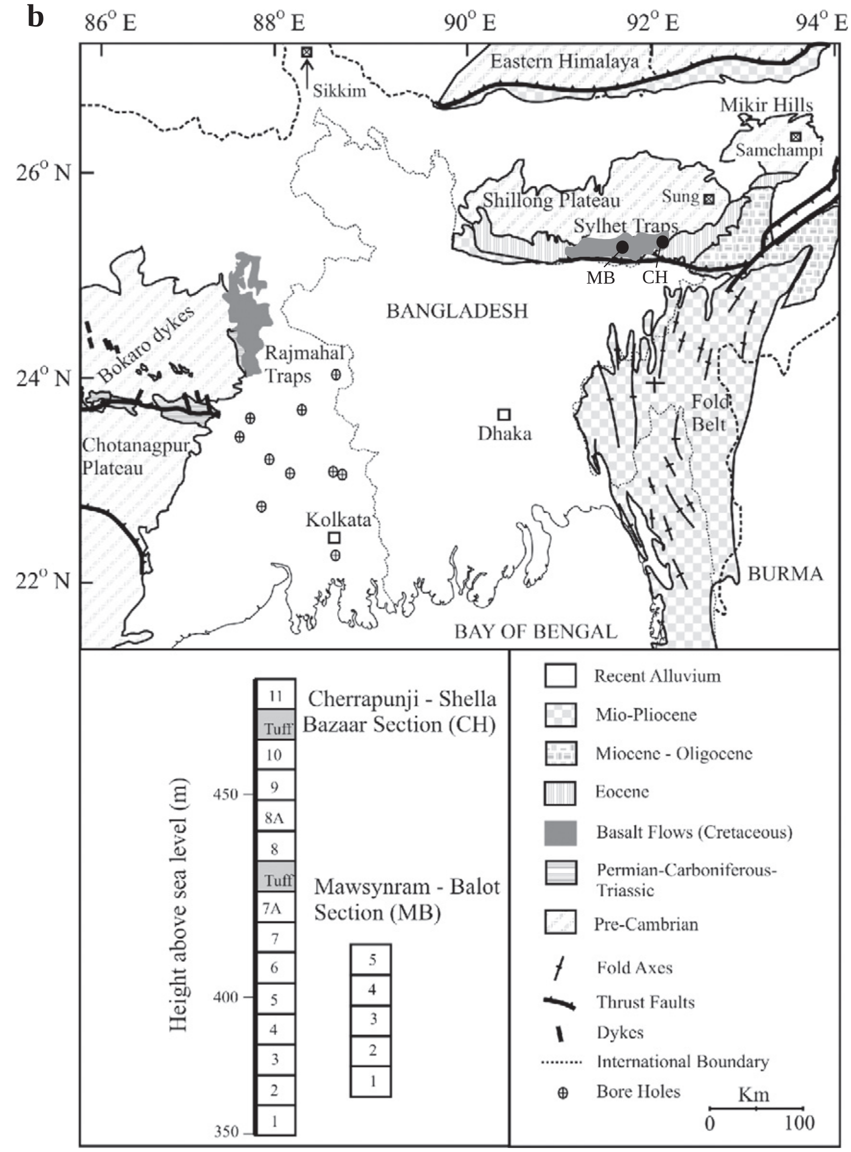

Fig. 1 (*continued*).

basalts broadly fall into two groups in this plot, one group of four samples including three MB basalts are clustered in or near the field of EM-I and the second group containing mostly CH basalts are in the dotted field, distinctly different from the NER, DMM, and EM-2 (Fig. 4c).

4.3. Nd–Sr–Pb isotopic geochemistry

Rb–Sr and Sm–Nd isotope data of the Sylhet rocks are reported in Table 2. Initial ε_{Nd} and $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb_{(I)}$ at 117 Ma are shown in Fig. 5a–b and compared with relevant Kerguelen-plume related basalts in the Southern Indian Ocean. Indian mid-ocean ridge basalt (MORB), and possible crustal and lithospheric contaminants from the Eastern Ghats Belt (EGB), including the Chilka granulite are also plotted here. A general correspondence of the CH basalts with all the ODP site lavas (numbered fields) in the southern and central Kerguelen Plateau, Bunbury and Rajmahal Group I basalts data is noteworthy (Fig. 5a–b).

Basalts from the CH section are shown in an ε_{Nd}(I) vs. Ce/Pb plot (Fig. 6) and compared with modeled-mixing lines between end member reservoirs of continental crust (Taylor and McLennan, 1995), depleted mantle (Salters and Stracke, 2004), average Indian Ocean E-MORB (Mahoney et al., 2002), early differentiated bulk Earth as defined by Boyet and Carlson (2006), and bulk silicate chondritic Earth. It is interesting to note that seven of the CH lavas fall along the mixing line between bulk silicate Earth and Indian Ocean E-MORB.

The initial ε_{Nd} and $^{87}Sr/^{86}Sr_{(I)}$ of the Sylhet Trap basalts are shown in Fig. 7a–b. The initial ε_{Nd} values for CH lavas range from +3.2 to −3.4, with the exception of CH-4 which has $\varepsilon_{Nd(I)} = -5.5$. One Sylhet lava reported by Baksi (1995) also falls within this range. Lavas from the MB section show more negative ε_{Nd}(I), between −5.1 and −8.6. The initial $^{87}Sr/^{86}Sr$ values of CH basalts range from 0.70420 to 0.70663, with sample CH-4 displaying the most radiogenic value of 0.70965. The MB lavas show more radiogenic Sr-isotopic ratios, with initial values in the range 0.70646–0.71504. One CH sample (CH-1) shows abnormally high $^{87}Sr/^{86}Sr_{(I)}$ even after repeated analyses (n = 4) of Sr and Nd-isotopic ratios with the same results. We do not have an adequate explanation for this high $^{87}Sr/^{86}Sr_{(I)}$ isotopic ratio except to suggest preferential removal of Rb due to weathering (Weaver, 2000); although the Rb/Sr of this sample is similar to other rocks of this group.

In Fig. 7a, the basalts from the CH and MB sections are compared to volcanic rocks (data sources in figure caption) associated with the Kerguelen plume in the southern Indian Ocean such as Bunbury

Table 1
Trace element concentrations of the Sylhet Trap basalts from the Cherrapunji-Shella Bazaar (CH) and the Mawsynram-Balot (MB) sections. Analytical uncertainties are less than 5% for all the elements analyzed and usually less than 2% for the REEs. Also shown are analytical results (averaged, n = 4) for two rock standards run as unknowns during the course of these analyses.

Sample	CH 1	CH 2	CH 3	CH 4	CH 5	CH 6	CH 7	CH 7A	CH 8	CH 8A	CH 9	CH 10	CH 11	MB1	MB 2	MB 3	MB 4	MB 5	AVG-2	BHVO-1
Rb	5.1	2.85	1.31	12.2	0.44	3.33	0.65	3.07	5.50	2.52	3.08	2.87	8.08	9.52	37.5	32.2	35.7	29.5	70.4	9.51
Ba	96	212	84	154	62.1	100	93	101	94.8	58	54	64.3	195	124	453	262	512	278	1143	127
Pb	1.21	2.40	1.74	7.81	1.20	1.41	2.00	2.07	0.64	1.21	0.91	1.87	1.70	3.24	11.7	5.56	6.51	5.45	13.4	2.32
Sr	334	261	196	470	243	242	228	224	214	229	103	205	254	266	258	252	344	281	656	377
La	7.6	9.06	7.80	33.3	6.64	8.77	9.74	9.51	4.37	4.89	4.35	10.9	9.15	8.20	32.0	17.2	38.5	18.3	38.7	15.3
Ce	19.9	22.0	20.2	71	15.7	22.8	24.2	23.9	11.2	12.0	10.4	27.6	22.1	17.9	70	36.6	79	37.5	71	36.1
Pr	2.93	3.17	2.90	8.46	2.18	3.30	3.64	3.55	1.63	1.78	1.49	4.05	3.30	2.61	8.52	4.73	10.5	5.02	8.66	15.01
Nd	13.6	14.6	13.9	34.0	10.3	15.7	17.3	16.8	7.50	7.98	6.89	18.4	15.6	13.2	33.2	19.9	42.7	20.5	31.0	23.4
Sm	4.09	4.50	4.33	7.58	3.28	4.97	5.61	5.49	2.26	2.43	2.20	5.64	4.86	4.83	8.02	5.29	9.50	5.45	6.06	5.93
Eu	1.48	1.58	1.53	2.40	1.26	1.63	1.92	1.88	0.86	0.92	0.85	1.93	1.68	1.81	2.24	1.74	2.79	1.77	1.63	2.00
Gd	4.86	5.67	5.41	7.93	3.95	6.17	6.83	6,74	2.68	2.80	2.86	6.58	5.99	6.00	8.68	6.15	9.60	6.43	5.06	6.23
Tb	0.81	0.95	0.89	1.22	0.64	1.03	1.13	1.13	0.46	0.47	0.52	1.11	0.99	0.93	1.33	0.98	1.39	1.03	0.70	0.93
Dy	4.95	5.76	5.53	7.01	3.81	6.23	6.84	6.81	2.88	0.48	3.54	6.79	6.00	5.40	7.75	5.90	7.75	6.15	3.81	5.10
Ho	1.05	1.24	1.17	1.42	0.78	1.32	1.45	1.46	0.64	0.65	0.82	1.47	1.27	1.06	1.60	1.23	1.52	1.28	0.76	1.00
Er	2.87	3.44	3.22	3.86	2.06	3.62	3.84	3.87	1.74	1.76	2.36	3.98	3.37	2.71	4.31	3.38	4.01	3.45	1.89	2.45
Tm	0.42	0.51	0.47	0.57	0.30	0.54	0.56	0.57	0.27	0.27	0.37	0.60	0.50	0.38	0.62	0.49	0.56	0.50	0.27	0.34
Yb	2.66	3.34	2.97	3.65	1.85	3.41	3.50	3.61	1.74	1.75	2.52	3.82	3.21	2.27	3.87	3.07	3.46	3.10	1.7	2.04
Lu	0.38	0.47	0.42	0.51	0.26	0.48	0.50	0.52	0.25	0.26	0.38	0.57	0.46	0.32	0.55	0.45	0.47	0.49	0.26	0.27
Y	27.9	34.1	31.1	37.0	20.8	35.4	40.2	39.0	17.0	17.9	22.2	39.4	32.6	28.1	43.5	33.8	40.7	35.1	21.2	26.9
Th	0.89	1.25	0.89	4.85	0.71	1.02	1.09	1.12	0.53	0.57	0.42	1.40	0.94	1.08	7.35	3.10	4.83	3.18	6.62	1.14
U	0.18	0.16	0.13	0.69	0.15	0.14	0.16	0.21	0.11	0.12	0.08	0.28	0.11	0.20	0.73	0.31	0.83	0.31	1.93	0.38
Zr	100	118	101	212	75.8	127	129	129	56	61	44.2	144	111	87	226	133	294	141	238	152
Hf	2.60	3.01	2.70	5.45	1.88	3.32	3.36	3.42	1.45	1.52	1.23	3.73	3.04	2.18	5.83	3.36	7.31	3.46	5.23	4.26
Nb	8.84	7.90	6.14	40.2	8.70	8.68	8.46	8.37	5.32	5.69	4.11	12.0	7.39	7.83	16.1	8.93	32.4	9.36	15.8	19.2
Ta	0.56	0.48	0.39	2.49	0.98	0.53	0.53	0.53	0.35	0.37	0.25	0.79	0.48	0.48	0.93	0.50	1.92	0.54	0.97	1.22
Sc	38.2	39.3	35.9	25.4	25.0	38.8	39.2	37.5	28.7	29.5	54	44.2	36.5	19.6	21.8	19.4	27.4	20.2	13.6	30.7

basalts, Broken Ridge, Naturaliste Plateau, Kerguelen Archipelago, and Kerguelen Plateau, as well as the Rajmahal Groups I and II basalts, Indian MORB, Chilka granulite, ancient continental fragments from ODP site 1137 on Elan Bank, and mafic granulites from the EGB.

Initial ε_{Nd} and $^{87}Sr/^{86}Sr$ isotopic ratios of the Sylhet basalts are also compared with data for massif anorthosite and gabbroic granulites from the Chilka Complex as well as enderbites (mafic granulites) from the EGB in Fig. 7b. Two mixing curves are constructed (DePaolo, 1988), with the average of the most primitive CH basalts (Mg-numbers ~60, Table T1) as a common end member P, and two ends of the EGB field, granulites 1 and 2, as the second end members (Fig. 7b). Granulites 1 and 2 are a tonalite-geniss (KR47-1) and an enderbite (KR76-1), respectively, from Rickers et al. (2001) and their compositions are shown in Table 2. The results of this mixing are discussed in Section 5.3 below.

5. Discussion

We discuss here the results presented in Section 4 to evaluate the possible link between Kerguelen plume-derived volcanism and the Sylhet Traps. We also discuss the geochemical correlation of the Sylhet basalts with the Rajmahal Traps 550 km to the west across the Bengal basin, and finally we comment on the relatively primitive nature of the Kerguelen plume based on these larger correlations of the reconstructed Early Cretaceous magmatism of the Kerguelen plume during the breakup of Gondwana. Our geochemical data also have implications for contamination of some of the Kerguelen plume derived Sylhet basalts by the granulitic crust of the Indian continental lithosphere.

5.1. Trace element geochemistry

The relatively flat REE patterns of the Group I Rajmahal Trap rocks have been attributed to decompressional melting of the asthenosphere and ascent of these basalts through the rifted margin of eastern India (e.g. Baksi et al., 1987; Kent et al., 1997). Another possible scenario is that the relatively primitive nature of some the CH lavas (Fig. 2a, CH-5, CH-8, CH-8A, CH-9), as reflected in their high Mg# (~60, Table T1) and low, positive $\varepsilon_{Nd}(I)$ values (0.6–2.9), is due, as shown in Fig. 2c, to ~18% melting of a relatively primitive component of the Kerguelen plume. This modeling that requires ~18% partial melting of a garnet peridotite, differs from that of Kent et al. (1997) who suggested <10% melting of the mantle for generating similar Group I Rajmahal Basalts. The remaining CH basalts may have an E-MORB like component as reflected by their REE patterns (Fig. 2c). This E-MORB component may be sourced from the sub-Indian oceanic mantle (Mahoney et al., 2002). E-MORB mantle may be considered ubiquitous in sub-oceanic mantle without any plume influence (Donnelly et al., 2004).

The REE patterns of the MB basalts (except MB-1, which is similar to flat CH patterns, Fig. 2b), as well as sample CH-4 (Fig. 2a) are more LREE-enriched compared to the other CH lavas. These LREE enrichments are similar to the Group II Rajmahal basalts (Kent et al., 1997) as well as ODP sites 747, 1136, 1138, 1141, and 1142 lavas (Fig. 2d). This enrichment may be due to contamination from the lower continental crust or from the mantle lithosphere.

The CH section Sylhet basalts fall close to the primitive mantle in trace element plots of $(La/Nb)_{PM}$, $(Hf/Th)_{PM,}$ and $(Nb/Zr)_{PM}$ vs. $(Th/Nb)_{PM}$ (Fig. 3). Most of the CH basalts in this plot also overlap with the field of 1138 basalts which is considered to be the major mantle source in the Kerguelen plume-head by Neal et al. (2002). In contrast, the MB basalts show a mixing trend between the primitive 1138 type plume component and continental crust. The suggestion of an E-MORB type contaminant as seen in some of the enriched REE patterns of the CH basalts (Fig. 2a) is indicated also in the $(La/Nb)_{PM}$, $(Hf/Th)_{PM,}$ and $(Nb/Zr)_{PM}$ vs. $(Th/Nb)_{PM}$ plot (Fig. 3) with the bulk of the CH lavas falling close to primitive mantle with some samples showing a trend towards the E-MORB field.

E-MORB contamination for some of the CH basalts is also evident in their Ce/Nb vs. Th/Nb relationship (Supplementary Fig. A2), where the absence of an N-MORB component for the Sylhet samples is indicated. Also, three of the MB lavas show close correspondence with the CG field (Supplementary Fig. A2), representative of lower continental crust (Chakrabarti et al., 2011). Lower continental crust is

Table 2
Present day (0) and initial (I) Nd–Sr–Pb-isotopic ratios of Sylhet Trap Basalts at 117 Ma, obtained with the Rochester TIMS, and their Rb/Sr, Sm/Nd, U/Pb and Th/Pb isotopic ratios as estimated from the ICPMS trace element concentration data in Table 1. Data for granulites 1 and 2 used for modeling the contaminant source for these basalts are from Rickers et al. (2001) and corrected to 117 Ma. P is the inferred least contaminated composition of the Sylhet lavas.

Sample	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6	CH-7	CH-7A	CH-8	CH-8A	CH-9	CH-10	CH-11	MB-1	MB-2	MB-3	MB-4	MB-5	Granulite 1	Granulite 2	P
Sm (ppm)	4.09	4.50	4.33	7.58	3.28	4.97	5.61	5.49	2.26	2.43	2.20	5.64	4.86	4.83	8.02	5.29	9.50	5.45	2.00	4.16	3.28
Nd (ppm)	13.6	14.6	13.9	34.0	10.3	15.7	17.3	16.8	7.50	7.98	6.89	18.4	15.6	13.2	33.2	19.9	42.7	20.5	14.14	29.3	10.3
$^{147}Sm/^{144}Nd$	0.19	0.20	0.20	0.14	0.20	0.20	0.21	0.21	0.19	0.19	0.20	0.19	0.20	0.23	0.15	0.17	0.14	0.17	0.09	0.09	0.20
$^{143}Nd/^{144}Nd_{(0)}$	0.51279	0.51256	0.51269	0.51232	0.51274	0.51247	0.51268	0.51281	0.51278	0.51277	0.51267	0.51279	0.51274	0.51222	0.51224	0.51222	0.51234	0.51224	0.51043	0.51093	0.51274
$^{143}Nd/^{144}Nd_{(I)}$	0.51266	0.51242	0.51256	0.51222	0.51260	0.51233	0.51254	0.51266	0.51265	0.51264	0.51253	0.51265	0.51260	0.51206	0.51213	0.51210	0.51224	0.51212	0.51037	0.51087	0.51260
$\varepsilon_{Nd(I)}$	3.1	−1.5	1.1	−5.5	1.9	−3.4	0.7	3.2	2.9	2.7	0.6	3.0	2.0	−8.6	−7.2	−7.7	−5.1	−7.4	−41.6	−31.8	2.0
Rb (ppm)	5.10	2.85	1.31	12.2	0.44	3.33	0.65	3.07	5.50	2.52	3.08	2.87	8.08	9.52	37.5	32.2	35.7	29.5	9.34	194	0.44
Sr (ppm)	334	261	196	470	243	242	228	224	214	229	103	205	254	266	258	252	344	281	243	216	243
$^{87}Rb/^{86}Sr$	0.04	0.03	0.02	0.07	0.01	0.04	0.01	0.04	0.07	0.03	0.08	0.04	0.09	0.10	0.41	0.36	0.29	0.30	0.11	2.61	0.01
$^{87}Sr/^{86}Sr_{(0)}$	0.70667	0.70630	0.70479	0.70977	0.70457	0.70490	0.70451	0.70427	0.70461	0.70459	0.70574	0.70454	0.70530	0.70715	0.71364	0.70998	0.70694	0.71551	0.70892	0.76598	0.70457
$^{87}Sr/^{86}Sr_{(I)}$	0.70663	0.70621	0.70476	0.70965	0.70456	0.70484	0.70450	0.70420	0.70450	0.70454	0.70560	0.70448	0.70515	0.70696	0.71298	0.70940	0.70647	0.71504	0.70874	0.76179	0.70456
U	0.18	0.16	0.13	0.69	0.15	0.14	0.16	0.21	0.11	1.21	0.91	1.87	1.70	3.24	11.7	5.56	6.51	5.45			
Th	0.89	1.25	0.89	4.85	0.71	1.02	1.09	1.12	0.53	0.57	0.42	1.40	0.94	1.08	7.35	3.10	4.83	3.18			
Pb	1.21	2.40	1.74	7.81	1.20	1.41	2.00	2.07	0.64	0.12	0.08	0.28	0.11	0.20	0.73	0.31	0.83	0.31			
$^{206}Pb/^{204}Pb_{(0)}$	18.350	17.977	17.709	18.048	18.057	17.910	17.907	17.896	18.288	17.803	18.101	18.280	17.890	17.634	18.153	17.957	17.915	17.944			
$^{207}Pb/^{204}Pb_{(0)}$	15.595	15.629	15.612	15.709	15.562	15.578	15.541	15.555	15.575	15.561	15.577	15.570	15.587	15.498	15.699	15.667	15.518	15.675			
$^{208}Pb/^{204}Pb_{(0)}$	38.744	38.735	38.197	39.359	38.121	38.362	38.194	38.345	38.683	37.965	38.790	38.807	38.353	38.285	39.243	39.190	38.243	39.172			
$^{238}U/^{204}Pb$	9.50	4.34	4.73	5.63	7.74	6.29	4.97	6.28	11.30	6.39	5.31	9.60	3.94	3.82	4.01	3.51	7.97	3.63			
$^{235}U/^{204}Pb$	0.07	0.03	0.03	0.04	0.06	0.05	0.04	0.05	0.08	0.05	0.04	0.07	0.03	0.03	0.03	0.03	0.06	0.03			
$^{232}Th/^{204}Pb$	48.1	34.1	33.1	41.1	38.4	46.9	35.2	35.2	54.4	30.5	30.2	49.2	36.0	21.6	41.4	36.8	47.9	38.4			
$^{206}Pb/^{204}Pb_{(I)}$	18.182	17.901	17.625	17.949	17.920	17.800	17.818	17.785	18.085	17.690	18.007	18.110	17.821	17.567	18.083	17.895	17.774	17.880			
$^{207}Pb/^{204}Pb_{(I)}$	15.587	15.625	15.608	15.704	15.555	15.574	15.536	15.550	15.565	15.555	15.572	15.562	15.584	15.495	15.696	15.664	15.511	15.672			
$^{208}Pb/^{204}Pb_{(I)}$	38.227	38.367	37.841	38.916	37.707	37.855	37.815	37.966	38.098	37.637	38.465	38.277	37.966	38.052	38.797	38.793	37.727	38.756			

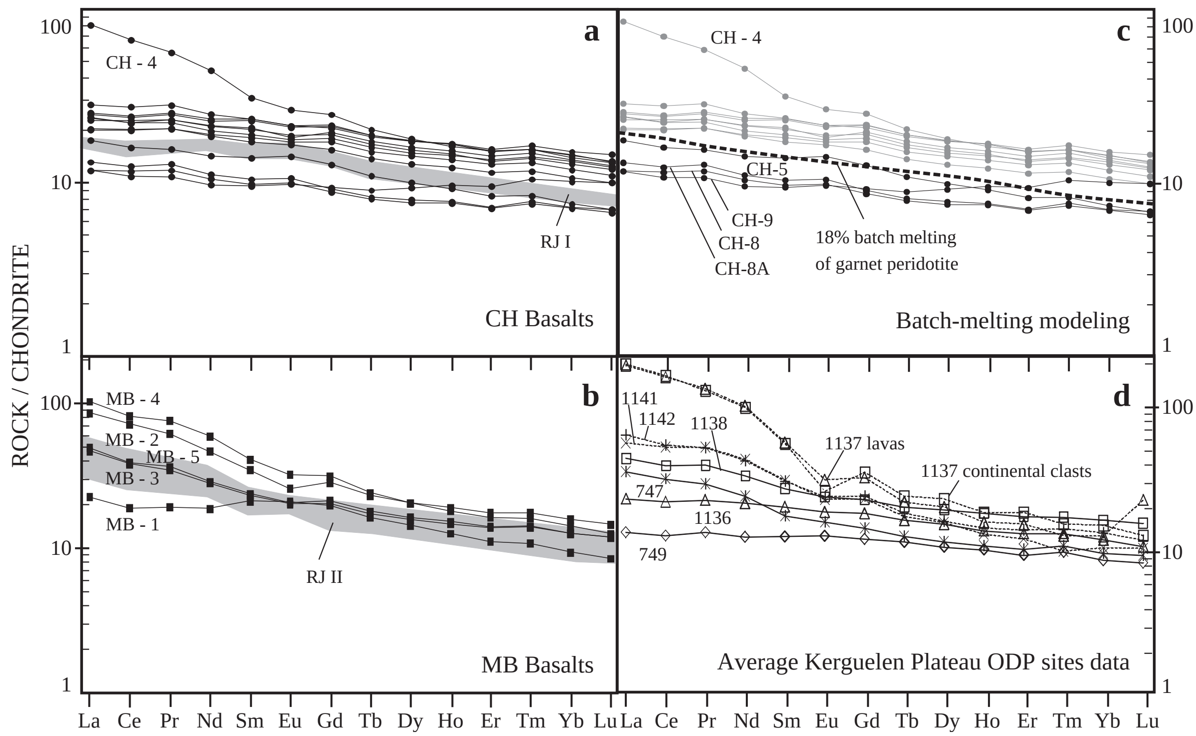

Fig. 2. Chondrite-normalized REE patterns of basalts analyzed from the two sections exposed in the Sylhet Traps: (a) CH lavas and (b) MB lavas. Sample numbers correspond to the lava flows in Fig. 2b. (c) Modeling result shown by the dotten line, of 18% batch melting of a garnet lherzolites source. Details of batch melting are shown in Supplementary text S2. (d) Average REE patterns from various Kerguelen Plateau ODP sites (Frey et al., 2000a, b; Frey et al., 2002; Ingle et al., 2002a; Neal et al., 2002), and continental clasts from Site 1137 (Ingle et al., 2002a) are shown for comparison.

a major contaminant of continental flood basalts (e.g. Peng et al., 1994) and their influence has been proposed for several ODP site lavas of the South and Central Kerguelen Plateau (Frey et al., 2002).

Primitive-mantle normalized trace element data of the CH basalts (Fig. 2a) are similar to those of the least contaminated Rajmahal Group I basalts (Kent et al., 1997) with relatively low Rb, U and Pb and higher Ba, Th, and Sr. Sample CH-4 has higher concentrations of incompatible elements compared to other CH samples (Supplementary Fig. A1). The conspicuous Rb depletion and variable Rb content of the CH basalts contrast with the relatively flat pattern (except CH-4) of most of the other elements in Fig. A1-a. The CH basalts are exposed on the southern slopes of the Shillong Plateau in Cherrapunji with the highest rainfall (11.4 m annual) in the world that may have leached Rb out of the basaltic groundmass. Overall, the CH rocks are distinctly different from both N-MORB and average upper continental crust in trace element patterns and ratios (Supplementary Figs. A1–A2). This pattern could not have resulted from upper crustal contamination of a magma derived from N-MORB type mantle as has been proposed by several authors for the Rajmahal Traps (e.g. Baksi et al., 1987; Kent et al., 1997).

In contrast to the CH lavas, the MB basalts show different trace element patterns (Fig. A1-b) similar to those of Rajmahal Group II basalts (Kent et al., 1997), and to granitoid clasts recovered from ODP site 1137 (Ingle et al., 2002a) on the Kerguelen Plateau (Fig. 1a). In addition, three of the MB lavas show negative Nb–Ta anomalies. Two MB samples (MB-1 and MB-4) do not show such strongly negative Nb–Ta anomalies and may be variably contaminated by different amounts of continental material. The positive and negative variations of Zr–Hf relative to Sm and Gd, particularly in the MB samples (Fig. A1-b), is also exhibited by other Kerguelen Plateau lavas (Fig. A1-c). It is interesting that Kerguelen lavas that are inferred to be least affected by continental contamination (Sites 1138, 1141, 1142, Neal et al., 2002) and Site 1137 clasts and lavas (Ingle et al., 2002a) have positive Zr–Hf where as 749, 1136 lavas and CG (Chakrabarti et al., 2011) have negative Zr–Hf in normalized multi-element plots.

5.2. Pb–Pb isotopic geochemistry

The proximity of the CH basalts with the Rajmahal Group I field near the 4.45 Ga Geochron (at μ ~8.3) in the $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ plot (Fig. 4b) is noteworthy. This correspondence of the CH basalts (except CH-4) with Rajmahal Group I basalts is also consistent with their trace element patterns as discussed in Section 5.1. Although some of the CH and MB basalts fall close to the field of Indian MORB in the $^{206}Pb/^{204}Pb$—$^{207}Pb/^{204}Pb$—$^{208}Pb/^{204}Pb$ plots (Fig. 4), these rocks also overlap with the field of Rajmahal Group I, and some Kerguelen Plateau basalts considered to be derived from the Kerguelen plume (e.g. Frey et al., 1996; Frey et al., 2000a; Ingle et al., 2002b; Mahoney et al., 1992; Neal et al., 2002). Furthermore, we can eliminate the possibility of any significant N-MORB mantle contribution in these rocks by the interpretation of the trace element data (Section 5.1, Fig. 3, Supplementary Figs. A1–A2) and on the basis of Ce/Pb ratio and Nd–Sr–Pb isotopic data discussed below in Section 5.3.

Two MB lavas with no negative Nb–Ta anomaly (Fig. A1-b) fall in the field of average lower crust in Fig. 4b, close to the field of Site 750 basalts, considered contaminated by lower continental crust (Frey et al., 2002; Neal et al., 2002). Volcanic rocks obtained from Site 738 show the highest degree of crustal contamination compared to Kerguelen basalts of all other ODP sites (e.g. Frey et al., 2002) and interestingly they are very similar to the Chilka granulites (Fig. 4b) used in our modeling (Fig. 7b). The field for the ancient continental clasts from Site 1137 represents conglomerates, sandstones and granulites that are of unequivocal continental origin (Ingle et al., 2002a). Four Sylhet lavas, CH-4, MB-2, MB-3, and MB-5, show higher values of both $^{207}Pb/^{204}Pb_{(I)}$ (Fig. 4a) and $^{208}Pb/^{204}Pb_{(I)}$ (Fig. 4b), suggesting a greater degree of crustal/lithospheric contamination for

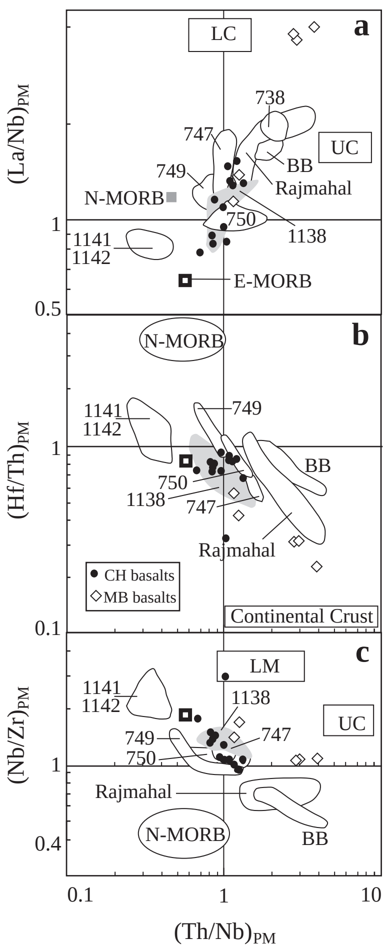

Fig. 3. Primitive mantle normalized element ratio plots with some possible end-member compositions that may have been involved in the formation of the Sylhet–Rajmahal and Kerguelen provinces. Abbreviations: LC — lower crust, UC — upper crust, LMlithospheric mantle.Data sources: sites 1141, 1142 (Mahoney et al., 1995); site 738 (Alibert, 1991; Mahoney et al., 1995); Sites 747, 749, 750 (Frey et al., 2000a; Storey et al., 1992); Site 1138 (Neal et al., 2002); Bunbury basalts (Frey et al., 1996; Storey et al., 1992); Rajmahal Traps (Kent et al., 1997); average continental crust estimates (Weaver and Tarney, 1984; Rudnick and Fountain, 1995); E-MORB (Mahoney et al., 2002); other primitive mantle values (Sun and McDonough, 1989).

these rocks; data for these rocks fall closer to the fields of the CG as well as the contaminated Kerguelen Plateau basalts from Sites 1137 and 738 (Fig. 1a).

There is no correspondence of any Sylhet basalts with the NER basalts and average upper continental crust in their Pb-isotopic compositions (Fig. 4). This observation suggests that the contaminants in the Sylhet–Rajmahal and some Kerguelen Plateau basalts (e.g. Site 750) are probably of lower crustal affinity (e.g. Frey et al., 2002) without significant upper crustal component.

Pb-isotopic ratios plotted as $^{208}Pb/^{206}Pb_{(I)}$ and $^{207}Pb/^{206}Pb_{(I)}$ (Fig. 4c) are useful in distinguishing the sub-oceanic mantle reservoirs, EM-I, EM-II, depleted mantle (DMM), and HIMU (e.g. Saal et al., 1998). The Sylhet basalts broadly fall into two clusters in this figure, one consisting of four samples falling in EM-I and the remaining samples as shown in the dotted field. The latter group displays relatively flat REE patterns whereas the samples in the EM-I field (CH-4, MB-2, MB-3, MB-5) are enriched in LREEs (Fig. 2) with highly radiogenic Sr isotopes (Table 2, Fig. 7a). Note that the dotted field in Fig. 4c also encompasses Kerguelen Plateau basalts from ODP Sites 749, 1136 and 1138 indicating a strong correspondence between the Sylhet Traps and Kerguelen plume derived lavas. A likely contaminant for the lavas of this study as well as some of the Kerguelen Plateau basalts is a lower crustal end member similar to the contaminant in site 750 (Frey et al., 2002) (Fig. 4c). It is noteworthy from Fig. 4c that both EM-II, considered as upper continental crustal, and depleted mantle (DMM) components are unlikely sources in the Sylhet basalts as well as in Rajmahal–Bunbury–Kerguelen Plateau basalts. It is noteworthy that the Sylhet basalts in the EM-1 field in Fig. 4c display LREE enrichment (Fig. 2), with characteristic Nb–Ta depletion (Fig. A1), and an affinity with the lower continental crust-derived eastern Indian granulites in Nd–Sr–Pb isotopic space (Figs. 4, 5, and 7a).

5.3. Nd–Sr–Pb isotopic geochemistry

The distinction between the less contaminated basalts of the CH section (except CH-4) and the clearly contaminated MB section rocks can be seen in the plots of $^{87}Sr/^{86}Sr_{(I)}$ and $\varepsilon_{Nd(I)}$ against $^{206}Pb/^{204}Pb_{(I)}$ (Fig. 5). In Fig. 5 and 7a, a general correspondence of the CH basalts, except CH-4, with those of the South and Central Kerguelen Plateau and Rajmahal Groups I and II lavas is significant. We suggest the four CH samples that have the highest Mg-numbers (~60, Table T1) to be representative of the least contaminated Rajmahal–Sylhet Traps-Kerguelen plume source in their Nd–Sr isotopic ratios, as represented by the gray field in Fig. 7a–b. This suggestion is consistent with the REE and multiple trace element data (Figs. 2, 3, and A1) as discussed in Section 5.1.

Based on the analysis of a single kimberlite sample of Group II type occurring as an intrusive in the Bokaro field (Fig. 1b), Kumar et al. (2003) proposed its isotopic composition to be that of the “pristine” component of the Kerguelen plume in the middle Cretaceous (Km in Fig. 5 and 7a), similar to the Cenozoic Kerguelen plume field proposed by Weis et al. (1993, 1998) in Nd–Sr–Pb-isotopic space. The kimberlite field is distinctly different from the bulk of the CH lavas as well as the RJI lavas and ODP Sites 1136, 1138, 1141, and 1142 that are considered the least contaminated lavas of the Rajmahal–Sylhet Traps and the Kerguelen Plateau respectively (Fig. 5a and b). Sites 1138, 1141, and 1142 lavas are likely the most representative of the main component of the Kerguelen plume in the middle Cretaceous (Neal et al., 2002). These lavas also have higher $\varepsilon_{Nd}(I)$ (0–1) than those proposed by Weis et al. (1993) and Kumar et al. (2003) as representative of the Kerguelen plume composition.

In contrast with the CH basalts, the MB lavas are similar in Nd–Sr–Pb-isotopic space (Fig. 5) to the CG and contaminated basalts from Sites 738. The MB and CH-4 samples fall distinctly away from the fields of Rajmahal–Bunbury–Kerguelen lavas except for the site 738 lavas, the most contaminated Kerguelen basalts in Fig. 5. An elongate array, which we interpret as a contamination trend, is seen clearly in Fig. 5b, with the MB basalts showing the most radiogenic Sr-isotopic ratios. While some of the MB samples fall close to the fields of CG and Site 738 (Fig. 5), others have even higher initial $^{87}Sr/^{86}Sr_{(I)}$ (as high as ~0.715) similar to the EGB granulites (Fig. 7, Rickers et al., 2001).

The absence of an N-MORB source for the Sylhet basalts is further evident in Fig. 6 where none of the CH section Sylhet basalts fall on the modeled mixing line of depleted mantle and continental crust. Some of the most primitive Sylhet basalts with highest Mg-numbers (Table A1) and relatively low positive $\varepsilon_{Nd}(I)$ values fall close to Ce/Pb = 11, near the primitive mantle value of 10 (Miller et al., 1994).

In the Nd–Sr-isotopic diagram (Fig. 7a–b) most of the Sylhet Trap CH basalts show affinity with the lower end of Rajmahal Group I trend, Rajmahal Group II basalts, some Kerguelen Plateau basalts, and Bunbury–Casuarina fields. Based on these correlations, a Rajmahal–Sylhet–Kerguelen Plateau connection can be suggested. Although some of the CH data fall close to the field of Indian MORB (Fig. 7a–b), they also overlap with some Kerguelen Plateau data, close to Rajmahal Group I values (also seen in Fig. 4). These CH basalt samples also show non-N-MORB like trace element patterns (Fig. 2a) as discussed previously in Section 5.1. Thus, based on the evidence of the trace

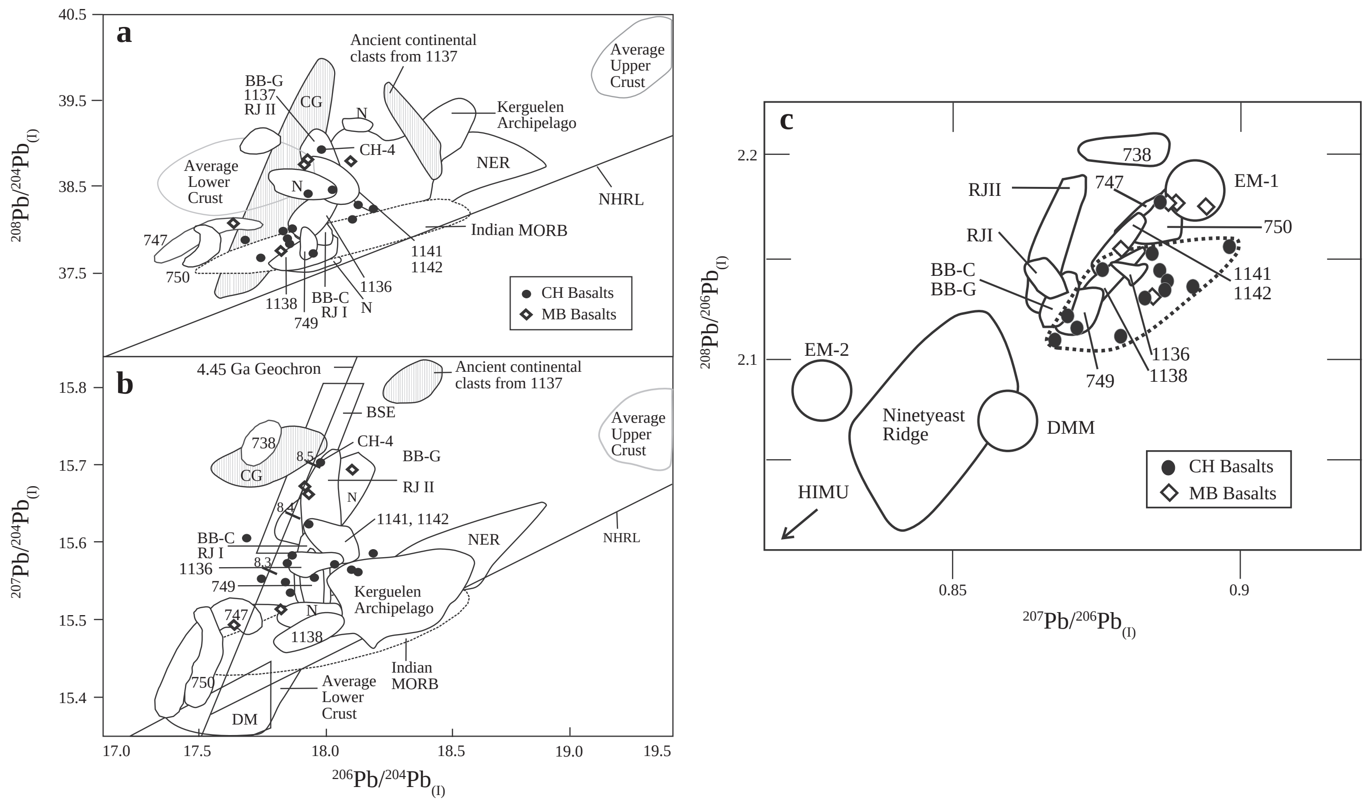

Fig. 4. (a) $^{208}Pb/^{204}Pb_{(I)}$ vs. $^{206}Pb/^{204}Pb_{(I)}$; (b) $^{207}Pb/^{204}Pb_{(I)}$ vs. $^{206}Pb/^{204}Pb_{(I)}$; and (c) $^{207}Pb/^{206}Pb_{(I)}$ vs. $^{208}Pb/^{206}Pb_{(I)}$ plots for the CH and MB section basalts of the Sylhet Traps at the 117 Ma age of eruption compared with South and Central Kerguelen Plateau basalts, Bunbury basalts, Naturaliste Plateau lavas, Rajmahal Traps, NER, CG, BSE, NHRL, DM, and upper and lower continental crust. μ values of 8.3, 8.4, and 8.5 are shown in (b) where $\mu = {}^{238}U/^{204}Pb$. The field of ancient continental crustal clasts at ODP Site 1137 (Ingle et al., 2002a) uses present day values. The field of Indian MORB includes the Southeast Indian Ridge (Mahoney et al., 2002). In (c) mantle reservoirs EM-I, EM-II, DMM, and HIMU from Saal et al. (1998). The dotted line encloses most of the CH section lavas of the Sylhet Traps that are far removed from EM-2, NER and DMM. Abbreviations: NER — Ninetyeast Ridge; BB-C — Bunbury, Casuarina; BB-G — Bunbury, Gosselin; N — Naturaliste Plateau; RJ I — Rajmahal Traps Group I; RJ II — Rajmahal Traps Group II; CG — Chilka Granulites; BSE — bulk silicate Earth; NHRL — Northern Hemispheric Reference Line; DM, DMM — Depleted mantle. Data sources: Indian MORB (Mahoney et al., 1992; Weis and Frey, 1996); NER (Weis and Frey, 1991); Bunbury (Frey et al., 1996); Rajmahal basalts (Kent et al., 1997); South and Central Kerguelen Plateau sites 738, 749, 750, 747, 1138 (Frey et al., 2000a; Frey et al., 2002; Mahoney et al., 1995; Neal et al., 2002); Elan Bank 1137, and ancient continental fragment from 1137 (Ingle et al., 2002a); Kerguelen Archipelago (Frey et al., 2000b; Mahoney et al., 1996; Weis et al., 1998; Weis et al., 2002a,b); Chilka Granulites (Chakrabarti et al., 2011); NHRL (Hart, 1984); DM (Hart and Zindler, 1989); and upper and lower continental crust (Zartman and Doe, 1981).

element and Nd–Sr–Pb-isotopic data, a major N-MORB component for these Sylhet lavas, as suggested previously for Rajmahal Groups I and II basalts by Kent et al. (1997) is untenable in our opinion. However, as discussed in Section 5.1, some CH basalts show E-MORB like trace element patterns. This is also implied by the higher ε_{Nd} value of these lavas (>+3). In this context it should be noted that some low-ε_{Nd} Indian MORB mantle (Fig. 7a) has been suggested to be a Kerguelen plume component (Hamelin et al., 1986; Mahoney et al., 1992; Weis and Frey, 1996). These low ε_{Nd}-Indian MORBs have been reported from deep sea drilling sites 213, 212, and 256 in the eastern Indian Ocean by Weis and Frey (1996).

We suggest a relatively primitive Kerguelen plume source that was responsible for some CH as well as Bunbury–Casuarina, Rajmahal Group I and least contaminated Kerguelen Plateau basalts, in contrast with the previous proposal by several workers (e.g. Kumar et al., 2003; Weis et al., 1993; Weis et al., 1998) for a generally enriched end-member for the Kerguelen plume without the signature of continental crust (Km in Fig. 7a). On the basis of the collective geochemical signatures, we propose the Kerguelen plume-head composition in Nd–Sr-isotopic space to be represented by the average of the CH lavas having Mg-numbers ~60 represented by the gray area in Fig. 7a–b with $\varepsilon_{Nd}(I) = +2.0$ and $^{87}Sr/^{86}Sr_{(I)} = 0.7046$ (P in Fig. 7b). This relatively primitive plume source (P) is in excellent agreement with the average value for site 1138 basalts ($\varepsilon_{Nd}(I) = +0.6$ and $^{87}Sr/^{86}Sr_{(I)} = 0.7048$), suggested to be representative of the Kerguelen starting plume-head by Neal et al. (2002). We note similar isotopic signatures were proposed for the Siberian, Deccan-Reunion, and the Ethiopian flood basalt provinces (Basu et al., 1993; Basu et al., 1998; Pik et al., 1999).

^{142}Nd evidence in chondrites and terrestrial rocks (Boyet and Carlson, 2005, 2006) indicate very early differentiation of the Earth, causing enriched and depleted layers in the mantle. Based on a super-chondritic bulk silicate Earth Sm/Nd ratio, these authors estimated a more positive present day ε_{Nd} of +4.9 and suggested that all terrestrial samples are derived from this mantle reservoir. Although many OIB lavas support this estimate, our estimate for some large igneous provinces falls short of this ε_{Nd} +4.9 value. However, as discussed previously, the Sr–Pb isotopes of these large magmatic provinces match the estimated values of early depleted reservoir (EDR, Boyet and Carlson, 2006).

The above Nd–Sr–Pb correspondence (Figs. 5, 7a) reaffirms the suggestion that the Sylhet basalts are indeed an extension of the Rajmahal Traps through the Bengal basin, where a few drill core samples (Fig. 1b) also show Nd–Sr-isotopic and REE signatures (Baksi, 1995) identical to those of the Sylhet Traps and Rajmahal Groups I and IIa basalts. This observation suggests the Kerguelen plume-generated flood basalts that erupted at 117 Ma gave rise to a large igneous province with an approximate diameter of 600 km, whose vestiges are present in eastern India (Fig. 1b).

Sample CH-4 shows strong incompatible element enrichment compared to the other samples of the CH section (Figs. 2a and A1-a).

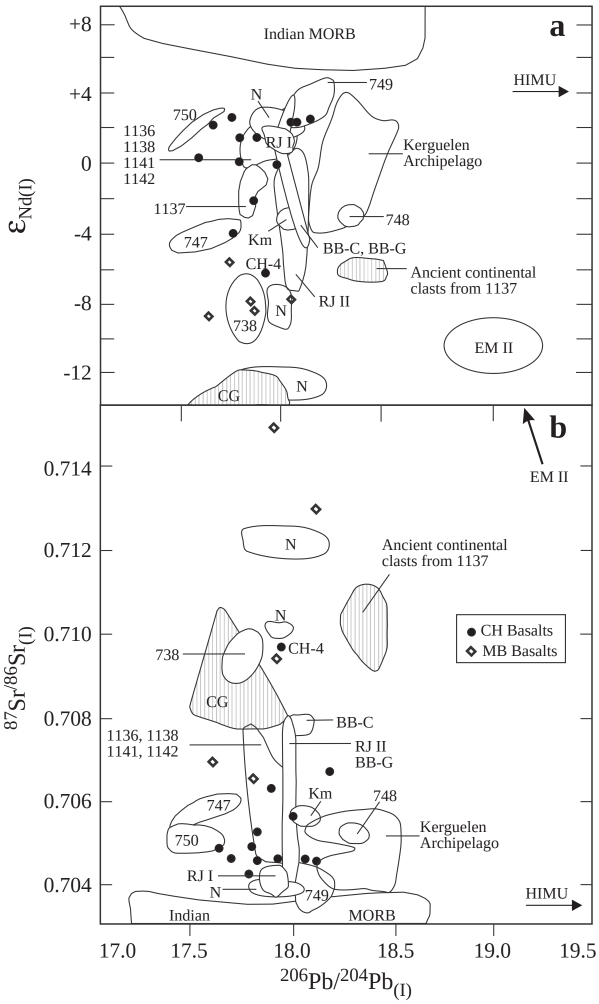

Fig. 5. (a) Initial ε_{Nd} vs. $^{206}Pb/^{204}Pb_{(I)}$ and (b) $^{87}Sr/^{86}Sr_{(I)}$ vs. $^{206}Pb/^{204}Pb_{(I)}$ for the Sylhet basalts compared with Indian MORB, including Southeast Indian Ridge (Mahoney et al., 2002), Bunbury basalts, Rajmahal basalts, Kerguelen Plateau basalts, possible crustal contaminants, Chilka Granulites (CG), ancient continental clasts from ODP Sites 1137, and 738 (Alibert, 1991; Mahoney et al., 1995). Group II kimberlite (Km) related to the Rajmahal flood basalt province (Kumar et al., 2003) is also shown. Other data sources as in Fig. 4.

In the Nd–Sr plot (Fig. 7a–b), CH-4 and MB basalts fall close to the fields of Site 738, ancient continental clasts from Site 1137 and the EGB granulites. The most likely candidates for the non-volcanic continental clasts of Site 1137 are the Chilka granulites (Chakrabarti et al., 2011) and the EGB granulites of the eastern Indian margin (Fig. 1a). This correspondence in Fig. 7a suggests the presence of lower crustal contaminants in the Sylhet lavas. The contaminants and contaminated lavas are bound by two modeled curves, with the tick marks representing the amount of plume component in Fig. 7b. These mixing curves result from modeling of the Sylhet lavas as products of mixing of relatively uncontaminated plume magma with granulitic end members as explained below (Fig. 7b).

The mixing curves are constructed with a mantle end member “P”, which is the average of Sr–Nd-isotopic ratios as well as concentrations (Table 2) of the most primitive CH basalts (based on Mg-numbers) in Fig. 7a, and two granulite end members (Granulite 1 and 2; Table 2) in the field of the Eastern Ghats Belt (EGB) granulites (Fig. 7b). In this model, P represents a melt of the relatively primitive Kerguelen plume component, whereas granulites 1 and 2 are from the EGB (Rickers et al., 2001), believed to constitute the lower continental crust (Chakrabarti et al., 2011) in the eastern Indian continental margin

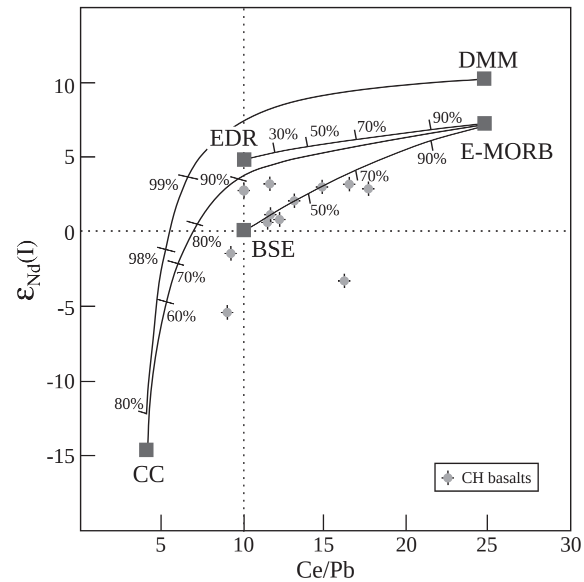

Fig. 6. Plot of $\varepsilon_{Nd}(I)$ vs. Ce/Pb for CH basalts, with modeled mixing lines between continental crust (CC), depleted mantle (DMM), Southeast Indian Ocean E-MORB, early differentiated Earth (EDR), and bulk silicate Earth (BSE). Mixing lines are modeled using mixing equations of DePaolo, 1988.Data sources: CC (Taylor and McLennan, 1995); DMM (Salters and Stracke, 2004); Southeast Indian Ocean E-MORB (Mahoney et al., 2002); EDR (Boyet and Carlson, 2006); BSE (Miller et al., 1994). Ratios are as follows: Ce/Pb;DMM, E-MORB = 25; EDR, BE = 10; CC = 4. ε_{Nd}: DMM = 10, E-MORB = 7, EDR = 4.9, BE = 0 and CC = −15.

(Fig. 1a) that are exposed along the EGB (Yin et al., 2010). This modeling indicates 0–10% of the granulite contamination in all of the CH lavas except CH-4, and less than 20% contamination for CH-4 and all the MB lavas.

Of the two Sylhet sections described in this study, the MB section basalts show the clearest evidence of mixing between a plume end member and a lower crustal end member similar to the EGB granulites. The traps reside on a late Archean craton that once had deep lithospheric roots as evidenced by the presence of diamond-bearing Proterozoic kimberlites intruding the Indian craton (Basu and Tatsumoto, 1979; Rao et al., 2004). Thus the contamination in the MB section rocks as well as other similarly contaminated rocks from the Kerguelen Plateau (e.g. Sites 738 and 1137) may have been caused by the lower crustal EGB-type mafic granulites that are common along the eastern margin of the Indian craton (Fig. 1a).

6. Conclusions

In this study, we have correlated the Rajmahal basalts with the Sylhet Traps, ~550 km to the east, by their geochemical and Nd, Sr and Pb isotopic signatures, thus extending the Rajmahal flood basalt province through the Bengal basin to the Shillong Plateau. By extending the database geochemically and geographically, we show a general similarity of these basalts to lavas recovered from the Kerguelen Plateau by drilling (Fig. 1a). This geochemical similarity is particularly strong among the least contaminated Kerguelen plume components, as seen in the CH lavas of this study that are similar to the Rajmahal Group I lavas, Bunbury basalts, and some Kerguelen Plateau lavas.

We document from our geochemical results that the Sylhet volcanic rocks may have 80–100% of the primitive Kerguelen plume component, and less than 20% contamination (Fig. 7b) from a lower crustal source that can be identified as the Proterozoic mafic granulites of the Eastern Ghats in India. We also show that there are no major normal MORB (N-MORB)/asthenospheric or upper continental crustal components in primitive Kerguelen plume-derived volcanic rocks, as previously

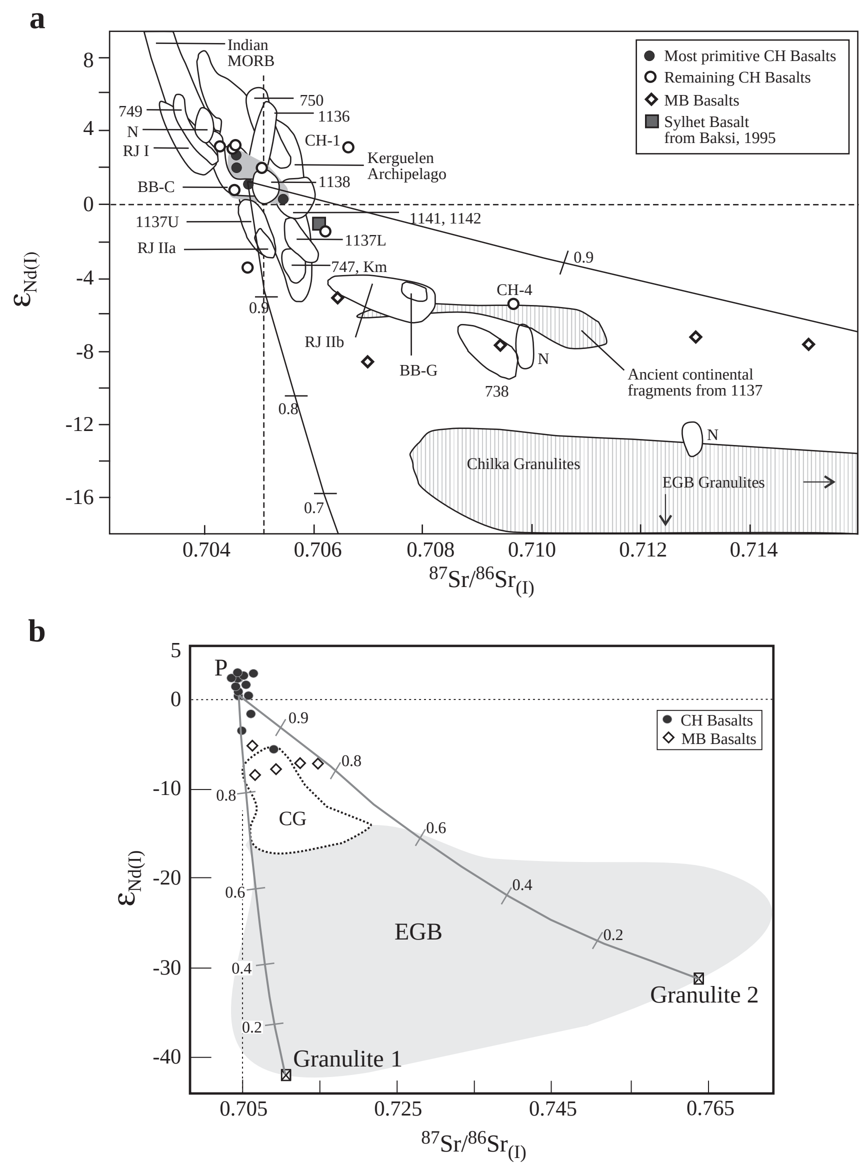

Fig. 7. a. Initial ε_{Nd} vs. $^{87}Sr/^{86}Sr$ at 117 Ma for the Sylhet Traps, CH and MB sections are shown and compared with data from the Rajmahal Traps, Bunbury basalts, Kerguelen Plateau basalts, and Eastern Ghat Belt (EGB) granulites (Rickers et al., 2001). The field of Indian MORB includes the Southeast Indian Ridge (Mahoney et al., 2002). Data sources and abbreviations as in Figs. 4–5. Partial mixing curves resulting from modeling the Nd–Sr data in Fig. 7b are shown with plume-melt in gray as the common end-member with two EGB granulites as the other end members.b. Initial ε_{Nd} and $^{87}Sr/^{86}Sr$ isotopic ratios of the Sylhet Traps shown with massif Chilka anorthosite-granulites, CG (Chakrabarti et al., 2011) as well as enderbites (mafic granulites), all from the Eastern Ghats Belt (EGB) of India (Rickers et al., 2001). Two mixing curves are shown resulting from modeling a common end member P, the most primitive CH lavas, and granulites 1 and 2 from the EGB, considered as the second end members. This modeling indicates 0–10% contamination for most of the Sylhet lavas by the EGB granulites.

suggested for some of the Rajmahal basalts (Baksi et al., 1987; Kent et al., 1997). However, modeling with Ce/Pb and ε_{Nd}(I) between two component mixtures of Indian Ocean E-MORB and chondritic bulk Earth revealed presence of an E-MORB in the primitive plume. The ε_{Nd} of this least contaminated plume appears to be +2, similar to large igneous provinces, but less than +5 commonly observed for many OIBs.

The data presented in this study suggest the Sylhet Traps are the remnants of part of the larger Rajmahal flood basalt province. These lavas are results of partial melting of a relatively primitive Kerguelen plume source with components of the Indian Ocean E-MORB and contaminants derived from the lower continental granulites. We speculate that this lower crustal contamination resulted from the incorporation by thermal convective erosion of eastern Indian continental lithosphere by the Kerguelen plume. Our geochemical data are consistent with the scenario in which the plume head eroded parts of the continental mantle lithosphere including lower crust during ascent and storage of melts in the crust, resulting in the eruption of the Rajmahal–Bengal–Sylhet Traps.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2011.05.023.

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