

# Kerguelen Hotspot Magma Output since 130 Ma

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*The Kerguelen hotspot (Indian Ocean) has produced basalt for ~130 Myr, among the longest known volcanic records from a single source. New and published <sup>40</sup>Ar/<sup>39</sup>Ar age determinations from the Kerguelen Plateau, Broken Ridge, Rajmahal Traps, and Bunbury basalts, and of Indian and Antarctic dikes help to document the hotspot's history. Using radiometric dates and crustal structure determined from geophysical data and drilling results, we calculate the magmatic output of the Kerguelen hotspot through time. Output rates have varied in ways not predicted by current geodynamic models; maximum eruption volumes postdate the initial surface manifestation of the hotspot as well as break-up between Antarctica and India by ≥15 Myr, and magma output rates were high, as well as geographically diverse, over an interval of 25 Myr, from ~120 to ~95 Ma. We propose two alternatives to the standard mantle plume paradigm, one involving multiple plume sources, and another consisting of a single, but dismembered plume source.*

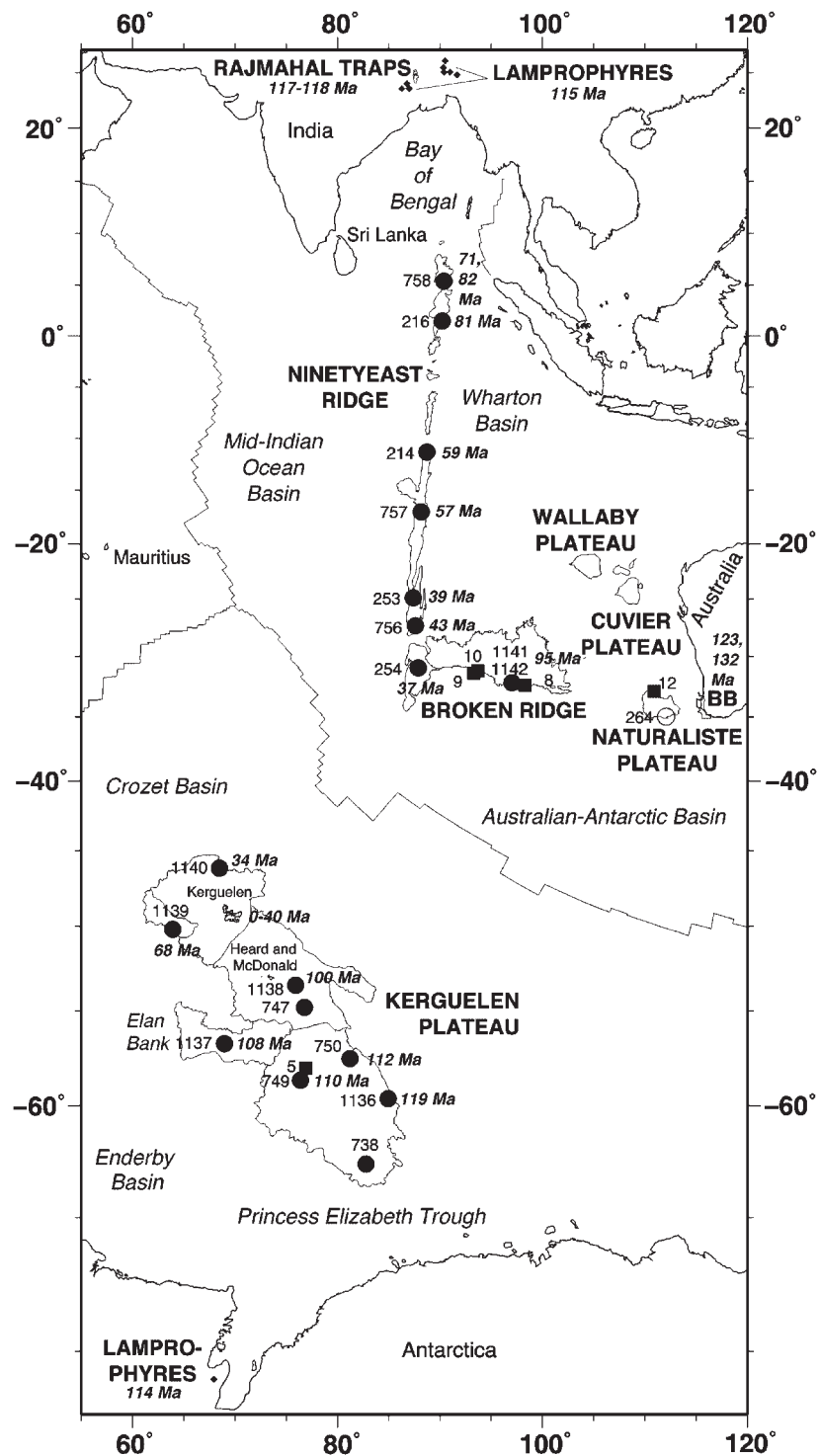
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## INTRODUCTION

Most models for the origin of continental flood basalts and oceanic plateaux predict initially voluminous magmatism over a relatively short period of 1–2 Myr, followed by steady-state magma output at much lower rates (Richards *et al.*, 1989; Duncan & Richards, 1991). Furthermore, massive magma output from hotspots is commonly, but not always associated in space and time with continental break-up (White & McKenzie, 1989). To test the applicability of such ideas and models, we present the first integrated study on the age and eruption volumes of one of Earth's largest flood basalt provinces (Coffin & Eldholm, 1994), the Kerguelen Plateau and Broken Ridge in the southern Indian Ocean and associated Cretaceous magmatism found near the continental margins of India, Antarctica, and Australia (Fig. 1).

Widespread Cretaceous and Cenozoic basaltic volcanism in the eastern Indian Ocean region has been

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**Fig. 1.** Basalt provinces in the Indian Ocean region, most of which are attributed to the Kerguelen hotspot. Locations of DSDP and ODP igneous basement sites (●), and dredges that recovered igneous basement (■), are shown. ♦, Lamprophyres. ○, a DSDP site where overlying sediment provides a minimum age for the igneous basement. Radiometric age determinations (*italics*) are summarized in Table 2.

related to the Kerguelen hotspot (Duncan, 1978; Mahoney *et al.*, 1983; Davies *et al.*, 1989; Storey *et al.*, 1989); changing motions of the Antarctic, Australian, and Indian plates have dispersed these igneous rock complexes from their original sites of emplacement (Müller *et al.*, 1993). Radiometric ages of magmatic rocks attributed to the Kerguelen hotspot range from  $\sim 130$  Ma to Recent; in decreasing age order, mafic rocks forming the Kerguelen large igneous province (LIP) include Bunbury (Australia), Rajmahal (India), lamprophyre dikes of the conjugate Indian and Antarctic margins, Southern Kerguelen Plateau, Elan Bank, Central Kerguelen Plateau, Broken Ridge, Ninetyeast Ridge, Skiff Bank, Northern Kerguelen Plateau, and the recent expressions of the activity of the hotspot on the Kerguelen Archipelago, and Heard and McDonald Islands (Fig. 1, Tables 1 and 2). Here, we present new, high-precision  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations for the Cretaceous volcanic rocks of Bunbury (Australia), Rajmahal (India), and the Kerguelen Plateau, and for Cretaceous lamprophyre dikes of the conjugate Indian and Antarctic margins (Table 1). We calculate crustal volumes for the various flood basalt provinces attributed to the Kerguelen hotspot, and then use our new and previously published  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations (Tables 1 and 2) to determine a first-order magma output rate for the Kerguelen hotspot since its first attributed surface manifestation at  $\sim 130$  Ma in Western Australia (Bunbury). We then show how Kerguelen hotspot activity relates to the break-up of Eastern Gondwana and sea-floor spreading in the Indian Ocean. We conclude by speculating on the mantle plume sources that could account for these data.

## METHODS

Estimating magma flux rates for the Kerguelen hotspot requires first evaluating which basaltic provinces may be attributed to the hotspot, using geophysical, volcanological, petrological, and geochemical data. Following Coffin *et al.* (2000), we include: (1) the continental basaltic rocks of Bunbury on the Western Australian continental margin, Rajmahal in eastern India, and lamprophyre dikes of the conjugate Indian and Antarctic continental margins; (2) the oceanic basaltic rocks of the Kerguelen Plateau, Broken Ridge, and the Ninetyeast Ridge. Iterating among the aforementioned data plus all available geochronological data (Tables 1 and 2), we interpret the ages of the various basaltic provinces, and, where necessary, subdivide them into different age provinces. Then we calculate the crustal volume of each of the interpreted age provinces; subtract continental crust that is indicated from geophysical, petrological or geochemical data, or, where continental crust is absent, normal thickness oceanic crust from those volumes; and

calculate magma flux rates for the entire Kerguelen LIP. Relevant data on crustal volumes of the oceanic portions of the Kerguelen LIP have been acquired mostly during the past decade, as have radiometric ages for the entire Kerguelen LIP (Tables 1 and 2). Reliable data with which to calculate crustal volumes of the continental portions of the Kerguelen LIP await acquisition.

We calculate crustal volumes from areal and vertical dimensions, the former from analyses of the satellite-derived free-air gravity field, bathymetry and seismic reflection data, and the latter primarily from seismic reflection and refraction investigations of crustal structure, augmented by gravity modeling. For the upper crust, geophysical data are commonly correlated with outcrop and/or drilling results to arrive at structural and stratigraphic interpretations. It is important to bear in mind that only the uppermost extrusive components of the Kerguelen LIP have been sampled and dated; the greatest igneous basement penetration into any oceanic portion of the LIP is  $<250$  m. Unexposed or inaccessible extrusive rocks, and intrusive material form the major proportion of the crustal volume, and these rocks remain unsampled except for Cenozoic plutons (Weis & Giret, 1994) and xenoliths (Grégoire *et al.*, 1994; Hassler & Shimizu, 1998; Mattielli *et al.*, 1999) on the Kerguelen Archipelago.

Additionally, continental crust forms part of the Kerguelen Plateau, and has been both identified on the basis of petrological and geochemical studies (Coffin *et al.*, 2000; Frey *et al.*, 2000) and interpreted from seismic data (Operto & Charvis, 1995, 1996; Borissova *et al.*, 2000). Using primarily geophysical data, we have attempted to identify and subtract any continental material from the crustal volumes of the various age provinces. Similarly, for those portions of the Kerguelen LIP that formed predominantly within oceanic lithosphere, we have subtracted a layer 7.1 km thick (White *et al.*, 1992). In this respect, our study resembles the approaches of White (1993) and Saunders *et al.* (1994), who excluded the thickness of normal oceanic crust in their calculations, only considering the volume of net oceanic crustal thickening.

We have determined new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the Bunbury basalts, Rajmahal basalts, Indian and Antarctic lamprophyres, and the Kerguelen Plateau (Table 1), all samples originally described by Storey *et al.* (1992). Samples were irradiated, loaded under ultrahigh vacuum, heated with an Ar-ion laser, and analyzed at the Free University of Amsterdam following Wijbrans *et al.* (1995). Plagioclase and whole-rock analyses were incremental heating experiments on  $\sim 10$  mg of material each; biotite analyses were total-fusion experiments on individual crystals. We report on both concordant and discordant

Table 1: Summary of new Ar/Ar ages of basalts attributed to the Kerguelen hotspots

Sample	Material*	K/Ca	Age spectrum analysis			Isochron analysis							
			No. of steps	<sup>39</sup> Ar (%)	Age <sub>t</sub> (Ma)	±1σ	MSWD	Age <sub>t</sub> (Ma)	±1σ	Sums/(n-2)	<sup>40</sup> Ar/ <sup>36</sup> Ar intercept	±1σ	
<i>Kerguelen Plateau (ODP Legs 119 and 120)</i>													
120-750B-16R-2, 102-108	plagioclase	0.007	9 of 9	100.0	112.6	±0.5	1.44	112.3	±0.8	1.75	297.9	±18.5	
			6 of 9	84.2	112.1	±0.6	0.78	111.4	±1.1	0.70	311.4	±21.9	
			<b>Weighted mean age:</b>			<b>112.4</b>	<b>±0.4</b>	<b>0.42</b>	<b>112.0</b>	<b>±0.6</b>	<b>0.44</b>		
120-749C-16R-5, 127-131	plagioclase	0.002	7 of 8	92.7	114.2	±1.7	10.6	108.9	±8.6	13.1	315.5	±39.3	
119-738C-35R-2, 106-110	leached basalt	0.0878	11 of 14	81.9	108.6	±3.0	230.0	111.6	±2.3	259.1	304.5	±22.9	
120-747C-15R-2, 120-124	leached basalt	0.072	7 of 13	62.2	86.4	±0.4	15.6	84.8	±1.4	9.53	436.2	±183.5	
			6 of 12	62.4	85.6	±0.5	36.8	83.7	±1.0	9.28	466.8	±64.4	
<i>Rejmahal Basalts</i>													
KP-7	plagioclase	0.008	6 of 10	75.9	118.0	±0.4	0.87	118.3	±0.8	1.56	267.8	±42.0	
			5 of 9	67.4	118.2	±0.4	1.40	117.5	±0.8	0.94	278.7	±30.0	
			<b>Weighted mean age:</b>			<b>118.1</b>	<b>±0.3</b>	<b>0.08</b>	<b>117.9</b>	<b>±0.6</b>	<b>0.50</b>		
<i>Bumbury Basalts</i>													
BB-1	plagioclase	0.007	5 of 10	78.8	132.0	±0.5	1.81	131.4	±1.0	2.24	303.5	±19.0	
			7 of 10	87.7	132.4	±0.4	0.71	132.1	±0.6	0.74	311.0	±28.6	
			<b>Weighted mean age:</b>			<b>132.2</b>	<b>±0.3</b>	<b>0.36</b>	<b>131.9</b>	<b>±0.5</b>	<b>0.36</b>		
<i>Lamprophyres</i>													
D17 (Antarctica)	biotite	8.7	6 of 6	all	<b>114.0</b>	<b>±0.3</b>	<b>0.50</b>	113.7	±0.5	0.59	305.9	±30.9	
KUST-1 (India)	biotite	195	6 of 6	all	<b>114.9</b>	<b>±0.3</b>	<b>0.55</b>	115.2	±0.5	0.60	236.6	±74.0	

Bold type indicates best estimates for crystallization ages of samples. Italic type indicates discordant experiments, which are best considered minimum age estimates only (especially discordant whole-rock experiments) and are not utilized further in this study.

\*Plagioclase separates (125-250 μm) made with typical heavy liquid and magnetic techniques and leached with cold 7% HF for 5 min and warm 6N HCl for 30 min; similar size whole-rock separates leached with warm 6N HCl for 30 min and some, but not all alteration products removed by flotation at a specific gravity of 2.65. Individual biotite crystals c. 250-500 μm in diameter were hand-picked.

†All ages reported here are relative to USGS sanidine 85G003 equal to 28.34 Ma and ( $\lambda_{39} + \lambda_{40}$ )/ $\lambda_{39}$  equal to  $1.804 \times 10^9$ ; all errors are reported as 1σ of analytical precision. Complete set of Ar/Ar incremental-heating and total-fusion analyses is available from the *Journal of Petrology* Web site at <http://www.petrology.oupjournals.org>.

Table 2: Areas, volumes, ages, and output rates of Kerguelen hotspot basalts

Province	Area (10 <sup>5</sup> km <sup>2</sup> )	Volume <sup>a</sup> (10 <sup>6</sup> km <sup>3</sup> )	Sample	Age (Ma ± 1 SD)	Emplacement rate (km <sup>3</sup> /yr)
Bunbury Basalts	n.a.	<<0.1 <sup>b</sup>	Casuarina	132.2 ± 0.3 <sup>c</sup>	<<0.1
			Casuarina	128.3 ± 1.4 <sup>b</sup>	
			Gosselin	122.9 ± 1.7 <sup>b</sup>	
Rajmahal Traps	n.a.	<<0.1 <sup>d,e,f,g</sup>	KP-7	118.2 ± 0.3 <sup>c</sup>	<<0.1
			1-30-4	117.9 ± 0.4 <sup>h</sup>	
			A-531	117.5 ± 0.5 <sup>d</sup>	
			Bengal Basin boreholes	117.1 ± 0.4 <sup>d</sup>	
Lamprophyres	n.a.	n.a.	India (KUST-1)	114.9 ± 0.3 <sup>c</sup>	n.a.
			Antarctica (D17)	114.0 ± 0.3 <sup>c</sup>	
Southern Kerguelen Plateau	4.50 <sup>c</sup>	8.5 <sup>c</sup>	ODP 1136	118.9 ± 1.5 <sup>i</sup>	0.9
			ODP 750	112.4 ± 0.4 <sup>c</sup>	
			ODP 749	109.9 ± 1.0 <sup>j</sup>	
Elan Bank	1.39 <sup>c</sup>	0.3 <sup>c</sup>	ODP 1137	107.7 ± 0.5 <sup>i</sup>	0.1
Central Kerguelen Plateau	4.32 <sup>c</sup>	4.5 <sup>c</sup>	ODP 1138	100.4 ± 0.7 <sup>i</sup>	0.9
Broken Ridge	4.75 <sup>c</sup>	4.1 <sup>k</sup>	ODP 1141	95.1 ± 0.8 <sup>i</sup>	0.8
			ODP 1142	94.5 ± 0.6 <sup>i</sup>	
Ninetyeast Ridge and Skiff Bank	n.a. and 0.53 <sup>c</sup>	4.7 <sup>c,l</sup> and 0.3 <sup>c</sup>	ODP 758	81.8 ± 2.6 <sup>m</sup>	0.1
			ODP 758	71.3 ± 7.6 <sup>m</sup>	
			DSDP 216	81.2 ± 0.8 <sup>n</sup>	
			ODP 1139	68.3 ± 0.3 <sup>i</sup>	
			DSDP 214	58.5 ± 0.4 <sup>n</sup>	
			ODP 757	57.0 ± 1.6 <sup>m</sup>	
			DSDP 253	38.5 ± 0.9 <sup>n,o</sup>	
			ODP 756	43.2 ± 0.5 <sup>m</sup>	
			DSDP 254	37.4 ± 1.2 <sup>n</sup>	
			Onshore	~40–0 <sup>p,q</sup>	
ODP 1140	34.3 ± 0.6 <sup>i</sup>				
Northern Kerguelen Plateau	3.64 <sup>c</sup>	2.3 <sup>c</sup>			0.1
Kerguelen hotspot		Σ24.7 <sup>r</sup>			

Discordant experiments from Table 1 are not included. n.a., not available.

<sup>a</sup>For oceanic portions of the Kerguelen LIP, both intrusive and extrusive rocks are included; for continental portions, only extrusive rocks are included. <sup>b</sup>Frey *et al.* (1996). <sup>c</sup>This paper. <sup>d</sup>Baksi (1995). <sup>e</sup>Baksi *et al.* (1987). <sup>f</sup>Kent *et al.* (1997). <sup>g</sup>Storey *et al.* (1992). <sup>h</sup>Kent *et al.* (2002). <sup>i</sup>Duncan (2002). <sup>j</sup>Whitechurch *et al.* (1992). <sup>k</sup>Coffin & Eldholm (1994). <sup>l</sup>Grevemeyer *et al.* (2001). <sup>m</sup>Duncan (1991). <sup>n</sup>Duncan (1978). <sup>o</sup>Radiometric dates are younger than overlying 49–44 Ma sediment. <sup>p</sup>Nicolaysen *et al.* (2000). <sup>q</sup>Nougier *et al.* (1983). <sup>r</sup>25.7 assuming a 95–85 Ma segment of the Ninetyeast Ridge lies buried beneath the Bengal Fan and was emplaced at the same rate as the 85–35 Ma portion of the feature.

experiments (Table 1, in roman and italic text, respectively); the complete dataset is available for downloading from the *Journal of Petrology* Web site at <http://www.petrology.oupjournals.org>. With 62–100% of the argon released included in the individual age plateaux and single-variable F ratio statistics (MSWD) all <1.44 (Table 1; Fig. 3, below), we consider the concordant experiments to be robust estimates of the crystallization ages of the sampled basalts [see, for example, criteria given by Pringle (1993) and Singer & Pringle (1996)]. The other experiments are highly discordant (MSWD >10), are probably best considered minimum age estimates only, and are not considered further here. Thus, we utilize only the concordant experiment results in our age assignments and magma flux calculations.

### SUMMARY OF AGE RELATIONSHIPS

We describe below the results of our present study in order of decreasing age of the volcanism related to the Kerguelen hotspot.

#### Bunbury Basalts

The oldest rock attributed to the Kerguelen hotspot is the Bunbury Basalt of southwestern Australia (Fig. 1) (Davies *et al.*, 1989; Duncan & Storey, 1992; Frey *et al.*, 1996; Ingle *et al.*, 2002). Our new date of  $132.2 \pm 0.3$  Ma for the Casuarina-type of Bunbury Basalt (Fig. 1; Tables 1 and 2) is corroborated by two other  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $\sim 130$  Ma from the same unit (Frey *et al.*, 1996); the Gosselin-type of Bunbury basalt has been dated at  $\sim 123$  Ma (Frey *et al.*, 1996). Geochemical studies of Bunbury tholeiites indicate a strong continental signature for the younger basalts, whereas the older basalts resemble oceanic lavas from Ninetyeast Ridge and the Kerguelen Archipelago (Frey *et al.*, 1996; Ingle *et al.*, 2002). Although the latter similarities do not uniquely define a Kerguelen hotspot source for the Casuarina-type Bunbury Basalt, geochemical evidence permits such a conclusion (Frey *et al.*, 1996; Ingle *et al.*, 2002).

Areal, the Bunbury Basalt appears insignificant on the scale of flood basalts, which typically cover  $10^5$ – $10^6$  km<sup>2</sup> of the Earth's surface (e.g. Macdougall, 1988). The areal extent of lava sections of  $\leq 85$  m thickness is documented from outcrop, drill holes, and geophysical surveys (Frey *et al.*, 1996), and from these we estimate a basalt volume of  $\sim 10^3$  km<sup>3</sup>.

#### Rajmahal Traps

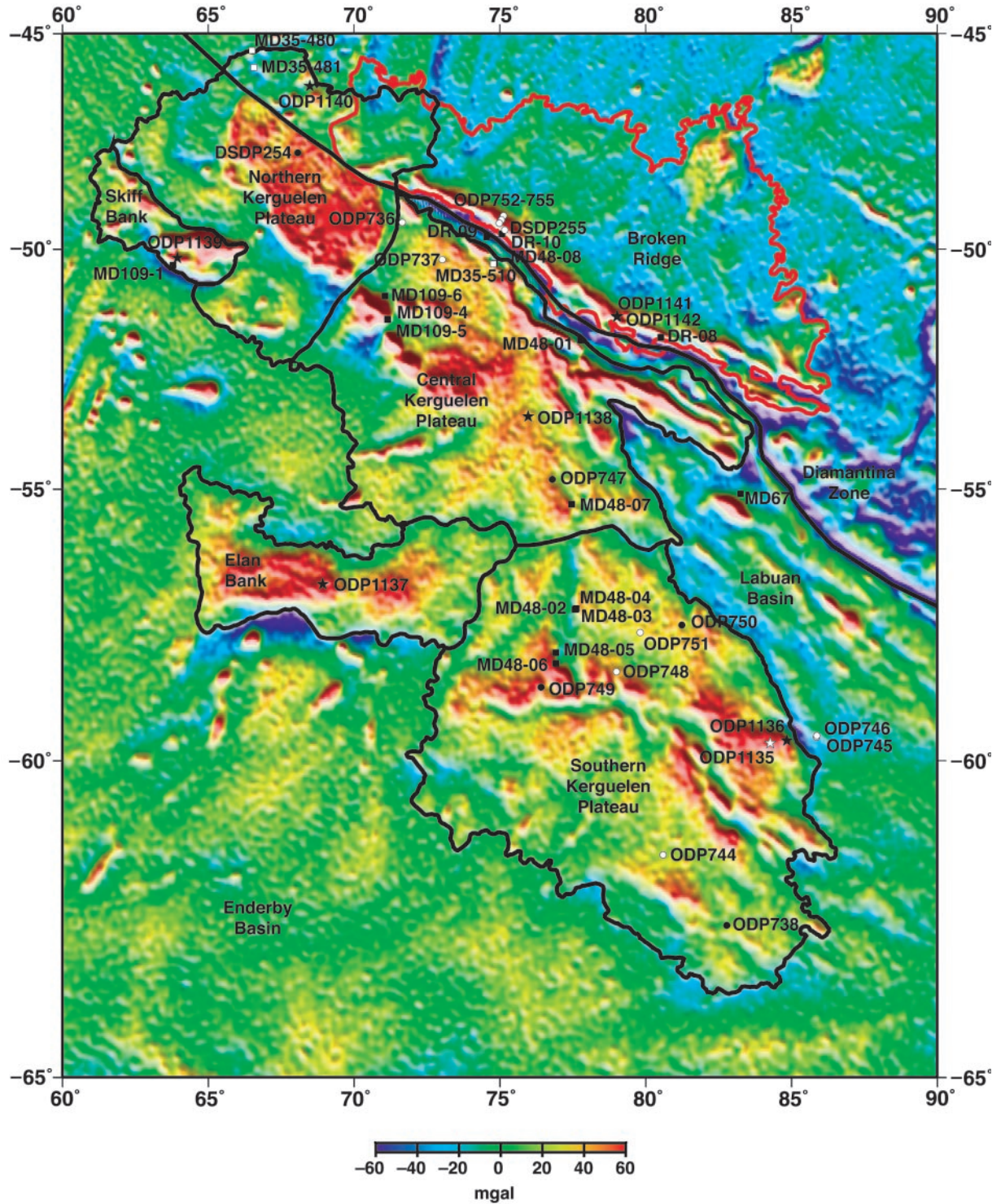
The Rajmahal basalts (Tables 1 and 2) from NE India (Fig. 1) are contemporaneous with those of the Southern

Kerguelen Plateau (see below). Our new age determination of  $118.2 \pm 0.3$  Ma (Fig. 3, below; Table 1) closely resembles previously reported ages (Table 2). We calculate the volume of extrusive rock using an area of  $2 \times 10^5$  km<sup>2</sup> (Kent *et al.*, 1997) and an estimated average thickness of 150 m; the total volume is  $\sim 3.0 \times 10^4$  km<sup>3</sup>. The subaerial Rajmahal Traps are characterized by two distinct geochemical groups. Group I Rajmahal lavas show strong geochemical similarities to Bunbury's Casuarina type. These basalts resemble Site 749 lavas on the Southern Kerguelen Plateau, and probably contain a depleted mantle component (Kent *et al.*, 1997; Frey *et al.*, 2002; Ingle *et al.*, 2002). In contrast, Group II Rajmahal rocks have geochemical characteristics more comparable with Bunbury's Gosselin type, and are variably contaminated by ancient upper continental crust (Mahoney *et al.*, 1983; Storey *et al.*, 1992; Baksi, 1995; Frey *et al.*, 1996; Ingle *et al.*, 2002). In this respect, they are similar to basalts from Kerguelen Plateau Site 1137 (Weiss *et al.*, 2001; Ingle *et al.*, 2002).

#### Southern Kerguelen Plateau

The initial manifestation of the Kerguelen hotspot in an oceanic environment is the Southern Kerguelen Plateau (Figs 1 and 2). Our new age determination of  $112.4 \pm 0.4$  Ma for Ocean Drilling Program (ODP) Site 750 basalts falls within the 120–110 Ma range of two other high-quality radiometric ages from Sites 1136 and 749 (Fig. 3; Tables 1 and 2). Our new analyses of basalts from Sites 738 and 749 show similar, but considerably less reliable apparent ages (Fig. 3; Table 1).

We subdivide the main Cretaceous Kerguelen Plateau into  $\sim 120$  to  $\sim 110$  Ma (southern) and  $\sim 105$  to  $\sim 100$  Ma (central; see below) provinces on the basis of age determinations and a prominent negative free-air gravity lineament (Coffin & Gahagan, 1995) just south of ODP Site 747 (Fig. 2). To calculate the volume of the  $\sim 120$  to  $\sim 110$  Ma portion of the Kerguelen Plateau, we used its areal and vertical dimensions, the latter obtained primarily through wide-angle seismic data (Operto & Charvis, 1995, 1996) and gravity modeling (Gladchenko & Coffin, 2001) delineating crust  $\sim 22$  km thick on the Southern Plateau. We subtracted a continental layer of variable thickness at the base of the crust interpreted from the wide-angle seismic data analysis (Operto & Charvis, 1995, 1996) and gravity modeling (Gladchenko & Coffin, 2001). This is also justified by the geochemical and isotopic evidence for the role of a continental component at Sites 738 and 750 (Mahoney *et al.*, 1995; Frey *et al.*, 2002). The calculated volume of the magma produced between  $\sim 120$  and  $\sim 110$  Ma by the Kerguelen hotspot to form the Southern Kerguelen Plateau is  $8.5 \times 10^6$  km<sup>3</sup>, at least two orders of magnitude



**Fig. 2.** Plate reconstruction of the satellite-derived free-air gravity field (Sandwell & Smith, 1997) at C18n.2n[o] (40.1 Ma), using rotation poles of Royer & Rollet (1997), for Broken Ridge (outlined in red) and the Kerguelen Plateau; the latter has been subdivided into Northern, Central, Southern, Elan Bank, and Skiff Bank age provinces (black polygons). ODP Leg 183 drill sites (stars), ODP Leg 119, 120, 121 and DSDP Leg 26 drill sites (circles), and dredge or piston core locations (squares) where igneous basement was sampled are in black; where only sediment was recovered, the symbols are white.

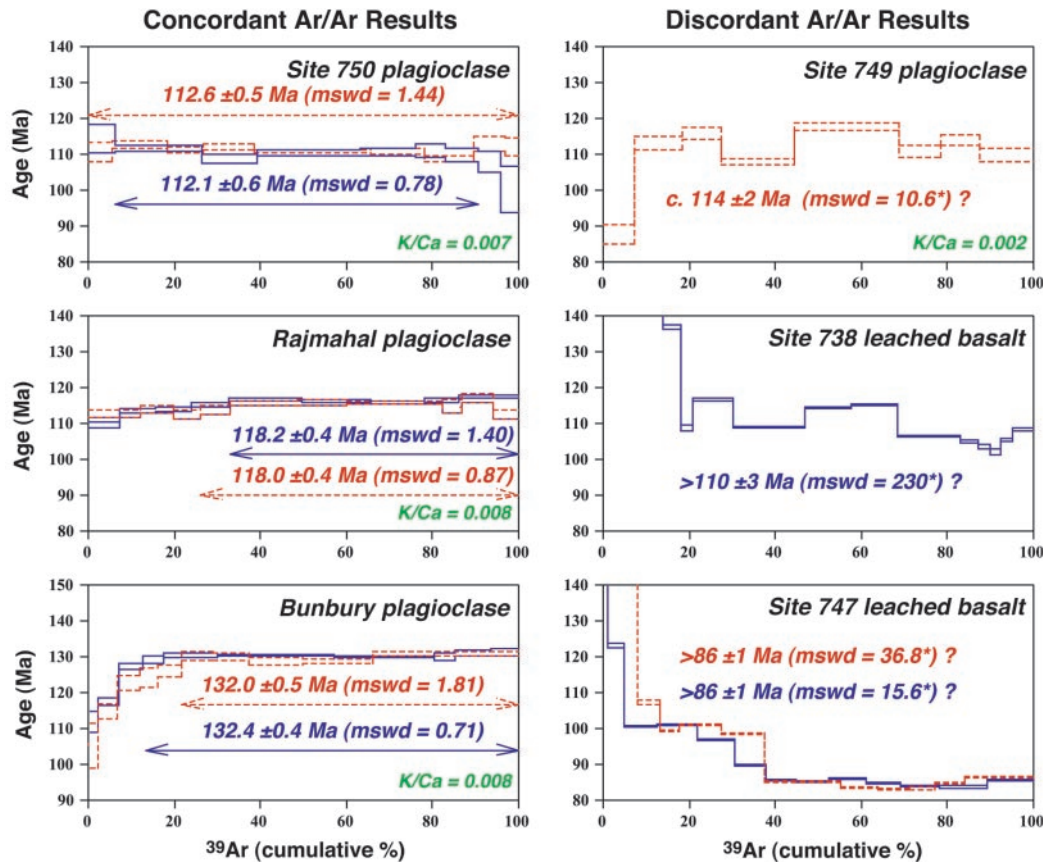


Fig. 3.  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectrum plots for Bunbury, Rajmahal, Antarctic and Indian lamprophyres, and Kerguelen Plateau basalts. Uncertainties are shown  $\pm 1$  SD ( $\sigma$ ) high.

more magma than the hotspot produced in the preceding 10 Myr.

### Lamprophyres

Lamprophyres are found along the conjugate Indian and Antarctic margins (Fig. 1). In India both alkaline and ultramafic varieties occur as horizontal tubes, dikes, and sills. We have determined an age of  $114.9 \pm 0.3$  Ma for a dike (Fig. 3; Tables 1 and 2), which resembles ages determined by Kent *et al.* (1998). Rare ultramafic lamprophyres (alnöites) occur as sills and dikes in Antarctica, and these yield an age of  $114.0 \pm 0.3$  Ma (Fig. 3; Tables 1 and 2). Both the Indian and Antarctic dikes appear to be temporally associated with the Rajmahal Traps and the Southern Kerguelen Plateau, and have been attributed to the Kerguelen hotspot (Storey *et al.*, 1989, 1992; Kent, 1991; Kent *et al.*, 1992, 1998). These rocks probably reflect small degrees of partial melt from the sub-continental mantle heated by the nearby Kerguelen hotspot, and their total volume is likely to be relatively small, although volumes of undocumented, but probably

contemporaneous sills and associated underplating could be significant.

### Elan Bank

Continental material recovered from ODP Site 1137 (Coffin *et al.*, 2000; Frey *et al.*, 2000; Nicolaysen *et al.*, 2001), corroborated by seismic data (Charvis *et al.*, 1997; Könnecke *et al.*, 1997; Borissova *et al.*, 2000), suggests that Elan Bank is a microcontinent capped and flanked by  $\sim 110$  to  $\sim 105$  Ma volcanic rock (Table 2). Geochemically, the basalts are related to the Kerguelen hotspot source and are contaminated by continental crust (Weis *et al.*, 2001; Ingle *et al.*, 2002).

We used the areal and vertical dimensions of Elan Bank to calculate its total crustal volume of  $1.4 \times 10^6$  km<sup>3</sup>, and interpreted the volcanic and plutonic component to be 20% of the total volume on the basis of both seismic refraction and reflection data (Charvis *et al.*, 1997; Borissova *et al.*, 2000).



### Central Kerguelen Plateau

ODP Site 1138 (Figs 1 and 2) tholeiitic basalt, dated at  $\sim 100$  Ma (Table 2), is slightly younger than the Elan Bank and Southern Kerguelen Plateau basalts. The geochemical characteristics of the basalt support a Kerguelen hotspot source, with no indications of any continental lithospheric component (Coffin *et al.*, 2000; Frey *et al.*, 2000; Neal *et al.*, 2002).

To calculate the volume of the  $\sim 105$  to  $\sim 100$  Ma portion of the Kerguelen Plateau, we used its area, a maximum crustal thickness of 23.5 km determined from wide-angle seismic data (Charvis *et al.*, 1995; Charvis & Operto, 1999), and the results of gravity modeling using the seismic data as control (Gladczenko & Coffin, 2001). We subtracted a section of normal oceanic crust of 7.1 km thickness (White *et al.*, 1992) from the crustal section. The calculated volume of the magma produced between  $\sim 105$  and  $\sim 100$  Ma by the Kerguelen hotspot to form the Central Kerguelen Plateau is  $4.5 \times 10^6$  km<sup>3</sup>.

### Broken Ridge

Igneous basement of Broken Ridge was first drilled during ODP Leg 183 (Coffin *et al.*, 2000; Frey *et al.*, 2000). Dating of the basalt has yielded ages of  $\sim 95$  Ma, slightly younger than the Central Kerguelen Plateau (Table 2). We choose to place all of Broken Ridge into the 5 Myr bin between 95 and 100 Ma, although alternative assignments are possible. Most basalt from Broken Ridge is tholeiitic, although several samples fall in the alkalic field (Mahoney *et al.*, 1995; Coffin *et al.*, 2000; Frey *et al.*, 2000; Neal *et al.*, 2002). Basalts from the western Broken Ridge, presumably more distal from continental influence, show no evidence for the involvement of continental lithospheric material in their petrogenesis. In contrast, basalts from the eastern part of the ridge are characterized by elemental and isotopic evidence for continental lithospheric contamination.

We use a published crustal thickening estimate of  $4.1 \times 10^6$  km<sup>3</sup> for the volume of Broken Ridge attributable to the Kerguelen hotspot (Coffin & Eldholm, 1994). This estimate lies fairly close to a previous figure of  $5.2 \times 10^6$  km<sup>3</sup> (Schubert & Sandwell, 1989) for the volume of crustal thickening in excess of normal oceanic crust.

### Ninetyeast Ridge and Skiff Bank

Tholeiitic basalts from the Ninetyeast Ridge (Fig. 1) range in age from  $\sim 82$  to  $\sim 37$  Ma, with a consistent decrease in age to the south (Table 2). The source of these basalts was the Kerguelen hotspot (e.g. Duncan, 1978; Mahoney *et al.*, 1983; Weis *et al.*, 1991; Duncan & Storey, 1992) and geochemical evidence suggests a purely oceanic origin (e.g. Hekinian, 1974; Frey *et al.*,

1977, 1991; Saunders *et al.*, 1991; Weis *et al.*, 1991). Grevemeyer *et al.* (2001) have calculated the total crustal volume of the Ninetyeast Ridge to be  $13.6 \times 10^6$  km<sup>3</sup>. We subtracted a section of normal oceanic crust of 7.1 km thickness from the total crustal volume, leaving  $4.7 \times 10^6$  km<sup>3</sup> attributable to the Kerguelen hotspot. This volume does not include probable Ninetyeast Ridge rocks buried beneath the Bengal Fan, presumably emplaced from  $\sim 95$  to  $\sim 85$  Ma. If we assume that the Kerguelen hotspot produced the northernmost Ninetyeast Ridge during this interval at the same rate as from  $\sim 85$  to  $\sim 35$  Ma, then the total volume of Ninetyeast Ridge crust attributable to the Kerguelen hotspot would be  $5.7 \times 10^6$  km<sup>3</sup>.

Basalts and more silicic rocks drilled at ODP Site 1139 on Skiff Bank have yielded ages of  $\sim 68$  Ma (Table 2). To calculate the crustal volume of Skiff Bank, we applied the technique of Coffin & Eldholm (1994) to the entire Northern Kerguelen Plateau as defined areally by Coffin & Gahagan (1995) (Fig. 2). Crustal thickness has been determined to be 15–20 km beneath the Kerguelen Archipelago (Charvis *et al.*, 1995), and we used a median value of 17.5 km. We subtracted a section of oceanic crust of 7.1 km thickness from the crustal section to determine the net amount of thickened crust. The calculated thickened crustal volume of the Northern Kerguelen Plateau is  $2.5 \times 10^6$  km<sup>3</sup>. As Skiff Bank encompasses  $\sim 10\%$  of the Northern Kerguelen Plateau, we interpret Skiff Bank's crustal volume to be 10% of the total volume, or  $0.3 \times 10^6$  km<sup>3</sup>.

### Northern Kerguelen Plateau

Kerguelen hotspot activity since  $\sim 40$ – $\sim 35$  Ma has produced the Kerguelen Archipelago (Nougier *et al.*, 1983; Nicolaysen *et al.*, 2000), and presumably the Northern Kerguelen Plateau on which it is situated (Figs 1 and 2). Basalts and associated rocks from ODP Site 1140, the Kerguelen Archipelago, Heard Island, and the McDonald Islands are available for study. Radiometric dates suggest that basalts now exposed at the surface of the Kerguelen Archipelago formed from  $\sim 30$  to  $\sim 24$  Ma (Nicolaysen *et al.*, 2000) whereas more alkaline plugs and dikes are distinctly younger (Weis *et al.*, 1993, 1998). No evidence exists for a geochemically distinct continental component in lavas from the Kerguelen Archipelago (Weis *et al.*, 1993; Frey & Weis, 1995; Doucet *et al.*, 2002).

As described above for Skiff Bank, we calculated the total crustal volume of the Northern Kerguelen Plateau (including Skiff Bank) to be  $2.5 \times 10^6$  km<sup>3</sup>. We estimate the total volume of magma produced by the Kerguelen hotspot to form the Cenozoic Northern Kerguelen Plateau to be 90% of that total, when the volume of Skiff Bank is subtracted, or  $2.3 \times 10^6$  km<sup>3</sup>.

### Heard and McDonald Islands

Heard and McDonald Islands, although situated on the interpreted  $\sim 105$  to  $\sim 110$  Ma portion of the Kerguelen Plateau (Figs 1 and 2), have erupted recently (Barling & Goldstein, 1990). Their igneous rocks form a highly potassic suite, and geochemical data suggest an enriched component in the young lavas (Barling *et al.*, 1994). Heard and McDonald Islands, separated by  $\sim 43$  km, are arguably strong candidates for the current location of the Kerguelen hotspot. No other currently active submarine or subaerial volcanism has been observed in the Kerguelen Plateau region, although some models suggest that the Kerguelen Archipelago is the current location of the Kerguelen hotspot (e.g. Steinberger, 2000; Kent *et al.*, 2002). A chain of gravity highs interpreted as volcanic centers extends between the Kerguelen Archipelago and Heard and McDonald Islands (Fig. 2) (Coffin *et al.*, 1986). Basalts dredged from one volcanic center yield radiometric ages of  $\sim 21$  Ma, suggesting an age-progressive track of the Kerguelen hotspot from the Kerguelen Archipelago to Heard and McDonald Islands (Weis *et al.*, 2002). Volumetrically, Heard and McDonald Islands do not appear to contribute significantly to the Kerguelen hotspot output manifested by the Northern Kerguelen Plateau.

### MAGMA OUTPUT RATES AND PLATE TECTONICS

$^{40}\text{Ar}/^{39}\text{Ar}$  age determinations of Kerguelen hotspot basalts (Tables 1 and 2), and crustal volumes determined from wide-angle seismic experiments and gravity modeling permit calculation of the magma output rate of the Kerguelen hotspot through time (Fig. 4). Although existing data are limited, they nevertheless provide a first-order idea of how rates may have varied through time.

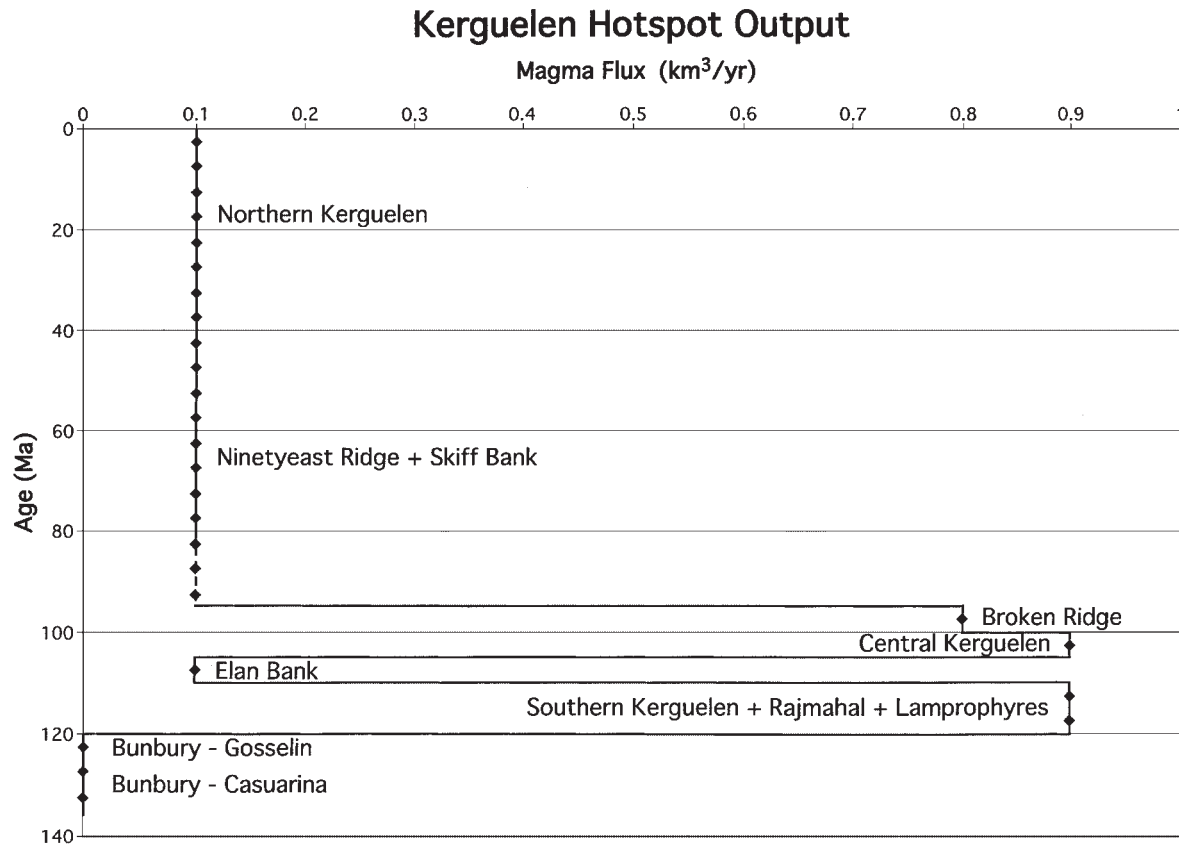
Magma output associated with the Kerguelen hotspot commenced at a relatively low rate ( $\ll 0.1 \text{ km}^3/\text{yr}$ ) at  $\sim 132$  Ma with the Casuarina-type Bunbury Basalt. Such low production rates continued, probably intermittently, to  $\sim 123$  Ma with the Gosselin-type Bunbury basalt. Then, between  $\sim 120$  and  $\sim 110$  Ma, magma output rate increased by several orders of magnitude, to  $\sim 0.9 \text{ km}^3/\text{yr}$ , with emplacement of the Southern Kerguelen Plateau, Rajmahal Traps, and lamprophyres on the Indian and Antarctic continental margins.

Following the  $\sim 120$  to  $\sim 110$  Ma peak in magma production, Kerguelen hotspot output appears to have waned by nearly an order of magnitude, to  $\sim 0.1 \text{ km}^3/\text{yr}$ , for several million years, although this may be an artifact of sparse sampling or errors in assessing the contribution of hotspot magmatism to the crustal volume of Elan Bank. The Central Kerguelen Plateau formed between  $\sim 105$  and  $\sim 100$  Ma at a rate of  $0.9 \text{ km}^3/\text{yr}$ ,

similar to that of the Southern Kerguelen Plateau. Next, Broken Ridge formed from  $\sim 100$  to  $\sim 95$  Ma at a slightly lower rate of  $0.8 \text{ km}^3/\text{yr}$ . Magma output rates for the Kerguelen hotspot between  $\sim 120$  and  $\sim 95$  Ma exceed those of most known hotspot tracks (White, 1993). No rocks have been definitively identified as products of the Kerguelen hotspot between  $\sim 95$  and  $\sim 82$  Ma, although, as previously noted, the oldest part of Ninetyeast Ridge, buried beneath the Bengal Fan, may consist of rocks formed during this time interval. Whether the Kerguelen hotspot magma flux diminished abruptly or gradually by nearly an order of magnitude, to  $\sim 0.1 \text{ km}^3/\text{yr}$ , between  $\sim 95$  and  $\sim 82$  Ma is open to interpretation; we assume an abrupt change at  $\sim 95$  Ma (Fig. 4).

Between  $\sim 82$  and  $\sim 38$  Ma, the Kerguelen hotspot generated the Ninetyeast Ridge and Skiff Bank at a rate of  $\sim 0.1 \text{ km}^3/\text{yr}$ . Finally, from  $\sim 40$  Ma to the present, the hotspot has produced the Northern Kerguelen Plateau, including the Kerguelen Archipelago, and Heard and McDonald Islands, at about the same rate as during the  $\sim 82$  to  $\sim 38$  Ma interval. Tertiary and Quaternary rates for the Kerguelen hotspot are typical of many hotspots, including Hawaii (White, 1993). Since  $\sim 40$  Ma, some changes in hotspot magma flux are suggested by a  $\sim 30$  to  $\sim 24$  Ma episode of volcanism in the Kerguelen Archipelago (Nicolaysen *et al.*, 2000). Our integrated value for Kerguelen hotspot excess magma output since  $\sim 130$  Ma totals  $\sim 2.5 \times 10^7 \text{ km}^3$  (Table 2), considerably less than a previous estimate (Saunders *et al.*, 1994). The difference may be attributed at least in part to better seismic control on crustal thicknesses, improved gravity modeling, and elimination of continental components of the Kerguelen Plateau.

We note that variation in lithospheric thickness, including topography at the lithospheric–asthenospheric interface (e.g. Artyushkov *et al.*, 1980; White & McKenzie, 1989, 1995; Thompson & Gibson, 1991; Sleep, 1996, 1997), is a major control on magma output from hotspots. Thick lithosphere (e.g. continental cratons) inhibits decompressional melting as well as vertical melt migration, whereas thin lithosphere (e.g. spreading centers, rift zones) enhances both. Furthermore, buoyancy of a hotspot's mantle source material can result in laterally ascending flow, which also enhances decompressional melting and vertical melt migration. Plate motions since  $\sim 130$  Ma have resulted in both continental and oceanic lithosphere of variable thickness transiting over the Kerguelen hotspot (Fig. 5). Rare earth element inversions of basalt compositions (McKenzie & O'Nions, 1991, 1995; White *et al.*, 1992; White & McKenzie, 1995) have provided some insight into melting depths and therefore spatial relationships between the Kerguelen hotspot and nearby spreading centers (Kent & McKenzie, 1994; Kent *et al.*, 1997). Below we summarize what is known about Indian

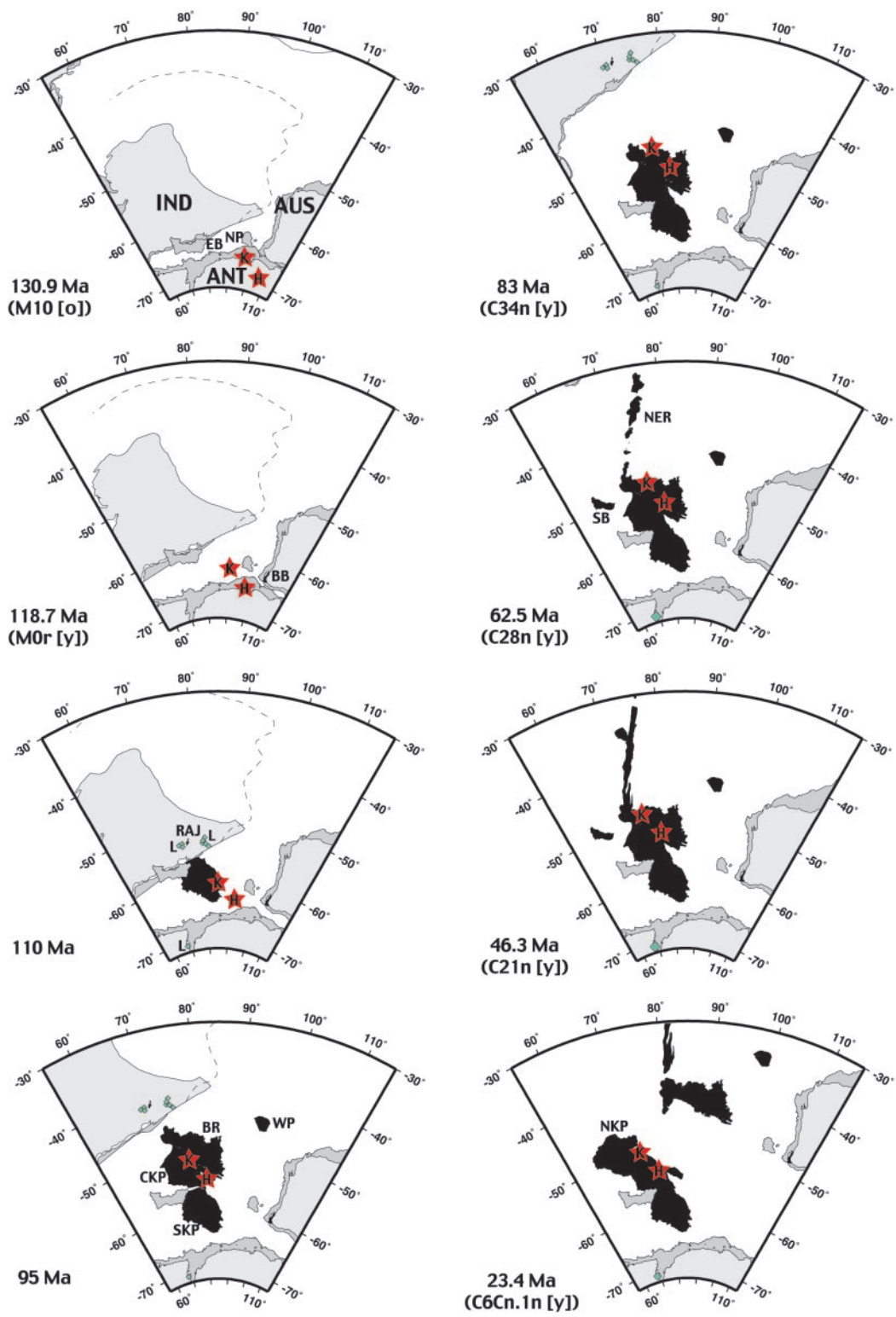


**Fig. 4.** Estimated Kerguelen hotspot magma output since  $\sim 130$  Ma. Analytical uncertainties vary, but  $2\sigma$  values are generally  $<5$  Myr. Therefore, we chose to assign ages to various portions of the province in 5 Myr bins ( $\blacklozenge$ ) for the purpose of calculating the hotspot magma flux. Dashed line between 95 and 85 Ma indicates assumed Ninetyeast Ridge crust of that age buried beneath the Bengal Fan, produced at the same rate as Ninetyeast Ridge and Skiff Bank crust from 85 to 35 Ma. (See Tables 1 and 2 for input ages and crustal volumes.)

Ocean plate reconstructions and lithospheric thicknesses in relation to the Kerguelen hotspot.

A plate reconstruction model for the Indian and Southern Ocean since 130 Ma [Royer & Sandwell (1989); as modified by Lawver *et al.* (1992; 2001) and Royer *et al.* (1992)] (Fig. 5), indicates that sea-floor spreading initiated between Western Australia and Greater India during chron M11 ( $\sim 133$  Ma) (Markl, 1974, 1978) [geomagnetic polarity time scales of Gradstein *et al.* (1994) for Mesozoic time, and Cande & Kent (1995) for Late Cretaceous and Cenozoic time, used throughout]. The age of initiation of sea-floor spreading between India and Antarctica, however, is more problematic (Kent *et al.*, 2002). Only preliminary, differing Mesozoic magnetic anomaly interpretations offshore the portion of the East Antarctic margin conjugate to the eastern Indian margin have been published to date (Ishihara *et al.*, 2000; Rotstein *et al.*, 2001). Offshore eastern India in the Bay of Bengal (Fig. 1), magnetic anomalies M11 ( $\sim 133$  Ma) to M0 ( $\sim 119$  Ma) have been identified (Ramana *et al.*, 1994). However, the presence of continental lithosphere within the Kerguelen Plateau (Elan Bank, Southern Kerguelen

Plateau) and possibly Broken Ridge, and of apparent oceanic crust in the Enderby Basin and Princess Elizabeth Trough between the Kerguelen Plateau and Antarctica (Fig. 1), indicates that when India and Antarctica first broke up, continental portions of Elan Bank and the Southern Kerguelen Plateau were attached to Greater India. Subsequently, at least portions of the Early Cretaceous mid-ocean ridge system between Antarctica and India jumped northward towards India one or more times as the Enderby Basin continued to open, creating the Elan Bank microcontinent and dispersing continental fragments in the Southern Kerguelen Plateau. This, in turn, suggests the existence of one or more abandoned, Early Cretaceous spreading centers between Antarctica and the Kerguelen Plateau, and that the Enderby Basin opened before chron M11 ( $\sim 133$  Ma). However, because of a lack of definitive geophysical or geological data, the initial age of continental break-up between India (with continental components of the Kerguelen Plateau and Broken Ridge attached) and Antarctica could be anywhere between  $\sim 133$  Ma (e.g. Lawver *et al.*, 1992) and  $\sim 165$  Ma (e.g. Roeser *et al.*, 1996). This uncertainty



makes evaluation of the initial effects of various plume models, including impact and incubation, difficult, especially with respect to cause and effect of plume activity and continental break-up. Furthermore, because the  $\sim 120$  to  $\sim 95$  Ma peak in Kerguelen hotspot magma output coincides with the long Cretaceous Normal Superchron ( $\sim 119$  to  $\sim 84$  Ma), prospects for identifying plate tectonic settings, especially interactions between the hotspot and Cretaceous mid-ocean ridge system, appear to be slim.

Appearance of the Kerguelen hotspot's apparent initial magmas, the Casuarina and Gosselin types of Bunbury Basalts in SW Australia (Figs 1 and 5), correlates both temporally and spatially with continental break-up, and therefore, in all probability, with the existence of thinned continental lithosphere. Casuarina ages of  $\sim 128$  to  $\sim 132$  Ma (Tables 1 and 2) coincide approximately with the oldest magnetic anomaly, M11 ( $\sim 133$  Ma), offshore southwestern Australia (Markl, 1974, 1978) that marks the onset of sea-floor spreading between Australia and Greater India. The Gosselin age of  $\sim 123$  Ma roughly coincides with an estimate of  $\sim 125$  Ma for the initiation of sea-floor spreading between Australia and Antarctica (Stagg & Willcox, 1992). Interpreted Lower Cretaceous volcanic rock capping the Naturaliste Plateau (Figs 1 and 5), due west of the Bunbury Basalts, could be correlative with them (Coleman *et al.*, 1982). Continental rocks dredged from the southern flank of the Naturaliste Plateau suggest that the feature is cored by continental crust (Beslier *et al.*, 2001), so the volume of volcanic rock potentially related to Bunbury is unknown. However, as noted previously, the Bunbury Basalts do not appear to be of flood basalt magnitude either in area or volume, nor does the Perth Basin continental margin appear to be more than weakly volcanic (Symonds *et al.*, 1998). So

if indeed the Bunbury Basalts  $\pm$  Naturaliste Plateau volcanic rocks represent the initial output of the Kerguelen hotspot, the underlying anomalous mantle was not significantly hot, wet, or voluminous enough to produce either a continental flood basalt province or a volcanic passive margin despite the enhancing effects of thin, weakened lithosphere on decompressional melting. In marked contrast, voluminous magmatism accompanied  $\sim 136$  to  $\sim 158$  Ma continental break-up between Greater India and Australia to the north, creating volcanic margins and perhaps the younger Cuvier and Wallaby plateaux (Figs 1 and 5) northward along the margin of Western and NW Australia (Symonds *et al.*, 1998). To date, no hotspot source or sources have been identified for that voluminous magmatism.

The next phase of magmatism attributed to the Kerguelen hotspot began at least 15 Myr, and perhaps as many as 45–50 Myr, after sea-floor spreading started between India and Antarctica (Fig. 5). During this phase, the Kerguelen hotspot produced its only features of flood basalt scale, i.e.  $10^5$ – $10^6$  km<sup>2</sup> areal extent, on both thinned continental crust (Rajmahal Traps; Kent *et al.*, 1997) and in an ocean basin (Southern Kerguelen Plateau, Central Kerguelen Plateau, Broken Ridge) (Figs 1, 2 and 5). Between  $\sim 120$  and  $\sim 110$  Ma, the Southern Kerguelen Plateau grew at a rate of  $\sim 0.9$  km<sup>3</sup>/yr (Fig. 4). Magma output rates were also high from  $\sim 105$  to  $\sim 100$  Ma ( $\sim 0.9$  km<sup>3</sup>/yr) and  $\sim 100$  to  $\sim 95$  ( $\sim 0.8$  km<sup>3</sup>/yr) Ma, with the formation of the Central Kerguelen Plateau and Broken Ridge, respectively.

The peak output rates of the Kerguelen hotspot from  $\sim 120$  to  $\sim 95$  Ma (Fig. 4) lag initial break-up between India and Antarctica by 15–75 Myr. Corroborating evidence is that the East Antarctic continental margin south of the Kerguelen Plateau does not exhibit seismic

**Fig. 5.** Plate reconstructions of the southern Indian Ocean region [after Royer & Sandwell (1989), modified by Lawver *et al.* (1992, 2001), Royer & Coffin (1992) and Royer *et al.* (1992)] using the hotspot reference frame of Müller *et al.* (1993). Possible reconstructed positions of the Kerguelen hotspot (after Müller *et al.*, 1993) are indicated by red stars; those labeled 'K' assume that the Kerguelen Archipelago is the current location of the Kerguelen hotspot, and those labeled 'H' assume that Heard Island is the hotspot's current location. Magmatism associated with the Kerguelen hotspot is indicated in black, and lamprophyres as diamonds, as they have appeared through geological time (see Figs 1 and 2 for current locations of individual igneous complexes, and Tables 1 and 2 for their ages). Dashed line indicates a possible northern boundary for Greater India. IND, India; ANT, Antarctica; AUS, Australia. Compare the reconstructions by Kent *et al.* (2002), which take into account the motion of hotspots in a convecting mantle. *130.9 (M10[o]) and 118.7 (M0r[y]) Ma.* Sea-floor spreading initiated during chron M11 ( $\sim 133$  Ma) between Western Australia and Greater India, and at  $\sim 125$  Ma between Australia and Antarctica. This model assumes break-up between India and Antarctica at  $\sim 133$  Ma, although the timing of this event is not well known. The Bunbury Basalts (BB) of SW Australia erupted close to these break-up events in both time and space. Continental portions of Elan Bank (EB) and the Southern Kerguelen Plateau (unknown dimensions) remained attached to Greater India at these times. The Naturaliste Plateau (NP) also contains continental crust. *110 and 95 Ma.* Sea-floor spreading continued between India, Antarctica, and Australia. The initial massive pulse of Kerguelen magmatism created the Southern Kerguelen Plateau (SKP), the Rajmahal Traps (RAJ), and Indian–Antarctic lamprophyres (L) from  $\sim 120$  to  $\sim 110$  Ma (Fig. 4), and may be linked to break-up and separation between Elan Bank and Greater India. The Central Kerguelen Plateau (CKP) formed between  $\sim 105$  and  $\sim 100$  Ma, and Broken Ridge (BR) between  $\sim 100$  and  $\sim 95$  Ma (Fig. 4). Igneous basement of the Wallaby Plateau (WP) is not well characterized geochemically and has not been dated, but its age is inferred to lie between  $\sim 120$  and  $\sim 100$  Ma (Colwell *et al.*, 1994). *83 (C34n[y]) and 62.5 (C28n[y]) Ma.* The hotspot generated the Ninetyeast Ridge (NER) and Skiff Bank (SB) as India continued its northward drift relative to Antarctica. *46.3 (C21n[y]) and 23.4 (C6Cn.1n[y]) Ma.* At  $\sim 40$  Ma, sea-floor spreading commenced between the Central Kerguelen Plateau and Broken Ridge. The hotspot generated the Northern Kerguelen Plateau (NKP), and, since 40 Ma, as Broken Ridge and the Kerguelen Plateau have continued to separate, has produced the Kerguelen Archipelago, Heard and McDonald Islands (Fig. 2), and the chain of volcanoes between Kerguelen and Heard (Fig. 2).

characteristics that would classify it as volcanic (Stagg, 1985; P. A. Symonds, personal communication, 2001). Neither does the conjugate continental margin of East India (e.g. Gopala Rao *et al.*, 1997; Chand *et al.*, 2001), although thick sediments of the Bengal Fan mask the margin's basement structure due south of the Rajmahal Traps (e.g. Kent *et al.*, 1997; Subrahmanyam *et al.*, 1999). Thus, unlike the Iceland hotspot and the associated North Atlantic volcanic province, and the Tristan hotspot and the associated Paraná–Etendeka flood basalt province, the peak output of the Kerguelen hotspot cannot be correlated temporally or spatially with a major phase of continental break-up and volcanic margin formation. Rather, like the relationship between the Réunion hotspot, the Deccan flood basalts, and the break-up between the Seychelles and West India (e.g. Müller *et al.*, 2001), the peak output of the Kerguelen hotspot appears to coincide with one or more episodes of microcontinent formation as pieces of East India, most obviously Elan Bank, broke off and became isolated within oceanic lithosphere. If this hypothesis, the Mesozoic magnetic anomaly identifications in the Bay of Bengal (Ramana *et al.*, 1994), and the geometry of plate reconstructions (Fig. 5) are correct, the age of oceanic crust abutting East India would be diachronous, younging to the NE. This hypothesis would also predict that the portion of the East India continental margin from which Elan Bank and portions of the Southern Kerguelen Plateau broke up and separated would be volcanic, a prediction that awaits acquisition of high-quality, deep seismic data along that margin.

Spatially, volcanic rocks attributed to the Kerguelen hotspot are at their maximum geographical extent from ~120 to ~110 Ma. At ~110 Ma, for example, the distance between the Antarctic lamprophyres and the Rajmahal Traps is ~2000 km (Figs 1 and 5). New and published  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations (Tables 1 and 2) indicate simultaneous volcanism in India (Rajmahal Traps, lamprophyres), Antarctica (lamprophyres), and the Enderby Basin (Southern Kerguelen Plateau). That volcanism occurs over such a broad region is not surprising; what is surprising is that magmatic products from a single plume would apparently bypass the relatively young oceanic lithosphere of the Enderby Basin south of the Southern Kerguelen Plateau, including active spreading centres, and the continent–ocean transition lithosphere of East Antarctica and much of eastern India, to erupt on old continental lithosphere, albeit probably rifted and thinned, of India and Antarctica (Fig. 5).

From ~82 (possibly ~95) to ~35 Ma, the Kerguelen hotspot produced the ~5000 km long Ninetyeast Ridge. Geochemical evidence suggests that much of it formed relatively close to or at a spreading ridge axis (Saunders *et al.*, 1991; Weis *et al.*, 1991), but the lack of any conjugate feature on the Antarctic plate (compare the Iceland

hotspot and the Greenland–Faeroe–Shetland Ridge) casts considerable doubt that the Kerguelen hotspot coincided with a spreading center from ~82 Ma until break-up between the Central Kerguelen Plateau and Broken Ridge at ~40 Ma (Fig. 5). Subsequently, the Antarctic plate moved over the Kerguelen hotspot, and the Northern Kerguelen Plateau was constructed on relatively old oceanic lithosphere. Some evidence exists for variable Tertiary hotspot output in the Kerguelen Archipelago (Nicolaysen *et al.*, 2000) as well as more recent intrusive and extrusive magmatism (Weis *et al.*, 1993, 1998; Weis & Giret, 1994). Since at least 21 Ma, Kerguelen hotspot magmatism has constructed volcanic edifices on the Cretaceous Central Kerguelen Plateau, including Heard and McDonald Islands (Coffin *et al.*, 1986; Weis *et al.*, 2002).

## MANTLE SOURCES AND PLUME–LITHOSPHERE INTERACTIONS

The interplay between Kerguelen hotspot magmatism and Indian Ocean plate motions since Early Cretaceous time has produced a complicated record to decipher. What is clear, however, from the preceding discussion, as well as from a large body of published work, is that the Kerguelen hotspot challenges many widely held assumptions about mantle plumes (Wilson, 1963, 1965; Morgan, 1971, 1972). Current plume models predict massive magmatism coeval with continental break-up (e.g. White & McKenzie, 1989; Anderson, 1995), voluminous magmatism associated with an individual plume exploiting thin and weak lithosphere (e.g. Artyushkov *et al.*, 1980; White & McKenzie, 1989, 1995; Thompson & Gibson, 1991; Sleep, 1996, 1997), and temporal scales of <5 Myr for plume-head-type magmatism (e.g. Campbell & Griffiths, 1990). Large volumes of magmatism apparently did not accompany the break-up of India and Antarctica, but perhaps did accompany the break-up between India and Elan Bank. Extensive Early Cretaceous magmatic activity did not affect large areas of relatively young oceanic and transitional lithosphere between the Southern Kerguelen Plateau and Antarctica, including active spreading centres, and along much of the margin of East India, yet produced lamprophyres by partial melting of the relatively old continental lithosphere of eastern India and East Antarctica. Finally, peak output rates for magmatism attributed to the Kerguelen plume lasted for ~25 Myr. Thus, our results indicate more complex plume–lithosphere interactions and longer-lived voluminous magmatism for the Kerguelen hotspot than predicted by current models.

As alternatives to incubating single plume-head models (e.g. Kent *et al.*, 1992; Saunders *et al.*, 1992; Storey *et al.*,

1992), we suggest two possibilities: (1) that the magmatism attributed to the Kerguelen plume did not arise from a single plume source, but from multiple plume sources (e.g. Burke, 2001; Wilson & Patterson, 2001); or (2) that a single plume source accounts for the magmatic products attributed to the Kerguelen plume, but that vigorous mantle circulation during Early Cretaceous time (e.g. Stein & Hofmann, 1994) caused strong mantle shear flow that split the initial Kerguelen plume conduit into several 'diapirs' of varying sizes, buoyancies, and mantle ascent rates (e.g. Olson, 1990; Steinberger & O'Connell, 1998).

Multiple sources for regional hotspot volcanism are suggested by tomographic images of the lowermost mantle that show heterogeneous slow regions in which slower, D" 'hotspots' are embedded (e.g. Garnero, 2000). Multiple, finger-like convective instabilities in the upper mantle have recently been proposed to explain the Tertiary–Quaternary volcanism of western and central Europe (Wilson & Patterson, 2001). If multiple mantle plumes can arise from individual heterogeneous slow regions at either the core–mantle boundary or the 670 km discontinuity, then much, if not all, of the temporal and spatial variability displayed by the volcanic products attributed to the Kerguelen hotspot could be explained. This scenario might also explain the geochemical heterogeneity characterizing Kerguelen hotspot-related magmatism (e.g. Frey *et al.*, 1977, 1991; Storey *et al.*, 1989, 1992; Saunders *et al.*, 1991; Weis *et al.*, 1991; Frey & Weis, 1995). Additionally, multiple plumes ascending from a single source region could account for massive Cretaceous volcanism offshore Western Australia that has not so far been linked to the Kerguelen hotspot (e.g. Symonds *et al.*, 1998).

Different 'diapirs' from the same sub-lithospheric mantle source could also explain the Kerguelen hotspot products' distribution in time and space. In Early Cretaceous time, separate mantle diapirs could have produced the Bunbury Basalts, the Southern Kerguelen Plateau, the Rajmahal Traps–Indian lamprophyres, the Antarctic lamprophyres, and the Central Kerguelen Plateau–Broken Ridge. As mantle circulation rates slowed during Late Cretaceous time, a single plume conduit could have become continuous and long-lived, producing the Ninetyeast Ridge. Thereafter, old oceanic lithosphere, slow Antarctic plate motion relative to the plume conduit, and thickened Cretaceous Kerguelen Plateau lithosphere may account for the lack of a well-defined hotspot trace since 40 Ma.

Little is known about how the mass and energy flux of mantle plumes varies with time. Hawaii, the prototypical plume with its continuity of magma output over time (e.g. Duncan & Clague, 1985), is probably an end-member of the spectrum. At the other end of the spectrum are short-lived, massive bursts of flood basalt volcanism that lack any obvious subsequent volcanic record, e.g.

the Central Atlantic magmatic province (Marzoli *et al.*, 1999). Kerguelen appears to lie somewhere in the middle of this spectrum, as well-defined hotspot tracks are difficult to discern both before and after the creation of Ninetyeast Ridge.

## CONCLUSIONS

The Kerguelen hotspot source has produced  $\sim 2.5 \times 10^7$  km<sup>3</sup> of mafic crust since  $\sim 130$  Ma. Magma output has varied significantly through time (Fig. 4), beginning with low volumes contemporaneous with or postdating continental break-up in Early Cretaceous time (Fig. 5); extending through at least one and possibly two peaks in Early and Late Cretaceous time into a pre-existing and growing ocean basin; and finally tapering to relatively steady-state output in Late Cretaceous and Cenozoic time. The 25 Myr duration of peak hotspot output at geographically and tectonically diverse settings is difficult to reconcile with current plume models. We propose two alternatives to the standard Hawaii model for hotspots, one involving multiple mantle plume sources, and the other a single, but dismembered plume source.

Although we believe that our calculated trends in the Kerguelen hotspot magma output curve are relatively robust, more high-precision age determinations, additional geophysical investigations of crustal structure, improved means to attach realistic volume estimates to the age determinations, better petrological and geochemical control on the hotspot's magma output, and increased understanding of hotspot melting, melt migration, and magmatism will significantly improve quantification of magma output. However, in light of currently available data, the possibilities of multiple plume sources or of a single plume source separating into a number of separate diapirs to account for the Cretaceous and Cenozoic volcanism in the eastern Indian Ocean region appear to require serious consideration and critical evaluation.

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