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Temporal evolution of the Kerguelen plume: geochemical evidence from ~ 38 to 82 Ma lavas forming the Ninetyeast Ridge

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Abstract Basaltic basement has been recovered by deep-sea drilling at seven sites on the linear Ninetyeast Ridge in the eastern Indian Ocean. Studies of the recovered lavas show that this ridge formed from ~ 82 to 38 Ma as a series of subaerial volcanoes that were created by the northward migration of the Indian Plate over a fixed magma source in the mantle. The Sr, Nd and Pb isotopic ratios of lavas from the Ninetyeast Ridge range widely, but they largely overlap with those of lavas from the Kerguelen Archipelago, thereby confirming previous inferences that the Kerguelen plume was an important magma source for the Ninetyeast Ridge. Particularly important are the ~ 81 Ma Ninetyeast Ridge lavas from DSDP Site 216 which has an anomalous subsidence history (Coffin 1992). These lavas are FeTi-rich tholeiitic basalts with isotopic ratios that overlap with those of highly alkalic, Upper Miocene lavas in the Kerguelen Archipelago. The isotopic characteristics of the latter which erupted in an intraplate setting have been proposed to be the purest expression of the Kerguelen plume (Weis et al. 1993a,b). Despite the overlap in isotopic ratios, there are important compositional differences between lavas erupted on the Ninetyeast Ridge and in the Kerguelen Archipelago. The Ninetyeast Ridge lavas are dominantly tholeiitic basalts with incompatible element abundance ratios, such as La/Yb and Zr/Nb, which are intermediate between those of Indian Ocean MORB (mid-ocean ridge basalt) and the transitional to alkalic basalts erupted in the Kerguelen Archipelago. These compositional differences reflect a much larger extent of melting for the Ninetyeast Ridge lavas, and the proximity of the plume to a spreading ridge axis. This tectonic setting contrasts with that of the recent alkalic lavas in the Kerguelen Archipelago which formed beneath the thick lithosphere of the Kerguelen Plateau. From ~ 82 to 38 Ma there was no simple, systematic temporal variation of Sr, Nd and Pb isotopic ratios in Ninetyeast Ridge lavas. Therefore all of the isotopic variability cannot be explained by aging of a compositionally uniform plume. Although Class et al. (1993) propose that some of the isotopic variations reflect such aging, we infer that most of the isotopic heterogeneity in lavas from the Ninetyeast Ridge and Kerguelen Archipelago can be explained by mixing of the Kerguelen plume with a depleted MORB-like mantle component. However, with this interpretation some of the youngest, 42–44 Ma, lavas from the southern Ninetyeast Ridge which have $^{206}Pb/^{204}Pb$ ratios exceeding those in Indian Ocean MORB and Kerguelen Archipelago lavas require a component with higher $^{206}Pb/^{204}Pb$, such as that expressed in lavas from St. Paul Island.

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Introduction

Volcanism associated with mantle plumes provides important constraints on mantle composition and processes because mantle plumes have geochemical characteristics that differ significantly from the mantle sources of mid-ocean ridge basalt (MORB). In order to understand the origin and evolution of mantle plumes, it is necessary to determine how the compositions of lavas derived from long-lived plumes vary on time scales of several million years. The Ninetyeast Ridge in the eastern Indian Ocean is interpreted as a long-lived (~ 90 to 38 Ma), 5000 km, volcanic chain resulting from the northward migration of the Indian Plate over

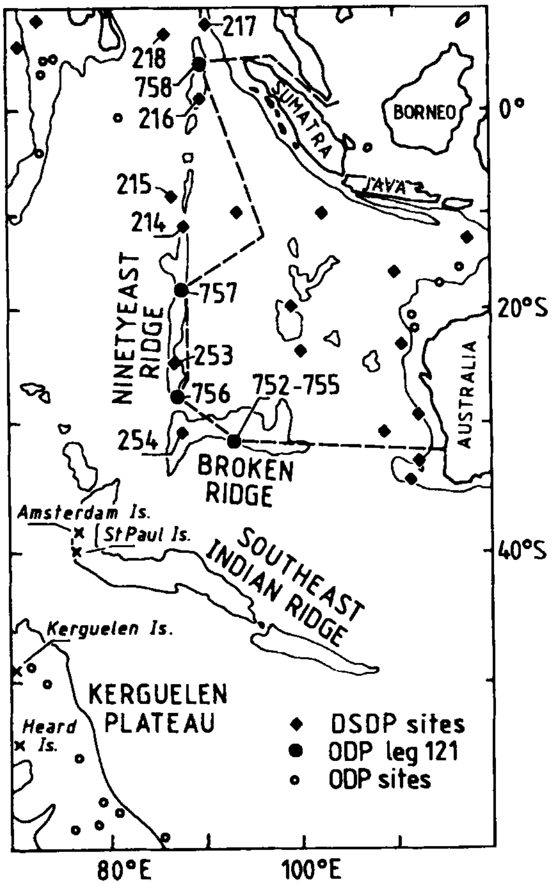


Fig. 1 Location map for the Eastern Indian Ocean showing Ninetyeast Ridge, DSDP and ODP drill sites, and other tectonic features relevant to this paper

the Kerguelen plume (Fig. 1). This interpretation is based on diverse evidence such as paleolatitudes inferred from paleomagnetics (Peirce 1978; Klootwijk et al. 1991), a south to north increase in basement age along the Ninetyeast Ridge (Duncan 1978, 1991); the geochemical characteristics of lavas forming the ridge (e.g., Frey et al. 1977; Mahoney et al. 1983; Weis et al. 1991; Saunders et al. 1991; Weis et al. 1992) and plate tectonic reconstructions showing plate movements over the Kerguelen hotspot whose present location is inferred to be slightly west of the Kerguelen Archipelago (Curray and Munasinghe 1991; Duncan and Storey 1992; Müller et al. 1993). In addition, the shallow water sediments overlying basement, thick ash sequences indicating shallow water volcanism and subaerially erupted basalts, indicate that, like the Hawaiian Ridge, much of the Ninetyeast Ridge formed subaerial volcanic islands which subsided rapidly as volcanism ceased when the volcano moved away from a fixed magma source, the plume (Coffin 1992). During formation of the Ninetyeast Ridge it is likely that a spreading ridge axis was close to the hotspot (e.g., Royer et al. 1991). Although this ridge axis was migrating northward, a proximal position with respect to the hotspot was maintained by southerly jumps of the spreading ridge axis; e.g., the ridge axis jumped to the south by a total of 11° between 68 and 46 Ma (Royer et al. 1991). Therefore in detail the age progression of the basement along the Ninetyeast Ridge is complex. Since ~ 38 Ma the Kerguelen plume has been beneath the Antarctic Plate, and it has created the Kerguelen Archipelago.

The oldest volcanics that have been attributed to the Kerguelen plume are continental basalts: the ~ 130 Ma Bunbury Basalt in southwest Australia and the ~ 117 Ma Rajmahal Basalt in northeast India (Mahoney et al. 1983; Baksi et al. 1987; Davies et al. 1989; Kent 1991; Storey et al. 1989, 1992; Frey et al. 1994a). Some plate reconstructions, however, indicate that these continental basalts were not erupted above the Kerguelen hotspot (Curray and Munasinghe 1991; Müller et al. 1993). Nevertheless, there is a consensus that prior to forming the Ninetyeast Ridge the Kerguelen plume formed important oceanic features on the Australian/Antarctica Plate; i.e., the ~ 109 to 118 Ma southern Kerguelen Plateau and the ~ 88 Ma Broken Ridge and the conjugate central Kerguelen Plateau (e.g., Duncan and Storey 1992).

During the Deep Sea Drilling Project (DSDP) the Ninetyeast Ridge basaltic basement was cored at four sites on Legs 22 and 26 and more recently Leg 121 of the Ocean Drilling Program (ODP) recovered basaltic basement from three additional sites on this ridge (Fig.1). Sampling at seven sites over the 5000 km ridge length is not sufficient to define the detailed evolution of the ridge. Nevertheless, the similarity of Sr, Nd and Pb isotopic ratios in the ~ 81 Ma tholeiitic basalts from Ninetyeast Ridge drill site 216 and the youngest alkalic lavas erupted in the Kerguelen Archipelago is additional evidence that the Kerguelen plume was an important magma source for the Ninetyeast Ridge. However, the significant compositional differences between Ninetyeast Ridge lavas and the youngest lavas erupted in the Kerguelen Archipelago and the diversity in Sr, Nd and Pb isotopic ratios have important implications for the interpretation that the Ninetyeast Ridge formed as a trace of the Kerguelen plume. For example, only tholeiitic lavas, dominantly basalts, have been recovered from the Ninetyeast Ridge (e.g., Frey et al. 1991; Saunders et al. 1991) which contrasts with the alkalic lavas that have erupted in the Kerguelen Archipelago over the last 20 Ma (Gautier et al. 1990; Weis et al. 1993a). Also, the wide range of $^{206}Pb/^{204}Pb$ in lavas associated with the Kerguelen plume have led to contrasting interpretations. Class et al. (1993) propose that the present $^{206}Pb/^{204}Pb$ of the Kerguelen plume can be inferred from the highest ratios, ~ 18.80, in lavas from Heard Island, a volcanically active island on the Kerguelen Plateau southeast of the Kerguelen Archipelago (Fig.1). In contrast Weis et al. (1993a,b) propose that the low $^{206}Pb/^{204}Pb$ ratios, 18.06 to 18.27 in recent lavas of the Kerguelen Archipelago are characteristic of the Kerguelen plume.

Table 1 Incompatible element abundances in Ninetyeast Ridge lavas from DSDP cores (P_2O_5 in wt%, others in ppm).
This summary table for DSDP samples includes data from Frey et al. (1977), Saunders et al. (1991 - samples with * superscript) and new data obtained for this study. New data for Sc, Hf, Ta and REE obtained by neutron activation at MIT. Data for other elements obtained by X-ray fluorescence at University of Massachusetts. Data for lavas from Sites 756, 757 and 758 are in Frey et al. (1991) and Saunders et al. (1991). For evaluations of accuracy and precision see Frey et al. (1991)

Site 254 (30°58′S)	Intersedimentary flow			Basement basalt										
	31–1 88–90	31–1* 100-103	31–1 138-140	35–1 56-59	35–1 99-101	35–1* 100-108	35–2 140-142	35–3 27-30	35–3 118-120	36–1 43-46	36–1 148-150	36–3 36-39	36–3* 122–124	38–1* 117-119
P_2O_5	–	0.21	–	–	0.22	0.26	–	–	–	–	–	–	0.26	0.16
Rb	1.5	4	1.1	1.8	1.8	2	2.1	1.6	5.7	1.9	1.7	1.1	1	17
Sr	185	171	215	104	124	117	143	142	173	150	137	164	179	111
Ba	69	58	87	72	85	75	55	103	99	69	75	59	63	49
Sc	43	39	–	–	42	–	–	39	–	41	–	42	–	–
V	287	246	412	313	273	287	365	302	311	365	321	309	325	285
Cr	495	402	529	473	575	506	358	560	294	525	315	430	244	148
Ni	194	230	176	233	227	249	175	226	154	178	174	171	129	86
Zn	107	–	135	128	116	–	133	131	126	132	131	124	–	–
Ga	19.4	–	23.4	18.8	18.0	–	19.8	17.9	20.3	18.9	20.7	20.9	–	–
Y	41.9	41	43.3	35.1	32.4	37	38.6	32.8	36.9	42.7	37.2	34.2	43	31
Zr	133	118	172	135	135	138	149	134	141	149	149	148	158	118
Nb	9.8	10	12.7	10.6	10.3	10	11.6	10.6	10.4	11.5	11.9	10.9	11	8
Hf	–	3.35	–	–	–	–	–	–	–	–	–	–	–	–
Ta	–	0.62	–	–	–	–	–	–	–	–	–	–	–	–
Th	–	0.84	–	–	–	–	–	–	–	–	–	–	–	–
La	12.0	11.9	–	–	10.1	–	–	8.8	–	10.4	–	9.7	–	–
Ce	24	26.6	30.5	24.1	26	32	29	28	24	30	28	26	30	19
Nd	16	19	–	–	15	–	–	15	–	18	–	17	–	–
Sm	4.33	5.0	–	–	4.83	–	–	4.59	–	5.30	–	4.97	–	–
Eu	1.68	1.56	–	–	1.51	–	–	1.53	–	1.84	–	1.87	–	–
Tb	0.81	1.12	–	–	0.85	–	–	0.89	–	1.0		1.0	–	–
Yb	3.0	3.49	–	–	3.2	–	–	3.2	–	3.9	–	3.6	–	–
Lu	0.48	0.51	–	–	0.56	–	–	0.46	–	0.67		0.52	–	–

Table 1 (continued)

Site 253 (24°53′S)	Uper flow		Basement picrites		
	24-1 84-85	24-1*	58CC #1	58CC #3	58CC*
P_2O_5	0.35	0.61	–	–	0.05
Rb			3.60	1.6	6
Sr			62.5	70.8	100
Ba			11	1	52
Sc			46	58	65
V			224	250	254
Cr			755	580	624
Ni			510	224	274
Zn			52	126	–
Ga			11.6	13.2	–
Y			20.2	19.9	29
Zr			25	27	24
Nb			0.73	0.4	2
Hf	3.6	3.40	0.98	1.1	1.20
Ta	0.66	0.4	–	–	0.24
Th		1.28			0.8
La	9.2	14.9	2.3	3.3	4.2
Ce	22.2	31	6.2	7.5	14.4
Nd	11.1	17.1	5.0	4.9	10.7
Sm	3.1	4.0	1.66	1.96	3.1
Eu	1.2	1.28	0.65	0.67	1.13
Tb	0.78	0.92	0.39	0.52	0.9
Yb	2.9	4.09	2.3	2.8	3.8
Lu	0.54	0.67	0.36	0.47	0.52

In this paper we (1) summarize our geochemical studies of Ninetyeast Ridge lavas obtained on ODP Leg 121 (Frey et al. 1991; Weis and Frey 1991); (2) present new trace element and isotopic data for Ninetyeast Ridge lavas from the DSDP cores (Tables 1 and 2); (3) use these and earlier data sets to evaluate the origin and evolution of the lavas forming the Ninetyeast Ridge.

Basement drill sites on the Ninetyeast Ridge

The DSDP Site 254 is the youngest and most southerly site drilled on the Ninetyeast Ridge (Fig. 1). A ~2 m lava flow occurs 25 m above the basement (core 31-1, Table 1). Basement penetration was 42.5 m and 11.1 m of basalt was recovered. Based on total fusion ^{40}Ar-^{39}Ar ages and an isochron age from incremental heating, Duncan (1978) inferred a basement age of 38 Ma. This age is similar to the oldest ages found in the Kerguelen Archipelago (Giret and Lameyre 1983).

At ODP Site 756D, 26.9 m of basalt was recovered from basement penetration of 82 m. Duncan (1991) reports ^{40}Ar-^{39}Ar plateau ages of 42–44 Ma.

At DSDP Site 253, 388 m of altered, vitric volcanic ash and lapilli were drilled before bottoming into an olivine-rich basalt. This ash sequence contains two thin scoriaceous basalt flows. Only 35 cm of presumed basement was recovered and based on the paleontologic age of shelf deposits within the ash the basement basalt has a minimum age of 44–49 Ma.

Table 1 (continued)

DSDP Site 214 (11°20′S)

	Andesite										Basalt
	48-1* 55-57	48-1 94-100	48-2 9-13	48-2* 137-138	49-1* 129-130	49-2 0-7	50-1* 133-135	50-1 145-150	51-1 108-114	51-1* 122-125	53-1 26-30
P_2O_5	0.67	0.60	0.64	0.67	0.67	0.65	0.68	0.67	0.84	0.64	0.15
Rb	38	22.6	34.6	39	46	44.4	44	42.1	10.5	39	6.0
Sr	295	297	287	293	278	282	286	285	351	286	111
Ba	293	279	244	287	362	293	290	239	268	305	–
Sc	–	–	17	–	18	–	–	17	–	–	44.1
V	38	25	21	41	42	30	42	24	34	34	347
Cr	–	3	40	–	–	2	–	–	2	2	68
Ni	3	8	4	2	2	5	4	5	13	3	69
Zn	–	143	111	–	–	134	–	105	158	–	109
Ga	–	23.9	23.6	–	–	23.1	–	23.7	27.5	–	19.3
Y	67	61	61	67	86	61	67	60	80	65	29.3
Zr	380	343	268	374	351	309	368	254	419	385	129
Nb	28	27.0	22.6	27	26	25.3	28	21.4	32.3	29	8.0
Hf	–	–	8.7	–	8.7	–	–	8	–	–	3.08
Ta	–	–	10.4	–	2.07	–	–	–	–	–	–
Th	–	–	–	–	4.0	–	–	–	–	–	0.62
La	–	–	30.8	–	35.5	–	–	33	–	–	7.45
Ce	84	105	85	88	93	117	82	73	111	85	22.1
Nd	–	–	46.1	–	58	–	–	44	–	–	14.1
Sm	–	–	10.9	–	12.9	–	–	11.1	–	–	3.99
Eu	–	–	3.25	–	3.40	–	–	3.1	–	–	1.46
Tb	–	–	1.98	–	1.83	–	–	1.9	–	–	0.81
Yb	–	–	4.85	–	5.71	–	–	4.6	–	–	2.82
Lu	–	–	0.97	–	0.89	–	–	1.0	–	–	0.41

Table 1 (continued)

DSDP Site 216 (1°28′N)

	Basalt						
	36-4* 14-16	37-1* 23-25	37-2 80	37-3* 126-128	38-1* 53-55	38-2 143-150	38-5*
P_2O_5	0.26	0.24	0.23	0.23	0.23	0.22	0.22
Rb	18	25	2.6	18	9	9.3	13
Sr	199	178	177	184	182	174	180
Ba	117	142	127	120	126	121	99
Sc	–	–	39.0	–	42	40.2	–
V	335	435	401	407	417	359	370
Cr	202	132	42	45	48	44	60
Ni	52	49	51	40	37	43	54
Zn			128			117	–
Ga			22.1			22.5	
Y	27	42	31.8	38	36	34	33
Zr	156	179	167	178	183	152	158
Nb	14	15	14.2	15	15	13.1	14
Hf			3.9		4.2	4.2	
Ta			–		1.01	–	
Th			1.21		1.5	1.4	
La			13.0		14.4	12.9	
Ce	41	31	33.8	35	35.8	33.5	31
Nd			19.7		20.6	18.9	
Sm			4.97		5.7	5.25	
Eu			1.75		1.58	1.76	
Tb			1.02		1.08	1.01	
Yb			3.15		2.8	3.44	
Lu			0.45		0.52	0.48	

Table 1 (continued)

St. Paul Island

	21	38	39	41	Dosso	Michard
P_2O_5	0.35	0.40	0.20	0.80	0.20	–
Rb	10.3	4.5	31.3	8.6	8.3	11.6
Sr	299	288	247	257	336	216
Ba	138	133	253	218	–	–
Sc	33	32	25	35	–	–
V	265	240	156	303	198	–
Cr	132	71	124	58	3	–
Ni	519	278	611	294	12	–
Zn	118	160	160	152	–	–
Ga	21.3	20.7	22.6	25.2	–	–
Y	28.6	28.6	56.9	41.6	22.2	–
Zr	197	167	375	337	120	–
Nb	22.6	18.9	41.6	38.3	13.2	–
Hf	4.11	3.87	8.19	7.24	2.9	–
Ta	3.2	2.6	5.9	5.5	1.01	–
Th	1.79	1.44	3.64	3.18	1.27	–
La	13.5	13.0	28.2	19.6	9.9	7.42
Ce	34.2	32.2	68.6	57.0	–	18.22
Nd	17.5	17.2	34.3	29.8	13.4	11.15
Sm	4.75	4.41	8.88	7.26	3.39	3.11
Eu	1.62	1.52	2.46	2.32	1.45	1.43
Tb	0.89	0.84	1.56	1.17	0.60	–
Yb	2.64	2.50	4.85	3.67	–	2.07
Lu	0.38	0.36	0.75	0.53	–	–

New data for samples from St. Paul Island were also obtained by neutron activation and X-ray fluorescence. The high Ni contents of the first 4 samples are not consistent with MgO contents of 4–5% (Girod et al., 1971) and they probably reflect contamination; these samples were obtained as powders from Girod. Other data from Dosso et al. (1988) and Michard et al. (1986).

Table 2 Sr, Nd and Pd isotopic data and Pb and U isotope dilution concentrations for DSDP sites of the Ninetyeast Ridge "Initial" $^{87}Sr/^{86}Sr$ and ^{143}Nd ^{144}Nd ratios calculated for leached samples on the basis of the measured XRF Rb and Sr concentrations and INAA Sm and Nd concentrations on unleached samples (from Table 1). The "initial" ratios were calculated at the age given (Duncan 1978). Pb and U concentrations were measured on leached samples by isotope dilution and have been used to age correct the Pb isotopic ratios. The reader is referred to Weis and Frey (1991) for a detailed description of the analytical procedures. During the course of these measurements, repeated analyses of NBS987 gave 0.702740 ± 6 normalized to $^{86}Sr/^{88}Sr = 0.1194$ and 0.511732 ± 10 normalized to $^{146}Nd/^{144}Nd = 0.7219$ for the Merck Nd standard

Leg	Site	Sample no.	Age Ma	$^{87}Sr/^{86}Sr$ measured	$2\sigma_m$	$^{87}Sr/^{86}Sr$ age corrected	$^{143}Nd/^{144}Nd$ measured	$2\sigma_m$	ε_{Nd}	$^{143}Nd/^{144}Nd$ age corrected	ε_{NdI}	Pb ppm	U ppm
22	214	48-2 9-13	59.0	0.704653	7	0.70441	0.512833	9	3.8	0.512758	3.8	3	0.83
				0.704703	14		0.512811	21					
	214	50-1 145-150	59.0	0.704725	6	0.70437	0.512798	12	3.1	0.512739	3.5	3.9	0.81
	214	53-1 30-35	59.0	0.704070	5	0.70394	0.512930	9	5.7	0.512864	5.9	0.28	0.04
				0.703996	13		0.512896	18					
22	216	37-2 80-	81.0	0.705467	6	0.70542	0.512652	19	0.3	0.512571	0.7	0.86	0.46
				0.705454	11								
	216	38-2 143-150	81.0	0.705649	6	0.70547	0.512652	39	0.3	0.512563	0.6	0.71	0.25
				0.705614	7								
26	253	58cc #3	46.0	0.704738	5	0.70469						0.09	0.01
26	254	31-1 88-90	38.0	0.704494	5	0.70448	0.512757	18	2.3	0.512716	2.5	0.27	0.05
				0.704499	14		0.512778	18					
		Saint-Paul 21	0	0.703650	11		0.512896	11	5.0	–	–	1.1	0.33
				0.703672	11								

At ODP Site 757C, 155.3 m of volcaniclastics overly highly plagioclase phyric basalt. Approximately 25 m of basalt was recovered from a basement penetration of 48 m. Although the ^{40}Ar-^{39}Ar systematics of these samples are complex, an evaluation of total fusion and slightly discordant plateau and isochron ages led Duncan (1991) to infer an eruption age of 58 Ma which is consistent with the overlying late Paleocene sediments.

At DSDP Site 214, 100 m of interbedded lignite, volcanic clay and tuff overlie a 28 m sequence (6.2 m recovered) of differentiated (high SiO_2, low MgO) lavas (oceanic andesites). Below an intervening 17.9 m of tuffaceous sediment the hole penetrated 23.5 m of basalt with a recovery of 7 m. Duncan (1978) reported ^{40}Ar-^{39}Ar total fusion, plateau and isochron ages for an oceanic andesite and inferred an eruption age of 59 Ma.

At DSDP Site 216, 109 m of glauconitic volcanic clay and chalk overlie basement which consists of lithic tuff interbedded with basalt. The lowermost cores penetrated 15 m of basalt and recovered 11.2 m. Total fusion ^{40}Ar-^{39}Ar ages for the basalts average 81 Ma, and Duncan (1978) concluded this is a likely maximum age.

At ODP Site 758A the basement is overlain by 63.9 m of volcanic clay and 67.4 m of ash. The largest basement penetration, 178 m, of the Ninetyeast Ridge was achieved at this site, and 118.5 m of basalt were recovered. In contrast to all of the other sites, the lowermost flows in this core are pillow basalts. Duncan (1991) reported ^{40}Ar-^{39}Ar plateau ages of 81–83 Ma which are concordant with isochron ages; thus, these are the oldest basalts recovered from the Ninetyeast Ridge.

Results

Compositional data for the four DSDP sites on the Ninetyeast Ridge were summarized and discussed by Frey et al. (1977). Additional compositional and isotopic data for lavas from these DSDP sites were reported by Subbarao et al. (1977), Reddy et al. (1978), Whitford and Duncan (1978), Mahoney et al. (1983), Dupré and Allègre (1983), Hart (1988) and Saunders et al. (1991). Tables 1 and 2 include our new trace element and isotopic data for Ninetyeast Ridge lavas from DSDP cores and data for tholeiitic basalts from St. Paul Island which is part of an elevated platform on the southeast Indian Ridge (Fig. 1) that is interpreted as reflecting a relatively small plume. Our data and preliminary interpretations for lavas recovered at ODP sites on the Ninetyeast Ridge are in Frey et al. (1991) and Weis and Frey (1991).

Postmagmatic alteration

Basalts recovered from the Ninetyeast Ridge are moderately to highly altered; e.g., H_2O^+ contents in most of the ODP Leg 121 basalts range from 1 to 2%. The alteration principally occurred in a low temperature environment under both reducing and oxidizing conditions. Abundances of Na, K and Rb, and probably other major elements were modified during these alteration processes. Most but not all of the Ninetyeast Ridge lavas lie either within the tholeiitic field or are transitional; i.e., close to tholeiitic-alkalic boundary in a Na_2O + K_2O versus SiO_2 plot (Fig. 2). Because of alkali mobility this is not a reliable classification plot for altered basalts. For example, the several Site 757 samples that are within the alkalic field in Fig. 2 are plagioclase-rich samples whose calcic-plagioclase has been altered to albitic plagioclase thereby resulting in whole-rock Na_2O contents > 4.5% (Frey et al. 1991); i.e., these samples are tholeiitic lavas which are in the alkalic field because their Na_2O contents were increased during late-stage alteration. The tholeiitic to transitional melt compositions of the magmas at the

$^{238}U/^{204}Pb$	$^{206}Pb/^{204}Pb$ measured	$^{207}Pb/^{204}Pb$ measured	$^{208}Pb/^{204}Pb$ measured	$^{206}Pb/^{204}Pb$ age corrected	$^{207}Pb/^{204}Pb$ age corrected
17.6	18.35	15.571	38.71	18.19	15.56
13.2	18.30	15.543	38.57	18.18	15.54
9.05	18.32	15.580	38.44	18.24	15.58
33.2	18.09	15.585	38.81	17.67	15.57
22.4	18.07	15.588	38.85	17.79	15.58
6.32	18.61	15.593	38.76	18.57	15.59
11.7	18.06	15.519	38.55	17.99	15.52
	18.04	15.506	38.52	17.97	15.50
19.2	18.75	15.561	38.90		

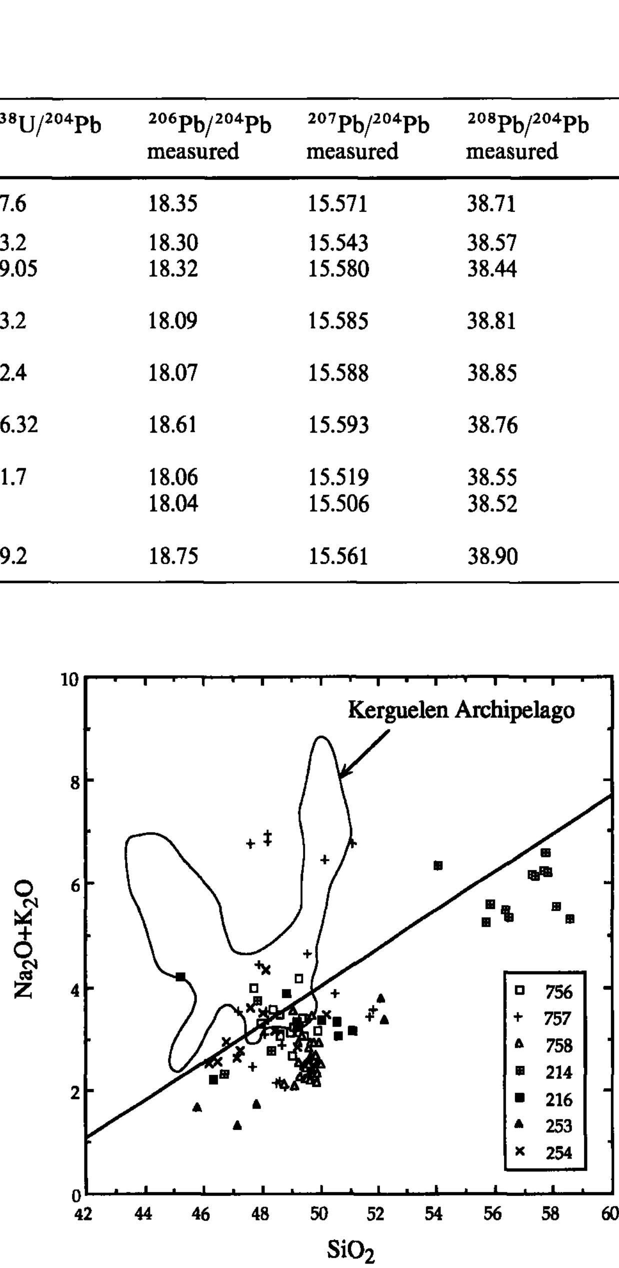


Fig. 2 Total alkalis ($Na_2O + K_2O$) versus SiO_2 (all in wt%) classification plot. The *solid diagonal line* is the alkalic (*upper* field)-tholeiitic (*lower* field) boundary line from MacDonald and Katsura (1964). Most of the analyzed lavas from the Kerguelen Archipelago are alkalic (data from Watkins et al. 1974; Storey et al. 1988; Gautier et al. 1990; Weis et al. 1993a,b). In contrast, most of the lavas from the Ninetyeast Ridge (designated by *drill site number*) are tholeiitic basalts; notable exceptions are some highly altered basalts from ODP Site 757 which are in the alkalic field because of postmagmatic alteration (data from Frey et al. 1977; Frey et al. 1991; Saunders et al. 1991)

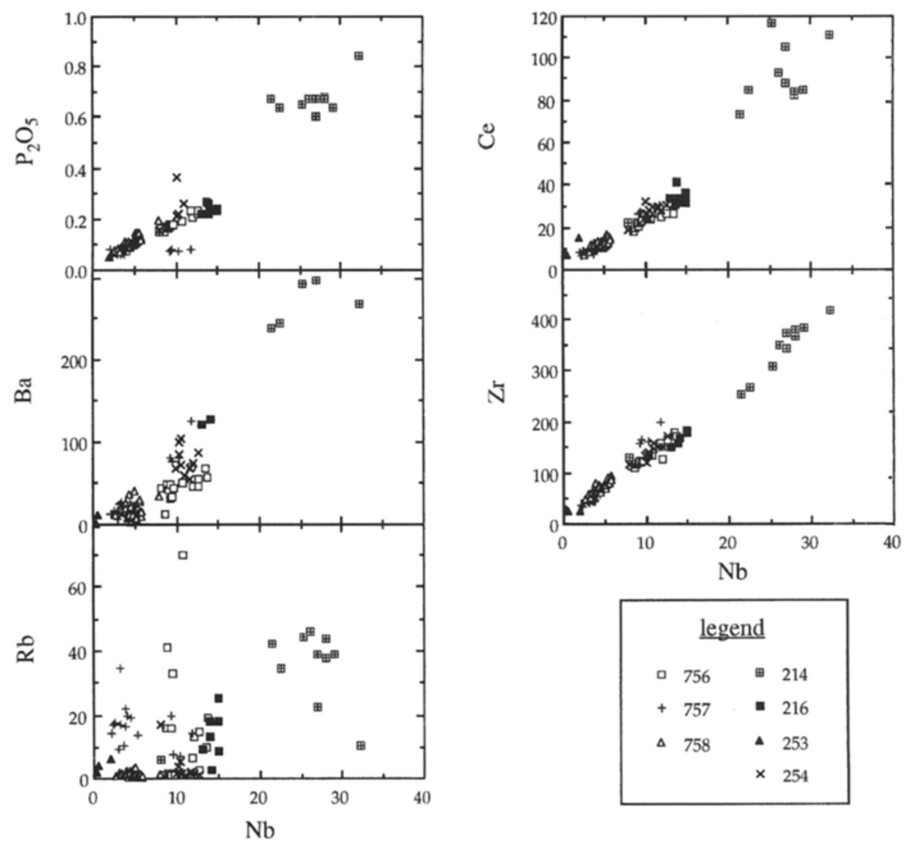
Ninetyeast Ridge drill sites are indicated by the compositions of clinopyroxene microphenocrysts (see Fig. 6 of Ludden et al. 1980 and Fig. 5 of Frey et al. 1991).

Another approach for evaluating the effects of post magmatic alteration is to evaluate correlations between abundances of highly incompatible elements. For example, Fig. 3 shows that, except for Rb, abundances of highly incompatible elements such as P, Ba, light REE (e.g., Ce), Zr and Nb are strongly correlated in lavas from the Ninetyeast Ridge. The highest abundances are in the oceanic andesite lavas from Site 214. The erratic Rb (and K_2O, Frey et al. 1991) abundances reflect formation of secondary minerals such as smectites, but we infer that abundances of P, Ba, Ce, Zr and Nb reflect magmatic abundances.

Typically, the isotopic ratios of Nd and Pb in oceanic basalts are not significantly changed by post magmatic alteration processes, but formation of secondary phases with relatively high $^{87}Sr/^{86}Sr$ is common (e.g., Staudigel et al. 1981; Mahoney 1987; Mahoney and Spencer 1991). Consistent with these previous results, acid-leaching (up to eight steps) of powdered Ninetyeast Ridge lavas resulted in markedly lower $^{87}Sr/^{86}Sr$, but no significant change of Nd and Pb isotopic ratios (Weis and Frey 1991). These lower $^{87}Sr/^{86}Sr$ ratios are interpreted to reflect the magmatic ratios.

The evolution of isotopic ratios with time must be considered when comparing radiogenic isotopic ratios in lavas of different ages; e.g., comparisons of lavas from various positions along the Ninetyeast Ridge, 38 to 82 Ma, to the < 40 Ma lavas from the Kerguelen Archipelago. Mahoney and Spencer (1991) considered this problem in regard to ~ 122 Ma lavas recovered from the Ontong Java Plateau. They concluded that over 120 Ma the U/Pb, Rb/Sr and Sm/Nd ratios typical of oceanic basalts lead to age corrections in isotopic

Fig. 3 Abundance of various incompatible elements (P_2O_5 in wt%, others in ppm) versus Nb content (ppm) in Ninetyeast Ridge lavas. The highest abundances are in the oceanic andesites from Site 214. Except for Rb which has been affected by postmagmatic alteration, the abundances of these incompatible elements are positively correlated. Data for Sites 214, 216, 253 and 254 from this paper and Saunders et al. (1991); data for Sites 756, 757 and 758 from Frey et al. (1991)



ratios which are small relative to the differences between ocean island basalts and MORB. Age-corrected Sr and Nd isotopic ratios (Table 2) of Ninetyeast Ridge lavas are shown in Fig. 4a. The post magmatic mobility of Rb, however, introduces uncertainty into the age correction for Sr; e.g., the oldest lavas studied, those from Site 758, would be expected to require the largest age correction in $^{87}Sr/^{86}Sr$, but because they were depleted in Rb by alteration processes (most of these lavas have < 1 ppm Rb, Fig. 3), these lavas have the smallest age correction in $^{87}Sr/^{86}Sr$ (Fig. 4a). Compared to intersite differences in isotopic ratios these uncertainties in age correction are not significant. Lavas from each site form coherent groups in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ that overlap with the general inverse trend defined by recent MORB and lavas of varying age from the Kerguelen Archipelago (Fig. 4b). Our subsequent discussion uses age-corrected Sr and Nd isotopic ratios, and our conclusions are unlikely to be affected by the uncertainties in inferring age-corrected isotopic ratios.

Age corrections for $^{206}Pb/^{204}Pb$ are significant because the unleached powders range widely in $^{238}U/^{204}Pb$ (5–52, Weis and Frey 1991), probably reflecting U mobility during postmagmatic alteration. In Fig. 5a, as in Fig. 4a, each site is represented by two fields indicating the measured and an age-corrected $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ based on the inferred age and measured U/Pb in unleached ODP samples (Weis and Frey 1991) and in the acid-leached residues of DSDP samples (Table 2). Although the present U/Pb ratios may not be appropriate for age corrections, most of the $^{238}U/^{204}Pb$ ratios are relatively high compared to fresh basalts; thus they probably provide maximum age corrections. As expected, age corrections for in situ U decay since basalt eruption increase with age, and they are especially significant for the $^{206}Pb/^{204}Pb$ in oldest lavas, i.e. Sites 216 and 758 in Fig. 5a. Because of the low abundance of ^{235}U, age corrections for $^{207}Pb/^{204}Pb$ are small. Precise abundance data are not available for Th; therefore, no age correction is given for $^{208}Pb/^{204}Pb$.

Geochemical variations at individual drill sites on Ninetyeast Ridge

Variations in lava compositions as a function of eruption age provide important constraints on the evolution of individual volcanoes. Basement penetration exceeded 40 m at five drilling sites on the Ninetyeast Ridges: ODP - Leg 121 Holes 756D, 757C, and 758A, DSDP Leg 22 Site 214 and DSDP Leg 26 Site 254. Each of these cores provides information about the temporal compositional changes during the waning stage of volcanism forming the Ninetyeast Ridge. Within most of these cores there are variations in geochemical characteristics which require derivation from more

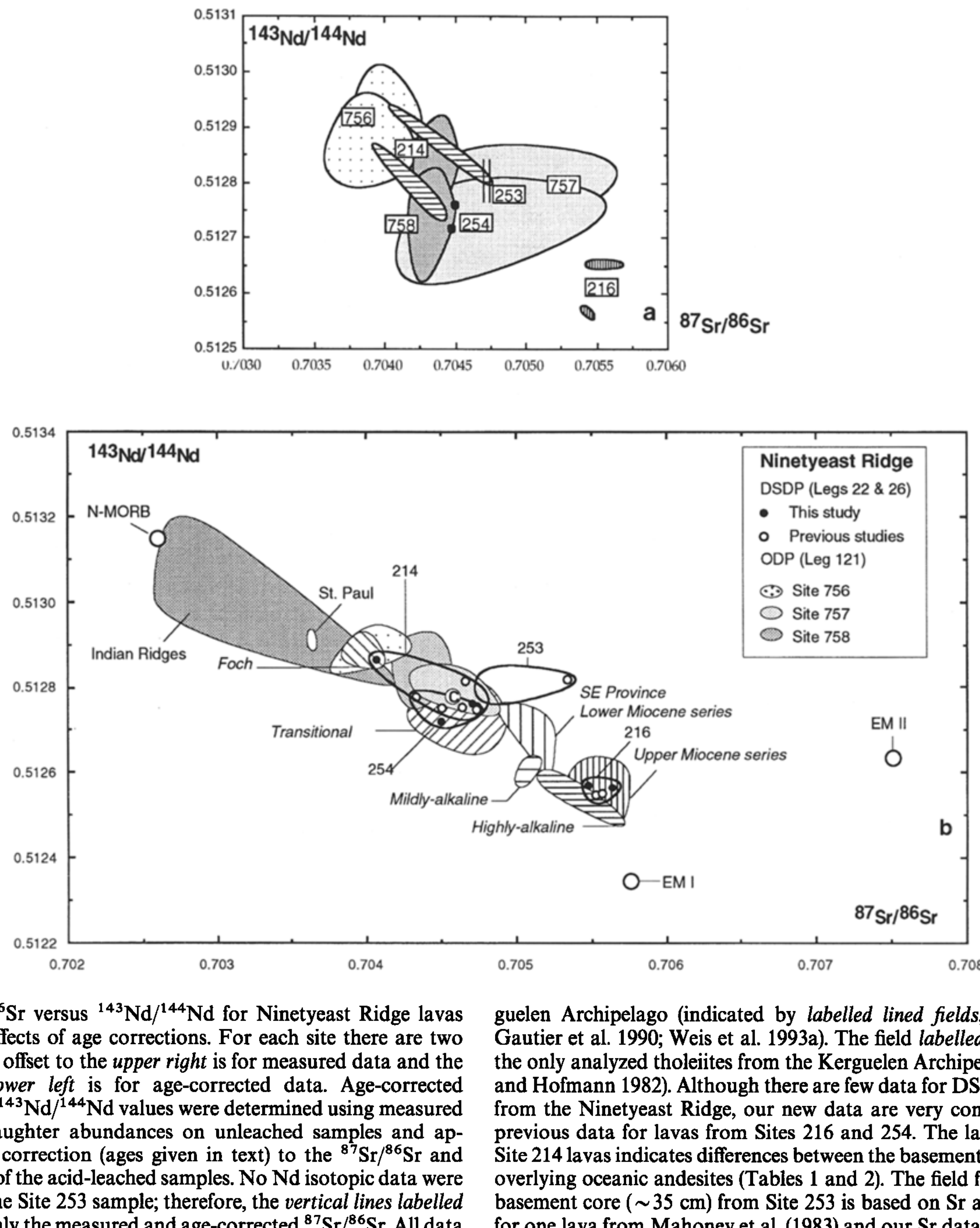


Fig. 4a $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ for Ninetyeast Ridge lavas showing the effects of age corrections. For each site there are two fields; the field offset to the *upper right* is for measured data and the one to the *lower left* is for age-corrected data. Age-corrected $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values were determined using measured parent and daughter abundances on unleached samples and applying an age correction (ages given in text) to the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ of the acid-leached samples. No Nd isotopic data were obtained for the Site 253 sample; therefore, the *vertical lines labelled 253* indicate only the measured and age-corrected $^{87}Sr/^{86}Sr$. All data from Weis and Frey (1991) and this paper. **b** $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ plot comparing fields for lavas from Ninetyeast Ridge drill sites (age-corrected data from this paper; Weis and Frey 1991; Saunders et al. 1991; Mahoney et al. 1983; Hart 1988) to the fields for Indian Ocean MORB, St. Paul Island (see references in Weis et al., 1992), and various age and compositional groups from the Kerguelen Archipelago (indicated by *labelled lined fields*, data from Gautier et al. 1990; Weis et al. 1993a). The field *labelled Foch* is for the only analyzed tholeiites from the Kerguelen Archipelago (White and Hofmann 1982). Although there are few data for DSDP samples from the Ninetyeast Ridge, our new data are very consistent with previous data for lavas from Sites 216 and 254. The large field for Site 214 lavas indicates differences between the basement basalts and overlying oceanic andesites (Tables 1 and 2). The field for the short basement core (~35 cm) from Site 253 is based on Sr and Nd data for one lava from Mahoney et al. (1983) and our Sr data for another sample assuming it has a $^{143}Nd/^{144}Nd$ ratio similar to the sample analyzed by Mahoney et al. (1983). This sample was not acid-leached by Mahoney et al., and its higher $^{87}Sr/^{86}Sr$ probably reflects alteration. *Encircled C* indicates present day estimate for Kerguelen Plume from Class et al. (1993)

than one parental magma composition. In cores from Holes 756D (14 flow units) and 758A (29 flow units), this heterogeneity is restricted to only one flow unit which has slightly different incompatible element abundance and isotopic ratios (Frey et al. 1991; Weis and Frey 1991). More substantial geochemical heterogeneities occur in cores from Holes 757C and 214. Compared to the upper basalts in core from Hole 757C, the lowermost basalts require a parental magma with unusually low ratios of Ti/Zr (Fig. 6), P/Nb (Fig. 3), Ti/Eu (5700–6300) and P/Nd (20–24) (Frey et al. 1991), and slightly lower $^{206}Pb/^{204}Pb$ (Weis and Frey 1991). At Site 214 oceanic andesites with low Ti/Zr overlie FeTi-rich basalt with Ti/Zr ~ 100 (Fig. 6). This difference in Ti/Zr was initially attributed to fractional crystallization (Ludden et al. 1980), but isotopic differences between the basalts and andesites show that these lavas are not related by simple fractional crystallization (Mahoney et al. 1983 and Table 2 of this paper). In addition, the flows within the thick ash sequence at Site 253 are markedly enriched in incompatible elements relative to the basement picritic basalt (Table 1).

In summary, all Ninetyeast Ridge lavas have transitional to tholeiitic major element composition (Fig. 2) and are enriched in highly incompatible elements, such as light REE and Nb, relative to depleted MORB (Fig. 7 and 8). They define Sr, Nd and Pb isotopic fields which overlap with those defined by lavas erupted in the Kerguelen Archipelago (Fig. 4b and 5b,c). In detail, however, there are geochemical variations within the cores, particularly at DSDP Site 214 ($\sim$59 Ma) and ODP Site 757 ($\sim$58 Ma), that indicate significant short-term variations in the geochemical characteristics of primary magmas which must reflect source heterogeneities.

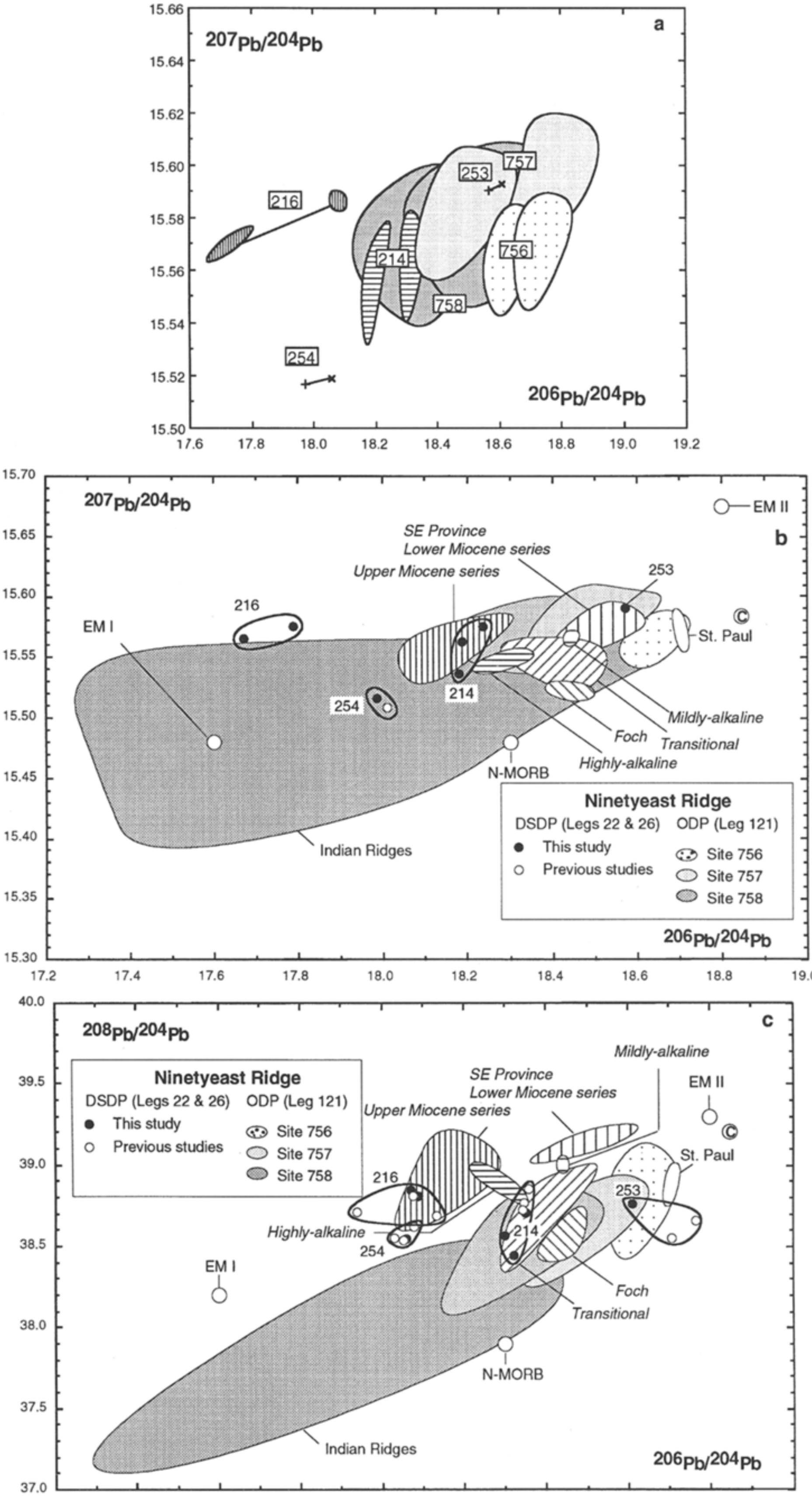
An important result is that alkalic basalts have not been recovered from any site on the Ninetyeast Ridge. The absence of alkalic volcanism is significant because the youngest lavas ($<$22 Ma) in the Kerguelen Archipelago are alkalic (Gautier et al. 1990; Weis et al. 1993a,b), and a tholeiitic to alkalic transition is characteristic of the waning phases of volcanism at plume related volcanoes in Hawaii (e.g., Clague and Dalrymple 1987).

Comparisons of different sites along the Ninetyeast Ridge

Although geochemical data for each drill core require more than one geochemically distinct parental magma, lavas from each site share important geochemical characteristics, and these lead to significant geochemical differences between sites. At DSDP Site 253 ($<$44–49 Ma) the basement picritic basalt is slightly depleted in LREE and has Zr/Nb similar to depleted MORB (Fig. 7 and 8), but its Sr and Nd isotopic ratios are distinct from the Indian MORB field (Fig. 4b); at Site 756 (42–44 Ma) some of the lavas have relatively high $^{206}Pb/^{204}Pb$ ratios which exceed those of lavas erupted in the Kerguelen Archipelago (Fig. 5b,c); at Site 757 ($\sim$58 Ma) all of the lavas were derived from parental magmas with relatively high Al_2O_3 and low total iron contents (Frey et al. 1991); at Site 216 ($<$81 Ma) the tholeiitic lavas have the relatively high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ that is characteristic of the youngest alkalic lavas erupted in the Kerguelen Archipelago (Fig. 4b); and at Site 758 (81–83 Ma) the lavas have relatively high MgO contents (7.4–10.2%; Frey et al. 1991) and near chondritic Zr/Nb = 13.1 to 18.4 and $(La/Yb)_N = 0.96$ to 1.69 (N = chondrite − normalized) (Figs. 7 and 8). The most enriched, i.e., relatively high La/Yb, Ce/Y and low Zr/Nb, Ninetyeast Ridge lavas are the oceanic andesites from Site 214 ($\sim$59 Ma) and the FeTi-rich basalts from Site 216 (Fig. 7 and 8).

In summary, there is surprisingly little compositional and isotopic overlap among Ninetyeast Ridge lavas from the different drill sites. Some of the intersite geochemical differences reflect post-melting magmatic processes. For example, many Hole 757C lavas have unambiguous petrographic and geochemical evidence for crustal processes involving segregation and accumulation of plagioclase; specifically, most of the Hole 757C lavas have very high Al_2O_3 contents ($>$22%; Frey et al. 1991) and positive Eu anomalies (Fig. 8). Other intersite geochemical differences reflect differences in source components. For example, there are important intersite differences in isotopic ratios: lavas from Site 756 (42–44 Ma) and the FeTi-rich basalts from Site 214 ($\sim$59 Ma) have the lowest $^{87}Sr/^{86}Sr$ and highest $^{143}Nd/^{144}Nd$, and they overlap with the field for Foch Island tholeiites from the Kerguelen Archipelago; in contrast, lavas from Site 216 ($\sim$81 Ma) have the highest $^{87}Sr/^{86}Sr$ and lowest $^{143}Nd/^{144}Nd$ (Fig. 4b). Although the Site 216 lavas are FeTi-rich tholeiitic basalts, they overlap in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ with the relatively young alkalic lavas erupted in the Kerguelen Archipelago which have been interpreted as being representative of the Kerguelen plume (Weis et al. 1993a,b). The different sites also define distinct Pb isotope fields. Specifically, lavas from Site 756 have the highest $^{206}Pb/^{204}Pb$ and range to ratios exceeding those found in lavas from the Kerguelen Archipelago (Fig. 5b,c). As emphasized by Class et al. (1993) lavas from Sites 758 ($\sim$82 Ma), 757 ($\sim$58 Ma) and 756 ($\sim$43 Ma) define a trend of increasing $^{206}Pb/^{204}Pb$ with decreasing eruption age. Although there are fewer

Fig. 5a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for Ninetyeast Ridge lavas showing the effects of age corrections for in situ U decay (for each site the measured fields are on *right* and age-corrected fields on *left*). For ODP samples (Sites 756, 757 and 758) the measured U and Pb abundances are for unleached samples; for DSDP samples (214, 216, 253 and 254) U and Pb abundances were determined on acid-leached samples. Ages used for each site are given in text. Note that the relative positions of the fields are unchanged by the age corrections. All data from Weis and Frey (1991) and this paper. **b** $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot comparing age-corrected fields for lavas from Ninetyeast Ridge drill sites (Fig. 5a) to the fields for Indian Ocean MORB, St. Paul Island and various age and compositional groups (*lined fields*) from the Kerguelen Archipelago. Data sources are as given for Fig. 4b. **c** $^{208}Pb/^{204}Pb$ versus $^{206}Pb^{204}Pb$ plot comparing fields for lavas from the Ninetyeast Ridge drill sites to the fields for Indian Ocean MORB, St. Paul Island and various age and compositional groups (*lined fields*) from the Kerguelen Archipelago. In this panel the ratios are not age corrected because precise Th abundances are not available. Note that the $^{206}Pb/^{204}Pb$ ratios in lavas from Sites 216 and 254 overlap with Upper Miocene lavas from the SE province of the Kerguelen Archipelago, perhaps indicating that the age corrections for these high U/Pb lavas (Table 2) shown in Fig. 5b are overcorrections. This plot includes data from Dupré and Allègre (1983) and Saunders et al. (1991) that are not indicated in Fig. 5b because U and Pb abundances were not reported and the ratios could not be age corrected. Other data sources are as given for Fig. 4b


a
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
216
253
757
214
756
758
254
b
$^{207}Pb/^{204}Pb$
EM II
SE Province
Lower Miocene series
Upper Miocene series
253
216
EM I
St. Paul
254
214
Mildly-alkaline
Foch
Transitional
Highly-alkaline
N-MORB
Indian Ridges
Ninetyeast Ridge
DSDP (Legs 22 & 26)
This study
Previous studies
ODP (Leg 121)
Site 756
Site 757
Site 758
$^{206}Pb/^{204}Pb$
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Ninetyeast Ridge
DSDP (Legs 22 & 26)
This study
Previous studies
ODP (Leg 121)
Site 756
Site 757
Site 758
Mildly-alkaline
SE Province
Lower Miocene series
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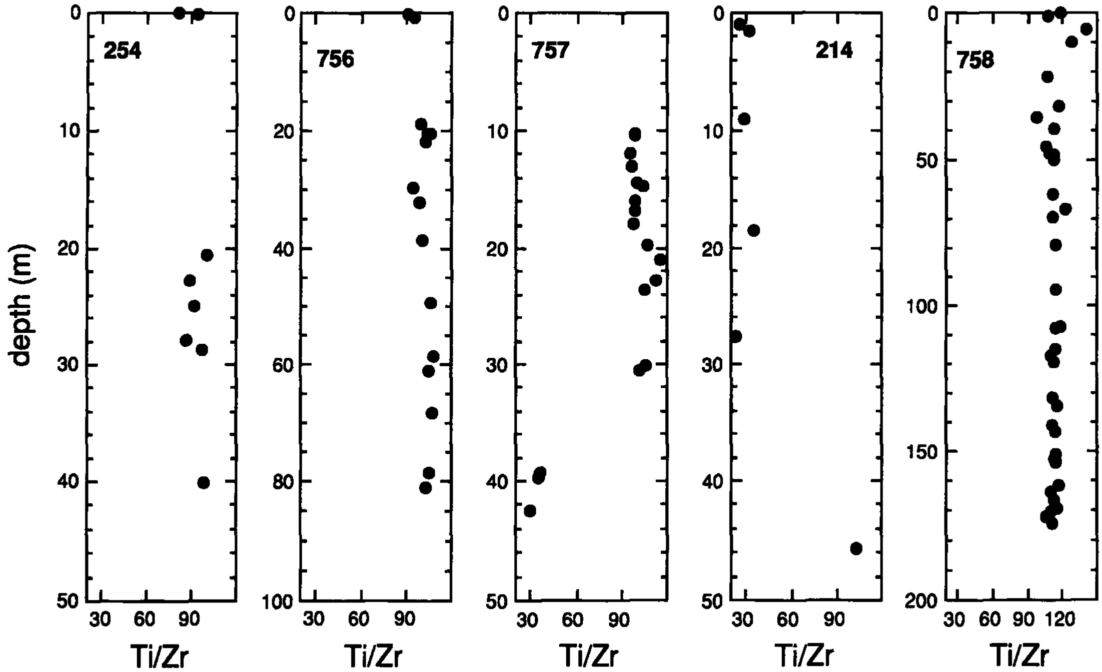


Fig. 6 Ti/Zr as a function of depth (in meters measured from first occurrence of lavas in the core) in the five longest drill cores recovered from the Ninetyeast Ridge (data sources as in Fig. 3). The largest variations are at Site 757 where the lowermost units, > 38 m, are compositionally and isotopically distinct and at Site 214 where isotopically distinct oceanic andesites (0 to 28 m) overlie basalts

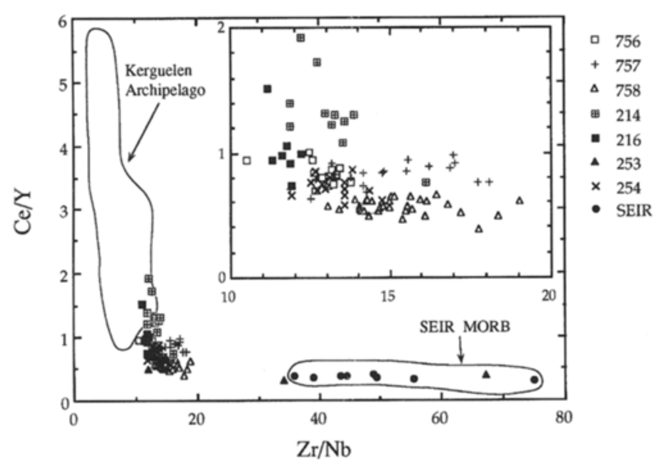


Fig. 7 Ce/Y versus Zr/Nb in basaltic lavas from the Kerguelen Archipelago (Storey et al. 1988; Gautier et al. 1990; Weis et al. 1993a), Ninetyeast Ridge (data sources as in Fig. 3), and southeast Indian Ridge (SEIR MORB) (Price et al. 1986). These incompatible element abundance ratios show that lavas from the Ninetyeast Ridge are intermediate between depleted MORB and the transitional to alkalic lavas erupted in the Kerguelen Archipelago. *Inset* shows on an expanded scale the data for all Ninetyeast Ridge sites, except for Site 253 lavas which have high Zr/Nb

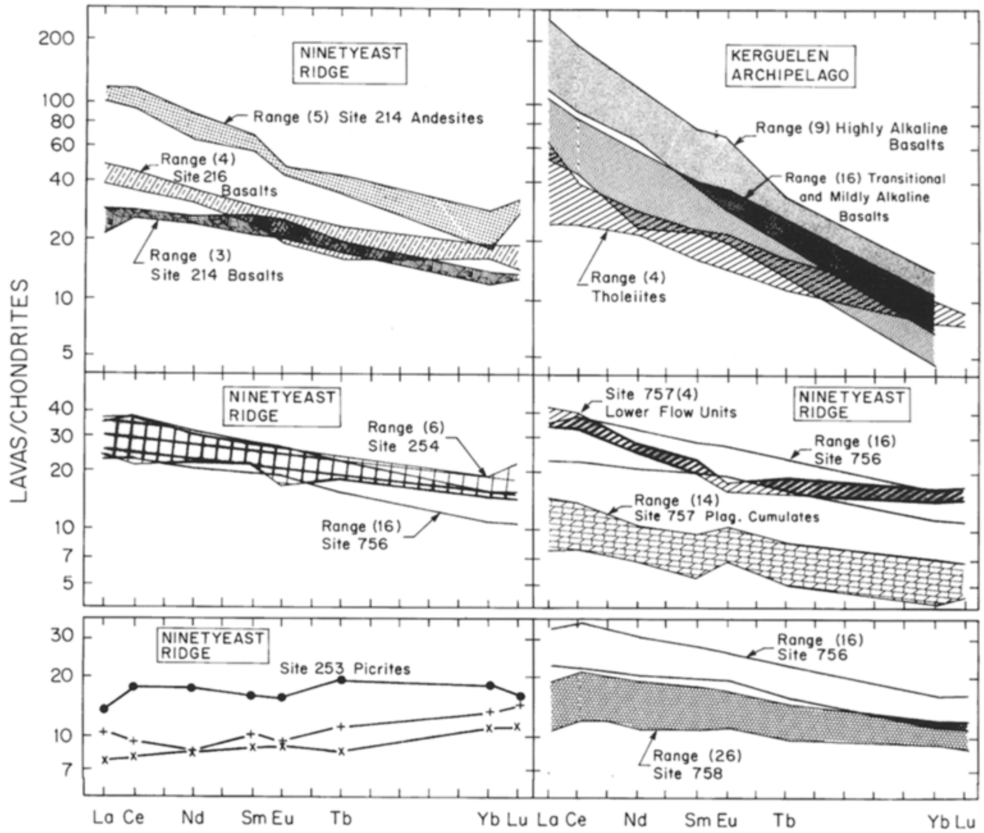
data points for the youngest Ninetyeast Ridge lavas from the ~38 Ma Site 254, four samples have been analyzed for Pb isotopes in three different laboratories, and their relatively low $^{206}Pb/^{204}Pb$ are not consistent with a systematic temporal trend (Fig. 9). Also discrepant are lavas from Site 216 (<81 Ma) which have lower $^{206}Pb/^{204}Pb$ than lavas from Site 758 (81–83 Ma) (Fig. 9). Compared to lavas from the Kerguelen Archipelago, lavas from the Ninetyeast Ridge have a restricted range in major element composition and incompatible element abundances (Figs. 2, 7 and 8), but they have an equally wide range in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ and a greater range in $^{206}Pb/^{204}Pb$ (Figs. 4b and 5b,c).

Discussion

Temporal evolution of the Kerguelen Plume

Based on Sr, Nd and Pb isotopic data for lavas of varying age (~0 to 115 Ma) from the Kerguelen Plateau, ODP Sites on the Ninetyeast Ridge and Heard Island, Class et al. (1993) concluded that these data reflect in part an evolving plume composition with secular changes in isotopic ratios resulting only from radioactive decay in the source. Lavas of similar age range widely in isotopic ratios, and Class et al. (1993) proposed that at a given age, lavas with the lowest $^{87}Sr/^{86}Sr$ and highest $^{206}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, and $^{143}Nd/^{144}Nd$ provide the best estimate of isotopic ratios in the plume source; Sr and Nd isotopic ratios in Site 756 lavas are an exception. They infer that the compositionally homogeneous plume has present day ratios of $^{206}Pb/^{204}Pb = 18.85$, $^{143}Nd/^{144}Nd = 0.51278$ and $^{87}Sr/^{86}Sr = 0.7046$. Although Class et al. (1993) emphasized the importance of aging of a compositionally homogeneous plume to explain a subset of the isotopic data, we note that a significant fraction of the

Fig. 8 Chondrite-normalized REE abundances for lavas from the Ninetyeast Ridge (data sources as in Fig. 3) and the Kerguelen Archipelago (data sources as in Fig. 7). Relatively *horizontal patterns* characterize lavas from Sites 253 and 758 which differ significantly in age and location (Fig. 1). In general, basalts from the Kerguelen Archipelago have higher relative enrichment of LREE than those from the Ninetyeast Ridge



isotopic data for Ninetyeast Ridge lavas is not explained by this hypothesis. This is obvious from the temporal trends of initial ratios in Fig. 9. The following discussion focuses on some of the major inconsistencies. The relatively high $^{206}Pb/^{204}Pb$ ratios of the young (42–44 Ma) lavas from Site 756 are consistent with the hypothesis, but their relatively low Sr isotopic ratios are inconsistent (Fig. 9); consequently, Class et al. (1993) argued that Sr and Nd isotopic ratios in lavas from Site 756 reflect a MORB component whereas $^{206}Pb/^{204}Pb$ ratios reflect the plume. Indeed a MORB component in Ninetyeast Ridge lavas has been proposed (e.g., Weis et al. 1992). In a two component MORB-plume mixing model the Site 756 lavas require a higher Pb/Sr and Pb/Nd in the Kerguelen plume component. Although plausible, the first order uniformity of Pb/Ce ratios, analogous to Pb/Nd, in MORB and oceanic island basalts (Hofmann et al. 1986), and the similar range of Pb/Ce in Ninetyeast Ridge lavas from different sites (see Fig. 11 of Frey et al. 1991) provide no evidence for a plume component with relatively high Pb/Sr and Pb/Nd. Moreover, the relatively high $^{206}Pb/^{204}Pb$ ratios in Site 756 lavas (42–44 Ma) are not found in the younger basalts (38 Ma) at Site 254 or in any of the < 38 Ma lavas erupted in the Kerguelen Archipelago, although higher $^{206}Pb/^{204}Pb$ ratios, up to 18.80, are found in some lavas from Amsterdam, St. Paul and Heard Islands (Fig. 9). Also isotopic data for the relatively old, ~81 Ma, Ninetyeast Ridge lavas from DSDP Site 216 are not explained by an aging plume model. Specifically, these lavas have relatively high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ that are not close to the proposed plume evolution trend (Fig. 9, this paper and Fig. 3 of Class et al. 1993). Although there may be a significant age correction for $^{206}Pb/^{204}Pb$ in Site 216 lavas (Fig. 5a), the present day ratios for five different Site 216 basalts analyzed in three different laboratories are tightly grouped (17.9–18.1, Fig. 5c) and significantly lower than that proposed (18.41) for the aging plume at 82 Ma (Fig. 9 and Class et al. 1993). Consequently, if the aging plume hypothesis is accepted, Site 216 lavas were not derived from the plume.

In summary, a significant proportion of the isotopic data for lavas from the Ninetyeast Ridge, especially when data for DSDP samples are considered, and the Kerguelen Archipelago are not explained by the aging plume hypothesis. Note that none of the relatively young lavas from the Kerguelen Archipelago have the isotopic characteristics proposed by Class et al. (1993) for the present day plume (Figs. 4, 5, and 9). If they have correctly identified the isotopic ratios of the plume, the isotopic characteristics of Kerguelen Archipelago lavas reflect non-plume components. A possible explanation is that the plume-like characteristics of these relatively young island lavas were modified during their ascent through the thick (20–25 km) lithosphere of the Kerguelen Plateau, (Coffin and Eldholm 1994). An

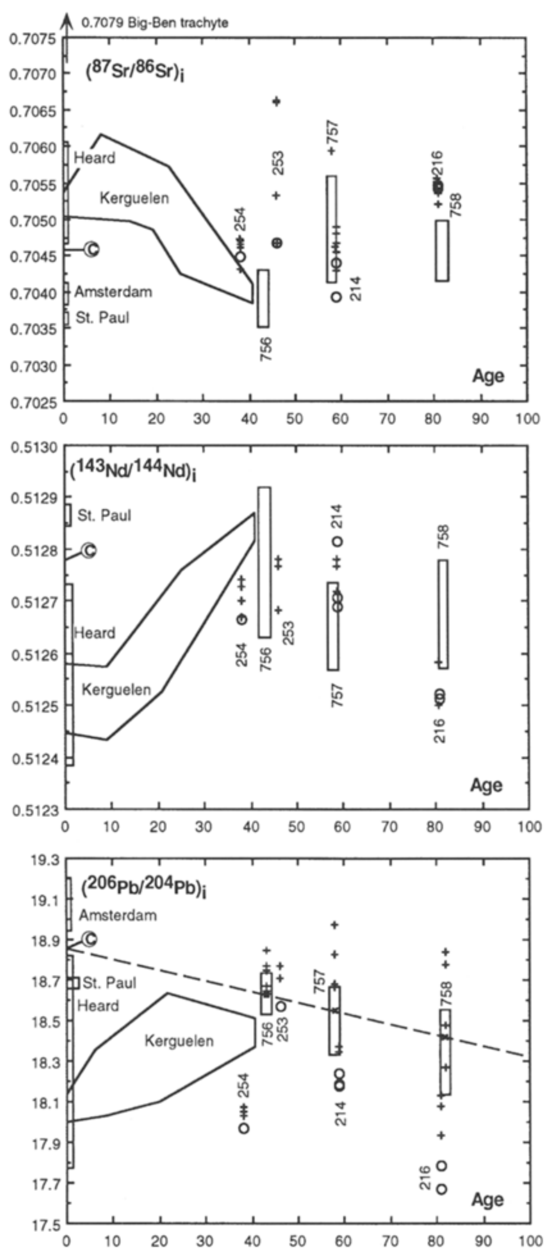


Fig. 9 Initial isotopic ratio versus eruption age for lavas from the Ninetyeast Ridge, Kerguelen Archipelago, Heard, Amsterdam and St. Paul Islands. Ages of Ninetyeast Ridge lavas from Duncan (1978, 1991). For DSDP Sites 214, 216, 253 and 254 *open circles* are data from this paper (Table 2) and *plus symbols* are data from Subbarao et al. (1977), Reddy et al. (1978), Whitford and Duncan (1978), Mahoney et al. (1983), Dupré and Allegre (1983), Hart (1988) and Saunders et al. (1991). *Rectangles* for initial Sr and Nd isotopic ratios in lavas from ODP Sites 756, 757 and 758 include all data in Weis and Frey (1991) and Saunders (1991). For $^{206}Pb/^{204}Pb$ the *rectangles* include only data from Weis and Frey (1991); the Saunders et al. (1991) data for these ODP sites cannot be age corrected and are shown as *plus symbols*. The *dashed line* in the $^{206}Pb/^{204}Pb$ panel indicates the temporal evolution of a compositionally homogeneous plume as defined by Class et al. (1993). This line was defined by data from ODP Sites 756, 757 and 758, but it is not a good fit for new data from DSDP Sites 254, 214 and 216. Data for Heard Island lavas are from Barling et al. (1994); the Big Ben trachyte defines the high $^{87}Sr/^{86}Sr$ - low $^{206}Pb/^{204}Pb$ component in Heard lavas. Data for Kerguelen, St. Paul and Amsterdam Islands from references cited in captions for Fig. 4 and 5. The present day ratios proposed for the Kerguelen plume by Class et al. (1993) are indicated by the *circled C*

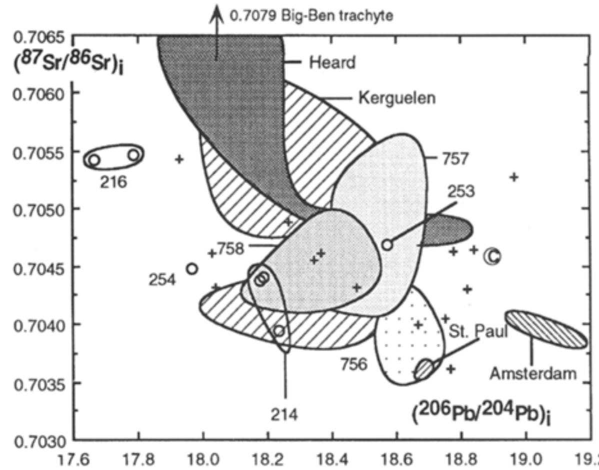


Fig. 10 Initial $^{87}Sr/^{86}Sr$ versus initial $^{206}Pb/^{204}Pb$ in lavas from the Ninetyeast Ridge compared to data for lavas for Kerguelen, Heard, Amsterdam and St. Paul Islands. *Open circles* indicate data for DSDP lavas from this paper, *plus symbols* indicate literature data for Ninetyeast Ridge lavas. Data sources as listed in Fig. 9 caption. The important point is that the trend to low $^{87}Sr/^{86}Sr$ and high $^{206}Pb/^{204}Pb$ for Ninetyeast Ridge lavas is not consistent with a role for the low $^{87}Sr/^{86}Sr$ component expressed in Heard lavas, but it is consistent with lavas from St. Paul Island.

argument against this interpretation is that some Kerguelen Plateau lavas have distinctive geochemical characteristics which have been interpreted to reflect the presence of a continental lithosphere component (Storey et al. 1989, 1992; Mahoney et al. 1995). There is no evidence in lavas from the Kerguelen Archipelago that they assimilated such a component from the thick Kerguelen Plateau lithosphere (Fig. 14 of Frey et al. 1991); however, it may be present in the enriched, high $^{87}Sr/^{86}Sr$ endmember at Heard Island which is 440 km south of the Kerguelen Archipelago (Barling and Goldstein 1990; Barling et al. 1994).

Currently there is a consensus that the overlap in Sr, Nd and Pb isotopic ratio of lavas from the Ninetyeast Ridge and the Kerguelen Archipelago reflects an important role of the plume throughout the formation of the Ninetyeast Ridge and Kerguelen Archipelago, but the isotopic diversity hinders identification of the isotopic characteristics of the plume. We suggest that the overlap in Sr, Nd and Pb (measured ratios)[1] in the ~81 Ma lavas from Site 216 on the Ninetyeast Ridge and the youngest lavas (Upper Miocene series) erupted in the Kerguelen Archipelago (Figs. 4b and 5c) is unlikely to be a coincidence. In contrast to the conclusion of Class et al. (1993), we propose that the present day Kerguelen Plume has the isotopic characteristics of the Upper Miocene lavas

[1] We infer that the large age correction for $^{206}Pb/^{204}Pb$ in Site 216 lavas (Fig. 5a and cf. Fig. 5b and c) is an over correction resulting from their high $^{238}U/^{204}Pb$ (Table 2) which probably reflect post-magmatic alteration.

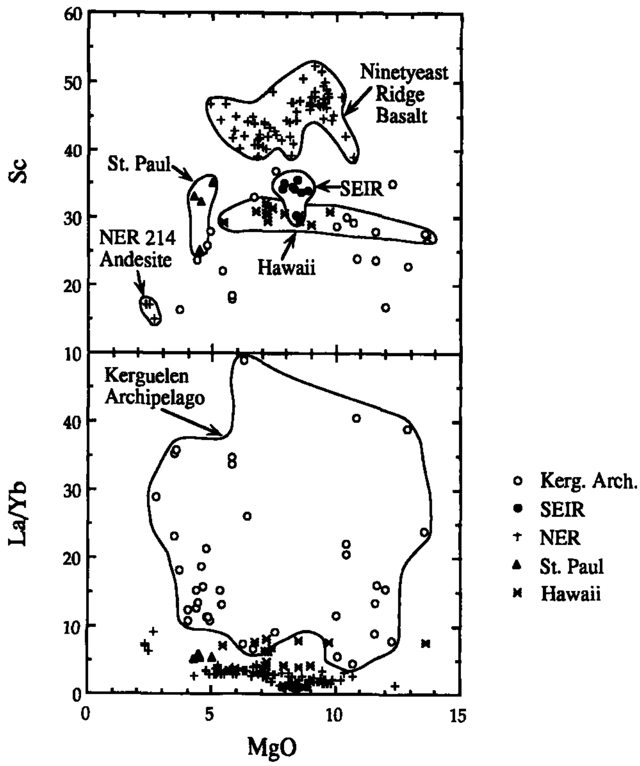


Fig. 11 Sc (ppm) and La/Yb versus MgO (wt%) in lavas from the Ninetyeast Ridge (data sources as in Fig. 3), Kerguelen Archipelago (data sources as in Fig. 7), southeast Indian Ridge (Price et al. 1986), Hawaiian shields (BVSP 1981) and St. Paul Island (this paper and Girod et al. 1971). Important features are that lavas from the Ninetyeast Ridge have higher Sc and lower La/Yb than lavas from the Kerguelen Archipelago

(Weis et al. 1993a,b). With this interpretation the range of isotopic ratios in lavas associated with the Kerguelen plume reflects mixing between components from the Kerguelen plume, a depleted MORB-like component and another component with relatively high $^{206}Pb/^{204}Pb$ which is only apparent in relatively young Ninetyeast Ridge lavas from Sites 756 and 253 (Figs. 5c and 9). Relatively high $^{206}Pb/^{204}Pb$ is characteristic of some recent lavas from Heard Island and lavas from Amsterdam and St. Paul Islands (Fig. 9). The trend of initial $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$ defined by lavas from the Ninetyeast Ridge cannot be explained by the high $^{206}Pb/^{204}Pb$ component expressed in Heard lavas, but it is consistent with that in lavas from St. Paul Island (Fig. 10).

Our interpretation and that of Class et al. (1993) have the common features that (1) isotopically diverse components are represented in most of the lavas that are plausibly related to the Kerguelen plume; (2) at a given time the plume is assumed to be homogeneous, in isotopic ratios. The principal difference between these interpretations are the isotopic characteristics proposed for the present day plume. In fact, isotopic heterogeneity is typical of plume-related magmas in oceanic intraplate settings such as Hawaii (e.g., West et al. 1987) and in plumes on or near ridge axes such as Iceland (Hemond et al. 1993) and the Galápagos (White et al. 1993). This isotopic diversity is commonly interpreted to reflect mixing of plume, asthenosphere and lithosphere components intrinsic. In some well studied cases, such as Hawaii and the Galápagos, systematic spatial and temporal variations in isotopic ratios have led to specific mixing models between plume, asthenosphere and lithosphere components (e.g., Chen and Frey 1985; White et al. 1993). Nevertheless, a significant amount of isotopic heterogeneity has been attributed to these plumes (e.g., Frey and Rhodes 1993; White et al. 1993). Therefore, the assumption of an isotopically homogeneous Kerguelen plume is probably erroneous.

Origin of the Ninetyeast Ridge

Ninetyeast Ridge lavas are tholeiitic to transitional in major element composition (Fig. 2), and they have higher incompatible element abundances than MORB (e.g., Figs. 7 and 8). These compositional characteristics are also typical of the lavas forming large oceanic plateaus, such as the Kerguelen Plateau (Davies et al. 1989; Frey et al. 1991; Storey et al. 1992) and the Ontong Java Plateau (Mahoney et al. 1993), and some oceanic islands such as the Hawaiian shields, and Amsterdam and St. Paul islands which are near the southeast Indian Ridge (e.g., La/Yb panel in Fig. 11). Within the Kerguelen Archipelago the oldest lavas are also tholeiitic to transitional in composition, but the youngest lavas are alkalic (Gautier et al. 1990; Weis et al. 1993a,b). Most of the lavas from the Ninetyeast Ridge have Sr, Nd and Pb isotopic ratios which overlap with those of lavas from the Kerguelen Archipelago (Figs. 4b and 5b,c), and this is the strongest geochemical evidence that the Ninetyeast Ridge is related to the Kerguelen Plume. However, at a given MgO content, lavas from the Kerguelen Archipelago have higher La/Yb and lower Sc contents than Ninetyeast Ridge lavas (Fig. 11). These compositional features are consistent with the following interpretations.

Plate tectonic reconstructions indicate that much of the Ninetyeast Ridge formed when the hotspot was at or close to a spreading ridge axis (Royer et al. 1991). In fact, the southerly jumps of spreading ridge axis towards the Kerguelen hotspot (Royer et al. 1991) may reflect the tendency for a spreading ridge axis to become trapped in the vicinity of a plume (Brozena and White 1990; Sleep 1990; Mahoney and Spencer 1991). Therefore, the absence of alkalic lavas on the Ninetyeast Ridge may reflect the high magma supply rates that are expected of a ridge-centered hotspot, such as Iceland (Saunders et al. 1991). That is, the decrease in magma production that accompanies the well-known tholeiitic to alkalic transition in the intraplate Hawaiian volcanoes (e.g., Clague and Dalrymple 1987) did not occur on the Ninetyeast Ridge because the near ridge-centered location did not result in an analogous gradual decrease in magma supply. Apparently, magmatism at volcanic centers on the Ninetyeast Ridge stopped abruptly as they were disconnected from the plume source.

Another expected consequence of hotspot volcanism close to a spreading ridge axis is melt segregation at relatively low pressure. Compositional features of Ninetyeast Ridge lavas consistent with melt segregation at low pressures are the high Al_2O_3 and low total iron contents inferred for the parental magmas at Site 757 (Frey et al. 1991). The relatively high Sc and low La/Yb of Ninetyeast Ridge lavas relative to lavas erupted in the Kerguelen Archipelago (Fig. 11) are also consistent with formation of Ninetyeast Ridge lavas at relatively low pressures; that is, there is no evidence that these lavas equilibrated with garnet. In contrast, lavas erupted through thick oceanic lithosphere such as Hawaiian shield lavas (e.g., Frey et al. 1994b) and young Kerguelen Archipelago lavas have the relatively low Sc content and high La/Yb (Fig. 11) created by equilibration with garnet.

The oldest lavas in the Kerguelen Archipelago are also consistent with formation at a ridge-centered hotspot. Storey et al. (1988) and Gautier et al. (1990) proposed that the change in the Kerguelen Archipelago from older tholeiitic–transitional plateau basalts to younger alkalic lavas reflects the change from a ridge-centered environment at $\sim$45 Ma to the present intraplate setting. With this interpretation the variation from tholeiitic to alkalic volcanism reflects a systematic decrease in the proportion of a MORB-like component relative to a Kerguelen plume component, and the youngest alkalic lavas erupted on the Kerguelen Archipelago are the purest representation of the Kerguelen plume composition. A similar model can be evaluated for the Ninetyeast Ridge; that is, variable proportions of source components along the Ninetyeast Ridge are expected if the spreading ridge axis migrated north away from the plume with subsequent southerly jumps back to the hotspot location. The similarities in Sr, Nd and Pb isotopic ratios of lavas from Site 216 and recent alkalic lavas in the Kerguelen Archipelago (Figs. 4b and 5b,c) are consistent with Site 216 lavas forming when the plume was distant from a spreading ridge axis. Sites 216 and 758 are in the northern segment of the Ninetyeast Ridge which is relatively wide and formed of discontinuous blocks. Royer et al. (1991) concluded that this portion of the Ninetyeast Ridge was emplaced as intraplate volcanism on the Indian Plate. Based on an analysis of subsidence histories of the Ninetyeast Ridge drill sites, Coffin (1992) concluded that Site 216 was unique and that basement at "this site was probably kept elevated by dynamic forces, i.e., thermal or mechanical for a period ($\sim$11 Ma) after emplacement in the Campanian". This anomalous subsidence history could reflect a relatively stronger plume influence at this site. Therefore, the tectonic setting, subsidence history, and isotopic characteristics of Site 216 lavas are consistent with a source that was dominated by a plume component. Presumably, the tholeiitic nature of Site 216 lavas indicates a higher extent of melting than that reflected by young alkalic basalts in the Kerguelen Archipelago which formed beneath the thick Kerguelen Plateau.

Although lavas from Sites 216 and 758 are similar in age, the geochemical characteristics of tholeiitic basalts from Site 758 are different. As with Site 214 lavas, the isotopic characteristics of Site 758 lavas largely overlap with the transitional lavas erupted in the Kerguelen Archipelago which are interpreted by Gautier et al. (1990) to contain a large amount of a MORB component. Consistent with this interpretation, the Site 758 lavas have the highest Zr/Nb and lowest Ce/Y of Ninetyeast Ridge lavas, except for the picrite from Site 253 (Fig. 7). Their tholeiitic composition and incompatible element abundance ratios are consistent with a large extent of melting. In addition, relative to most of the analyzed Ninetyeast Ridge lavas, basalts from Site 758 have relatively high MgO contents (8–10%, Frey et al. 1991) indicating that they have experienced lesser amounts of fractionation within the crust. This site is also distinctive because the lavas erupted in a submarine environment (Gibson and Saunders 1991), and it is the only Ninetyeast Ridge site without evidence of subaerial volcanism (Coffin 1992). Consequently, the relatively high MgO contents may reflect the absence of crustal processing in a large, plume-related, volcanic structure.

As discussed earlier, mixing of a Kerguelen plume component (as expressed in the youngest lavas of the Kerguelen Archipelago) with an Indian Ocean MORB-like component is not suitable as an explanation for all of the intersite isotopic variations along the Ninetyeast Ridge because lavas from Sites 253 and 756 range to higher $^{206}Pb/^{204}Pb$ than found in lavas of the Kerguelen Archipelago (Fig. 5c). Consequently, some Ninetyeast Ridge lavas are interpreted to reflect a significant role for another isotopically distinct component such as that seen in lavas from St. Paul Island (Figs. 5c and 10). However, none of the Ninetyeast Ridge and Kerguelen Archipelago lavas have the extreme isotopic ratios and relative Nb and Ta depletion that characterizes lavas from the southern Kerguelen Plateau (e.g., Alibert 1991; Storey et al. 1992; Mahoney et al. 1995). These features are attributed to a continental lithosphere component; apparently this component was not available during formation of the Ninetyeast Ridge. Although it is also absent from mafic and evolved lavas erupted in the Kerguelen Archipelago, a trachyte from Heard Island has the relatively high $^{87}Sr/^{86}Sr$ combined with low $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ that is characteristic of this component (Barling and Goldstein 1990; Barling et al. 1994).

In summary the Ninetyeast Ridge is a volcanic structure formed as the Indian Plate migrated northward over the Kerguelen hotspot. During formation of the Ninetyeast Ridge the hotspot was close to a spreading ridge axis, and this resulted in tholeiitic basalt magma formed by a relatively large extent of melting, melt segregation at relatively low pressures and variable extents of mixing between isotopically distinct components such as those represented by Indian Ocean MORB, the Upper Miocene lavas of the Kerguelen Archipelago and a high $^{206}Pb/^{204}Pb$ component that is similar to lavas from St. Paul Island.

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