

# $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology of the Rajmahal Basalts, India, and their Relationship to the Kerguelen Plateau

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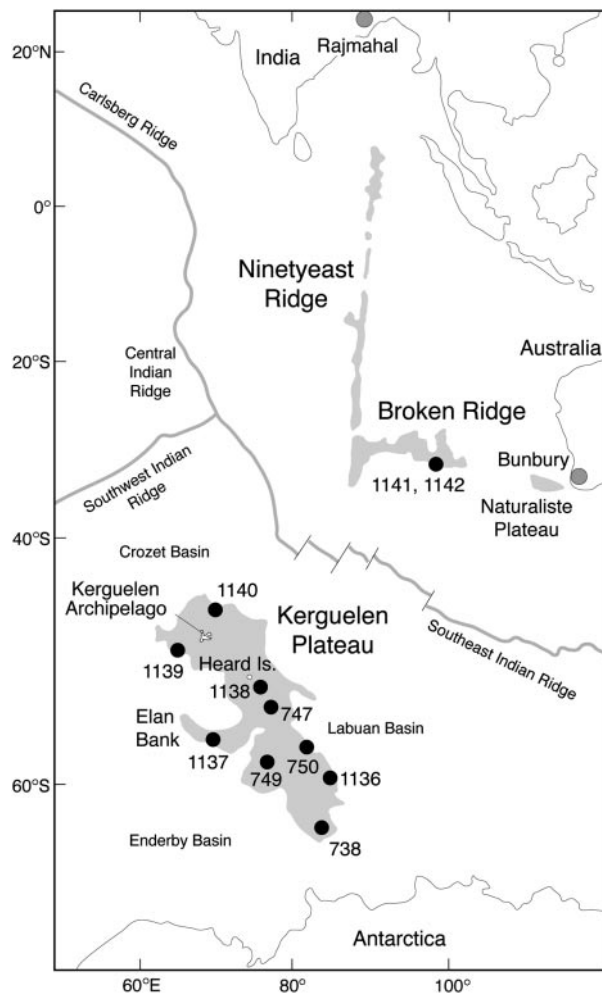
*During the mid-Cretaceous, extensive magmatism occurred in the Indian Ocean to form volcanic portions of the southern and central Kerguelen Plateau, Elan Bank and Broken Ridge. Basalt was erupted also along the rifted margin of eastern India (Rajmahal). We investigated the ages of these Indian basalts using  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental-heating experiments on whole-rocks. Our results are consistent with the hypothesis that the lava pile of  $\sim 230$  m thickness in the Rajmahal Hills, Jharkhand, and alkalic basalts in the Bengal Basin were emplaced at  $\sim 118$  Ma. Dykes intruded to the SW of the Rajmahal Hills appear to be 2–3 Myr younger than these lavas. Magmatic activity in eastern India therefore was contemporaneous with the final stage of volcanism at Ocean Drilling Program Site 1136 on the Southern Kerguelen Plateau (119–118 Ma), but older than final magmatism at Sites 749 and 750 on the Southern Kerguelen Plateau (112–110 Ma), Site 1137 on Elan Bank (108 Ma) and Site 1138 on the Central Kerguelen Plateau (100 Ma). By combining these age data with plate reconstructions that take into account the motion of hotspots in a convecting mantle, we suggest that eruption of the Rajmahal basalts, formation of the Southern Kerguelen Plateau, and Elan Bank's separation from India are best explained by the presence of the Kerguelen hotspot close to the eastern Indian margin just after 120 Ma.*

KEY WORDS: *Rajmahal; Kerguelen Plateau; argon; hotspot; plate reconstructions*

## INTRODUCTION

The Kerguelen large igneous province (LIP) is widely believed to be related to hotspot activity over a period of up to 130 Myr [Fig. 1; e.g. Frey *et al.* (2000)]. In addition to submarine parts of the province, the LIP includes Cretaceous basalts on the rifted margins of eastern India and Western Australia (the Rajmahal and Bunbury–Naturaliste Plateau basalts, respectively); mafic alkaline intrusive rocks contemporaneous with these lavas crop out in eastern India and East Antarctica. The Rajmahal and Bunbury lavas have been the subject of several studies (Mahoney *et al.*, 1983; Storey *et al.*, 1992; Baksi, 1995; Frey *et al.*, 1996; Kent *et al.*, 1997) which inferred a link between these rocks and the Kerguelen hotspot. However, Kent *et al.* (1997) noted that Pb–Nd–Sr isotope ratios and trace element data for the Rajmahal basalts are equivocal with respect to a material input from this hotspot, and Frey *et al.* (1996) reached a similar conclusion for the Bunbury lavas. These data have recently been supplemented with Hf isotope data for the Rajmahal, Bunbury and Elan Bank lavas (Ingle *et al.*, 2001), which show strong isotopic similarities to each other and to Kerguelen Archipelago basalts. These similarities were interpreted to imply a common hotspot source for magmatism at each location.

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**Fig. 1.** Map of the eastern Indian Ocean at the present day, showing location of the Kerguelen large igneous province (Rajmahal and Bunbury basalts, Kerguelen Plateau–Elan Bank, Broken Ridge and Naturaliste Plateau). ●, Ocean Drilling Program Leg 119, 120 and 183 sites.

In this study, we use  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental-heating experiments to investigate the age and duration of volcanism in the Rajmahal Hills and adjacent areas of eastern India. We compare our results with the Rajmahal  $^{40}\text{Ar}/^{39}\text{Ar}$  data of Baksi (1995) and with radiometric ages obtained from other (Cretaceous) parts of the Kerguelen LIP. Finally, we place these observations in a geodynamic context by providing new plate tectonic reconstructions of the Indian Ocean during the Cretaceous.

## THE RAJMAHAL BASALTS: GEOLOGICAL BACKGROUND

The Rajmahal basalts form a low-lying group of hills in eastern Jharkhand state, previously southern Bihar

*Table 1: Chemical characteristics of Rajmahal Group I and Group II basalts*

Ratio	Group I	Group II
Ti/Zr	82–120	45–78
Zr/Y	2.5–3.9	3.9–5.3
Ce/Y	0.4–1.0	0.9–1.4
$^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$	0.7037–0.7084	0.7050–0.7091
$\epsilon\text{Nd}_{(t)}$	+5.1 to +0.1	+0.1 to –6.7

After Kent *et al.* (1997).

( $24^{\circ}15'$  to  $25^{\circ}15'\text{N}$ ,  $87^{\circ}20'$  to  $87^{\circ}45'\text{E}$ ) [Fig. 2; Ball (1877)]. They consist mainly of quartz-normative tholeiites interbedded with thin bentonites or tuffs (Sengupta, 1988). Two tholeiitic magma types are present, as described by Storey *et al.* (1992) and Kent *et al.* (1997). Key geochemical characteristics of these magma types, termed Group I and Group II basalts, are listed in Table 1. In the Rajmahal Hills the maximum exposed thickness of lava is  $\sim 230$  m or approximately ten flows (Kent *et al.*, 1997). However,  $\sim 332$  m of basalt—including alkalic lava—was drilled in the western Bengal Basin, to the east of the Rajmahal Hills (Biswas, 1963). Subsequently, a basalt–rhyolitic tuff sequence some 550–600 m thick was mapped to the north of Sylhet, Meghalaya ( $25^{\circ}13'\text{N}$ ,  $91^{\circ}21'\text{E}$ ) (Talukdar & Murthy, 1970). In total, the Rajmahal–Sylhet–Bengal Basin lavas occupy an area of about  $2 \times 10^5$  km<sup>2</sup> [see Kent *et al.* (1997), Fig. 3].

Previous K–Ar,  $^{40}\text{Ar}/^{39}\text{Ar}$  and palaeomagnetic work on the Rajmahal and Sylhet basalts was summarized by Baksi (1995) and Kent *et al.* (1997). Their reviews and new  $^{40}\text{Ar}/^{39}\text{Ar}$  data presented by Baksi (1995) emphasized the difficulty of obtaining reliable ages from the fine-grained, slightly altered tholeiites that typify the exposed Rajmahal lava sequence. However, Baksi (1995) did obtain a concordant age plateau of  $117.5 \pm 0.5$  Ma (all errors here reported at  $1\sigma$  significance level) for tholeiite sample A-531 from the eastern Rajmahal Hills, the relative stratigraphic position of which is unknown. Baksi also reported concordant age plateaux for three basalts recovered from boreholes in the Bengal Basin:  $116.9 \pm 2.3$  Ma for an olivine tholeiite from the Jalangi borehole,  $117.0 \pm 0.3$  Ma for an alkali basalt from the Debagram borehole, and two ages ( $117.3 \pm 1.0$  Ma,  $117.1 \pm 0.3$  Ma) for an alkali basalt from the Galsi well [see Baksi (1995) for borehole locations]. Unfortunately, the stratigraphic positions of the borehole samples relative to tholeiites exposed in the Rajmahal Hills are uncertain. The alkalic lava sampled in the Galsi borehole lies

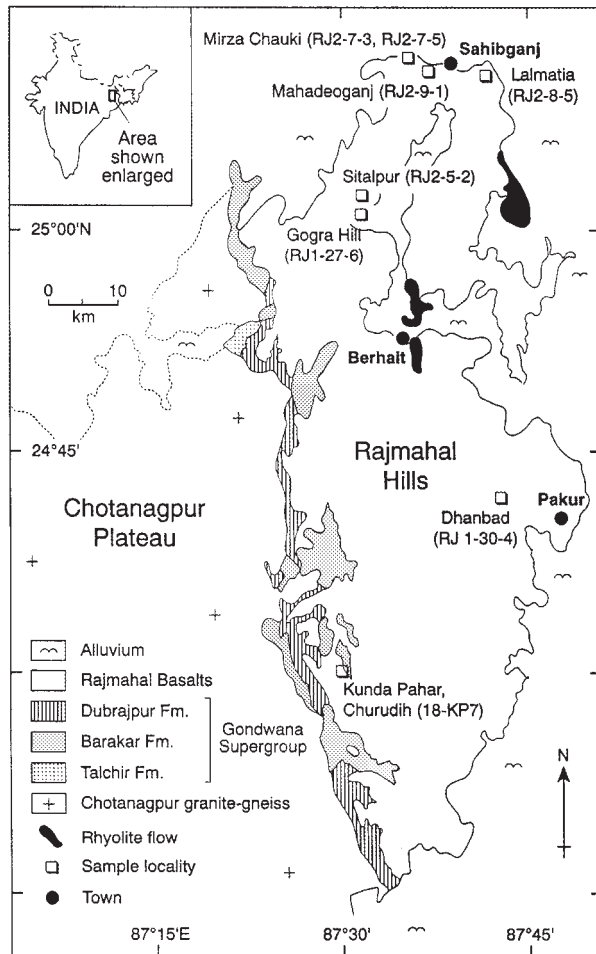


Fig. 2. Location map of the Rajmahal Hills, Jharkhand state, eastern India [modified from Kent *et al.* (1997)]. ■, Sample localities for lavas, with sample numbers identified in brackets.

beneath a sequence of tholeiitic lava flows of  $\sim 109$  m thickness. The borehole ultimately was abandoned in tholeiitic lava just below the depth at which the alkali basalt was encountered (Biswas, 1963); hence the total thickness of Rajmahal basalt in the subsurface at Galsi is unknown. The Debagram alkali basalt lies close to the top of a tholeiitic lava sequence that is overlain unconformably by Miocene–Pliocene sediments (Biswas, 1963). The well was abandoned in basalt and the total thickness of tholeiitic lava is unknown.

The ages noted above are consistent with the fact that most lavas in the Rajmahal Hills show normal magnetic polarity (Klootwijk, 1971), as expected for rocks formed during the Cretaceous Normal Polarity Superchron [120.4–83.5 Ma on the timescale of Gradstein *et al.* (1994)]. Continuing work involving palaeointensity measurements (Tarduno *et al.*, 2001) should determine whether reversed magnetizations recorded in lavas near the base of the basalt pile in the western Rajmahal Hills (e.g.

Klootwijk, 1971) reflect a true reversal event or an excursion.

Three questions remain unanswered from previous work: is there a difference in the age of lavas from the bottom and the top of the Rajmahal lava pile? Is there any difference in age between samples of the two Rajmahal tholeiitic magma types? Is there a difference in age between lavas in the Rajmahal Hills and the Bengal Basin?

## SAMPLES AND METHODS

Incremental-heating experiments were performed on seven lava samples from the Rajmahal Hills and three dyke samples from the Bihar Mica Belt and Damodar Valley, to the SW of the Rajmahal Hills. Sample localities for the lavas are shown in Fig. 2; those for the dykes have been given by Kent *et al.* (1997, fig. 3). Specimens were chosen on the basis of a lack of visible alteration and low weight loss on ignition (0–0.6 wt %).  $K_2O$  contents range from 0.2 to 1 wt %, with the highest values being recorded in Group II basalts (Kent *et al.*, 1997).

Small cores  $\sim 5.5$  mm in diameter were drilled from the freshest parts of whole-rock samples, trimmed with a water-cooled wafer saw to  $\sim 1$  mm thick, ultrasonically cleaned in reagent-grade acetone for 15 min, and sealed in air in quartz vials. Samples were irradiated for 18 h at 1 MW in the Cd-shielded CLICIT facility at the Oregon State University TRIGA reactor. The flux monitor Taylor Creek Rhyolite sanidine 85G003 [28.34 Ma, Renne *et al.* (1998)] was loaded into copper packets and placed every  $\sim 7$  mm in each of the vials; the neutron flux monitor  $\bar{f}$  is conservatively known to better than 0.3% at any given position in the vials. On the basis of previous analyses of optical grade  $CaF_2$  and degassed, Fe-doped K-silicate glass irradiated in the CLICIT facility at OSU, corrections for undesirable neutron-induced reactions on  $^{40}K$  and  $^{40}Ca$  are:  $[^{40}Ar/^{39}Ar]_K = 0.00086$ ;  $[^{36}Ar/^{37}Ar]_{Ca} = 0.000264$ ;  $[^{39}Ar/^{37}Ar]_{Ca} = 0.000673$ .

Samples were analysed at the Scottish Universities Environmental Research Centre, East Kilbride. Individual rock cores were loaded into a glass side-arm over a double vacuum furnace attached to a gas clean-up system. Incremental-heating experiments consisted of between nine and 18 individual steps. Following a 15 min heating step and 10 min additional clean-up stage, the purified gas was analysed on an EMI secondary electron multiplier operated at a gain of  $\sim 5000$ , with an MAP 215 rare gas mass spectrometer. Analytical procedures, blanks and corrections, and data reduction for each experiment were similar to those described by Singer & Pringle (1996). All errors are reported here as 1 SD of analytical precision. We follow Pringle's (1993) criteria

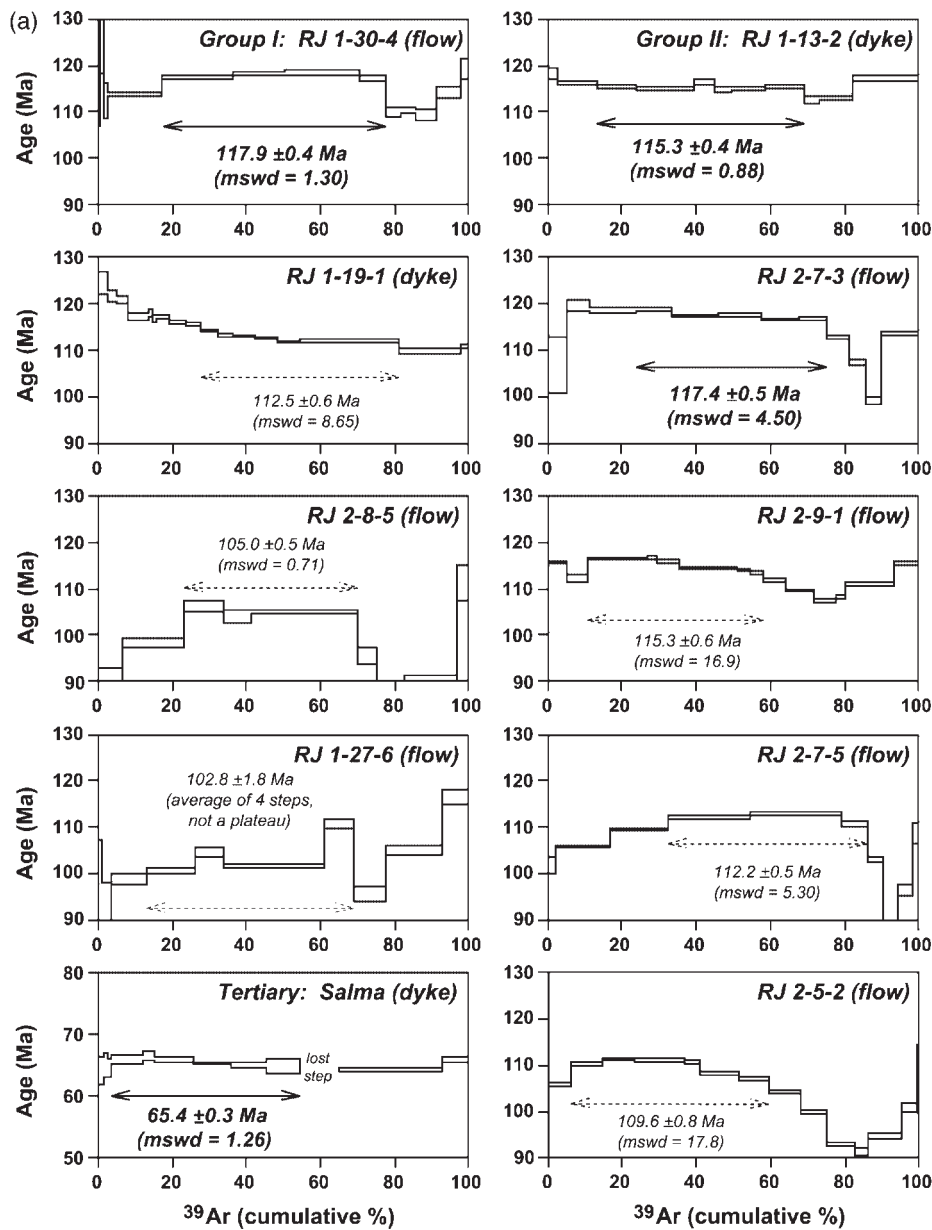
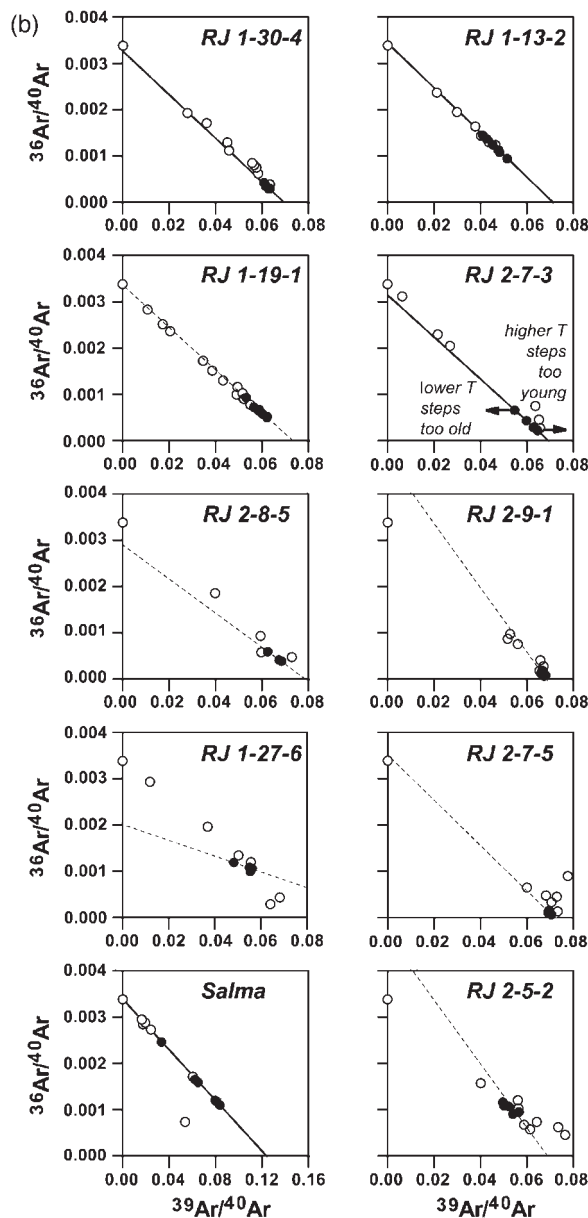


Fig. 3.

for testing whether  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental-heating experiments on (partially) altered basalts reveal accurate estimates of crystallization age. However, we now calculate a single-variable F-ratio statistic to test for significant scatter in the age plateau, in addition to a two-variable test for significant scatter in the isochron. We also prefer—for reasons discussed below—to use the weighted mean plateau age rather than the isochron age as the best estimate of crystallization age of a sample.

### $^{40}\text{Ar}/^{39}\text{Ar}$ RESULTS

Our results are summarized in Table 2, which also includes the reliable ages from Baksi (1995). The complete dataset from our experiments is available for downloading from the *Journal of Petrology* Web site (<http://www.petrology.oupjournals.org>). Age spectra for our samples are shown in Fig. 3a, and Fig. 3b shows inverse isochrons for the same samples.



**Fig. 3.** (a)  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental-heating age spectra for whole-rock samples from the Rajmahal basalt province, eastern India. Individual steps are shown  $\pm 1\sigma$  high. (b)  $^{40}\text{Ar}/^{39}\text{Ar}$  inverse isochron diagrams for the samples shown in (a). ●, steps included in the age plateau and isochron calculations. (See main text for discussion.)

### Rajmahal Group I samples

Sample RJ 1-30-4, an aphyric basalt from the lowermost lava flow exposed at Dhanbad in the eastern Rajmahal Hills, yielded the only reliable crystallization age estimate for the Group I lavas analysed in this study. Although both the lowest and highest temperature steps have low apparent ages, the mid-temperature steps with 60.2% of the  $^{39}\text{Ar}$  released reveal a concordant age plateau at  $117.9 \pm 0.4$  Ma and an acceptable mean square weighted deviation (MSWD) of 1.30 (Table 2). The isochron is

similarly concordant at  $117.4 \pm 2.0$  Ma, with a  $\text{SUMS}/(n - 2)$  of 1.80 and  $^{40}\text{Ar}/^{36}\text{Ar}$  intercept statistically indistinguishable from the atmospheric value of 295.5 (Table 2).

Sample RJ 1-19-1 was collected from a dolerite dyke at Kalidaspur in the Raniganj Basin, Damodar Valley. This sample displays an age spectrum typical of whole rocks that have undergone significant irradiation-induced  $^{39}\text{Ar}$  recoil redistribution (Fig. 3a; see also online dataset). A mid-temperature ‘plateau’ analysis yields an MSWD

Table 2: Summary of Ar–Ar step-heating experiments on whole-rock basalt samples from the Rajmahal Hills, Damodar Valley, and Bengal Basin, eastern India

Sample	Material	Source	Weight (g)	K/Ca (total)	Total-fusion age (Ma ± 1σ)	Age spectrum (plateau) analysis			Isochron analysis				
						Increments used (n of total) (°C)	<sup>39</sup> Ar (%)	Plateau age (Ma ± 1σ)	MSWD	Isochron age (Ma ± 1σ)	<sup>40</sup> Ar/ <sup>39</sup> Ar intercept ± 1σ	SUMS/(n – 2)	
<i>Rajmahal Quartz Tholeiite Group I</i>													
RJ 1-30-4	lava	this study	0.070	0.022	116.0 ± 0.4	5 of 14	750–920	60.2	117.9 ± 0.4	1.30	117.4 ± 2.0	308.5 ± 46.7	1.80
A-531	lava	Baksi (1995)	1.450	n.r.	117.3 ± 1.3	3 of 7	650–790	65	117.5 ± 0.5	n.r.	114.7 ± 3.8	420 ± 220	0.05
RJ 1-19-1	dyke	this study	0.071	0.183	113.6 ± 0.4	7 of 18	890–1100	53.6	112.5 ± 0.5	8.64*	112.2 ± 1.3	299.5 ± 14.1	11.71*
RJ 2-8-5	lava	this study	0.065	0.019	98.5 ± 0.5	3 of 9	820–880	47.1	105.0 ± 0.5	0.71†	102.3 ± 2.6	347.4 ± 49.3	0.15†
RJ 1-27-6	lava	this study	0.068	0.022	103.1 ± 0.5	4 of 10	750–1000	56.1	102.8 ± 1.8	24.64*	70.2 ± 13.1	499.4 ± 92.8	5.89*
<i>Rajmahal Quartz Tholeiite Group II</i>													
RJ 1-13-2	dyke	this study	0.064	0.155	115.5 ± 0.4	7 of 13	690–910	55.8	115.3 ± 0.4	0.88†	115.5 ± 0.9	294.5 ± 4.1	1.28†;
RJ 2-7-3	lava	this study	0.063	0.053	115.3 ± 0.5	5 of 12	670–890	51.3	117.4 ± 0.5	4.50†	116.3 ± 0.5	321.1 ± 7.9	1.38†
RJ 2-9-1	lava	this study	0.062	0.141	113.3 ± 0.3	6 of 14	690–890	47.2	115.3 ± 0.6	16.91*	116.3 ± 1.3	210.8 ± 84.2	18.94*
RJ 2-7-5	lava	this study	0.062	0.039	108.3 ± 0.3	4 of 12	750–880	53.6	112.2 ± 0.5	5.30*	112.3 ± 1.6	287.3 ± 146.6	8.14*
RJ 2-5-2	lava	this study	0.068	0.062	104.3 ± 0.3	6 of 14	650–860	53.5	109.6 ± 0.8	17.83*	112.4 ± 2.0	272.3 ± 14.9	17.67*
<i>Bengal Basin boreholes</i>													
Debagram	alkali basalt	Baksi (1995)	0.430	n.r.	117.6 ± 1.0	4 of 8	640–890	48	117.0 ± 0.3	n.r.	116.9 ± 1.1	297 ± 11	0.19
Galsi	alkali basalt	Baksi (1995)	0.100	n.r.	118.1 ± 1.1	5 of 9	740–1060	88	117.3 ± 1.0	n.r.	116.2 ± 0.3	329 ± 30	0.64
Jalangi	ol. tholeiite	Baksi (1995)	0.120	n.r.	118.0 ± 0.6	4 of 7	800–1080	70	117.1 ± 0.3	n.r.	combined, 2 experiments,	9 of 16 steps	
		Baksi (1995)	1.050	n.r.	113.8 ± 2.0	3 of 7	40–810	63	116.9 ± 2.3	n.r.	114.2 ± 2.5	430 ± 140	1.8
<i>Tertiary</i>													
Salma	dyke	this study	0.070	0.066	70.7 ± 0.3	6 of 13	750–1000	50.8	65.4 ± 0.3	1.26	65.1 ± 0.3	297.3 ± 1.2	1.19

\*Discordant experiments.

†Apparently concordant or only somewhat discordant experiments; see main text for discussion.

n.r., not reported. Ages from Baksi (1995) relative to 27.95 Ma for Fish Canyon Tuff biotite FCT-3, except for the Debagram basalt, which is relative to 162.9 Ma for USGS biotite SB-3. Ages from this study reported relative to 28.34 Ma for Taylor Creek Rhyolite sanidine 85G003 (Renne *et al.*, 1998). All errors reported as 1 SD of analytical precision. Ages shown in bold type are considered to be the most reliable.

of 8.64; the isochron  $\text{SUMS}/(n - 2)$  of 11.71 shows a similar discordance (Table 2). Both of these analyses indicate a statistically significant source of geological and/or experimental disturbance.

Sample RJ 2-8-5, from the topmost flow of two exposed lavas at Ambadiha in the northeastern Rajmahal Hills, shows an apparently concordant plateau age at  $105.0 \pm 0.5$  Ma and similar isochron analysis. However, the plateau incorporates only three of nine steps with less than half of the  $^{39}\text{Ar}$  released, and the rest of the experiment shows significantly younger ages (Fig. 3a). Therefore, we cannot accept this experiment as a reliable estimate of the crystallization age of the sample.

The age spectrum from the last Group I sample dated here, RJ 1-27-6 from the topmost of two exposed flows at Gogra Hill in the northwestern Rajmahal Hills, is clearly discordant (Fig. 3a). The  $\sim 103$  Ma weighted average of the four mid-temperature steps and the  $\sim 103$  Ma total gas age are best considered minimum age estimates.

### Rajmahal Group II samples

Sample RJ 1-13-2, from a dyke exposed in a quarry at Meghatari, 4 km NW of Koderma, Bihar Mica Belt, is a clinopyroxene–plagioclase–phyric dolerite. This sample yielded seven concordant steps with 55.8% of the  $^{39}\text{Ar}$  released, giving a plateau age of  $115.3 \pm 0.4$  Ma and MSWD of 0.88. The isochron age of  $115.5 \pm 0.9$  Ma, with  $\text{SUMS}/(n - 2)$  of 1.28 and  $^{40}\text{Ar}/^{36}\text{Ar}$  intercept of  $294.4 \pm 4.1$ , is similarly concordant, and both are considered reliable estimates of the crystallization age of this sample.

Sample RJ 2-7-3 is a fine- to medium-grained, clinopyroxene–phyric basalt from the second lava flow above the base of the section exposed at Mirza Chauki, northern Rajmahal Hills. This sample has the step-wise decreasing age spectrum attributed to  $^{39}\text{Ar}$  recoil as discussed above. A mid-temperature plateau, including five steps with 51.3% of the  $^{39}\text{Ar}$  released, has a weighted mean plateau age of  $117.4 \pm 0.5$  Ma but high MSWD of 4.5, indicating a statistically significant amount of excess scatter about the mean. The isochron analysis is not significantly different, yielding an apparently concordant age of  $116.3 \pm 0.5$  Ma and acceptable  $\text{SUMS}/(n - 2)$  of 1.28, but the  $^{40}\text{Ar}/^{36}\text{Ar}$  intercept of  $321.1 \pm 7.9$  is significantly higher than the atmospheric value of 295.5.

High  $^{40}\text{Ar}/^{36}\text{Ar}$  intercepts are typically interpreted as indicative of a trapped  $^{40}\text{Ar}/^{36}\text{Ar}$  component more radiogenic than the atmospheric composition—so-called ‘excess argon’—and the isochron age is usually taken as the most reliable estimate of the crystallization age for such samples. However, we would not expect an ‘excess argon’ trapped component in a holocrystalline, subaerial

lava flow such as sample RJ 2-7-3. Upon closer inspection, we observe that the decreasing ages of the plateau steps (i.e. decreasing radiogenic  $^{40}\text{Ar}/\text{K}$ -derived  $^{39}\text{Ar}$ ) are accompanied by an increasing radiogenic  $^{40}\text{Ar}$  composition as the experiment proceeds to higher temperature steps (see online dataset). The combination of these effects serves to rotate the isochron to a higher  $^{39}\text{Ar}/^{40}\text{Ar}$  intercept (i.e. lower apparent age) and a lower  $^{36}\text{Ar}/^{40}\text{Ar}$  intercept (i.e. apparent excess argon). The lower apparent age and apparent excess argon component are therefore an experimental artefact of the irradiation and extraction process, and have no geological significance. We conclude that for samples exhibiting signs of significant irradiation-induced  $^{39}\text{Ar}$  redistribution, it is best to assume a trapped argon component of atmospheric composition and use the plateau age as the best estimate of crystallization age. For sample RJ 2-7-3, the plateau age of  $117.4 \pm 0.5$  Ma must be treated with caution because of its significantly high MSWD. However, the plateau age is not significantly different from the isochron age of  $116.3 \pm 0.5$  Ma even using its artificially high  $^{40}\text{Ar}/^{36}\text{Ar}$  intercept; thus we can be relatively confident that this flow was erupted at 118–117 Ma.

The remaining three Group II samples analysed here all show discordance in their age spectra, and the apparent plateau ages are probably best considered minimum age estimates. Sample RJ 2-9-1, with a ‘plateau’ age of  $115.3 \pm 0.6$  Ma (MSWD = 16.9), is from the second flow above the base of the section exposed at Mahadeoganj, northern Rajmahal Hills. Sample RJ 2-7-5, with a ‘plateau’ age of  $112.2 \pm 0.5$  Ma (MSWD = 5.30), is from the third flow above the base of the lava section at Mirza Chauki. Sample RJ 2-5-2, with a ‘plateau’ age of  $109.6 \pm 0.8$  Ma (MSWD = 17.8), is from the second exposed flow above the base of the lavas at Sitalpur, northwestern Rajmahal Hills.

### Tertiary dyke sample

The final sample investigated is from the Salma ferrotholeiite dyke at Asansol in the Raniganj Basin, eastern Damodar Valley. This sample gave a concordant plateau age of  $65.4 \pm 0.3$  Ma (MSWD = 1.26), statistically indistinguishable from the isochron age of  $65.1 \pm 0.3$  Ma. This dyke is assumed to be part of the  $\sim 65$  Ma Deccan LIP and will not be considered further here.

### INTERPRETATION OF $^{40}\text{Ar}/^{39}\text{Ar}$ AGES

Coffin *et al.* (2002) have reported an age of  $118.1 \pm 0.3$  Ma for the average of two concordant laser incremental-heating experiments on plagioclase separated from sample 18-KP7, a Group I tholeiite that lies uppermost in the lava sequence exposed at Kunda Pahar,

near Churudih in the southern Rajmahal Hills (Fig. 2). We consider this age to be the most robust estimate for the crystallization age of any Rajmahal basalt analysed to date. This age is slightly, but not significantly, older than the concordant whole-rock ages on the Rajmahal Hills samples reported here and by Baksi (1995). Given the reported uncertainties, however, the plagioclase age is significantly older than the higher precision analyses on alkali basalts from the Bengal Basin reported by Baksi (Debagram,  $117.0 \pm 0.3$  Ma; Galsi,  $117.1 \pm 0.6$  Ma) and the  $115.3 \pm 0.6$  Ma age of RJ 1-13-2, our Group II dyke. We now consider whether these ages actually differ from one another.

The new ages reported here, and by Coffin *et al.* (2002), are difficult to compare precisely with those of Baksi (1995) because different standard minerals were used and internally consistent calibration factors between these standards are not available. For these reasons, Table 2 reports Baksi's ages as originally published. Our ages, and those of Coffin *et al.* (2002), are reported relative to 28.34 Ma for Taylor Creek Rhyolite sanidine (TCRs), which is equivalent to 28.02 Ma for Fish Canyon Tuff sanidine (FCTs) (Renne *et al.*, 1998). The concordant ages from Baksi (1995) are reported relative to 27.95 Ma for Fish Canyon Tuff biotite (FCTb), except for the Debagram basalt, which is reported relative to 162.9 Ma for USGS biotite SB-3 (see Baksi *et al.*, 1996). To compare Baksi's (1995) ages directly with our new ages we first assume that the age of biotite SB-3 is 162.9 Ma; our resulting calibration of TCRs vs SB-3 is  $27.92 \pm 0.05$  Ma, i.e. significantly younger than Renne *et al.*'s (1998) age of 28.34 Ma. Using our calibration of TCRs vs SB-3, Baksi's (1995) age for the Debagram sample then converts to  $117.7 \pm 0.3$  Ma relative to TCRs at 28.34 Ma. If we then assume that FCTb and FCTs have the same age, Baksi's age for the Galsi basalt converts to  $117.4 \pm 0.3$  Ma relative to FCTs at 28.02 Ma. Similarly, Baksi's age for Rajmahal Hills tholeiite A-531 (Table 2) converts to  $117.8 \pm 0.5$  Ma relative to FCTs at 28.02 Ma. Thus, the concordant ages of Rajmahal Hills and Bengal Basin samples can be considered indistinguishable from one another and from the plagioclase age reported by Coffin *et al.* (2002).

In contrast, the concordant age of Group II dyke sample RJ 1-13-2 ( $115.3 \pm 0.6$  Ma) is significantly younger than  $118.1 \pm 0.3$  Ma. Within the resolution of the analyses, it is also possible that some Rajmahal lavas with discordant age plateaux (minimum ages ranging from 115 to 110 Ma), were erupted a significant time after 118 Ma. The data presented here are thus consistent with an age difference between Rajmahal Group I and at least some Group II basalts, with some Group II rocks being slightly younger than Group I. Stratigraphic field relations also are consistent with this age difference: Group I lavas are sometimes overlain by Group II basalts,

but the reverse situation has not been observed (Kent *et al.*, 1997). Further evidence for magmatism after 118 Ma is provided by an age of  $115.2 \pm 0.5$  Ma for micaceous kimberlite in the Damodar Valley [Kent *et al.* (1998), reported here relative to 28.34 Ma for TCRs]. Therefore, we may conclude that magmatism in eastern India continued for 2–3 Myr after eruption of the Rajmahal Hills lava pile and Bengal Basin alkali basalts.

There is one potential 'fly in the ointment'. Duncan (2002) observed that some (slightly?) altered, fine-grained whole-rock samples give apparently concordant plateau ages that pass our relatively strict acceptance criteria but are significantly younger than the best estimate of the crystallization age of a sample as revealed by clean mineral separates from the same, or stratigraphically equivalent, samples. If this is the case for the Group II dyke age reported here, then it is possible that the entire Rajmahal basalt sequence was emplaced at  $\sim 118$  Ma. Further work on coarse-grained mineral separates is required to test this hypothesis.

## COMPARISON WITH AGES OF BASALTS ASSOCIATED WITH THE KERGUELEN HOTSPOT

The oldest lavas linked to the Kerguelen hotspot are basalt flows exposed at Bunbury, Western Australia (Fig. 1). Frey *et al.* (1996) and Coffin *et al.* (2002) provided  $^{40}\text{Ar}/^{39}\text{Ar}$  data suggesting that the Bunbury lavas, of  $\sim 85$  m thickness, were erupted in two phases, the first at  $\sim 130$  Ma and the second at  $\sim 123$  Ma. These ages are distinct from an  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $100.6 \pm 1.2$  Ma obtained from a basaltic andesite clast collected from the Naturaliste Plateau, located offshore of Western Australia [Fig. 1; Pyle *et al.* (1995)].

As a result primarily of the efforts of the Ocean Drilling Program (ODP Legs 119, 120, 121 and 183), we know the ages of basaltic lavas from 11 basement drill holes on the Kerguelen Plateau and Broken Ridge (Fig. 1). Initially, data for the Plateau basalts were obtained by K–Ar methods. More recently the preferred method has been  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology (Coffin *et al.*, 2002; Duncan, 2002). Reliable ages for Kerguelen Plateau basalts fall into four groups: a set of mid-Cretaceous ages (119–108 Ma) from ODP Sites 738, 749, 750, 1136 and 1137, and dredge MD48-05 on the Southern Kerguelen Plateau; slightly younger ages from the Central Kerguelen Plateau (ODP Site 1138,  $\sim 100$  Ma) and Broken Ridge (ODP Site 1141/1142,  $\sim 95$  Ma); late Cretaceous to Eocene ages for Skiff Bank (Site 1139,  $\sim 68$  Ma) and Ninetyeast Ridge (82–38 Ma); and an Oligocene age obtained by  $^{40}\text{Ar}/^{39}\text{Ar}$  and biostratigraphic studies of the Northern Kerguelen Plateau (ODP Site 1140,  $\sim 34$  Ma).

The most recent volcanism observed on the Plateau is on the Kerguelen Archipelago, seamounts to the south of this Archipelago, on Heard Island and on McDonald Islands [ $\sim 29$ – $0$  Ma; e.g. Nicolaysen *et al.* (2000)].

These ages indicate that the Kerguelen LIP formed in three discrete stages. The initial phase spanned  $>25$  Myr ( $>35$  Myr if Bunbury is part of the LIP), from  $\sim 120$  Ma to  $\sim 95$  Ma or less. This phase included large outpourings of lava in eastern India, on the Southern and Central Kerguelen Plateau, and on Elan Bank. It was followed by construction of Broken Ridge, Ninetyeast Ridge and Skiff Bank (part of the Northern Kerguelen Plateau) over a period of 57 Myr or more. The remainder of the Plateau was formed from the Eocene to the present day.

### RECONSTRUCTING THE KERGUELEN LARGE IGNEOUS PROVINCE

Palaeomagnetic data for basalts collected at ODP sites on the Southern and Central Kerguelen Plateau suggest that the Plateau lay at about  $43.6^\circ\text{S}$  at 110–100 Ma [e.g. Site 1138: maximum  $47.8^\circ\text{S}$ , minimum  $37.9^\circ\text{S}$ ; Antretter (2001)]. The Rajmahal lavas were erupted at a palaeolatitude of  $47^\circ\text{S}$  [maximum  $50.4^\circ\text{S}$ , minimum  $43.8^\circ\text{S}$ ; Klootwijk (1971)], whereas the Bunbury Basalt is too limited in extent (two lava flows) to allow a reliable palaeolatitude to be determined. By comparison, the Kerguelen hotspot is thought to be located at  $49^\circ\text{S}$  at the present day.

How do these palaeolatitude estimates fit with plate tectonic reconstructions using a hotspot reference frame? Reconstructions of the early to mid-Cretaceous Indian Ocean fall into two groups: those that assume that there is little or no M-sequence oceanic crust in the Enderby Basin off East Antarctica [Royer *et al.* (1992); Müller *et al.* (2000); see Fig. 1 for location] and reconstructions based on the premise that such crust exists, and that spreading in the Enderby Basin was roughly contemporaneous with the well-documented M-sequence off Western Australia [from M10 to M0: Powell *et al.* (1988); Mihut & Müller (1998)]. Until recently, the Enderby Basin was extremely poorly surveyed and there was no clear evidence for M-sequence crust. This situation has changed as a result of marine geophysical cruises to the Basin (Ishihara *et al.*, 2000; Joshima *et al.*, 2001), which found clear evidence for M-sequence anomalies. Following previous analyses of magnetic field vector data from the Enderby Basin (Nogi *et al.*, 1996), Gaina *et al.* (2002) have interpreted the new magnetic data as representing anomalies M10 to M0. Gaina *et al.*'s (2002) interpretation includes an extinct ridge axis, which separates two conjugate sets of anomalies, both of which

were left on the Antarctic plate as a result of a ridge jump to the north that separated the Elan Bank microcontinent from India.

The large-scale plate tectonic consequences of the presence of M-sequence anomalies for Indian Ocean plate tectonics are displayed in Fig. 4, which shows new reconstructions of India, Africa, Madagascar, Antarctica and Australia at 126.7 Ma (anomaly M4), 115 Ma, 99 Ma and 83.5 Ma (anomaly 34). The contemporaneous opening of the Enderby Basin and the abyssal plains west of Australia at  $\sim 132$  Ma results in a large ( $\sim 800$  km) left-lateral strike-slip offset between India and Madagascar, with Madagascar remaining attached to Antarctica as India moves away. After 120.4 Ma (anomaly M0), the mid-ocean ridge jumps onto the eastern Indian margin in our model, separating Elan Bank as a microcontinent and leaving two conjugate M-sequences in the Enderby Basin. When sea-floor spreading stops in the Somali Basin at  $\sim 120$  Ma, the rate of sea-floor spreading between India and Antarctica slows down, and the Southwest Indian Ridge forms between Madagascar and Antarctica. Sea-floor spreading at this ridge occurs at a faster rate than on the Central Indian Ridge. As a consequence, right-lateral strike-slip between India and Madagascar commences. This strike-slip motion continues until spreading in the Mascarene Basin between the two plates starts at  $\sim 86$  Ma. This model also implies that Cretaceous ocean floor was formed between India and Arabia during the time interval from 120 Ma or earlier, to 83.5 Ma. Müller *et al.* (2000) had dismissed this model, as the 'back-and-forth' strike-slip motion between India and Madagascar seemed improbable. However, the presence of M-sequence anomalies in the Enderby Basin leaves no other solution.

### Fixed vs moving hotspots

A problem in previous plate reconstructions is the relationship between the Kerguelen hotspot, the Rajmahal basalts and the formation of the Elan Bank microcontinent. The northward ridge jump following anomaly M0 (120.4 Ma), which presumably separated Elan Bank from the Indian margin, was probably triggered by ridge-hotspot interaction (Müller *et al.*, 2001). However, using a fixed hotspot model, the Kerguelen hotspot is far to the south of Elan Bank and the Rajmahal basalts ( $>1000$  km) at 115 Ma (Fig. 4b).

The absolute positions of continents bordering the Indian Ocean for times before 83.5 Ma are uncertain, because they are based on hotspot tracks in the Atlantic (New England and Walvis Ridge–Rio Grande Rise), age data for which are mostly not reliable. The Great Meteor and Tristan da Cunha hotspots, which produced these seamount chains, may have moved with respect to other

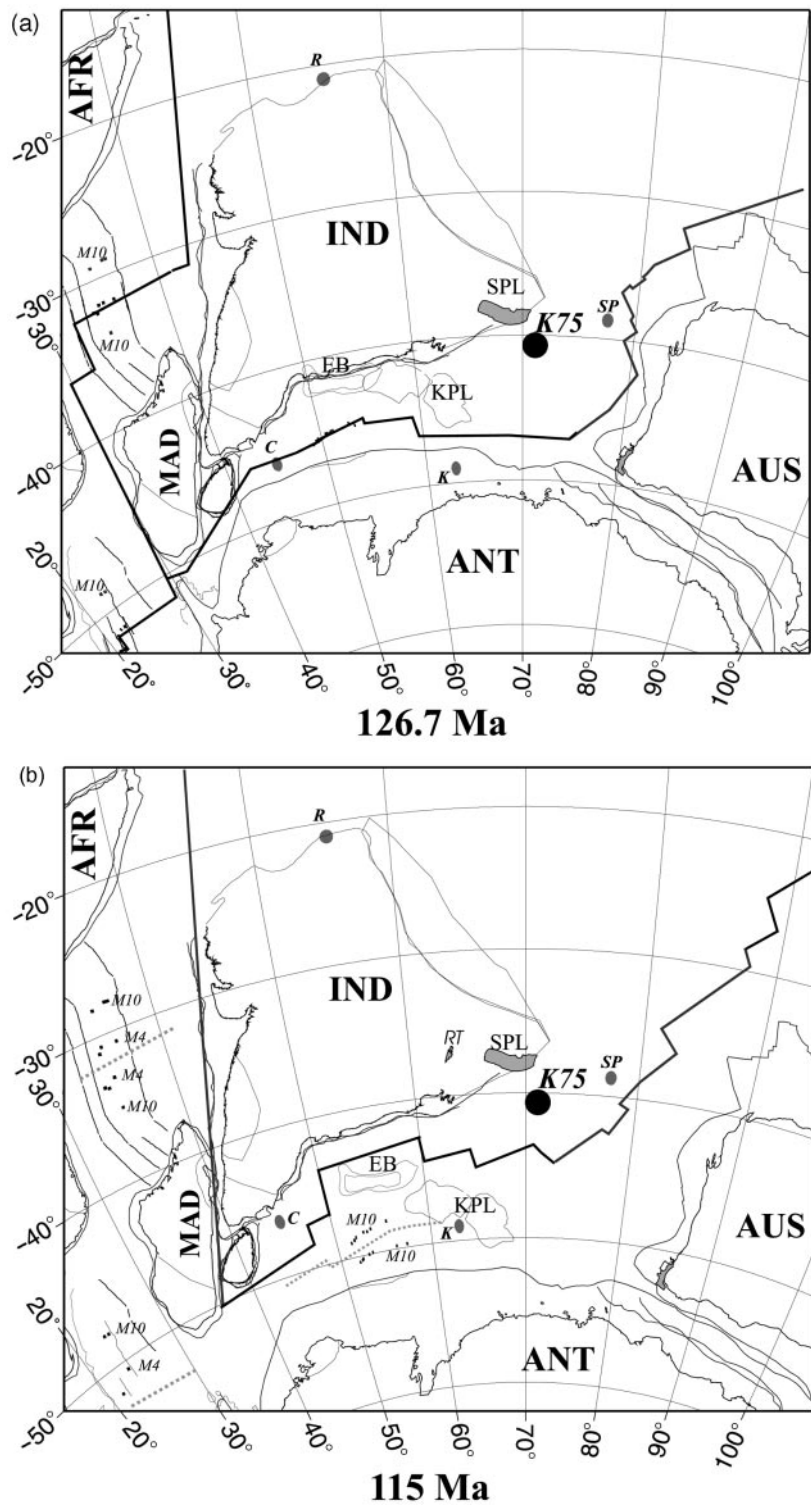
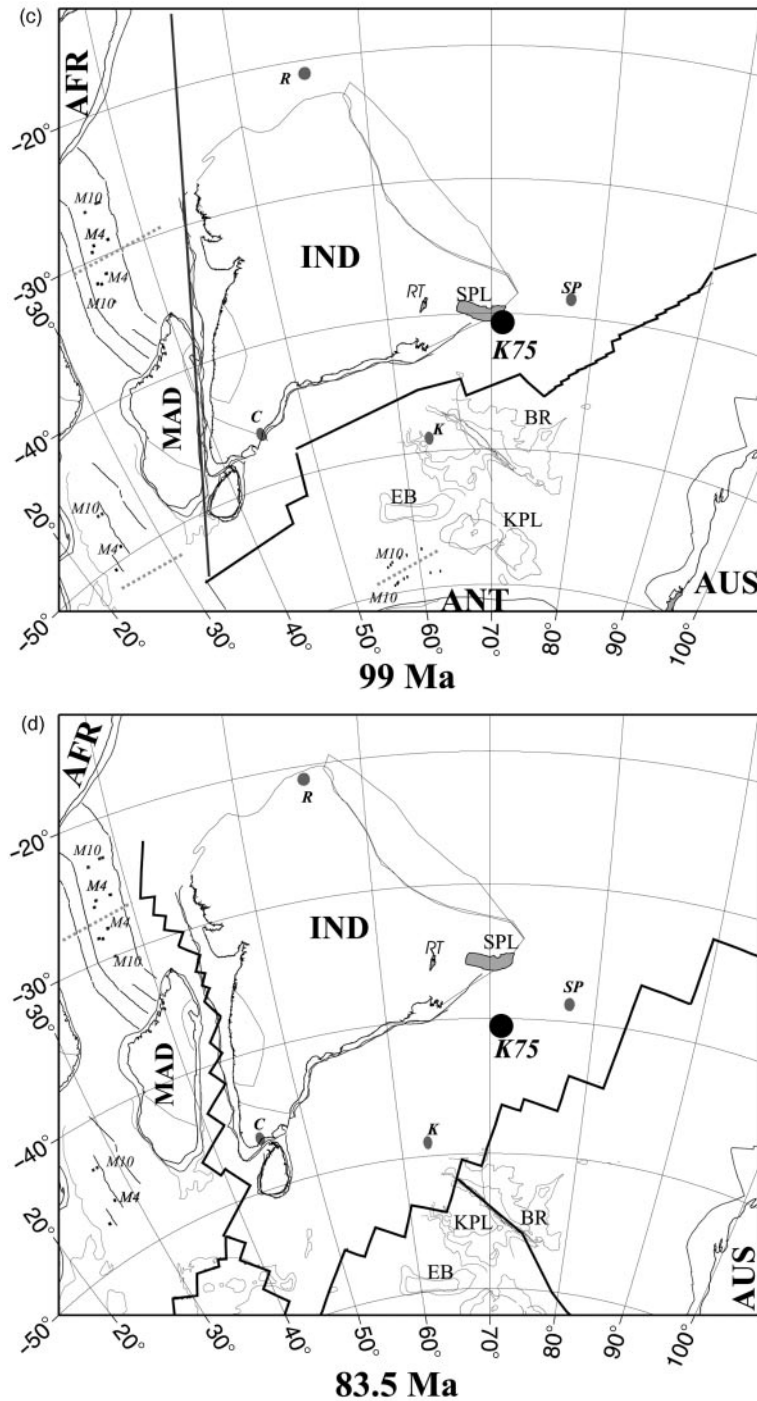


Fig. 4.

hotspots and/or to the Earth's spin axis (Steinberger & O'Connell, 1998). Thus, a comparison of mid-Cretaceous (122–80 Ma) palaeolatitudes of North America and Africa

from palaeomagnetic data with those from hotspot tracks (van Fossen & Kent, 1992) has provided evidence for an 11–13° discrepancy, providing strong evidence that



**Fig. 4.** Indian Ocean plate reconstructions at: (a) 126.7 Ma; (b) 115 Ma; (c) 99 Ma; (d) 83.5 Ma [timescale of Gradstein *et al.* (1994)]. The projection is Lambert azimuthal. The rotations for times at 126.7 Ma, 115 Ma and 99 Ma are based on a revised model for the early opening of the Indian Ocean, including M-sequence anomalies in the Enderby Basin (Ishihara *et al.*, 2000; Gaina *et al.*, 2002), and the model for the opening between Africa, Antarctica and Madagascar by Marks & Tikku (2001), which we have revised based on magnetic anomaly identifications and fracture zones in the Somali, Mozambique and Riser Larsen basins (R. D. Müller *et al.*, unpublished data, 2002). The 83.5 Ma reconstruction is from Müller *et al.* (2000). Relative plate motions are linked to Müller *et al.*'s (1993) absolute reference frame, which has been adapted to Gradstein *et al.*'s (1994) timescale for times older than 83.5 Ma. The large filled circle labelled 'K75' is the Kerguelen hotspot location calculated at 75 Ma. Bold lines indicate plate boundaries, which are for the most part uncertain. Dashed lines represent extinct spreading ridges. AFR, Africa; ANT, East Antarctica; AUS, Australia; IND, India; MAD, Madagascar; BR, Broken Ridge; EB, Elan Bank; KPL, Kerguelen Plateau; RT, Rajmahal Traps; SPL, Shillong Plateau. Hotspots: C, Crozet; K, Kerguelen; R, Reunion; SP, Saint Paul. M10 and M4 are sea-floor magnetic anomalies M10 (131.9 Ma) and M4 (126.7 Ma), respectively.

Atlantic hotspots were not fixed relative to the spin axis before 80 Ma, but moving southwards.

In the context of moving hotspots, uncertainties on palaeolatitudes calculated for lavas on the Central and Northern Kerguelen Plateau (ODP Leg 183, Sites 1138 and 1140, respectively) allow up to 20° of southward motion of the Kerguelen hotspot between ~100 Ma and ~34 Ma (Antretter, 2001). Actual southward motion of the hotspot was probably much less than this (~5.4°, but with a possible total range of 1–11°) based on mean palaeolatitudes for the Southern Kerguelen Plateau and Rajmahal lavas (see above).

To assess the possible role that a moving Kerguelen hotspot may have played in the eruption of the Rajmahal basalts and formation of the Elan Bank microcontinent, we used results from a numerical model previously described by Steinberger & O'Connell (1998) [see O'Neill *et al.* (2001)]. The code uses present-day tomography, and advects the density field back through time using past plate rotations and boundaries as surface conditions. The preferred viscosity structure and seismic conversion factors of Steinberger & O'Connell (1998) were used. The mantle convection model does not extend beyond 75 Ma, so the 75 Ma position of the Kerguelen hotspot in Fig. 4 (labelled 'K75') is a minimum estimate for how much this hotspot may have moved through time. The 75 Ma Kerguelen hotspot reconstruction places it much closer to the Rajmahal basalts than in the fixed hotspot model, i.e. ~900 km (~8°) farther north. The error in the model is hard to judge because it depends on which mantle tomography model one chooses as a starting point. On this basis it is plausible that the Rajmahal lavas are a product of the Kerguelen hotspot.

## SUMMARY AND CONCLUSIONS

(1) High-precision  $^{40}\text{Ar}/^{39}\text{Ar}$  dating indicates a common age (~118 Ma) for eruption of tholeiitic lavas in the Rajmahal Hills and alkalic basalt in the Bengal Basin. Dykes intruded to the SW of the Rajmahal Hills may have ages as young as 115 Ma. Thus, the duration of Rajmahal volcanism was probably 2–3 Myr.

(2) The Rajmahal basalts are equivalent in age to the uppermost lavas on the Southern Kerguelen Plateau (ODP Site 1136). The uppermost lavas at Sites 749 and 750 on the Southern Kerguelen Plateau, on Elan Bank (Site 1137) and on the Central Kerguelen Plateau (Site 1138) are 6–18 Myr younger than the Rajmahal basalts. It is possible, however, that lavas equivalent in age to the Rajmahal tholeiites lie beneath the sequences sampled at Sites 749 and 750, on Elan Bank and on the Central Kerguelen Plateau.

(3) New plate reconstructions of the Indian Ocean region between 126.7 and 83.5 Ma provide an improved

relative plate motion model between India and Antarctica. On the basis of geodynamic modelling we note a probable southward drift of the Kerguelen hotspot in the past 100 Myr, which is consistent with palaeomagnetic data. This drift suggests that eruption of Rajmahal lavas and Elan Bank's separation from eastern India can be explained by interaction between the Kerguelen hotspot and a spreading ridge located close to the eastern Indian margin, just after 120 Ma.

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