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[1] We report new Hf isotopic data for basalts from the Kerguelen large igneous province (LIP) obtained using high-precision multicollector inductively coupled mass spectrometry (MC-ICP-MS) analysis. All drill sites from the southern Indian Ocean Kerguelen Plateau–Broken Ridge, in addition to two volcanic suites from the Kerguelen Archipelago, are represented. These new data are integrated with other recently reported geochemical data for this LIP. We examine the geochemical signatures of the mantle sources and shallow-level contaminants present during the past ~120 Ma history of Kerguelen hot spot activity. Our results highlight the contribution of distinct mantle source compositions during Cretaceous (Kerguelen Plateau and Broken Ridge) and Cenozoic (northernmost Kerguelen Plateau and Kerguelen Archipelago) magmatism arising from melting of the Kerguelen plume head and plume tail, respectively. The Cretaceous Kerguelen plume basalts have primitive mantle-like Pb, Sr, and Nd isotopic compositions and moderately depleted Hf isotopic compositions and are different from the Cenozoic plume basalts, which extend to more radiogenic Pb isotopic compositions. Neodymium and Hf isotopes are decoupled in Kerguelen plume-derived rocks, and this, in combination with their Pb isotopic compositions, implies that the Kerguelen plume contains small amounts of ancient pelagic sediment mixed with old, recycled enriched oceanic crust. Different contributions from pelagic sediments relative to oceanic crust are able to account for the distinction between the isotopic compositions of the Cretaceous and Cenozoic mantle plume sources. Assimilation of shallow-level continental crust, left stranded in the Indian Ocean during

Gondwana breakup, by plume-derived magmas was the dominant process recorded in Cretaceous Kerguelen Plateau basalts. During the Cenozoic, magmas from the Kerguelen plume mixed to varying degrees with local, Indian Ocean depleted upper mantle and assimilated the overlying Cretaceous Kerguelen Plateau lithosphere. Despite the geochemical heterogeneity of the Kerguelen LIP, we find evidence for a finite number of components involved in the genesis of Kerguelen Plateau–Broken Ridge and Kerguelen Archipelago rocks.

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1. Introduction

1.1. Objectives of the Hf Isotope Investigation

[2] The Kerguelen hot spot is located in the southern Indian Ocean and has been active since at least 120 Ma [*Duncan*, 2002]. This long-lived volcanism has been attributed to a large mantle plume upwelling from deep in the mantle; the plume head created the Kerguelen Plateau–Broken Ridge and the plume tail created the Ninetyeast Ridge, Kerguelen Archipelago, Heard and McDonald Islands [*Davies et al.*, 1989; *Storey et al.*, 1989; *Weis et al.*, 1989, 1991; *Storey et al.*, 1996]. The Kerguelen LIP is extremely geochemically heterogeneous when compared with other oceanic plateaus [*Arndt and Weis*, 2002]. This complexity is probably largely the result of interaction between plume-derived magmas and continental fragments that are present in some parts of the plateau's structure [e.g., *Mahoney et al.*, 1995; *Frey et al.*, 2000]. The presence of continental lithosphere leads to many ambiguities regarding the number and origin of mantle components and shallow-level contaminants involved in the genesis of this LIP. Fortunately, numerous recent investigations have provided a large background dataset of major and trace elements and Sr, Nd and Pb isotopic compositions for lavas from the Kerguelen Plateau, Broken Ridge, 90°E Ridge, Kerguelen Archipelago, Kerimis seamounts and Heard and McDonald Islands. These recent investigations have helped to identify basalts reflecting assimilation of continental crust by plume-derived magmas, and basalts where little or no role for continental crust is implicated [*Mahoney et al.*, 1995; *Weis et al.*, 1998, 2001, 2002a; *Yang et al.*, 1998; *Doucet et al.*, 2002; *Frey et al.*, 2002a, 2002b; *Ingle et al.*, 2002a, 2002b; *Kieffer et al.*, 2002; *Neal et al.*, 2002; *Weis and Frey*, 2002]. However, despite this abundant data, an integrated picture of the geochemical evolution of the Kerguelen hot spot has yet to be presented. We investigate whole rock Hf isotopic compositions in an attempt to further define the mantle sources and shallow-level contaminants involved in the genesis of the Kerguelen Plateau, Broken Ridge and Kerguelen Archipelago rocks. Our study is intended to complement the work of *Mattielli et al.* [2002], who presented Hf isotopic compositions for many volcanic sections from the Kerguelen Archipelago.

[3] Hafnium in the Earth is primarily sequestered in zircons that are abundant in continental crust and high-energy terrigenous sediments [*Patchett et al.*, 1984]. Therefore Hf isotopes are a useful indicator of continental contamination and sediment recy-

cling; non-continental (i.e., pelagic) sediments can develop radiogenic Hf isotopic signatures (because of the lack of zircons) whereas continental crust and terrigenous sediments develop unradiogenic Hf isotopic signatures over time [*Patchett et al.*, 1984; *Vervoort et al.*, 1999]. The Lu-Hf isotope system behaves geochemically similarly to the Sm-Nd isotope system but important differences exist. Partition coefficients are more disparate for Lu and Hf, relative to Sm and Nd, and this, coupled with the shorter half-life of ^{176}Lu, relative to ^{147}Sm, creates a range in radiogenic Hf isotopic compositions nearly double the variation in Nd isotopic compositions [*Patchett and Tatsumoto*, 1980]. Also, Hf isotopes may help to discriminate between continental crust and subcontinental lithospheric mantle (SCLM) since initial investigations suggest that Hf isotopes may be strongly decoupled from Nd isotopes in the SCLM [*Schmidberger et al.*, 2002; *Simon et al.*, 2002; *Ionov and Weis*, 2002].

[4] Basalts from the Indian Ocean (both mid-ocean ridge basalts (MORB) and ocean island basalts (OIB)) are distinguished by their higher ^{87}Sr/^{86}Sr [*Hedge et al.*, 1973], higher ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb relative to ^{206}Pb/^{204}Pb [*Dupré and Allègre*, 1983; *Hart*, 1984] and lower ^{143}Nd/^{144}Nd relative to ^{206}Pb/^{204}Pb [*Hart*, 1984; *Mahoney et al.*, 1996] when compared to basalts from the northern hemisphere in the Pacific and Atlantic Oceans [*Hart*, 1984]. Hf isotopes have proved to be a powerful tool in investigating this distinctive isotopic feature of the Indian Ocean [*Chauvel and Blichert-Toft*, 2001; *Kempton et al.*, 2002], the so-called ''Dupal anomaly'' [*Hart*, 1984]. These Hf isotopic studies have demonstrated that MORB from the Indian Ocean are displaced to lower ^{143}Nd/^{144}Nd for a given ^{176}Hf/^{177}Hf. *Mattielli et al.* [2002] also documented this feature in some sections of the Kerguelen Archipelago. The Kerguelen Archipelago and the Kerguelen Plateau share the other above mentioned geochemical characteristics with Indian Ocean basalts [*Davies et al.*, 1989; *Weis et al.*, 1989; *Salters et al.*, 1992; *Storey et al.*, 1996; *Weis and Frey*, 1996]. Therefore it seems likely that the process or processes that created the special isotopic signature in Indian Ocean basalts should be applicable to Kerguelen basalts and, in this respect, we may test the various hypotheses invoked to explain the existence of the Dupal anomaly.

1.2. Geological Setting and Tectonic Evolution

[5] The currently submerged Kerguelen Plateau and Broken Ridge and a few volcanic, oceanic islands constructed upon the plateau, Kerguelen Archipelago, Heard and MacDonald Islands are believed to be the manifestation of the Kerguelen hot spot (Figure 1) [*Coffin et al.*, 2002]. Continental tholeiites on the margins of southwest Australia (Bunbury basalts, ~132, 123 Ma) and east India (Rajmahal Traps, ~118 Ma) may also be related to early Kerguelen hot spot activity [e.g., *Mahoney et al.*, 1983; *Frey et al.*, 1996; *Kent et al.*, 1997]. The Kerguelen Plateau, together with the Broken Ridge, cover a geographical area almost one-half the size of Australia, making it the world's second biggest LIP [*Coffin and Eldholm*, 1994]. This LIP has been sampled during Ocean Drilling Program (ODP) Legs 119, 120 and 183; drilling at each of the 11 basement sites (Figure 2) has penetrated between a few tens of meters and a few hundred meters maximum into the upper Kerguelen Plateau and Broken Ridge crust. Argon-argon ages of plateau basalts show a rough, general progression from oldest in the south to youngest in the north [*Duncan*, 2002]. On the basis of these ages, Cretaceous Kerguelen plume activity appears to have created the Southern Kerguelen Plateau (SKP) and the Central Kerguelen Plateau (CKP) plus Broken Ridge in two distinct pulses at 120–110 Ma and 100–95 Ma, respectively, with less voluminous volcanism on Elan Bank, a western salient, at 108 Ma, occurring between the two major pulses [*Duncan*, 2002; *Coffin et al.*, 2002]. Subsequent volcanic activity was volumetrically minor, but aerially extensive and resulted in the formation of the 90°E Ridge (~80 to ~40 Ma) [*Duncan*, 1978] and Skiff Bank (~68 Ma) [*Duncan*, 2002], followed by the Northern Kerguelen Plateau (NKP; ~34 Ma) [*Duncan*, 2002] and the Kerguelen Archipelago

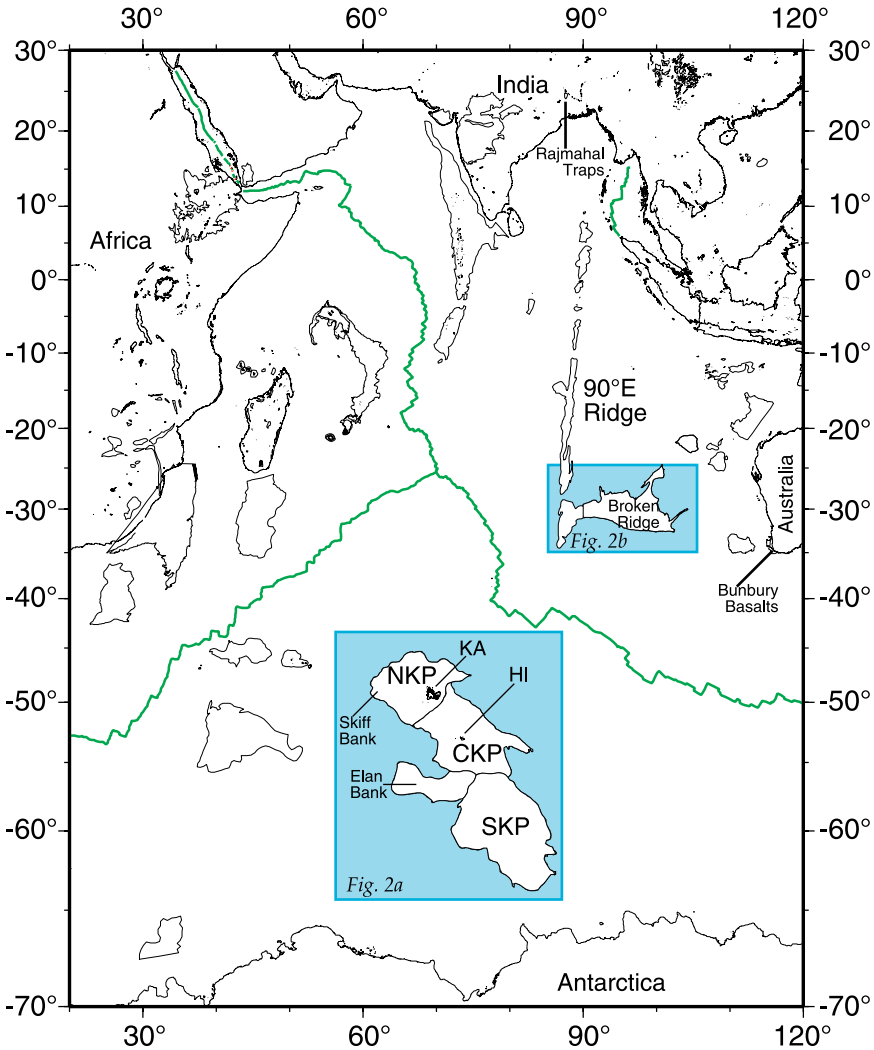


Figure 1. Physiographic map of the Indian Ocean and surrounding continents, showing the Kerguelen Plateau (including the various provinces: SKP, CKP and NKP are the Southern, Central and Northern Kerguelen Plateau, respectively, Elan Bank and Skiff Bank), Broken Ridge and 90°E Ridge. Precise locations of drill sites for samples analyzed in this study may be found in Figure 2. KA and HI are the Kerguelen Archipelago and Heard and MacDonald Island, respectively (see Figure 3 for a detailed map of the archipelago). Locations for continental tholeiites on the margins of eastern India (Rajmahal Traps) and southwestern Australia (Bunbury basalts) are also noted; these may be related to Kerguelen plume activity [e.g., *Frey et al.*, 1996; *Kent et al.*, 1997].

(constructed upon the NKP; <30 Ma to 0.1 Ma) [*Weis et al.*, 1993, 1998; *Nicolaysen et al.*, 2000; *Doucet et al.*, 2002]. Additionally, Heard and MacDonald Islands are younger than the Kerguelen Archipelago but lie farther to the south, on the CKP [*Barling et al.*, 1994]. The Kerimis seamounts also record recent volcanic activity, of intermediate age between the peaks of activity on Kerguelen and Heard Islands, and are located between these islands [*Weis et al.*, 2002a]. Since Heard and McDonald Islands are volcanically active at the present time, they represent the most likely current location of the Kerguelen hot spot [*Coffin et al.*, 2002].

[6] The Cretaceous Kerguelen Plateau was constructed primarily within the newly formed eastern Indian Ocean, well after true oceanic crust had been created between Greater India and Australia (anomaly M11, ~133 Ma [*Lawver et al.*, 1992; *Ramana et al.*, 1994] using magnetic polarity timescales of [*Gradstein et al.*, 1994]). Seismic

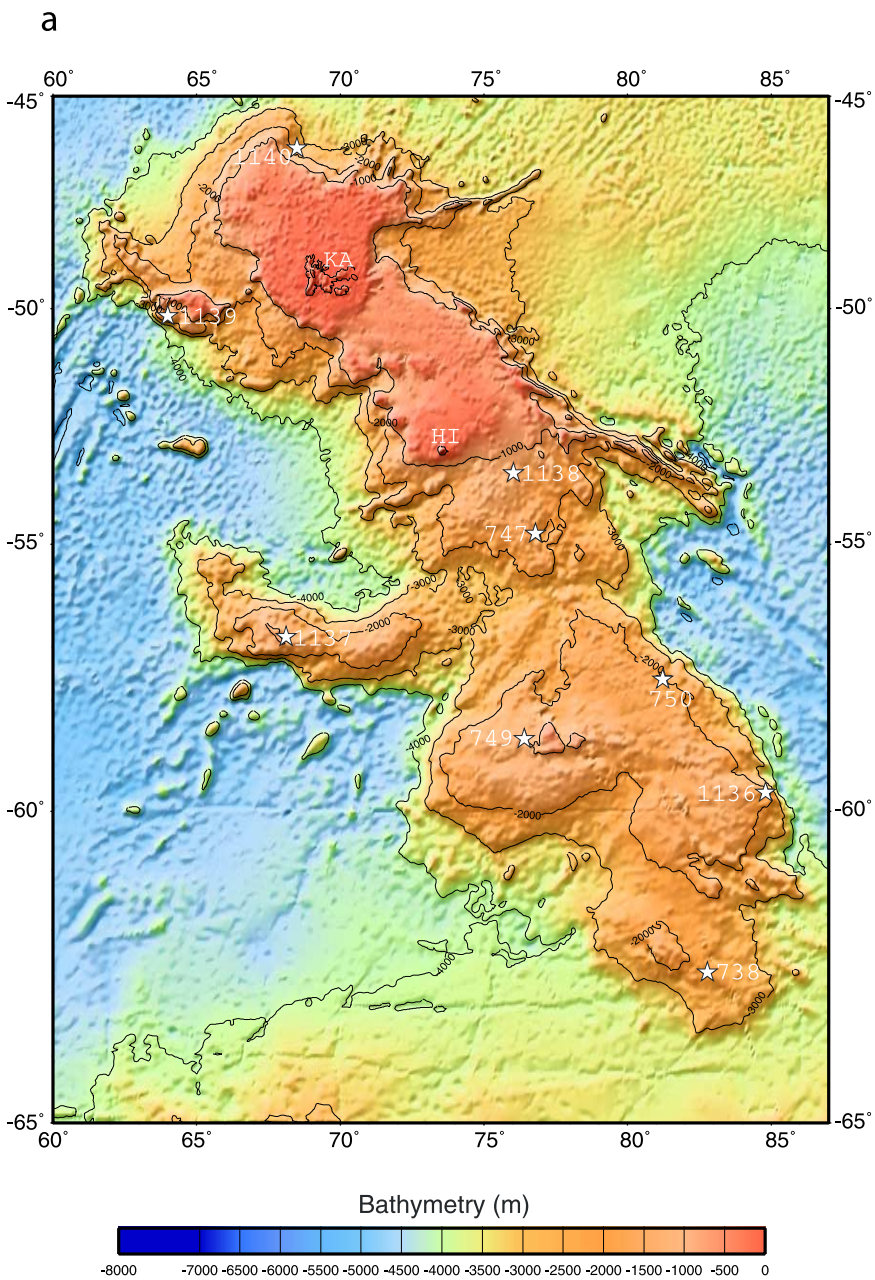


Figure 2. (a) Predicted bathymetry (in meters below seafloor) map of the Kerguelen Plateau depicting locations for drill site samples analyzed in this study. The locations for the Kerguelen Archipelago (KA) and Heard and MacDonald Islands (HI) are also indicated. (b) Predicted bathymetric map of the Broken Ridge showing the two drill site locations, Sites 1141 and 1142. Broken Ridge was conjugate with the eastern margin of the Central Kerguelen Plateau until spreading began on the Southeast Indian Ridge, ca. ~40 Ma [*Munschy et al.*, 1992]. Presently, Broken Ridge is located off the western coast of Australia (see Figure 1).

evidence suggests that continental crust exists beneath Elan Bank and parts of the SKP [*Operto and Charvis*, 1995, 1996; *Borissova et al.*, 2003]. The isolation of microcontinents (e.g., Seychelles) may be accomplished by ridge jumps during the interaction between mantle plumes and newly formed continental margins [*Müller et al.*, 2001]. Therefore, although the tectonic setting of the early Kerguelen Plateau is not well constrained [*Coffin et al.*, 2002; *Kent et al.*, 2002], it may be inferred that

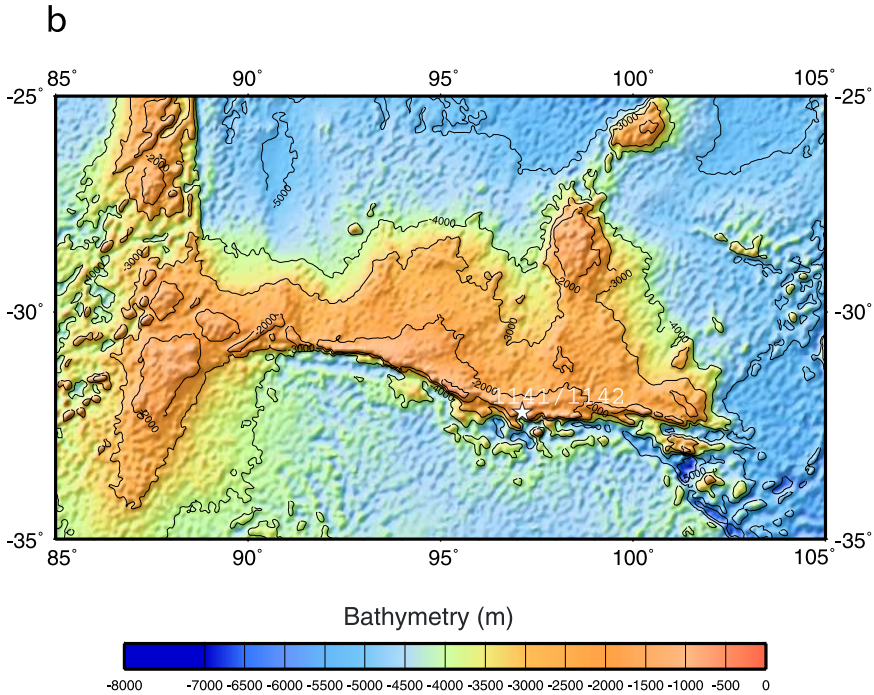


Figure 2. (continued)

it was most likely situated nearby or on a ridge and proximal to a continental margin [*Coffin et al.*, 2002; *Borissova et al.*, 2003]. The Kerguelen Plateau may have changed to an intraplate setting as India migrated northward and the 90°E Ridge formed [*Duncan*, 1978]. Rifting along the Southeast Indian Ridge began ~40 Ma and this event separated the Broken Ridge from the Kerguelen Plateau [*Munschy et al.*, 1992]. Relative migration between the Kerguelen hot spot (located on the Antarctic plate) and the Broken Ridge (located on the Australian plate) continues, since ~40 Ma, to the present-day by spreading along the Southeast Indian Ridge; during this time, and with increasing distance to the ridge over time, the Kerguelen Archipelago, Kerimis Seamounts and Heard and MacDonald Islands were created.

2. Sampling Strategy

[7] The goal of this work is to present the first comprehensive Hf isotope investigation of the Kerguelen LIP. In order to accomplish this objective, we selected samples from every drill site on the Kerguelen Plateau and Broken Ridge, in order to cover its various stages of construction, as well as two volcanic sections on the Kerguelen Archipelago (Figures 2 and 3). We also included two rocks, possibly representative of contaminating continental crust, pebbles of a rhyolite and a garnet-biotite gneiss recovered at Site 1137 [*Shipboard Scientific Party*, 2000]. A large geochemical database exists for the Kerguelen Plateau and Archipelago, including major and trace elements and some radiogenic isotopes (Sr, Nd and Pb). This valuable data permitted selection of the best samples, in terms of geographic distribution, geochemical variability and minimum extents of alteration. More samples were analyzed for Hf isotopic composition in sites that have particularly heterogeneous geochemistry (Sites 747, 749, 750, 1137 and 1140) whereas fewer samples were included for sites with more homogeneous character (Sites 738, 1136, 1138, 1141, 1142). To complement the investigation of the Hf isotopic compositions on the archipelago from *Mattielli et al.* [2002], we also selected samples from two volcanic sections from the older part of the archipelago not included in their study, Mont des Ruches and Mont Fontaine. Table 1 lists the

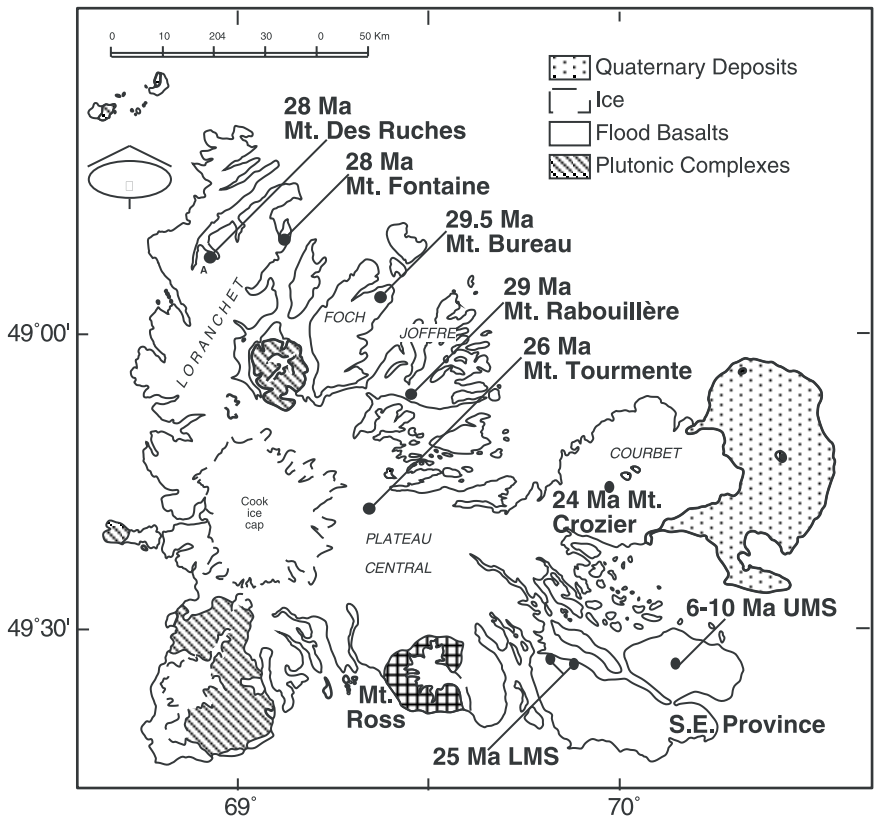


Figure 3. Map of the Kerguelen Archipelago with locations and ages indicated for all samples with Hf data from either this study or from *Mattielli et al.* [2002]. The Kerguelen Archipelago is located on the Northern Kerguelen Plateau (see Figures 1 and 2a). LMS and UMS are the Lower and Upper Miocene Series, respectively. Ages for the archipelago are from *Weis et al.* [1993, 1998]; *Yang et al.* [1998]; *Nicolaysen et al.* [2000]; *Doucet et al.* [2002]; and *Frey et al.* [2002b].

selected samples by their geographic province, drill site number or location and references for age and geochemical data. All sample locations are indicated on Figures 2 and 3.

3. Hf Isotopic Analytical Methods

[8] Hf separation was carried out on whole rock powders. The general procedure followed that of *Blichert-Toft et al.* [1997]. Basalt powders were dissolved using sub-boiled HF and HNO_3 in closed Savillex Teflon vials. The basalts were not leached with HCl prior to the dissolution because Lu and Hf are fairly immobile during post-eruptive alteration and previous studies have demonstrated leaching to be unnecessary [*Kempton et al.*, 2002; *Mattielli et al.*, 2002]. The rhyolite and gneiss were dissolved in Teflon bombs in an oven at 160°C for one week, to ensure dissolution of refractory minerals such as zircon. All dissolved powders were leached in concentrated HF to separate the rare earth elements (which precipitate out as fluoride salts) from the remaining sample. The conditioned supernatant was passed through an anion exchange column to separate high field strength elements from the bulk matrix. The high field strength element separate was passed through a final, cation exchange column to isolate Hf-Zr. This separate was then run on the Nu Plasma multicollector ICP-MS at the Université Libre de Bruxelles. Both Lu and Yb beams were monitored during each run; the Yb beam was negligible (average of zero for 60 ratio measurements) and the Hf isotopic composition was corrected for Lu interference (although the necessary correction

Table 1. Samples Selected for Hf Isotopic Analysis, Listed by Geographic Province of the Kerguelen Plateau, Broken Ridge, and Archipelago

Location[a]	Area ($\times 10^5$ km^2)[b]	Site	Age Ma ± 1σ	Ref.[c]	Number	Lava Type	Eruption Style	Ref.[c]
Southern KP	4.5	Site 1136	118.9 ± 1.5	1	1	Tholeiitic	Subaerial	5
		Site 750	112.4 ± 0.4	2	4	Tholeiitic	Subaerial	6
		Site 749	109.9 ± 1.0	2	5	Tholeiitic	Subaerial	6
		Site 738	>108	2	1	Tholeiitic	Subaerial	7
Elan Bank	1.4	Site 1137	107.7 ± 0.5	1	9	Tholeiitic	Subaerial	8
		Site 1137	Uncertain		1	Tephrite clast[d]	N/A	9
		Site 1137	>109	3	1	Rhyolitic clast[d]	N/A	9
		Site 1137	>550	3	1	Gneiss clast[d]	N/A	9
Central KP	4.3	Site 747	Uncertain		3	Tholeiitic	Subaerial	6
		Site 1138	100.4 ± 0.7	1	1	Tholeiitic	Subaerial	5
Broken Ridge	4.8	Site 1141	95.1 ± 0.8	1	1	Transitional	Subaerial	5
		Site 1142	94.5 ± 0.6	1	1	Transitional	Subaerial	5
Skiff Bank[e]	0.53	Site 1139	68.3 ± 0.3	1	2	Alkalic (bimod.)	Subaerial	10
Northern KP	3.64	Site 1140	34.3 ± 0.4	1	4	Tholeiitic	Submarine	11
KA (incl. with NKP)		Mt. des Ruches	28.3 ± 0.9	4	6	Thol. to trans.	Subaerial	4
		Mt. Fontaine	28.2 ± 0.7	4	5	Thol. to trans.	Subaerial	4

[a] KP, Kerguelen Plateau; KA, Kerguelen Archipelago.
[b] Area as calculated by *Coffin et al.* [2002].
[c] References for age, petrology, and geochemistry: 1, *Duncan* [2002]; 2, *Coffin et al.* [2002]; 3, *Nicolaysen et al.* [2001]; 4, *Doucet et al.* [2002]; 5, *Neal et al.* [2002]; 6, *Frey et al.* [2002a]; 7, *Mahoney et al.* [1995]; 8, *Ingle et al.* [2002a]; 9, *Ingle et al.* [2002b]; 10, *Kieffer et al.* [2002]; 11, *Weis and Frey* [2002].
[d] Clasts were recovered from a fluvial conglomerate between basalt flows (deposited contemporaneously with the lavas).
[e] Samples were selected from the mafic series only.

was generally well within the error of the analysis). This suggests that the HF leaching step effectively removes the rare earth elements as reported by *Blichert-Toft et al.* [1997]. One hundred and twenty analyses of Hf standard JMC-475 were completed during the days the specific samples reported here were run. The JMC-475 Hf standard was run several times (generally 5 or 6) before beginning a day of analyses, once between each two samples, and a few times after completion of the day in order to accurately assess reproducibility and drift during the day. The average of these analyses for the $^{176}Hf/^{177}Hf$ Lu-corrected value was 0.282160 ± 22 (2 standard deviations with an external, 2 standard deviation precision of 9 ppm; Figure 4a), which is within the range of previously published values of this standard [*Blichert-Toft et al.*, 1997; *Kempton et al.*, 2000; *Chauvel and Blichert-Toft*, 2001; *Woodhead et al.*, 2001]. Laboratory techniques and reproducibility may be assessed by our full-procedural duplicate analyses on seven samples, listed in addition to all samples analyzed in Table 2 and Figure 4b. Replicates, a re-run of the same sample solution, are also presented in Table 2 and Figure 4b. Procedural blanks were less than 23 pg of Hf and are negligible compared to the concentrations in the samples (>300 ng).

4. Hf Isotope Results

[9] Previous workers have documented the extreme isotopic heterogeneity associated with the Cretaceous-age Kerguelen Plateau and Broken Ridge volcanic rocks [*Salters et al.*, 1992; *Mahoney et al.*, 1995; *Frey et al.*, 2002a; *Ingle et al.*, 2002a; *Neal et al.*, 2002]. This heterogeneity is also present in the Hf isotopic compositions of these rocks that range in $\varepsilon_{Hf}(T)$ from −6.4 to +13 (Table 2; Figure 5). The Cenozoic Kerguelen hot spot products also cover a large isotopic range compared to other oceanic islands [e.g., *Storey et al.*, 1988; *Weis et al.*, 1993; *Yang et al.*, 1998; *Doucet et al.*, 2002] and Hf isotopic compositions do cover a comparably large range ($-3.3 < \varepsilon_{Hf}(T) < +13$), even when compared to that of the Cretaceous plateau (Table 2; Figure 5). Nevertheless, on the basis of distinct differences in tectonic setting and geochemical characteristics during Cretaceous and Cenozoic times, we divide the results into these two periods.

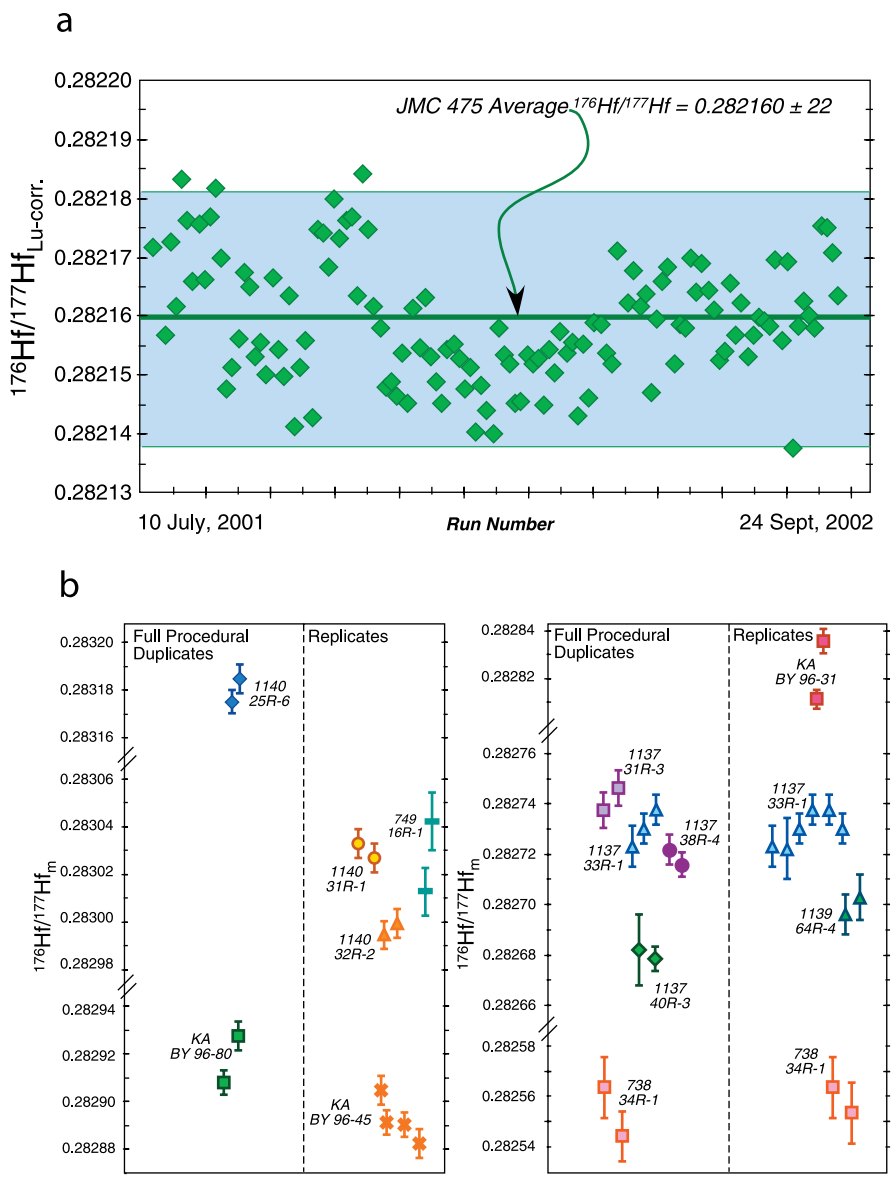


Figure 4. (a) Values for Hf Standard JMC 475 analyzed during days on which samples reported in this study were measured. Also shown is the average $^{176}Hf/^{177}Hf$ value for this standard from our measurements, 0.28160, and the 2 standard deviations, ±22, indicated by the shaded blue area. (b) Measured values for duplicates and replicates analyzed during the course of our analyses. Reproducibility of our chemical procedures may be assessed by the analysis of full procedural duplicates, depicted on the left-hand side of each graph (two graphs are shown to maintain the same scale). On the right-hand side of each graph, replicates are shown to illustrate the reproducibility of the measurements on actual samples on the Nu Plasma (Nu 015) at Université Libre de Bruxelles.

4.1. Hf Isotope Results for the Cretaceous Kerguelen Plateau and Broken Ridge

4.1.1. Southern Kerguelen Plateau Sites 738, 749, 750, and 1136 (~119 Ma to ~110 Ma)

[10] The SKP is believed to be the oldest part of the Kerguelen Plateau [*Coffin et al.*, 2002]. However, the 4 basement drill sites on the SKP span almost 10 myr (Table 1), from ~119 Ma (Site 1136) to ~110 Ma (Site 749) [*Duncan*, 2002; *Coffin et al.*, 2002]. The Hf isotopic compositions are highly variable between the different sites, but are also not homogeneous within each site, at least where more than one sample was studied. Site 1136, in the center of the SKP, has an $\varepsilon_{Hf}(T) = +5$. This value is very different compared to the values for Site 750,

Table 2. Hf Isotopic Composition of Kerguelen Plateau and Archipelago Samples[a]

Location	Sample	Age, Ma	Lu, ppm	Hf, ppm	$(^{176}Hf/^{177}Hf)_T$	2σ	$(^{176}Hf/^{177}Hf)_T$	$(\epsilon_{Hf})T$	Ref[b]	Ref[c]
				Kerguelen Plateau						
Site 1136	18R-3-Piece 2	119	0.39	2.54	0.282887	5	0.28284	5	1	6
Site 750	15R-1-103-108	112	0.32	0.84	0.283172	10	0.28306	13	2	7
	16R-2-50-56	112	0.32	0.78	0.283175	13	0.28305	12	2	7
	16R-4-42-47	112	0.33	0.88	0.283181	13	0.28307	13	2	7
	17R-3-23-27	112	0.41	1.43	0.283041	9	0.28296	8.9	2	7
Site 738	34R-1-85-86	112	0.44	3.89	0.282574	12			2	8
	34R-1-85-86 rep	112			0.282564	12			2	8
	34R-1-85-86 dupl	112			0.282554	10	0.28252	−6.4	2	8
Site 749	12R-3-55-60	110	0.24	1.59	0.283013	8	0.28297	9.4	2	7
	12R-5-76-79	110	0.35	2.37	0.282879	6	0.28284	4.7	2	7
	15R-4-36-40	110	0.4	2.43	0.282864	6	0.28282	4	2	7
	16R-1-22-29	110	0.43	2.75	0.283013	10	0.28297	9.3	2	7
	16R-6-50-60	110	0.21	1.24	0.283065	10	0.28302	11	2	7
Site 1137-U	25R-1-64-72	108	0.31	5.25	0.28272	3	0.2827	−0.1	1	9
	26R-1-31-43	108	0.33	4.77	0.2827	15			1	9
	26R-1-31-43 rep	108			0.282713	10	0.28269	−0.4	1	9
	27R-4-57-63	108	0.35	5.53	0.282724	8	0.28271	0	1	9
	31R-3-5-10	108	0.27	3.96	0.282738	7			1	9
	31R-3-5-10 dupl	108			0.282746	6	0.28273	0.8	1	9
	33R-1-53-60	108	0.29	4.88	0.282723	8			1	9
	33R-1-53-60 rep	108			0.282722	12			1	9
	33R-1-53-60	108			0.28273	6			1	9
	33R-1-53-60 rep	108			0.282738	6			1	9
	33R-1-53-60 dupl	108			0.282738	6	0.28272	0.5	1	9
	33R-1-53-60 dupl rep	108			0.28273	6			1	9
Site 1137	1137-34R-4 rhyolite	113	0.56	18.7	0.282505	4	0.2825	−7.4	3	3
clasts	1137-35R-2-gneiss	550	0.43	9.8	0.282192	6	0.28218	−19	4	3
	1137-35R-2 rep	550			0.282197	7			4	3
	1137-36R-2 tephrite	–	0.41	11.1	0.282616	6	0.28261	−3.5	-	3
Site 1137-L	38R-4-71-77	108	0.33	4.57	0.282722	6			1	9
	38R-4-71-77 dupl	108			0.282716	5	0.2827	−0.4	1	9
	40R-3-117-124	108	0.35	4.64	0.282682	14			1	9
	40R-3-117-124 dupl	108			0.282679	5	0.28266	−1.7	1	9
	41R-1-3-10	108	0.31	4.82	0.28269	7	0.28267	−1.2	1	9
	41R-1-3-10 rep	108			0.282677	8			1	9
	46R-1-51-56	108	0.39	4.96	0.28277	17			1	9
	46R-1-51-56 dupl	108			0.282752	6	0.28273	0.9	1	9
Site 1138	84R-5-Piece 3	100	0.61	4.97	0.282921	13	0.28289	6.3	1	6
Site 747	12R-4-53-56	100	0.36	2.69	0.282683	6	0.28265	−2.3	2	7
	14R-1-31-35	100	0.33	3.29	0.282651	6	0.28263	−3.2	2	7
	15R-1-15-19	100	0.27	2.61	0.282657	6	0.28263	−3	2	7
Site 1141	21R-2-Piece 1	94.7	0.35	3.56	0.282875	4	0.28285	4.8	1	6
Site 1142	10R-3-Piece 1	94.7	0.57	5.44	0.282928	7	0.2829	6.7	1	6
Site 1139	64R-1-136-146	68.3	0.54	8.57	0.282703	8	0.28269	−1.3	1	10
	64R-4-103-115	68.3	0.48	6.99	0.282696	8	0.28268	−1.6	1	10
	64R-4-103-115 rep	68.3			0.282703	9			1	10
Site 1140	25R-6-51-56	34.3	0.46	2.39	0.283175	5	0.28316	14	1	11
	25R-6-51-56 dupl	34.3			0.283185	6			1	11
	31R-1-57-67	34.3	0.47	4.03	0.283033	6	0.28302	9.6	1	11
	31R-1-57-67 rep	34.3			0.283027	6			1	11
	32R-2-45-50	34.3	0.52	5.46	0.282995	6	0.28299	8.3	1	11
	32R-2-45-50 rep	34.3			0.282999	6			1	11
	34R-6-33-39	34.3	0.45	2.16	0.283126	6	0.28311	13	1	11
				Kerguelen Archipelago						
M. d. Ruches	BY96-24	28.2	0.27	2.45	0.282911	5	0.2829	5.2	5	5
	BY96-27	28.2	0.23	3.1	0.282861	5	0.28286	3.6	5	5
	BY96-31	28.2	0.4	5.89	0.282812	4	0.28281	1.8	5	5
	BY96-31 rep	28.2			0.282836	5			5	5
	BY96-34	28.2	0.23	3.55	0.282731	5	0.28273	−1	5	5

Table 2. (continued)

Location	Sample	Age, Ma	Lu, ppm	Hf, ppm	$(^{176}Hf/^{177}Hf)_T$	2σ	$(^{176}Hf/^{177}Hf)_T$	$(\epsilon_{Hf})T$	Ref[b]	Ref[c]
	BY96-45	28.2	0.32	4	0.282965	6	0.28296	7.2	5	5
	BY96-46	28.2	0.46	7.35	0.282905	6			5	5
	BY96-46 rep	28.2			0.282882	6			5	5
	BY96-46 rep	28.2			0.282891	5			5	5
	BY96-46 rep	28.2			0.282891	5	0.28288	4.6	5	5
M. Fontaine	BY96-80	28	0.26	3.1	0.282908	7			5	5
	BY96-80 dupl	28			0.282927	6	0.28292	5.8	5	5
	BY96-82	28	0.29	2.89	0.282974	5	0.28297	7.5	5	5
	BY96-86	28	0.24	2.53	0.282873	4	0.28287	3.9	5	5
	BY96-89	28	0.21	1.29	0.282987	7	0.28297	7.8	5	5
	BY96-98	28	0.24	2.91	0.282974	5	0.28297	7.5	5	5

[a] Lu and Hf concentration measurements were made by ICP-MS except for Sites 1137 and 738 (INAA). Approximate ages for the clasts (recovered from a conglomerate deposited between lava flows at Site 1137) are listed, but these samples are age corrected only to the age of the basalt flows (~108 Ma) recovered at Site 1137. Reported 2σ applies to the sixth decimal place. Site 1137-U indicates "upper group," and -L is "lower group." A sample with "dupl" listed next to the sample name is a full procedural duplicate, while a sample listed as "rep" is a repeat analysis on the MC-ICP-MS using the same solution as the sample listed above. Age corrections are only applied to the analysis with the lowest reported error in the case of duplicates and replicates. $\epsilon_{Hf}(T) = [(^{176}Hf/^{177}Hf)_{sample}/(^{176}Hf/^{177}Hf)_{CHUR)} - 1]*10^4$, where both the sample and CHUR values are corrected to time T; CHUR values ($(^{176}Hf/^{177}Hf)_{Today} = 0.282772$, $^{147}Sm/^{144}Nd = 0.0332$) from *Blichert-Toft and Albarède* [1997] and Hf decay constant from *Scherer et al.* [2001].

[b] The references for the listed age are as follows: 1, *Duncan* [2002]; 2, *Coffin et al.* [2002]; 3, *Ingle et al.* [2002b]; 4, *Nicolaysen et al.* [2001]; 5, *Doucet et al.* [2002].

[c] The references for the Lu and Hf concentrations are as follows: 1, *Duncan* [2002]; 2, *Coffin et al.* [2002]; 3, *Ingle et al.* [2002b]; 4, *Nicolaysen et al.* [2001]; 5, *Doucet et al.* [2002]; 6, *Neal et al.* [2002]; 7, *Frey et al.* [2002a]; 8, *Mahoney et al.* [1995]; 9, *Ingle et al.* [2002a]; 10, *Kieffer et al.* [2002]; 11, *Weis and Frey* [2002].

on the eastern flank of the SKP, that are much more radiogenic ($+8.9 > \varepsilon_{Hf}(T) > +13$). Site 749, on the western flank of the SKP, has $\varepsilon_{Hf}(T)$ intermediate to those of Sites 1136 and 750 ($+4.0 - +11$). In strong contrast, a basalt from the southernmost site on the SKP, Site 738, has an $\varepsilon_{Hf}(T)$ of −6.4, much less radiogenic than the other sites from the SKP. Sites 749 and 750 have the highest documented $\varepsilon_{Hf}(T)$ and $\varepsilon_{Nd}(T)$ of all basalts studied from the Cretaceous Kerguelen Plateau (Figures 5 and 6); however, they have very different $(^{87}Sr/^{86}Sr)_T$ and are distinct in their Pb isotopic compositions as well (Figure 7) [*Frey et al.*, 2002a]. Site 1136 lies at the unradiogenic end of the Site 749 range of $\varepsilon_{Hf}(T)$ values (Figure 5). In plots of $\varepsilon_{Hf}(T)$ vs. $\varepsilon_{Nd}(T)$ or $(^{87}Sr/^{86}Sr)_T$, the Site 1136 sample is displaced slightly toward more radiogenic ($^{87}Sr/^{86}Sr$) and less radiogenic $\varepsilon_{Nd}(T)$ than the Site 749 samples (Figure 6); Site 1136 also has Pb isotopic compositions quite comparable to, but slightly more radiogenic in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than those of Site 749 (Figure 7) [*Neal et al.*, 2002].

4.1.2. Elan Bank Site 1137 (~108 Ma)

[11] The ~108 Ma basalts [*Duncan*, 2002] from Site 1137 have been divided into a lower and upper group distinguished by distinctive isotopic values reflecting more extensive contamination by upper continental crust in the lower basalt group [*Weis et al.*, 2001; *Ingle et al.*, 2002a]. Hf isotopes for these basalts cluster around chondritic compositions, with the upper group basalts having $\varepsilon_{Hf}(T)$ from −0.4 to +0.8, similar to the lower group with $\varepsilon_{Hf}(T)$ from −1.7 to +0.9 (Table 2). Site 1137 basalts have $\varepsilon_{Hf}(T)$ values that do not overlap with those of any basalts from the SKP (Figure 5), and this is coherent with the fact that the Site 1137 basalts are completely out of the range of $\varepsilon_{Nd}(T)$ measured in basalts from Sites 749, 750 and 1136 (Figure 6). The Site 1137 lower basalts have $(^{87}Sr/^{86}Sr)_T$ comparable to those of the Site 750 basalts (Figure 6). One of the most characteristic features of Site 1137 basalts is a vertical trend in Pb-Pb isotope plots, with variable $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for nearly constant $^{206}Pb/^{204}Pb$ (Figure 7) [*Ingle et al.*, 2002a]. Site 749 basalts form a similar type of trend (Figure 7) [*Frey et al.*, 2002a]. The three clasts from the fluvial conglomerate that were analyzed include a tephrite, a rhyolite and a gneiss which have $\varepsilon_{Hf}(T)$ of −3.5, −7.4 and −19, respectively. All values of $\varepsilon_{Hf}(T)$ for the clasts

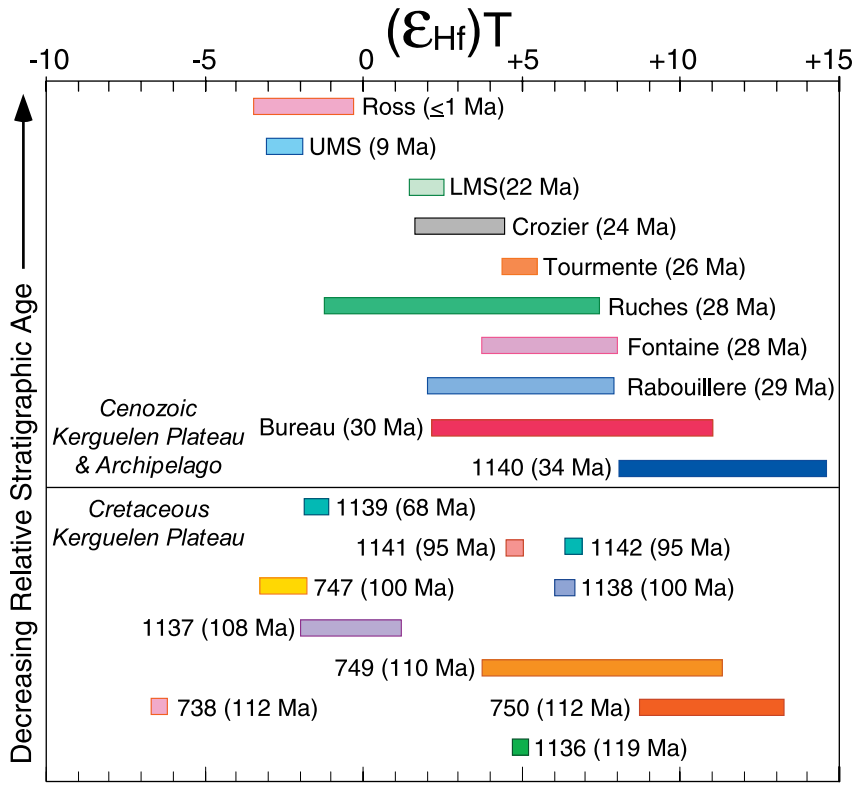


Figure 5. ε_{Hf}(T) vs. relative stratigraphic age (true age noted next to each locale) for all Kerguelen Plateau and Kerguelen Archipelago samples analyzed during this study or during the study of *Mattielli et al.* [2002] (archipelago only). Hf isotopic composition is given in epsilon units ε_{Hf} and age-corrected (T) for the Ar-Ar ages (references given in Table 1 and Figure 3 caption). The horizontal line divides samples from the Cretaceous Kerguelen Plateau (older than 68 Ma) and the Cenozoic Kerguelen Plateau and Kerguelen Archipelago. Note that there is no trend of either increasing or decreasing ε_{Hf}(T) in the Cretaceous samples but that a general trend of decreasing ε_{Hf}(T) is present in the Cenozoic samples.

are much less radiogenic than those of the basalt flows (Table 2).

4.1.3. Central Kerguelen Plateau Sites 747 and 1138 (~100 Ma) and Broken Ridge Sites 1141 and 1142 (~95 Ma)

[12] The CKP and Broken Ridge formed between 100–95 Ma and were conjugate until around 40 Ma [*Munschy et al.*, 1992]. The CKP has been sampled at Site 747 in the south and at Site 1138 slightly farther to the north. The single sample from Site 1138 has ε_{Hf}(T) of +6.3, this is a very different value from those obtained for the 3 samples from Site 747 which range in ε_{Hf}(T) from −3.2 to −2.3 (Table 2, Figure 5). The Site 1138 sample has an ε_{Hf}(T), ε_{Nd}(T) and $(^{87}Sr/^{86}Sr)_T$ similar to those values found in the Site 1136 sample (Figure 6). The $^{206}Pb/^{204}Pb$ for the Site 1138 basalts is ~18, similar to the values for basalts from Sites 749, 1136 and 1137; however, Site 1136 basalts do not form a vertical distribution in Pb-Pb plots. On the Broken Ridge, both Sites 1141 and 1142 were drilled from the southeastern margin. Despite their proximity, these sites have slightly different Hf isotopic compositions: Site 1141 has ε_{Hf}(T) = +4.8 and Site 1142 has ε_{Hf}(T) = +6.7 (Table 2, Figure 5). The two samples from Sites 1141 and 1142 are also slightly different from each other in ε_{Nd}(T) and $(^{87}Sr/^{86}Sr)_T$ but Pb isotopic compositions overlap in some Site 1141 and 1142 samples and are similar to Pb isotopes in Site 1137 basalts (Figure 7) [*Neal et al.*, 2002].

4.1.4. Skiff Bank Site 1139 (~68 Ma)

[13] The small topographic high on the western part of the NKP, Skiff Bank, was drilled at Site 1139. It

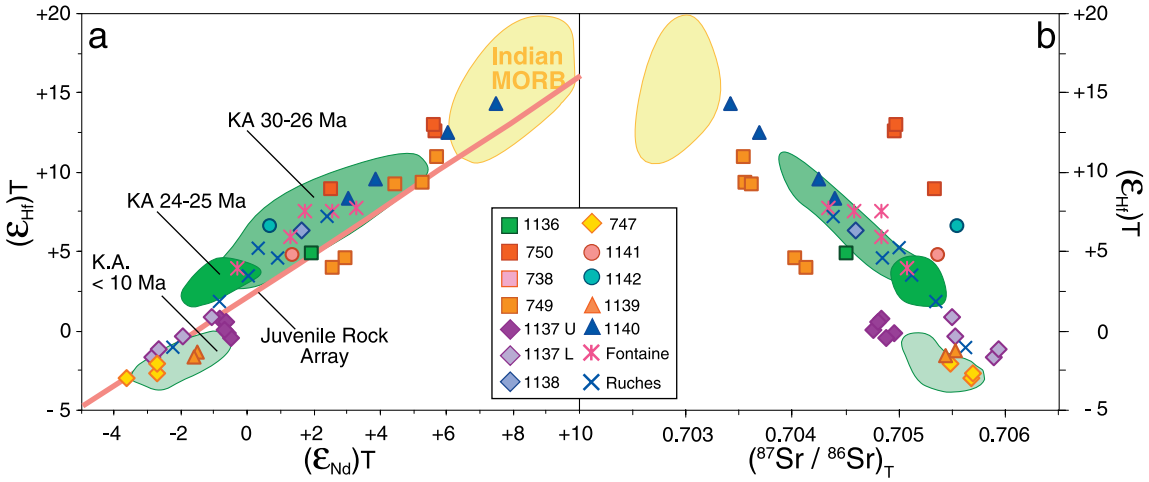


Figure 6. (a) ε_{Hf}(T) vs. ε_{Nd}(T) and (b) ε_{Hf}(T) vs. $(^{87}Sr/^{86}Sr)_T$ for samples from the Kerguelen Plateau and Archipelago. Samples analyzed during this study are shown as the individual points and are included in the key. Kerguelen Archipelago (KA) samples analyzed by *Mattielli et al.* [2002] are grouped in the different green-shaded fields by age and composition. The Indian MORB field is data from *Chauvel and Blichert-Toft* [2001], and references therein. The new data on the Kerguelen Plateau samples analyzed in this study greatly extends the range of ε_{Hf}(T) associated with the archipelago. The Site 738 sample does not fit in the plotted area but has $\varepsilon_{Hf}(T) = -6.4$, $\varepsilon_{Nd}(T) = -7.6$ and $(^{87}Sr/^{86}Sr)_T = 0.70910$ (Sr, Nd and Pb isotopes from [*Mahoney et al.*, 1995]). The new data for the Kerguelen Archipelago mostly fall in the field of the archipelago corresponding to their age, but one sample from Mont des Ruches falls in the field associated with the youngest lavas on the archipelago, and near plateau samples from Sites 1137, 747 and 1139. The juvenile rock array from *Vervoort and Blichert-Toft* [1999] is shown for reference; note that most Kerguelen samples, except for those most contaminated by continental crust, lie to the left of this array. Nd and Sr isotopic data for the Kerguelen Plateau sites: *Mahoney et al.* [1995]; *Frey et al.* [2002a]; *Ingle et al.* [2002a]; *Kieffer et al.* [2002]; *Neal et al.* [2002]; *Weis and Frey* [2002] and Kerguelen Archipelago: *Weis et al.* [1993, 1998]; D. Weis, unpublished data (2001); *Yang et al.* [1998]; *Doucet et al.* [2002]; *Frey et al.* [2002b].

has been dated as Late Cretaceous in age, ~68 Ma [*Duncan*, 2002], and it therefore erupted during the timing of the 90°E Ridge construction (~40 to ~80 Ma) [*Duncan*, 1978]. Its relationship to the remainder of the NKP is unknown as the northern part of the NKP (Site 1140) appears to be significantly younger (~34 Ma; see discussion below) [*Duncan*, 2002]. The two Site 1139 samples have $\varepsilon_{Hf}(T) = -1.6$ and -1.3 (Table 2, Figure 5). Basalts from Site 1139 have similar isotopic characteristics to basalts from Site 747 from the CKP, either overlapping in some plots or lying very close to each other in other plots (Figures 5, 6, and 7) [*Kieffer et al.*, 2002; *Frey et al.*, 2002a; this study].

4.2. Hf Isotopic Results for the Cenozoic Kerguelen Plateau and Kerguelen Archipelago

[14] The NKP was drilled on its northernmost margin at Site 1140, and these basalts are the youngest yet recovered from the Kerguelen Plateau (~34 Ma) [*Duncan*, 2002]. The 4 samples analyzed from this site range in ε_{Hf}(T) from +8.3 to +14 (Table 2; Figure 5). Some Site 1140 basalts extend into the Indian MORB field in ε_{Hf}(T), ε_{Nd}(T) and Pb isotopes and only have $(^{87}Sr/^{86}Sr)_T$ slightly outside of the reported field for Indian MORB (Figures 6 and 7) [*Weis and Frey*, 2002; this study]. We have plotted the new Site 1140 and the new archipelago data from Mont Fontaine and Mont des Ruches as individual points but have divided the previously reported Kerguelen Archipelago data into three groups (plotted as fields in the various diagrams): basalts >26 Ma, 24–25 Ma basalts and the <10 Ma lavas.

[15] The Kerguelen Archipelago was constructed upon the NKP and there is a general age progression from the northwest (~30 Ma) to the southeast (~24 Ma) but some younger lavas and dikes (>0.1 Ma) are also present in the southeast [e.g.,

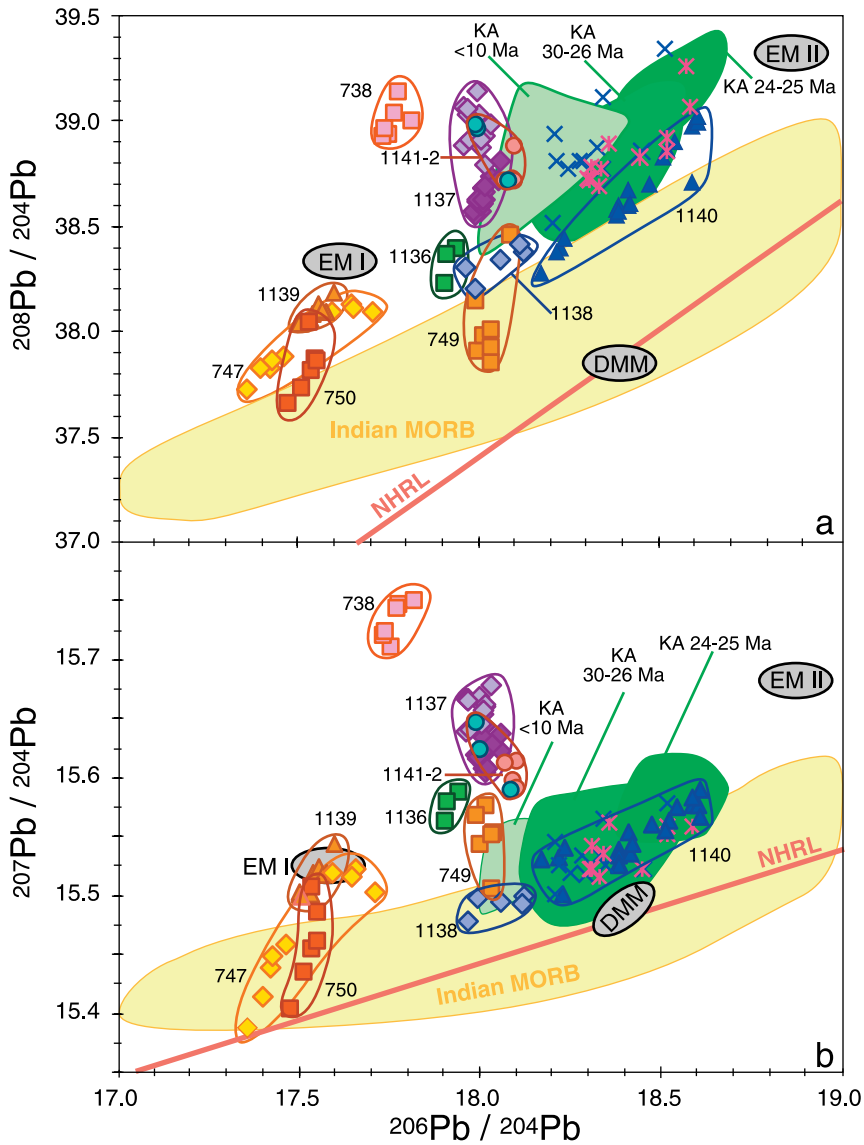


Figure 7. (a) Measured $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and (b) Measured $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for rocks from the Kerguelen Plateau and Kerguelen Archipelago. All sites from the plateau are grouped and labeled in individual fields for clarity. Kerguelen Archipelago samples are divided into the fields as presented in Figure 6 and individual Mont des Ruches (blue X) and Mont Fontaine (pink asterisk) samples are shown as their Hf isotopic compositions were analyzed during this study (all Pb isotopic compositions from *Doucet et al.* [2002]). The large range covered by Kerguelen Plateau and Archipelago data is reinforced by the plotting of the mantle end-members (gray fields) [*Hart*, 1988]. Note the displacement of the Indian Ocean MORB and Kerguelen basalts to the left of the northern hemisphere reference line (NHRL as defined by *Hart* [1984]). All Pb isotopic references for Kerguelen samples are as in Figure 6. Indian MORB data sources: *Hamelin et al.* [1985]; *Michard et al.* [1986]; *Price et al.* [1986]; *Dosso et al.* [1988]; *Pyle et al.* [1992]; *Klein et al.* [1988]; *Klein et al.* [1991]; *Mahoney et al.* [1989, 1992]; *White* [1993]; *Schiano et al.* [1997].

Storey et al., 1988; *Weis et al.*, 1993, 1998; *Yang et al.*, 1998; *Nicolaysen et al.*, 2000; *Doucet et al.*, 2002]. Previous workers have noted an isotopic distinction in the Kerguelen Archipelago lavas between the >26 Ma sections, that are tholeiitic to transitional in composition, the 24–25 Ma mildly alkalic sections and the <10 Ma lavas, that are highly alkalic [e.g., *Gautier et al.*, 1990; *Weis et al.*, 1998; *Damasceno et al.*, 2002]. *Mattielli et al.* [2002] reported Hf isotopes for 39 samples from the

Kerguelen Archipelago from all 3 groups. We analyzed 11 additional samples for Hf isotopes from 2 previously unreported volcanic sections of the >26 Ma group, the Mont des Ruches and Mont Fontaine basaltic sections from the northwestern part of the archipelago (age = ~28 Ma and other isotopic values from [*Doucet et al.*, 2002]). The Mont des Ruches samples are quite variable and range in $\varepsilon_{Hf}(T)$ from −1.0 to +7.2 and the Mont Fontaine samples range in $\varepsilon_{Hf}(T)$ from +3.9 to +7.8 (Table 2; Figure 5). Although the majority of the studied samples fall within the reported range for the >26 Ma lavas from the Kerguelen Archipelago, one sample from Mont des Ruches lies well out of this field in $\varepsilon_{Hf}(T)$ vs. $\varepsilon_{Nd}(T)$ or $(^{87}Sr/^{86}Sr)_T$ (Figure 6) and closer to the <10 Ma lava values. Additionally, one Mont Fontaine sample is out of the range for the other similarly aged Kerguelen Archipelago samples, having slightly higher $(^{87}Sr/^{86}Sr)_T$ (Figure 6).

5. Identification of the Mantle Sources and Continental Contaminants Recorded in the Kerguelen Plateau–Broken Ridge and Kerguelen Archipelago Rocks

5.1. Cretaceous Kerguelen Plateau–Broken Ridge Sources and Contaminants

[16] The studied samples from the Cretaceous Kerguelen Plateau–Broken Ridge alone, excluding the continental clasts from Site 1137, span >20 ε_{Hf} units (Table 2; Figure 5). The large differences in the geochemical characteristics between basalts from the same geographic area and age leads us to group the samples on the basis of geochemical characteristics. Sites sharing some geochemical characteristics may then be grouped together and possible mechanisms to account for the diversity of the Hf isotopic compositions examined. We group the sites on the basis of their Pb isotopic compositions as the Pb-Pb plots provide a useful tool to discriminate the various Kerguelen Plateau–Broken Ridge sites that have similar isotopic characteristics but that are widely dispersed geographically. Then, we incorporate our Hf isotopic data to yield new insights to the origin of Kerguelen Plateau–Broken Ridge mantle sources and shallow-level interactions.

5.1.1. Sites With Basalts Having Limited $^{206}Pb/^{204}Pb$ Variation From 17.9 to 18.1

[17] This group includes basalts from various areas of the Kerguelen Plateau including Sites 749 and 1136 (SKP), Site 1137 (Elan Bank), Site 1138 (CKP) and Sites 1141 and 1142 (Broken Ridge). We use measured Pb isotopic ratios because U, Th and Pb concentration data are not available for all samples and because the total shift in Pb isotopic compositions resulting from age-correction is not significant for most of these samples. These sites have a narrow range in $^{206}Pb/^{204}Pb$ (~17.9–18.1), cover a wide range in all other isotopic systems and form a diffuse, vertical trend in Pb-Pb isotope diagrams (Figures 6, 7, and 8) [*Frey et al.*, 2002a; *Ingle et al.*, 2002a; *Neal et al.*, 2002; this study]. Binary mixing in Pb-Pb diagrams results in linear correlations and so the Pb compositions of these samples appear to originate from a common source having $^{206}Pb/^{204}Pb \approx 18$ and relatively low $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ that has been mixed with a contaminant also having $^{206}Pb/^{204}Pb \approx 18$ but high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Site 1138 may be the best representation of the mantle component during Cretaceous time, as suggested by *Neal et al.* [2002]. Site 1138 basalts have homogeneous Sr, Nd and Pb isotopic values and these values are characteristic of the primitive mantle [*Neal et al.*, 2002]. The $\varepsilon_{Hf}(T)$ for the Site 1138 sample is well within the range of many Kerguelen Plateau, Broken Ridge and Kerguelen Archipelago rocks. These basalts also have no trace element characteristics which reflect a continental lithosphere signature (e.g., La/Nb ≈ 1, La/Ta ≈ 1) [*Neal et al.*, 2002]. The Site 1138 sample has a moderately depleted signature in Hf isotopes, with an $\varepsilon_{Hf}(T) = +6.4$, despite the primitive mantle-like Sr-Nd-Pb isotopic values (Figures 6 and 8). A low $\varepsilon_{Nd}(T)$ for a given $\varepsilon_{Hf}(T)$ results in displacement to the left in the $\varepsilon_{Hf}(T)$ vs. $\varepsilon_{Nd}(T)$ diagram relative to the mantle array [*Vervoort and Blichert-Toft*, 1999]. This quality in Hf-Nd isotope space is also characteristic of most Kerguelen Archipelago lavas [*Mattielli et al.*, 2002] and of Indian MORB [*Chauvel and Blichert-Toft*, 2001]. In summary,

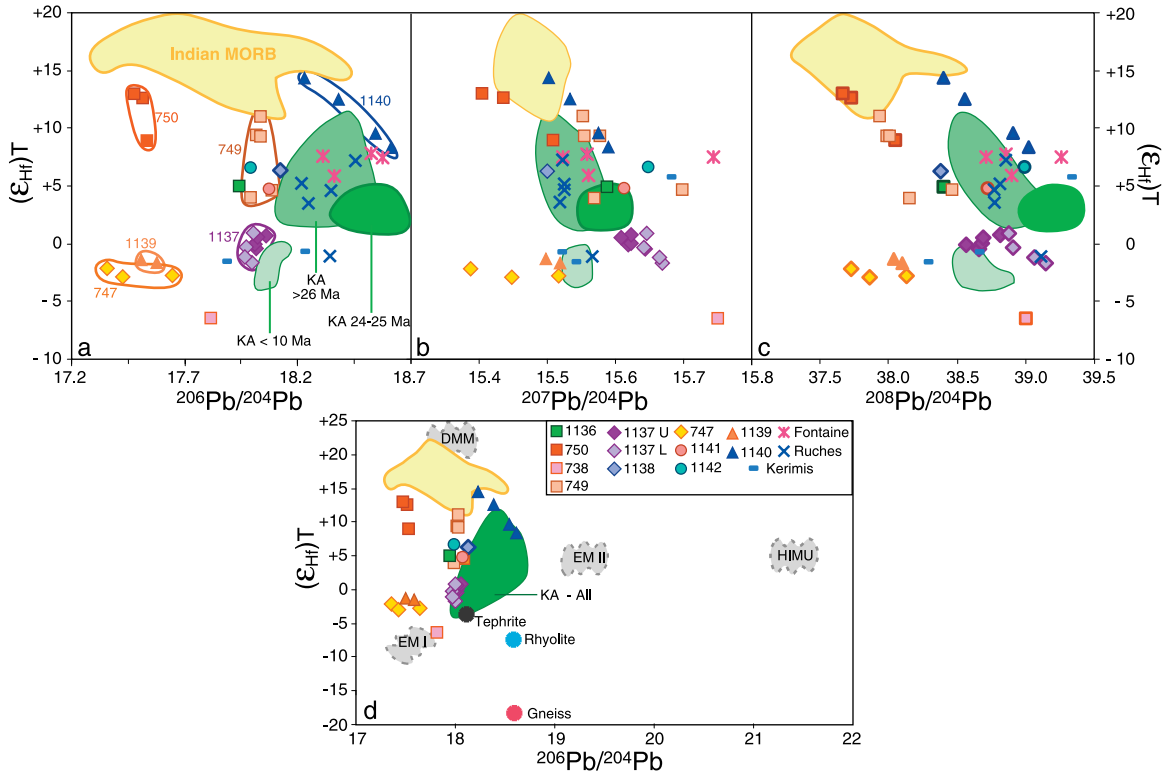


Figure 8. ε_{Hf}(T) vs. measured $^{206}Pb/^{204}Pb$ (a, d), $^{207}Pb/^{204}Pb$ (b) and $^{208}Pb/^{204}Pb$ (c) for rocks from the Kerguelen Plateau and Archipelago. The field for Indian Ocean MORB is also shown: [*Salters*, 1996; *Chauvel and Blichert-Toft*, 2001, and references therein]. Kerguelen Plateau sites are listed in the key individually (squares = SKP; diamonds = Elan Bank and CKP; circles = Broken Ridge; triangles = Skiff Bank and NKP) and archipelago samples are divided into age and composition groups with the exception of the new data for Mont des Ruches and Fontaine which are plotted individually. Kerimis volcanic rocks, recovered from seamounts between the Kerguelen Archipelago and Heard Island are also plotted [*Weis et al.*, 2002a]. In (a) fields are drawn around sites with multiple samples analyzed for Hf isotopes. Figure 8a is extended in (d) in order to show the mantle end-members (Pb from *Hart*, [1988]; Hf from *Salters and White* [1998]) for comparison to the Kerguelen samples, and to highlight the absence of any HIMU-like component in any Kerguelen rocks. Note the extreme isotopic values in the gneiss clast from Site 1137 on Elan Banks. References for Kerguelen isotopic data are as in Figures 6 and 7.

Site 1138 samples have (1) homogeneous Sr and Nd isotopic compositions typical of the values at many sites on the Kerguelen Plateau–Broken Ridge, (2) $^{206}Pb/^{204}Pb$ values of ~18, (3) high ε_{Hf}(T) for their ε_{Nd}(T) relative to non-Indian Ocean basalts samples, (4) trace element characteristics consistent with derivation from an enriched reservoir and (5) no signature indicative of crustal contamination [*Neal et al.*, 2002; this study]. Therefore, at the present time, these samples appear to be the best representation of the mantle source available for generating most Cretaceous Kerguelen Plateau–Broken Ridge basalts and may be inferred to represent the composition available in the Kerguelen plume head.

[18] The contaminant that would best account for the full isotopic variation in the other basalts from this group is upper continental crust [*Ingle et al.*, 2002a]. This hypothesis also is consistent with the Hf isotopic data: assimilation of upper crust having $^{206}Pb/^{204}Pb \approx 18$, high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, subchondritic ε_{Hf} and ε_{Nd} and radiogenic $^{87}Sr/^{86}Sr$. Minor input from a component more depleted than that of the Site 1138 basalts is required to explain the Sr, Nd, Hf and Pb isotopic compositions of Site 749 (SKP) basalts [*Frey et al.*, 2002a; *Ingle et al.*, 2002a; this study]. It is possible that this component could be the depleted, upper Indian MORB mantle (Figures 6–8).

5.1.2. Sites With Basalts Having Unusually Low $^{206}Pb/^{204}Pb$ (~17.3 to ~17.8)

[19] This group includes Sites 738 and 750 (SKP), Site 747 (CKP) and Site 1139 (Skiff Bank). Basalts from these sites have low $^{206}Pb/^{204}Pb$ (<17.8) but have variable isotopic compositions in all other systems. Sites 747 (CKP) and 1139 (Skiff Bank) have generally comparable Sr, Nd, Pb and Hf isotopic values [*Frey et al.*, 2002a; *Kieffer et al.*, 2002; this study]. Basalts from Site 750 (SKP) overlap with Sites 747 and 1139 in all Pb isotopic compositions but have other isotopic values quite distinct from those characterizing Sites 747 and 1139, and fall much closer to the Indian MORB field (Figures 6 and 8). Site 738 basalts have significantly higher $^{208}Pb/^{204}Pb$ (>38.9) and $^{207}Pb/^{204}Pb$ (>15.7) than Site 747, 750 and 1139 basalts [*Mahoney et al.*, 1995; *Frey et al.*, 2002a; *Kieffer et al.*, 2002]. The diversity of isotopic compositions in this low $^{206}Pb/^{204}Pb$ group suggests that either multiple mantle components or multiple continental contaminants (or both) are necessary to explain their variation.

[20] The origin of the low-$^{206}Pb/^{204}Pb$ component in Site 747 and 750 basalts has been explained by incorporation of delaminated lower continental crust in the Kerguelen plume, perhaps as a result of a ridge-centered tectonic environment, where the lithosphere would be thin and exposed to the hot mantle plume [*Frey et al.*, 2002a]. Basalts from Sites 747 and 1139 share comparable Sr, Nd, Pb and Hf isotopic compositions and it is reasonable to assume that their mantle sources and continental contaminants were similar. If Site 747 and 1139 basalts originated from melting in the plume head, the continental contaminant must have had low Pb, Nd and Hf and high Sr isotopic compositions [*Frey et al.*, 2002a; this study]. These basalts could therefore be mixtures between the plume head source and a lower crustal contaminant, comparable to the upper crust contaminant discussed in the previous section in all isotopic values except for Pb. Site 1139 basalts appear to be less contaminated than Site 747 basalts, since the Site 747 basalts extend to lower Pb isotopic compositions.

[21] Site 738 and 750 basalts must have developed their low-$^{206}Pb/^{204}Pb$ isotopic compositions for different reasons than those applicable to Site 747 and 1139 samples. This is clear because Site 750 basalts are very different from Site 747 and 1139 basalts in $\varepsilon_{Hf}(T)$ and $\varepsilon_{Nd}(T)$, having values considerably more MORB-like than those ratios in Site 747 basalts [*Frey et al.*, 2002a; this study]. *Frey et al.* [2002a] argued that Site 750 basalts may have been generated by the same mantle component as that of Site 747 basalts (and by inference, Site 1139) but that Site 747 and 750 basalts experienced contamination by different types of lower continental crust, to account for the discrepancies between the Sr and Nd isotopic compositions in basalts from these two sites. However, Site 747 and 1139 basalts are deflected toward higher $^{87}Sr/^{86}Sr$, and lower ε_{Hf} and ε_{Nd}, similar to those values in Site 1137 basalts, relative to the plume head composition (Site 1138). Lower crust may generally have lower Pb isotopic ratios than upper crust because of preferential removal of U, Th and Rb relative to their daughter products during partial melting [e.g., *Doe and Zartman*, 1979]. However, Nd and Hf isotopic compositions in the lower crust should not be significantly different than the those found in the upper crust [*Vervoort et al.*, 2000]. Thus the presence of the high Hf and high Nd isotopic values in Site 750 is inconsistent with contamination of enriched, plume-derived magmas by any likely lower continental crust component. An additional constraint is that the high $(^{87}Sr/^{86}Sr)_T$ in Site 750 basalts ($\geq$0.705) requires that a contaminant with sufficiently high Sr concentrations was involved.

[22] An alternative explanation is that the Site 738 and 750 basalts result from magmas derived from a depleted source having extremely unradiogenic Pb isotopic compositions, that subsequently assimilate upper continental crust, characterized by high Sr concentrations, high $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb \approx 18$ and unradiogenic $\varepsilon_{Hf}(T)$ and $\varepsilon_{Nd}(T)$. This upper crust contaminant could be quite comparable to that necessary in generating the Site 1137 basalts. Binary mixing between a depleted source with low-$^{206}Pb/^{204}Pb$ by

up to 10% of this upper crust could explain the distinctive isotopic characteristics of Site 750 basalts (Figure 9). One Site 750 sample falls below the mixing curve in $^{176}Hf/^{177}Hf$ vs. $^{87}Sr/^{86}Sr$ but this may be a result of alteration in this sample (>7% loss on ignition; [*Frey et al.*, 2002a]). Site 738 basalts reflect extensive contamination [*Mahoney et al.*, 1995]; their isotopic compositions are probably nearly equivalent to those of the contaminant. Although there is no sample to represent the proposed crustal contaminant, it most likely has isotopic characteristics slightly more extreme than those of the Site 738 basalts.

5.2. Cenozoic Kerguelen Plateau and Kerguelen Archipelago Mantle Sources and Possible Contaminants

[23] During the Cenozoic, spreading on the Southeast Indian Ridge changed the tectonic setting of the Kerguelen plume from ridge-centered (or nearby), around 40 Ma, to intraplate [*Munschy et al.*, 1992]. Of all the Cenozoic Kerguelen samples, an "extreme" in Pb isotopic compositions is present in the 24–25 Ma mildly alkalic basalts from Mont Crozier [*Mattielli et al.*, 2002; *Weis et al.*, 2002b]. The age of Mont Crozier samples also coincides with a change in depth of melting (alkali index increases) and style of magmatism (flood basalts to plugs and dikes) between the older, >26 Ma tholeiitic to transitional, and the younger, $\leq$10 Ma, highly alkalic groups on the archipelago [*Damasceno et al.*, 2002; J. S. Scoates et al., manuscript in preparation, 2003]. The Mont Crozier basalts, in addition to having relatively high $^{206}Pb/^{204}Pb$ ($\sim$18.6), are characterized by Sr, Nd and Hf isotopic compositions intermediate to those found in the >26 Ma group and the $\leq$10 Ma group [*Weis et al.*, 2002b; *Mattielli et al.*, 2002]. We discuss the other two groups from the Cenozoic period beginning with this apparent source composition, represented by the 24–25 Ma Mont Crozier basalts.

5.2.1. Tholeiitic to Transitional >26 Ma Basalts From the Kerguelen Plateau and Kerguelen Archipelago

[24] Site 1140 basalts from the NKP have Sr, Nd, Hf and Pb isotopic compositions previously reported to reflect binary mixing between the Kerguelen plume and the ambient depleted Indian MORB source [*Mattielli et al.*, 2000; *Weis and Frey*, 2002]. Most of the older Kerguelen Archipelago basalts have also been attributed to mixing between a depleted mantle component and the enriched Kerguelen plume source, with the depleted component variably represented by (1) normal Southeast Indian Ocean depleted upper mantle [e.g., *Storey et al.*, 1988; *Gautier et al.*, 1990; *Doucet et al.*, 2002], (2) assimilation of depleted gabbroic cumulates [*Yang et al.*, 1998] or (3) an intrinsic depleted component in the Kerguelen plume source [*Frey et al.*, 2002b]. Recently, *Fitton et al.* [2003] have discussed the depleted component in the Iceland volcanics, particularly whether this component is intrinsic to the plume or results from interaction with the surrounding North Atlantic MORB source mantle [*Hanan et al.*, 2000]. Using high-precision Hf-Nd isotopic analyses only, *Fitton et al.* [2003] were able to delineate separate fields for the normal Atlantic MORB and the samples from Iceland containing a depleted component, suggesting that the depleted component was not the same as the Atlantic MORB source. High-precision Hf-Nd isotopic data for the Indian MORB from *Chauvel and Blichert-Toft* [2001] do, however, overlap with our data for the most depleted samples from Kerguelen Site 1140 (Figure 6). This may suggest that the depleted component originates from the depleted, upper Indian Ocean mantle. An additional argument in favor of the depleted component originating from the ambient upper mantle, is that the depleted signature in Cenozoic Kerguelen basalts decreases over time (decreasing Nd isotopic composition and increasing Sr and Pb isotopic compositions) [e.g., *Storey et al.*, 1988; *Gautier et al.*, 1990; *Doucet et al.*, 2002]. Furthermore, unlike Iceland, which is situated on the ridge axis, the Kerguelen Archipelago has changed from ridge-centered to intraplate with increasing distance between the Kerguelen Archipelago and the Southeast Indian Ridge from $\sim$40 Ma to the present [*Munschy et al.*, 1992; *Royer and Sandwell*, 1989; *Coffin et al.*, 2002]. In summary, (1) the growing distance between the ridge and the archipelago correlates with the apparently decreasing amount of necessary depleted component and

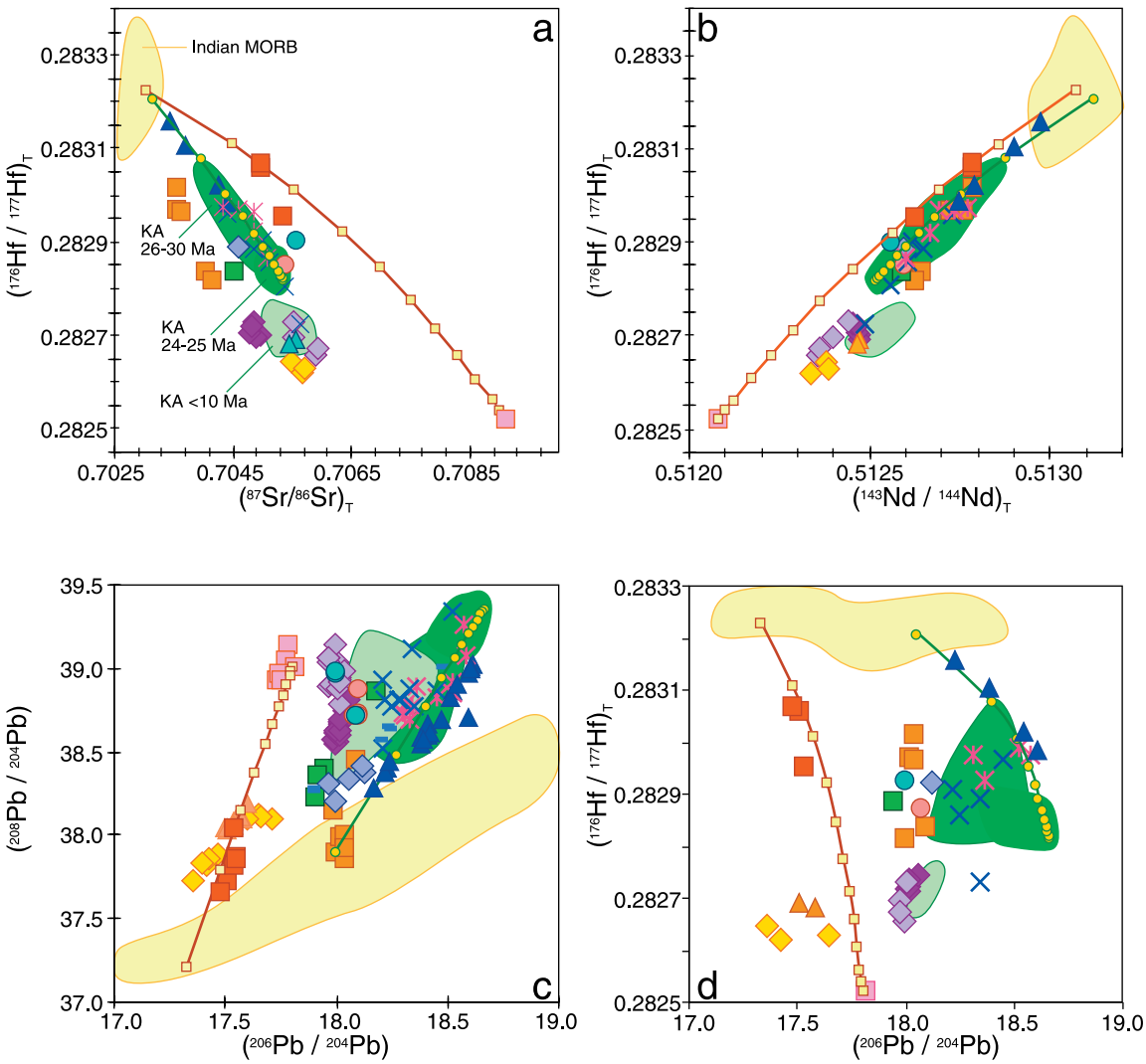


Figure 9. Mixing diagrams for SKP Site 750 and NKP Site 1140 in the isotopic systems of $(^{176}Hf/^{177}Hf)_T$ vs. $(^{87}Sr/^{86}Sr)_T$ (a), $(^{176}Hf/^{177}Hf)_T$ vs. $(^{143}Nd/^{144}Nd)_T$ (b), $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ (c) and $(^{176}Hf/^{177}Hf)_T$ vs. $^{206}Pb/^{204}Pb$ (d). Site 750 samples have unusual characteristics including very unradiogenic Pb isotopic compositions and radiogenic Hf, Sr and Nd isotopic compositions and generally do not fall near the field of other Kerguelen Plateau rocks [*Frey et al.*, 2002a; this study]. We calculate bulk mixing (red line, small yellow squares) between an unradiogenic depleted mantle component, chosen from within the Indian MORB field, and an upper crust-like component, here represented by the Site 738 basalts from the SKP, thought to be highly contaminated by continental material [*Mahoney et al.*, 1995]. Although the Site 738 sample could not be representative of the precise continental end-member involved in such a mix, and thus the proportions of each are not accurate, it should lie near the position of the crustal end-member. Site 1140 samples have been previously interpreted as representing bulk mixing between a MORB component from the southeast Indian Ridge and the Mont Crozier samples, which form an end-member in Pb and Hf isotopic compositions for the Kerguelen Archipelago rocks [*Mattielli et al.*, 2000; *Weis and Frey*, 2002]. In most isotopic systems, this mixing equation works rather well, with the possible exception of the $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ diagram where the Site 1140 samples lie somewhat below the projected mix (further discussion of this mixture may be found in [*Weis and Frey*, 2002]. It is important to note that, particularly in (c) and (d), the mixture between the Mont Crozier samples and the depleted component is insufficient to fully explain most of the archipelago data including the new reported Hf isotopic data in this study. For the young archipelago lavas (the <10 Ma group) this has been previously explained by either possible contamination by plateau material or a distinct heterogeneity in the Kerguelen plume [*Mattielli et al.*, 2002]. References are the same as given in Figures 6 and 7.

(2) high-precision Hf-Nd isotopic compositions for Indian Ocean MORB overlap with those from the most depleted Kerguelen basalts (i.e., Site 1140). Therefore the simplest explanation for the depleted component in the Kerguelen Archipelago lavas is that it is derived from local depleted MORB mantle, the same source as that available in generating the Southeast Indian Ridge MORB [*Mattielli et al.*, 2000; *Doucet et al.*, 2002; *Weis and Frey*, 2002].

[25] All of the sampled >26 Ma sections on the Kerguelen Archipelago have some basalts that reflect input from the depleted component in Hf isotopes [*Mattielli et al.*, 2002; this study], as has been also suggested from studies of the Sr-Nd-Pb isotopes [e.g., *Gautier et al.*, 1990; *Yang et al.*, 1998; *Doucet et al.*, 2002]. In these basalts, an additional, minor component is necessary to explain the full range of both Hf and Pb isotopic compositions (Figures 7 and 8). Binary mixing trends, between the Kerguelen plume and the depleted MORB mantle, account for the Site 1140 basalts but some of the basalts from the >26 Ma group on the archipelago fall in a field deflected toward the Kerguelen Plateau basalts that have $^{206}Pb/^{204}Pb \approx 18$. It is possible that magmas derived from variable proportions of Kerguelen plume tail and MORB mantle assimilated small amounts of the overlying Cretaceous Kerguelen Plateau lithosphere prior to eruption. This additional but minor plateau component more completely accounts for the range of isotopic compositions in the Kerguelen Archipelago basalts than binary mixing between plume tail and depleted components alone.

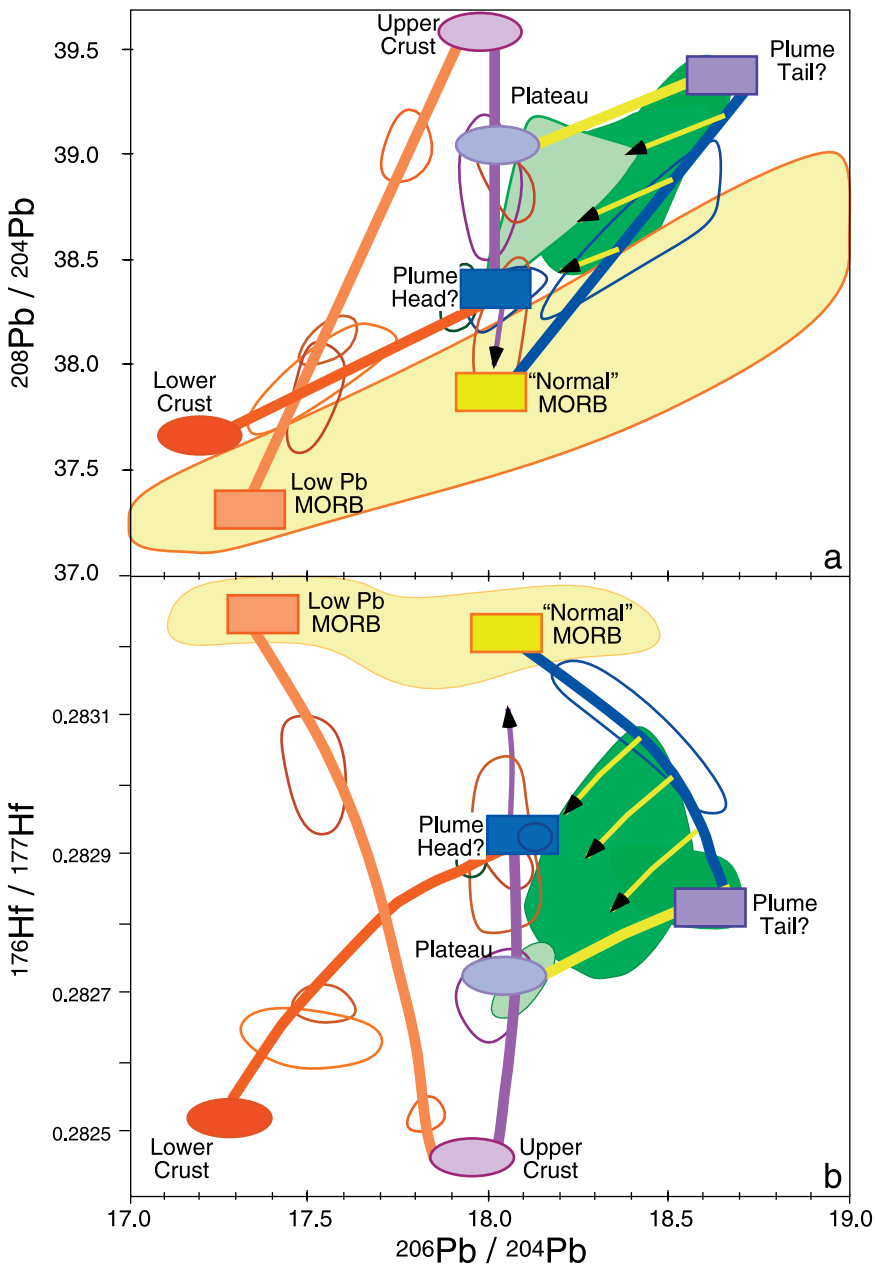
5.2.2. Mantle Sources and Contamination in Alkalic Lavas From the <10 Ma Part of the Kerguelen Archipelago

[26] As mentioned above, limited assimilation of Cretaceous Kerguelen Plateau lithosphere by plume (± depleted MORB) derived magmas accounts for much of the variation in isotopic data on the Kerguelen Archipelago. However, in the young (<10 Ma), evolved alkalic lavas from the Archipelago, the isotopic characteristics do not simply trend toward the plateau, but for many samples are almost indistinguishable from the plateau basalts, especially those from Site 1137 [*Weis et al.*, 1998; *Mattielli et al.*, 2002; this study]. Either the Kerguelen plume head source was available for the generation of these lavas or the plume tail magmas assimilated significant quantities of the overlying plateau lithosphere. Some of the <10 Ma archipelago lavas have slightly higher Sr and lower Nd isotopic compositions than either the Kerguelen plume head or plume tail compositions; all <10 Ma lavas have lower Hf isotopic values than those from either "head" or "tail" values. In Pb isotopic diagrams, these lavas trend between the Mont Crozier samples and values for the basalts from the plateau with the higher extents of continental crust contamination. Although we cannot rule out a distinct mantle source origin for the <10 Ma lavas, as suggested by *Mattielli et al.* [2002], the isotopic data are consistent with assimilation of the Cretaceous Kerguelen Plateau lithosphere by magmas derived from the plume tail source. It is probably also significant that the <10 Ma lavas are highly alkalic and fractionated, indicating that they come from small amounts of deep melting beneath the archipelago that have undergone extensive crystal fractionation; these conditions would facilitate assimilation of the thick, overlying plateau since the ascending magmas are (1) not voluminous and therefore more readily affected by smaller amounts of assimilate and (2) are in contact with the plateau's lithosphere for a longer time, both since the melting takes place at greater depths and because the magmas need time to extensively fractionate.

6. Summary of Mantle Sources and Contaminants Involved in the ~120 Ma History of the Kerguelen Hot Spot

[27] During Cretaceous time, two mantle sources were important in the generation of basalts recovered from the Kerguelen Plateau–Broken Ridge (Figure 10). The primary mantle source may have been the dominant component available in the Kerguelen plume head and is best represented by basalts from Site 1138, that have $^{206}Pb/^{204}Pb \approx 18$, primitive mantle-like Sr and Nd isotopic compositions and Hf isotopic compositions moderately

depleted compared to the primitive mantle (Figure 10) [*Neal et al.*, 2002; this study]. Basalts derived from this source whose magmas interacted with an upper crust contaminant can be recognized by their vertical trend in Pb-Pb isotope diagrams (Figure 7) and include those from Sites 749, 1136, 1137, 1141 and 1142. At Site 749, the basalts also record minor input from a normal-$^{206}Pb/^{204}Pb$ (of about 18) Indian MORB mantle source, needed to fully account for their isotopic characteristics (Figure 10) [*Frey et al.*, 2002a; *Ingle et al.*, 2002a; this study]. Some magmas derived from the Kerguelen plume head assimilated lower continental crust [*Frey et al.*, 2002a]; this lower crust must have had Sr, Nd and Hf isotopic compositions broadly consistent with the aforementioned upper crust contaminant but with very unradiogenic Pb isotopic values (Figure 10). Site 747 and 1139 basalts fall into this group. A secondary mantle source, in addition to the plume head source, is necessary to account for the remaining Cretaceous plateau basalts from Sites 738 and 750.We suggest that this



component had radiogenic Nd and Hf isotopic compositions, unradiogenic Pb isotopic values and is possibly represented by low-$^{206}Pb/^{204}Pb$ depleted Indian MORB (Figure 10). Magmas derived from this source assimilated upper continental crust, either to very small extents (Site 750) or to very large extents (Site 738).

[28] The post-Cretaceous Kerguelen Plateau and Kerguelen Archipelago samples also reflect two mantle sources, one potentially derived from the plume tail and the other from the normal, depleted Indian upper mantle, best represented by basalts from the Southeast Indian Ridge [e.g., *Storey et al.*, 1988; *Doucet et al.*, 2002; *Weis and Frey*, 2002]. The plume tail source, during the Cenozoic, is characterized by moderately radiogenic Pb isotopic compositions ($^{206}Pb/^{204}Pb \approx 18.6$), nearly primitive mantle-like Hf isotopic compositions and Sr and Nd isotopic values within the field defined by the older Kerguelen Archipelago basalts and is best represented by basalts from the Mont Crozier section on the archipelago (Figure 10) [*Mattielli et al.*, 2002; *Weis et al.*, 2002b]. Radiogenic ingrowth cannot account for the shift from the plume head to the plume tail isotopic composition. Minor extents of assimilation of the Cretaceous Kerguelen Plateau by magmas reflecting mixtures between the depleted MORB component and the Kerguelen plume component can explain the remaining isotopic variation in some of the older Kerguelen Archipelago basalts (Figure 10). More extensive assimilation of the Kerguelen Plateau lithosphere by plume-derived basalts is required to fully account for the younger than 10 Ma lavas on the archipelago (Figure 10).

7. Origin of the Mantle Sources in the Kerguelen Hot Spot

[29] The two Kerguelen plume sources can be described relative to each other by noting that the plume tail component has similar $\varepsilon_{Nd}(T)$, marginally lower $\varepsilon_{Hf}(T)$, higher $(^{87}Sr/^{86}Sr)_T$ and significantly more radiogenic Pb isotopic values than the plume head component. Both components fall between the fields associated with the enriched mantle end-members (EM I and EM II) [*Hart*, 1988], except that Site 1138 (plume head) basalts are slightly less radiogenic in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than either EM I or EM II. The most intriguing feature of both plume head and tail components is the low $\varepsilon_{Nd}(T)$ for a given $\varepsilon_{Hf}(T)$ [*Mattielli et al.*, 2002; this study] compared to the mantle array of *Vervoort and Blichert-Toft* [1999]. In fact, this is also a characteristic of Indian MORB [*Chauvel and Blichert-Toft*, 2001; *Kempton et al.*, 2002]. To generate the decoupling

Figure 10. (opposite) Schematic representation of the possible mantle components (squares) and contaminants (ovals) involved in the genesis of Kerguelen Plateau and Kerguelen Archipelago rocks as depicted in skeletal form in plots of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (a) and $(^{176}Hf/^{177}Hf)_T$ vs. $^{206}Pb/^{204}Pb$ (b). Primary bulk mixing trajectories are shown in the thick, vectorless lines whereas tertiary contamination trends are shown in the thinner lines with vectors. During Cretaceous time, the mantle sources available in generating the Kerguelen Plateau rocks include (1) the low $^{206}Pb/^{204}Pb$ depleted component (as discussed in the caption for the previous diagram) important in generating basalts at Sites 750 and 738 on the SKP, and (2) a "plume head" component with general geochemical characteristics consistent with those found in Site 1138 basalts from the CKP [*Neal et al.*, 2002] important for the genesis of Sites 747, 749 and 1136 (SKP), Site 1137 (Elan Bank), Site 1138 (CKP), Sites 1141 and 1142 (Broken Ridge) and Site 1139 (Skiff Bank). Also during Cretaceous times continental crust played a large role in generating the highly diverse isotopic compositions of the Kerguelen Plateau rocks. A minimum of two crustal contaminants may be accountable for the isotopic compositions in some Kerguelen Plateau basalts including lower crust, important at Site 747 (CKP) and Site 1139 (Skiff Bank) and upper crust, important for Sites 738, 749 and 750 (SKP), Site 1137 (Elan Bank) and Sites 1141 and 1142 (Broken Ridge). Minor contamination by a normal-type MORB may account for some "depleted" characteristics of Site 749 basalts. Cenozoic mantle sources include a "plume tail" component with general geochemical characteristics consistent with those found in the Mont Crozier basalts from the archipelago, and that is important for the generation of all post-Cretaceous lavas at Site 1140 (NKP) and on the archipelago. Large scale contamination of plume-tail-derived magmas with plateau-type material, as represented by the Site 1137 basalts (Elan Bank) can account for the isotopic characteristics of the Kerguelen Archipelago <10 Ma group. Smaller extents of contamination of mixtures between the normal-MORB and plume-tail sources with plateau-type lithosphere fully accounts for the total range of isotopic compositions in the Kerguelen Archipelago samples.

between ε_{Hf} and ε_{Nd} that results in samples plotting to the left of the mantle array requires an aged mantle source with a high Lu/Hf relative to Sm/Nd. Recycled continental sediments can be excluded on the basis that even small amounts of zircon in terrigenous sediments, incorporated in the mantle source, tends to move samples to below the mantle array in the Hf-Nd isotopic diagram [e.g., *Eisele et al.*, 2002]. Two possibilities exist that might carry a high Lu/Hf ("high" (ε_{Hf})T) relative to Sm/Nd ("normal" (ε_{Nd})T): recycled pelagic sediment plus oceanic crust [e.g., *Patchett et al.*, 1984; *Chauvel and Blichert-Toft*, 2001] or delaminated subcontinental mantle lithosphere (SCML) [*Schmidberger et al.*, 2002]. A third possibility has been discussed by *Kempton et al.* [2002] to account for a high time-integrated Lu/Hf in Indian Ocean MORB. They propose an upper mantle wedge that has been subjected to several depletion events during ancient subduction-generated melting events. Although this model may be appropriate for the upper Indian Ocean mantle, it probably cannot account for the enriched geochemical signatures associated with the Kerguelen hot spot, the volcanic products of which are presumably generated primarily from melting within a mantle plume and do not always reflect mixing with the ambient, depleted upper mantle. Therefore, of the crust + pelagic sediment or delaminated SCML model, which is more appropriate for the Kerguelen plume sources?

[30] It is difficult to fully evaluate the geochemical composition of "typical" SCML because it cannot be directly sampled and its composition is therefore determined by studying mantle xenoliths. Nevertheless, some general characteristics may characterize the SCML in terms of its isotopic compositions. Recent studies on xenoliths from the SCML document high ε_{Hf}(T) relative to ε_{Nd}(T) [*Schmidberger et al.*, 2002; *Simon et al.*, 2002; *Ionov and Weis*, 2002]. Pb isotopic values, although variable, are distinct from modern-day oceanic basalts and Sr and Nd isotopic compositions of SCML xenoliths are similar to present-day upper oceanic mantle [*Walker et al.*, 1989]. Isotopic compositions of Os are also variable but are generally unradiogenic [*Walker et al.*, 1989; *Pearson*, 1999]. The SCML is mostly comprised of highly depleted restite [e.g., *Pearson*, 1999; *Lee et al.*, 2001] and trace element contents in unmetasomatized xenoliths may be insufficient for SCML to be a major factor in contaminating any mantle source as large volumes would be required [*McDonough*, 1990]. Some isotopic characteristics of inferred SCML are consistent with those of the Kerguelen plume sources, specifically a high ε_{Hf} relative to ε_{Nd} but others are not, specifically low Os isotopic compositions are not characteristic of those associated with the Kerguelen plume tail (Mont Crozier), which has Os isotopic values overlapping with those of modern oceanic basalts [*Weis et al.*, 2000]. Therefore, unless metasomatism is ubiquitous in the SCML and unless large quantities of metsomatized SCML are involved, the SCML is not a good candidate for the origin of the Kerguelen plume mantle sources.

[31] The arguments for and against evidence favoring small additions of pelagic sediment to recycled oceanic crust as the cause of the distinctive isotopic signature of the Indian Ocean MORB have been discussed by *Rehkämper and Hofmann* [1997] and *Chauvel and Blichert-Toft* [2001] and so this potential source will be evaluated here, strictly as it applies to the Kerguelen plume. *Patchett et al.* [1984] and *Vervoort et al.* [1999] have described the fractionation of Hf from the REEs in pelagic sediments as arising from the lack of zircons in pelagic sediments. Pelagic sediments, injected back into the mantle along with oceanic crust, should be characterized by low U/Pb, leading to low-$^{206}Pb/^{204}Pb$ signatures over time [e.g., *Weaver*, 1991] and, as stated above, show decoupled Nd and Hf isotopes resulting in a low $^{143}Nd/^{144}Nd$ relative to a given $^{176}Hf/^{177}Hf$ [*Patchett et al.*, 1984]. Recycled oceanic crust alone should normally result in HIMU-like isotopic compositions as the crust contains high U/Pb and subchondritic Nd resulting, over the long term, in high $^{206}Pb/^{204}Pb$ [*Hofmann and White*, 1982] and $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ below the "juvenile rock array" [*Salters and White*, 1998]. Thus the Pb and Hf isotopic compositions of the Kerguelen plume

strongly support a source that is a mixture of recycled oceanic crust and pelagic sediments. The ^{235}U and Th contents in this recycled crust must have been somewhat elevated above those considered by *Rehkämper and Hofmann* [1997], because the Kerguelen mantle sources have ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb relative to ^{206}Pb/^{204}Pb that are well above the Indian Ocean MORB values. A possible way to account for this would be to invoke old oceanic crust characterized by higher ^{235}U and Th concentrations, perhaps significantly older than 1.5 Ga and more fractionated than the crust proposed by *Rehkämper and Hofmann* [1997] in order to account for the present-day isotopic compositions. The Sr, Nd and Hf isotopic compositions of this oceanic crust end-member could still be broadly consistent with those chosen by *Rehkämper and Hofmann* [1997] with Lu/Hf and ^{176}Hf/^{177}Hf of the oceanic crust represented by juvenile ~1.8 Ga basalts from *Vervoort and Blichert-Toft et al.* [1999]. The ratio of the pelagic sediment to oceanic crust mixture would necessarily be different during the Cretaceous and Cenozoic, with the proportion of pelagic sediment required reduced in the Cenozoic, in order to account for the more radiogenic Pb isotopic compositions. Melting extents would have been higher during the plume head stage (with sediments melting more readily than the crustal component) relative to the plume tail stage, and this could account for the decreased proportion of sediment signature in the plume tail-derived lavas.

8. Conclusions

[32] We present high-precision Hf isotopes for basalts from all stages of construction of the Kerguelen LIP. Integration of these data with other radiogenic isotopic systems results in several new conclusions regarding the geochemical origins of this large igneous province. During Cretaceous time, the primary mantle source for the Kerguelen Plateau–Broken Ridge basalts had primitive mantle-like Sr, Nd and Pb isotopic compositions but moderately depleted Hf isotopic compositions. This source, probably located in the head of the Kerguelen plume, produced voluminous magmas that interacted with stranded fragments of continental crust (both upper and lower) at shallow-levels beneath the Indian Ocean. An additional, minor mantle component with unradiogenic Pb isotopic compositions, similar to some Indian MORB today, is the source of basalts at two sites on the SKP. These magmas also assimilated upper continental crust. The origin of this mantle component (in the ambient upper mantle, or entrained from a depleted, mid-mantle boundary) cannot be determined at this time. In the post-Cretaceous evolution of the Kerguelen plume, the magmas derived from the plume tail source, having higher Sr and Pb, lower Nd and similar Hf isotopic compositions to the plume head source, mixed readily with depleted ambient Indian MORB mantle. These magmas erupted either with or without assimilation of the overlying, thick Cretaceous Kerguelen Plateau lithosphere. The extreme of this interaction is present in the youngest lavas from the Kerguelen Archipelago, which reflect extensive contamination by plateau lithosphere. The geochemical characteristics of the Kerguelen plume head and plume tail compositions may be accounted for by ancient, recycled oceanic crust that had high ^{235}U and Th contents mixed with ancient recycled pelagic sediments. The proportions of each must change from larger amounts of pelagic sediments in the plume head during the Cretaceous, compared to the plume tail during the Cenozoic.

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