Kimberlite from Rajmahal magmatic province: Sr-Nd-Pb isotopic evidence for Kerguelen plume derived magmas

Anil Kumar, A. M. Dayal, and V. M. Padmakumari
National Geophysical Research Institute, Hyderabad, India

Received 20 August 2003; accepted 15 September 2003; published 24 October 2003.

[1] Previous studies showed that the Rajmahal-Sylhet-Bengal (RSB) flood basalt province (117 ± 2 Ma) in eastern India was spatially close to the active Kerguelen hotspot about 118 Ma ago. Yet, it could not be unequivocally correlated to this hotspot due to wide variation in isotopic compositions of both the RSB and Kerguelen plateau basalts. However, we report Sr-Nd-Pb isotopic compositions ($^{87}Sr/^{86}Sr_i$: 0.70535 to 0.70561; $\varepsilon_{Nd}(T)$: −2.6 to −3.2; $^{206}Pb/^{204}Pb_i$: 17.88 to 18.07) of a co-eval (116 ± 2 Ma) Group II kimberlite from this flood basalt province that is identical to recently identified pristine Kerguelen plume basalts from the Kerguelen Plateau/Archipelago and Broken Ridge. This suggests that the Kerguelen hotspot could indeed be responsible for the ~117 Ma magmatic activity in Eastern India. *INDEX TERMS:* 1025 Geochemistry: Composition of the mantle; 1040 Geochemistry: Isotopic composition/chemistry; 4825 Oceanography: Biological and Chemical: Geochemistry; 9340 Information Related to Geographic Region: Indian Ocean; 8450 Volcanology: Planetary volcanism (5480). **Citation:** Kumar, A., A. M. Dayal, and V. M. Padmakumari, Kimberlite from Rajmahal magmatic province: Sr-Nd-Pb isotopic evidence for Kerguelen plume derived magmas, *Geophys. Res. Lett.*, *30*(20), 2053, doi:10.1029/2003GL018462, 2003.

1. Introduction

[2] A flood basalt province (Figure 1), consisting of the Rajmahal, Sylhet and Bengal (RSB) traps (117 ± 2 Ma old; *Baksi* [1995]; *Kent et al.* [2002]; *Pande and Ray* [1999]) occurs in eastern India (covering an area of $\sim 2 \times 10^5$ km^2). This province is part of a widespread Early Cretaceous magmatism along the Indian, Australian/Antarctic margins [*Kent et al.*, 2002]. Episodes of such large volcanism often mark the initiation of sub-continental hot spots, which subsequently produce chains of volcanic islands as oceanic plates move over them. There is disagreement over which plume was responsible for the RSB basaltic activity. According to one view, the Kerguelen hotspot that formed the 90°E ridge and now located in the Indian Ocean (Figure 1) was responsible for this basaltic outpouring [*Storey et al.*, 1992]. *Curray and Munasinghe* [1991] and *Subramanyam et al.* [1999] suggested that the east Indian magmatic province, the 85°E ridge was due to the Crozet plume, currently located beneath the Crozet plateau at ~46.2°S (Figure 1). *Muller et al.* [1993] matched the southern part of the 85°E Ridge (to 10°N) with the Conrad hotspot (~53.4°S). Contrary to these plume links *Anderson et al.* [1992] proposed that these Cretaceous lavas were manifestations of decompression melting above a 'hot cell'. Comparison of geochemical and Sr-Nd-Pb isotopic compositions of Kerguelen plateau basalts with Rajmahal traps led *Mahoney et al.* [1983] and *Kent et al.* [1997] to believe that the Kerguelen plume had not fed the Rajmahal magmas but could have provided the heat source for their production. *Storey et al.* [1992] and *Ingle et al.* [2002], however, argued that this plume could also have furnished magmas for the Rajmahal lavas. Disagreement over the source of the RSB basalts is because their isotopic data is affected by variable amounts of contamination by a MORB like component in Group I Rajmahal lavas and by crustal contamination in the Group II lavas [*Storey et al.*, 1992; *Kent et al.*, 1997] as they intruded a thick Precambrian continental crust. To overcome this problem, a kimberlite intrusion, with high abundances of Nd > 250 ppm, Sr > 2200 ppm and Pb > 39 ppm, having temporal affinity (Ar/Ar ages between 109 and 117 Ma, *Pringle et al.* [1994]; *Kent et al.* [1998] with the RSB and occurring to the southwest of the Rajmahal trap exposures (supplement-1a) has been studied for their age, Sr, Nd and Pb isotopic compositions. These data are presented here and compared with the Rajmahal basalts and the Kerguelen, Crozet and Conrad hotspot lavas.

2. Samples and Analytical Methods

[3] Kimberlite samples used are from three boreholes CMJP 32, CMJP 33, and CMJP 51, which are within about 3 km of each other and about 10 km southwest of Jharia town. The samples consist of euhedral olivine phenocrysts, pseudomorphed occasionally, macrocrystic and phenocrystic phlogopite, microphenocrystic diopside, apatite, opaques, in a groundmass of k-feldspar, phlogopite, carbonates, perovskite, clinopyroxene and minor amounts of amphibole.

[4] Carefully selected whole-rock fractions (matrix free of exotic material) were crushed to less than 200 mesh and dissolved in a HF+HNO_3 mixture. Rb-Sr, Sm-Nd and Pb isotopic analyses followed standard chemical separation and mass spectrometric isotope dilution procedures [*Anil Kumar et al.*, 1999; *Sarangi et al.*, 2003]. Total procedural blanks during the course of these analyses were,<250 pg for Rb and Sr and <30 pg for Sm, Nd and Pb.

3. Results and Discussion

[5] Results of Sm-Nd and Rb-Sr isotopic measurements on the Jharia kimberlites are listed in Table-1 and Pb isotopic data in Table-2 of supplement-1b[1]. Initial Sr, Nd and Pb isotopic ratios calculated using an emplacement age

0094-8276/03/2003GL018462$05.00

[1] Auxiliary material available at ftp.agu.org/apend/gl/2003gl018462.

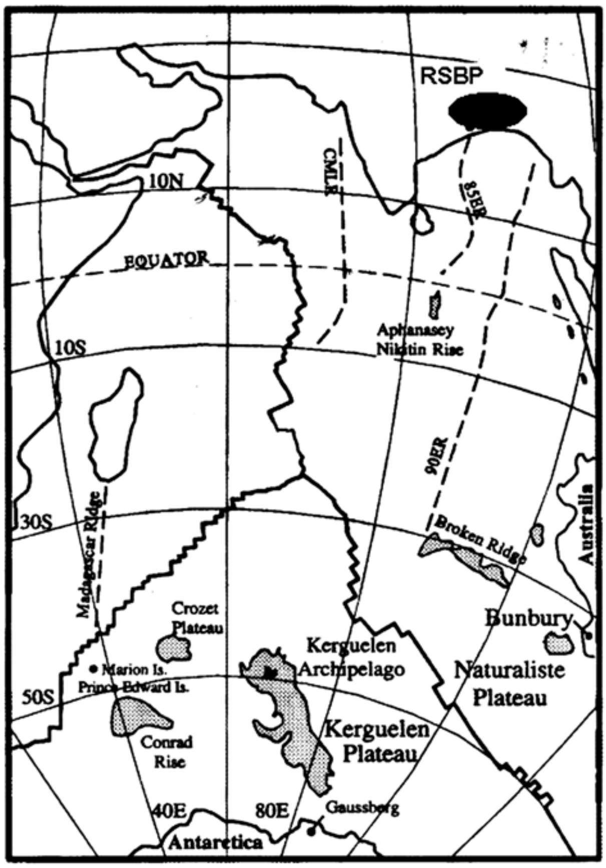

Figure 1. Physiographic elements of the Indian Ocean showing hotspots and their tracks. Location of Rajmahal, Sylhet and Bengal magmatic province (RSBP) is also indicated.

of 116 Ma (supplement-1c) are illustrated in Figures 2a and 2b, on plots of ε_{Nd} vs $^{87}Sr/^{86}Sr_i$ and $^{206}Pb/^{204}Pb_i$ vs. $^{87}Sr/^{86}Sr_i$ respectively. The initial Sr, Nd and Pb isotopic ratios of the kimberlite ($^{87}Sr/^{86}Sr_i$ = 0.70535 − 0.70561; ε_{Nd} = −2.6 to −3.2 and $^{206}Pb/^{204}Pb_i$ = 17.88 to 18.07, $^{207}Pb/^{204}Pb_i$ = 15.51 to 15.60, $^{208}Pb/^{204}Pb_i$ = 38.00 to 38.50) exhibit restricted variation and could reflect the composition of their mantle source, because minor amounts of contamination will not modify their isotopic compositions as these rocks have extremely high concentrations of Sr, Nd and Pb (Sr = 2203 to 3149, Nd = 249 to 397 and Pb = 39 to 47 ppm) in them. Their high 100 (Mg/(Mg + Fe) values of 60–75 and Ni contents of 215–930 ppm (author's unpublished data) support this inference.

[6] Our kimberlite Sr, Nd and Pb isotopic ratios are similar to data reported on coeval lamprophyric sills from the Jharia basin ($^{87}Sr/^{86}Sr_i$ = 0.70491 to 0.70573 and ε_{Nd} = −1.5 to −3.1; initial $^{143}Nd/^{144}Nd$ values were calculated using an assumed Sm/Nd ratio of 0.12 for some of these samples, *Rock et al.* [1992]) and for one sample each from a minette and a lamproite dyke ($^{87}Sr/^{86}Sr_i$ = 0.70596, ε_{Nd} = −3.1, $^{206}Pb/^{204}Pb_i$ = 17.82 and $^{87}Sr/^{86}Sr_i$ = 0.70493, ε_{Nd} = −2.7, $^{206}Pb/^{204}Pb_i$ = 17.82 respectively) occurring in the Ranigunj basin about 50 km to their east [*Middlemost et al.*, 1988]. On comparison (Figures 2a and 2b) of the Sr-Nd-Pd isotopic compositions, the Jharia kimberlites possess distinctly lower $^{87}Sr/^{86}Sr_i$ and higher ε_{Nd} and $^{206}Pb/^{204}Pb_i$ values compared to the Kaapvaal Group II kimberlites ($^{87}Sr/^{86}Sr_i$ = 0.7071 to 0.7109; ε_{Nd} = −6.2 to −13.4; $^{206}Pb/^{204}Pb_i$ = 17.06 to 17.63, except Finish, $^{206}Pb/^{204}Pb_i$ = 17.69 to 18.24, reviewed by *Mitchell* [1995]). This suggests distinctly different source compositions for the East Indian occurrences.

4. Comparison of Jharia Kimberlite With RSB and Indian Ocean Hotspot Lavas

[7] In Figures 2a and 2b, the Sr *vs.* Nd and Sr *vs.* Pb isotopic data of Jharia kimberlites are compared with fields

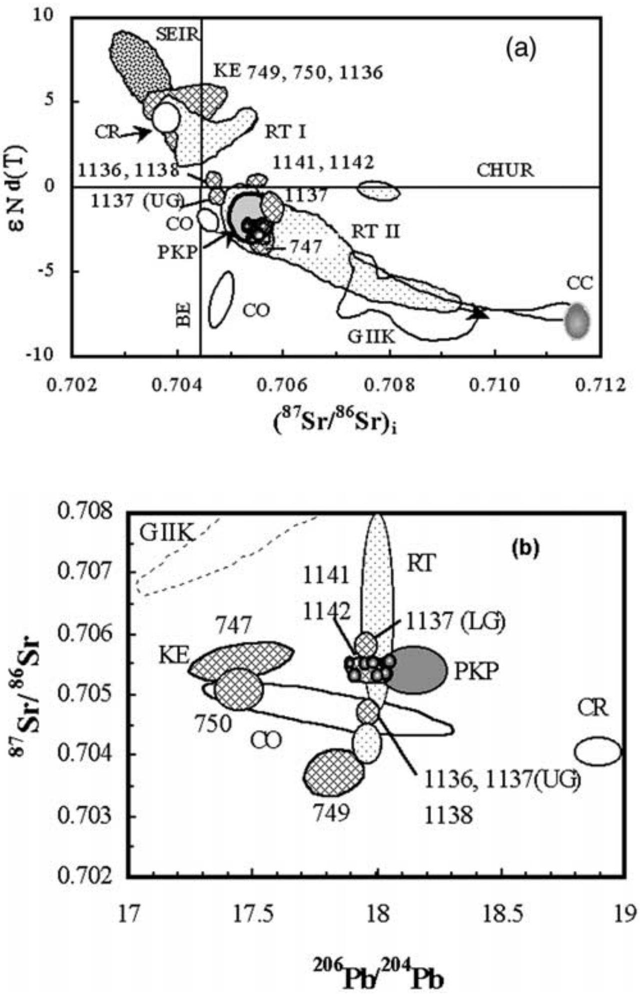

Figure 2. (a) $\varepsilon_{Nd}T$ vs initial $^{87}Sr/^{86}Sr$ and (b) initial $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ plot of Jharia kimberlite data (circular filled dots), Cretaceous Kerguelan plateau basalts (KE, *Storey et al.*, 1989; *Salters et al.*, 1992; *Frey et al.*, 2002; *Kent et al.*, 2002; *Neal et al.*, 2002), Pristine Kerguelen plume (PKP) basalts [*Weis et al.*, 1993, 1998], Rajmahal traps (RT I & II) [*Mahoney et al.*, 1983; *Storey et al.*, 1992; *Baksi*, 1995; *Kent et al.*, 1997), Crozet Archipelago basalts (CR) [*Mahoney et al.*, 1996], Conrad Rise lavas (CO) [*Borisova et al.*, 1996], and Southeast Indian Ridge (SEIR) [*Mahoney et al.*, 2002]. Fields for continental crust (CC) [*Taylor and McLennan*, 1985] and Kaapvaal Group II kimberlites (GIIK) [*Mitchell*, 1995] are also plotted. Numbers are DSDP sites. UG = upper group, LG = lower group.

for the RSB basalts [*Mahoney et al.*, 1983; *Storey et al.*, 1992; *Baksi*, 1995; *Kent et al.*, 1997], Cretaceous Kerguelen plateau and Broken Ridge basalts [*Frey et al.*, 2002; *Kent et al.*, 2002; *Neal et al.*, 2002], Cenozoic Kerguelen Archipelago basalts [*Weis et al.*, 1993, 1998], Recent Crozet Archipelago basalts [*Mahoney et al.*, 1996], Cretaceous (~80 Ma) lavas of the Ob and Lena sea mounts (Conrad Rise, *Borisova et al.* [1996]) and the Southeast Indian ridge basalts [*Mahoney et al.*, 2002].

[8] Sr-Nd isotopic data (Figure 2a) show that the Recent products of the Crozet plume ($^{87}Sr/^{86}Sr$ = 0.7040 to 0.7041 and ε_{Nd} = +3.5 to +4.3, *Mahoney et al.* [1996]) are dramatically different from the Jharia kimberlite. On the Sr-Pb isotope plot (Figure 2b), the Crozet lavas with appreciably higher $^{206}Pb/^{204}Pb$ ratios (18.79 to 19.18, *Mahoney et al.* [1996]) lie far outside the kimberlite field. Similarly, Sr, Nd and Pb isotopic compositions of the Cretaceous Conrad Rise lavas ($^{87}Sr/^{86}Sr$ = 0.7044 to 0.7053; ε_{Nd} = −0.8 to −7.7; $^{206}Pb/^{204}Pb$ = 17.33 to 18.28, *Borisova et al.* [1996]) are also different from the Jharia kimberlites.

[9] Though, earlier plate reconstructions of the Indian Ocean region for the Early Cretaceous by *Curray and Munasinghe* [1991] and *Muller et al.* [1993] suggested either Crozet or Conrad hotspots to be responsible for magmatism in eastern India, the distinctly different Sr-Nd-Pb isotopic compositions of the Conrad Rise and Crozet lavas do not suggest the influence of these hot spots in producing the Jharia kimberlites.

[10] On the other hand coeval RSB basalts show Pb isotopic similarity ($^{206}Pb/^{204}Pb$ − 17.97 to 18.03, $^{207}Pb/^{204}Pb$ − 15.52 to 15.66 and $^{208}Pb/^{204}Pb$ − 38.12 to 39.07; *Kent et al.* [1997]) with the Jharia kimberlite but large variations in both $^{87}Sr/^{86}Sr$ (Group I − 0.7040 to 0.7053; Group II − 0.7050 to 0.7084) and ε_{Nd} (Group I = 1.9 to 4.5; Group II = −6.7 to −0.2) isotopic compositions [*Mahoney et al.*, 1983; *Storey et al.*, 1992; *Baksi*, 1995; *Kent et al.*, 1997] in the former inhibit interpretation of the role of the kimberlite mantle source in the formation of the RSB basalts. The Early Cretaceous southern Kerguelen plateau basaltic flows from site 1136 (118–119 Ma; *Duncan* [2002]) also show Pb isotopic similarity ($^{206}Pb/^{204}Pb$ − 17.84 to 17.99, *Neal et al.* [2002]) but higher ε_{Nd} (+5.1 to +0.5) and lower $^{87}Sr/^{86}Sr$ (0.7046 to 0.7050) values. The slightly younger (112–110 Ma; *Kent et al.* [2002]) basalts at sites 749 and 750 from the same region have depleted Sr, Nd and lower $^{206}Pb/^{204}Pb$ isotopic compositions ($^{87}Sr/^{86}Sr$ = 0.7035 to 0.7053, ε_{Nd} = +2.6 to +5.5; $^{206}Pb/^{204}Pb$ = 17.38 to 17.92, *Frey et al.* [2002]). Basaltic lavas recovered at Élan Bank site 1137 (107–108 Ma; *Duncan* [2002]) have the following $^{87}Sr/^{86}Sr$ (Upper Group − 0.7048 to 0.7050; Lower Group − 0.7055 to 0.7059), ε_{Nd} (Upper Group −1.0 to 0.0; Lower Group −2.8 to −1.0) and $^{206}Pb/^{204}Pb$ (Upper Group − 17.99 to 18.02; Lower Group − 17.96 to 18.02) isotopic compositions (*Ingle et al.* [2002]). Compared to Jharia kimberlites the upper group of lavas have lower Sr and Nd isotopic compositions, whereas the lower group overlaps with them. Pb isotopic compositions of both the upper and lower groups are similar to the Jharia kimberlite field. Tholeiitic basalts at site 1138 (100–101 Ma; *Duncan* [2002]) in the central Kerguelen plateau have comparatively depleted Sr and Nd isotopic compositions ($^{87}Sr/^{86}Sr$ −0.7046 to 0.7048; ε_{Nd} +0.3 to +0.9) but $^{206}Pb/^{204}Pb$ isotopic compositions (17.90 to 17.98; *Neal et al.* [2002]) again overlap the kimberlite data. Still younger basalts (~85 Ma, *Pringle et al.* [1997]) from this region (site 747) have similar $^{87}Sr/^{86}Sr$ (0.7052 to 0.7057) and ε_{Nd} (−2.1 to −3.8; *Frey et al.* [2002]) but their $^{206}Pb/^{204}Pb$ ratios (17.28 to 17.64) are appreciably lower than the Jharia kimberlite. However, Broken Ridge basalts from sites 1141 and 1142 (94–95 Ma; *Duncan* [2002]) have identical $^{87}Sr/^{86}Sr$ (0.7053 to 0.7056), $^{206}Pb/^{204}Pb$ (17.90 to 18.02) and $^{207}Pb/^{204}Pb$ (15.59 to 15.62) with only marginally higher ε_{Nd} compositions (+0.3 to + 0.7; *Neal et al.* [2002]). Sr-Nd-Pb isotopic compositions of all the Cenozoic Kerguelen Archipelago basalts ($^{87}Sr/^{86}Sr$ = 0.7051 to 0.7058; ε_{Nd} = −0.2 to −2.9; $^{206}Pb/^{204}Pb$ = 18.02 to 18.27; $^{207}Pb/^{204}Pb$ = 15.54 to 15.58, *Weis et al.* [1993, 1998]) also overlap the kimberlite data. According to *Weis et al.* [1993, 1998] these basalts were the purest representatives of the Kerguelen plume (pristine Kerguelen plume 'PKP' lavas), because of their eruption in an intraplate setting, and due to their remarkable similarity in Sr-Nd-Pb isotopic signature despite diverse composition (transitional and alkali basaltic and basanitic) and age (30 to 0.1 Ma). Recently, *Ingle et al.* [2003] have however, assigned distinct compositions for the Kerguelen plume source during Cretaceous and Cenozoic periods. The Cretaceous Kerguelen plateau and Broken Ridge basalts characterized by primitive mantle like Sr, Nd and Pb isotopic compositions represent their Cretaceous composition, whereas, the Mont Crozier basalts with moderately radiogenic Pb isotopic compositions ($^{206}Pb/^{204}Pb$ = ~18.60; $^{87}Sr/^{86}Sr$ = 0.70501 to 0.70535; ε_{Nd} = −1.78 to 0.18) depicted the Cenozoic signature of the Kerguelen plume. Earlier, *Neal et al.* [2002] were also of the opinion that Broken Ridge lavas from sites 1141 and 1142 represented the Cretaceous Kerguelen plume composition. Therefore, the isotopic similarity of the Jharia kimberlites, Broken Ridge basalts, several Kerguelen Plateau basalts and also PKP lavas, combined with recent plate reconstruction of the Indian Ocean for the Early Cretaceous period [*Kent et al.*, 2002], and location (paleolatitudinal position) of the Kerguelen hot spot (based on new paleomagnetic results, *Antretter et al.* [2002]) close to the eastern Indian margin, just after 120 Ma ago, is clear evidence of their derivation from a common source in the Kerguelen plume.

[11] But the large variation in Sr-Nd isotopic compositions of the RSB lavas raise doubts about the extent of Kerguelen plume involvement in them. In fact, similarity of some of the RSB basalt samples (Group I, having depleted isotopic compositions) to SEIR basalts [*Mahoney et al.*, 2002] supports Anderson's contention that these [*Anderson et al.*, 1992] flood basalts were a manifestation of decompression melting within the depleted upper mantle. However, based on extensive trace element geochemistry, the Sr-Nd isotopic variations not only in the RSB but also in some of the Kerguelen plateau basalts (from sites 747, 750, 749, 1136, 1137, 1138) were inferred to have been caused due to variable assimilation of continental lithosphere into the Kerguelen starting plume head [*Frey et al.*, 2002; *Ingle et al.*, 2002; *Neal et al.*, 2002]. This inference is supported by identical $^{206}Pb/^{204}Pb$ isotopic ratios in the RSB, Kerguelen plateau basalts (sites 749, 1136, 1137 and 1138), Broken Ridge and Cenozoic Kerguelen Archipelago lavas (except

Mont Crozier). The $^{206}Pb/^{204}Pb$ values in these rocks preserved pristine Kerguelen signatures despite contamination because of their similarity with the contaminant material, whether upper mantle (SEIR basalts, avg. $^{206}Pb/^{204}Pb$-17.99, *Mahoney et al.* [2002]) or continental components (17.8–18.0, *Frey et al.* [2002]).

5. Conclusions

[12] The Sr-Nd-Pb isotopic compositions of Jharia kimberlite are very similar to those of Cretaceous Broken Ridge, Kerguelen Plateau and Cenozoic PKP basalts, which are inferred to represent the principle component in the Kerguelen plume. This close similarity suggests that the Kerguelen hotspot was responsible for the ~117 Ma magmatic activity in East India.

[13] **Acknowledgments.** We thank the Director of NGRI for his support and permission to publish this paper, Prof. D. Mukhopadhyay for providing the samples used in this study, Dr. I. H. Campbell, Dr K. V. Subbarao, Dr. S. Haggerty and an anonymous reviewer for their valuable comments on an earlier version of this paper. This study was supported by DST grants.

References

Anderson, D. L., Y. S. Zhang, and T. Tanimoto, Plume heads, continental lithosphere, flood basalts and tomography, in *Magmatism and the Causes of Continental break-up*, *Spec. Publ.*, *68*, edited by B. C. Storey, T. Alabaster, and R. J. Pankhurst, 99–124, The Geological Society, London, 1992.

Anil, Kumar, K. Gopalan, and K. Bhandari, Sm-Nd and Rb-Sr ages of the eucrite Piplia Kalan, *Geochim. Cosmochim. Acta*, *63*, 3997–4001, 1999.

Antretter, M., B. Steinberger, F. Heider, and H. Soffel, Paleolatitudes of the Kerguelen hot spot: New paleomagnetic results and dynamic modeling, *Earth Planet. Sci. Lett.*, *203*, 635–650, 2002.

Baksi, A. K., Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, northeastern India, *Chem. Geol.*, *121*, 73–90, 1995.

Borisova, A. Y., V. V. Nikutin, B. V. Belyatskii, G. V. Ovchinnikova, K. V. Levskii, and M. M. Sushohevskii, Late alkaline lavas of the Ob and Lena Seamounts (Conrad Rise, Indian Ocean): Geochemistry and characteristics of mantle sources, *Geochem. Internat.*, *34*, 503–517, 1996.

Curray, J. R., and T. Munasinghe, Origin of the Rajmahal traps and the 85°E Ridge: Preliminary reconstructions of the trace of the Crozet Hotspot, *Geology*, *19*, 1237–1240, 1991.

Duncan, R. A., A time frame for construction of the Kerguelen plateau and Broken Ridge, *J. Petrol.*, *43*, 109–1119, 2002.

Frey, F. A., D. Weis, A. Y. Borisova, and G. Xu, Involvement of continental crust in the formation of the Cretaceous Kerguelen Plateau: New perspectives from ODP Leg 120 sites, *J. Petrol.*, *43*, 1207–1239, 2002.

Ingle, S., D. Weis, J. S. Scoates, and F. A. Frey, Relationship between the earlier Kerguelen plume and continental flood basalts of the paleo-Eastern Gondwanan margins, *Earth. Planet. Sci. Lett.*, *197*, 35–50, 2002.

Ingle, S., D. Weis, S. Doucet, and Matlielli, Hf isotopic constraints on mantle sources and shallow-level contaminations during Kerguelen hotspot activity since ~120 Ma, *Geochim. Geophys. Geosyst.*, *4*, doi:10.1029/2002GL000482, 2003.

Kent, R. W., A. D. Saunders, P. D. Kompton, and N. N. Ghose, Rajmahal basalt's, Eastern India: Mantle sources and melt distribution at a volcanic rifted margin, in *Large Igneous provinces: continental, oceanic and planetary flood volcanism*, edited by J. J. Mohaney and M. F. Coffin, *Geophysical Monograph*, *AGU*, *100*, 145–182, 1997.

Kent, R. W., S. P. Kelley, and M. S. Pringle, Mineralogy and $^{40}Ar/^{39}Ar$ geochronology of orangeites (Group II kimberlites) from the Damodar Valley, eastern India, *Min. Mag.*, *62*, 313–323, 1998.

Kent, R. W., M. S. Pringle, R. D. Muller, A. D. Saunders, and N. C. Ghose, Ar/Ar geochronology of the Rajmahal basalt, India, and their relationship to the Kerguelen plateau, *J. Petrol.*, *43*, 1141–1153, 2002.

Mahoney, J. J., D. W. Graham, D. M. Christie, K. T. M. Johnson, L. S. Hall, and D. L. Vonderhaar, Between a hotspot and a cold spot: Isotopic variation in the Southeast Indian Ridge asthenosphere, 86°E–118°E, *J. Petrol.*, *43*, 1155–1176, 2002.

Mahoney, J. J., J. D. Macdougall, G. W. Lugmair, and K. Gopalan, Kerguelan hotspot source for Rajmahal Traps and Ninetyeast Ridge?, *Nature*, *303*, 385–389, 1983.

Mahoney, J. J., W. M. White, B. G. J. Upton, C. R. Neal, and R. A. Scrutton, Beyond EM-1: Lavas from the Afanasy-Nikitin rise and the Crozet Archipelago, Indian Ocean, *Geology*, *24*, 615–618, 1996.

Middlemost, E. A. K., D. K. Paul, and I. R. Fletcher, Geochemistry and mineralogy of the minette-lamproite association from the Indian Gondwanas, *Lithos*, *22*, 31–42, 1988.

Mitchell, R. H., (Eds.), *Kimberlites, orangeites, and related rocks*, Plenum Press, 1995.

Muller, R. D., J. Y. Royer, and L. A. Lowver, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracts, *Geology*, *21*, 275–278, 1993.

Neal, C. R., J. J. Mahoney, and W. J. Chazey, Mantle sources and the highly variable role of continental lithosphere in basalt petrogenesis of the Kerguelen plateau and Brocken Ridge LIP: Results from ODP Leg 183, *J. Petrol.*, *43*, 1177–1205, 2002.

Pande, K., and J. S. Ray, Ar/Ar ages of the Sylhet traps: Evidence for coeval Rajmahal Sylhet volcanism, paper presented at *8th Indian Soc. Mass Spec. Symp.*, *8*, 574–575, 1999.

Pringle, M. S., M. Storey, and J. Wijbrans, Ar/Ar geochronology of Mid-Cretaceous Indian ocean basalt's: Constraints on the origin of the large flood basalt provinces, *Eos Trans., AGU*, *75*, 728, 1994.

Pringle, M. S., M. F. Coffin, and M. S. Storey, Estimated melt production of the Kerguelen hot spot, *EOS Trans., AGU*, *78*, 728, 1997.

Rock, N. M. S., B. J. Griffin, A. D. Edgar, D. K. Paul, and J. M. Hergt, A spectrum of potentially diamondiferous lamproites and minettes from the Jharia coalfield, eastern India, *J. Volcanol. Geotherm. Res.*, *50*, 55–83, 1992.

Salters, V. J. M., J. H. Storey, J. H. Sevigny, and H. Whitechurch, Trace element and isotopic characteristics of Kerguelen-Heard Plateau basalts, *Proc. Ocean Drill. Prog., Sci. Results*, *120*, 55–62, 1992.

Sarangi, S., K. Gopalan, and S. Kumar, Pb-Pb age of earliest megascopic, enkaryotic algae bearing Rohtas Formation, Vindhyan Supergroup, India: Implications for Precambrian atmospheric evolution, *Precamb. Res*, in press, 2003.

Storey, M., A. D. Saunders, J. Tarney, I. Gibson, M. J. Norry, M. F. Thirlwall, P. Leat, R. N. Thompson, and M. A. Menzies, Contamination of Indian Ocean asthenosphere by the Kerguelen - Heard mantle plume, *Nature*, *338*, 574–576, 1989.

Storey, M., R. W. Kent, A. D. Saunders, V. J. Salters, J. Hergt, H. Whitechurch, J. H. Sevigny, M. F. Thirlwall, P. Leat, N. C. Ghose, and M. Gifford, Lower Cretaceous rocks in continental margins and their relationship to the Kerguelen plateau, *Proc. of the Ocean Drill. Prog., Sci. Results*, *120*, 33–53, 1992.

Subramanyam, C., N. K. Thakur, T. Gangadhar Rao, R. Khanna, M. V. Ramana, and V. Subrahmanyam, Tectonics of the Bay of Bengal: New insights from satellite-gravity and ship-borne geophysical data, *Earth Planet. Sci. Lett.*, *171*, 237–251, 1999.

Taylor, S. R., and S. M. McLennan (Eds.), *The continental crust: Its composition andevolution*, 312 pp., Blackwell, Oxford, 1985.

Weis, D., F. A. Frey, H. Leyrit, and I. Gautier, Kerguelen archipelago re-visited: Geochemical and isotopic study of the southeast province lavas, *Earth. Planet. Sci. Lett.*, *118*, 101–119, 1993.

Weis, D., F. A. Frey, A. Giret, and J. M. Cantagrel, Geochemical characteristics of the youngest volcano (Mont Ross) in the Kerguelen archipelago: Inferences for magma mixing and composition of the Kerguelen plume, *J. Petrol.*, *39*, 973–994, 1998.

A. Kumar, A. M. Dayal, and V. M. Padmakumari, National Geophysical Research Institute, Hyderabad 500 007, India. (ganilkumar@rediffmail.com)