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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