

15. MINERALOGY AND GEOCHEMISTRY OF A BASALT FROM SITE 738: IMPLICATIONS FOR THE TECTONIC HISTORY OF THE SOUTHERNMOST PART OF THE KERGUELEN PLATEAU¹

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ABSTRACT

The Lower Cretaceous tholeiitic basalt cored at Site 738, on the southernmost part of the Kerguelen Plateau, shows anomalous Sr, Nd, and Pb isotopic compositions compared to other lavas from Kerguelen Island and the Kerguelen Plateau. The strongly negative value of ϵ_{Nd} (-8.5) and high $^{207}\text{Pb}/^{204}\text{Pb}$ ratio (15.71) reflect a long-term evolution in a source high in Nd/Sm and μ . These geochemical properties, not observed in the Indian Ocean mantle plumes (St. Paul, Kerguelen Islands), have been reported for alkali lavas erupted in East Antarctica, thus suggesting that they originate from the Gondwana subcontinental lithosphere.

INTRODUCTION

Ocean Drilling Program (ODP) Leg 119 cored the basaltic basement of the southern part of the Kerguelen Plateau at Site 738 ($62^{\circ}42'S$, $82^{\circ}47'E$; Fig. 1). A pre-Turonian age has been deduced from the overlying limestones (Barron et al., 1988). This makes these lavas contemporaneous with other Cretaceous lavas recovered by dredging along the $77^{\circ}E$ Graben (MD48) during the *Marion Dufresne* 1986 cruise (Bassias et al., 1987) and from ODP Leg 120 drilling in the vicinity of the Ragatt Basin at Sites 747, 749, and 750 (Fig. 1; Schlich et al., 1988). The basalts recovered record the first stages of continental extension between India and Antarctica-Australia and were erupted not long after the breakup of Gondwana, which occurred at 130 Ma on the basis of the M10-M11 magnetic anomalies reported by Powell et al. (1988). This site was therefore of special interest for characterizing the chemical and isotopic compositions of the early melts associated with the upwelling mantle plume responsible for the thick volcanic and igneous pile that forms the Kerguelen Plateau.

A total of 27.2 m of basaltic material was recovered from Hole 738C, between 486 and 534 m below seafloor (mbsf) (Shipboard Scientific Party, 1989). Four zones of top-flow breccias separating massive basaltic units were recovered. All of the units are pervasively altered. A rapid emplacement of the flows is suggested by the absence of interbedded sediments, whereas the abundance of large vesicles, reddened top-flow breccias, and lack of pillows indicate that these lavas were erupted in sub-aerial conditions. Sample 119-738C-36R-1, 140–144 cm, a massive gray-green basalt with few calcite veins from the base of the hole, was selected for geochemical analyses on the basis of its relatively unaltered character.

ANALYTICAL TECHNIQUES

The mineral analyses reported in Table 1 were performed on a Camebax electron probe at the Université de Nancy I. Whole-rock chemical analyses, reported in Table 2, were determined by atomic absorption, colorimetry and flame spectroscopy (major elements, Ba, Cu, Ni, and Cr), X-ray fluorescence (XRF) (Zr, Nb, Y, and V), and isotope dilution (Rb, Sr, and the rare earth elements [REE]). Sr, Nd, and Pb isotopic compositions were

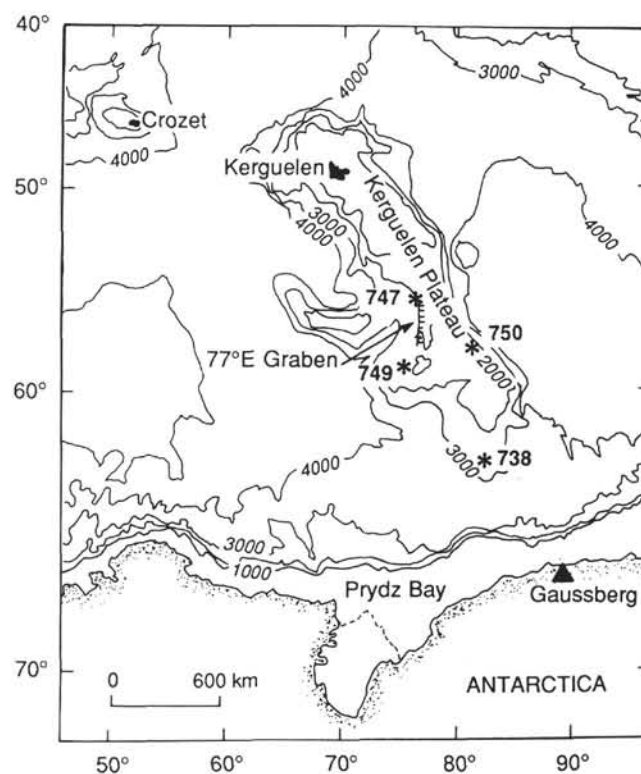


Figure 1. Simplified location map of the Kerguelen Plateau and eastern Antarctica showing the sites cored during Legs 119 and 120, the $77^{\circ}E$ Graben (ticked line), and Gaussberg volcano (triangle). Isobaths are in meters; Mercator map projection; scale bar is correct for $55^{\circ}S$.

measured on a Cameca 206 mass spectrometer following previously described methods (Alibert et al., 1986). The visible vesicle-filling clay minerals were removed by hand-picking before the sample was crushed. The rock powder was leached in 2.5 N HCl prior to dissolution for isotopic analysis. A biostratigraphic age of 90 Ma, deduced from the overlying limestones, was used to calculate initial isotopic ratios (Table 3).

MINERALOGY

The basalt from the selected unit is an aphyric quartz-tholeiite. Rare plagioclase microphenocrysts (An_{61-65}) are scattered in a fine-grained matrix of plagioclase (An_{55-62}), clinopyroxene

¹ Barron, J., Larsen, B., et al., 1991. *Proc. ODP, Sci. Results*, 119: College Station, TX (Ocean Drilling Program).

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Table 1. Representative analyses of plagioclase, clay minerals (vesicles), clinopyroxene, and Fe-Ti oxides in basalt Sample 119-738C-36R-1, 140–144 cm.

Plagioclase			Clay mineral vesicle			Clinopyroxene		Titanomagnetite	
Crystal type	Ground-mass	Micro-pheno-cryst	Center	Rim	Center	Ground-mass	Ground-mass	Crystal type	Groundmass
SiO ₂	52.85	52.68	53.26	48.33	56.82	50.7	51.5	TiO ₂	20.86
TiO ₂	—	—	—	—	—	1.11	0.79	Al ₂ O ₃	1.35
Al ₂ O ₃	29.73	29.39	2.44	4.63	3.95	2.41	2	^a FeO	68.62
^a FeO	0.76	0.8	16.88	14.49	21.33	12.14	11.22	MnO	2.3
MnO	—	—	—	—	—	0.29	0.25	MgO	0.83
MgO	0.16	0.11	7.44	17.08	4.74	15.62	15.29	Cr ₂ O ₃	0.23
CaO	12.19	13.2	0.21	0.89	0.61	17.17	18.44	Σ	94.19
Na ₂ O	4.03	3.8	0.16	0.16	0.04	0.21	0.26		
K ₂ O	0.24	0.18	8.41	0.52	6.32	—	—		
Σ	100.01	100.19	88.79	86.09	98.89	99.65	99.77	Recalculated	
								Fe ₂ O ₃	25.00
								FeO	46.11
Cations on the basis of 32 oxygens			Cations on the basis of 22 oxygens			Cations on the basis of 6 oxygens		Cations on the basis of 4 oxygens	
Si	9.595	9.572	Si	7.873	7.393	7.858	Si	1.906	1.93
Al	6.362	6.295	Al ^{IV}	0.127	0.607	0.142	Al ^{IV}	0.094	0.07
Fe	0.114	0.121	Al ^{VI}	0.299	0.228	0.501	Al ^{VI}	0.012	0.016
Ca	2.372	2.57	Fe ²⁺	—	1.854	2.463	Ti	0.031	0.022
Na	1.418	1.339	Fe ³⁺	2.085	—	—	Mg	0.875	0.854
K	0.056	0.042	Mg	1.639	3.887	0.976	Fe ²⁺	0.382	0.351
			Ca	0.033	0.146	0.09	Mn	0.009	0.008
An	61.7	65	K	1.586	0.048	1.115	Ca	0.692	0.74
Ab	36.9	33.9	Na	0.046	0.101	—	Na	0.015	0.019
Cr	1.4	1.1							
			Σ octahedral cations	4.02	5.97	3.94	Mg#	70	71
							Mg	44.9	43.9
							Fe	19.6	18.1
							Ca	35.5	38

^a Fe total as FeO.

(Wo_{33–40}, En_{42–46}, Fe_{18–21}), and Fe-Ti oxides (Table 1). Some devitrified glass is also present but is altered to clay minerals. The general texture is intergranular to intersertal (Fig. 2A).

The chemistry of the groundmass clinopyroxene shows low contents of Ti and Ca + Na consistent with a tholeiitic affinity for this lava (Letierrier et al., 1982). The clay minerals lining small vesicles (Fig. 2B and Table 1) consist mainly of celadonite (radiating green needles in the center and brown rim) and smectites (center and rim).

MAJOR AND TRACE ELEMENT CHEMISTRY

The chemical analysis and CIPW norm reported in Table 2 confirm a tholeiitic affinity and indicate a relatively fractionated character for this basalt: Mg number (100 Mg/Mg + Fe*) = 51 and low Cr (91 ppm) and Ni (26 ppm) contents.

Minor and trace elements—in particular, K, Rb, Ba, Sr, and the light REE—are enriched compared with mid-ocean ridge basalts (MORBs) (Fig. 3A). Clay minerals, observed both in vesicles and the groundmass, can partly account for the high K, Rb, and Ba contents, but based on the low REE content measured in a clay separate (Table 2), this secondary mineral, which is probably authigenic, can have only a minor effect on the whole-rock REE distribution. The light-REE enrichment of the basalt is therefore probably a primary feature. Similar REE patterns are observed in the transitional-type MORB defined in the Southwest Indian Ridge by Le Roex et al. (1983).

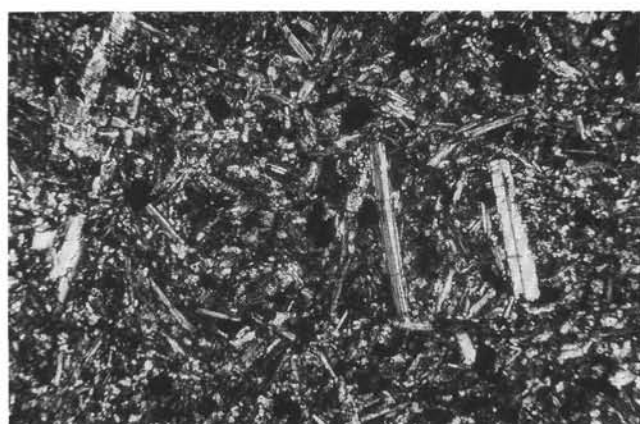
Compared to the transitional and alkali basalts from Kerguelen Island and the South Kerguelen Plateau (Gautier, 1987; Sevigny et al., 1989), the present sample is less enriched in light REE, relative to chondrites, with (Ce/Yb)_N = 3.2 as compared with 4.8–19 for Kerguelen Island. Only the transitional tholei-

ites from MD 48 (Davies et al., 1990) and from Site 750 (Sevigny et al., 1989) show a similar mild enrichment of light REE.

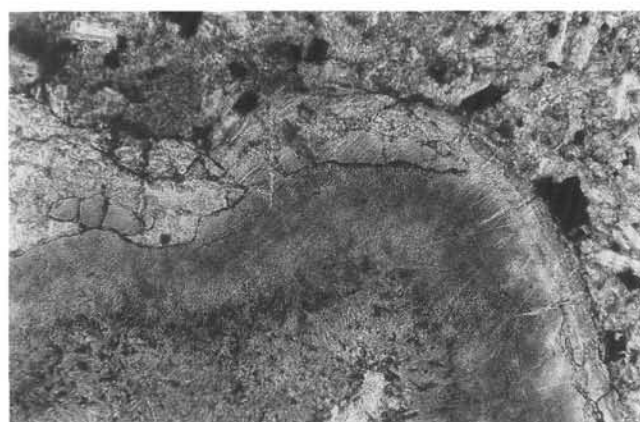
The present sample differs from typical transitional MORB by having a higher Zr/Nb ratio (17) correlated with a low Nb content relative to the light REE (Fig. 3A). The La/Nb ratio (1.6) is higher than in oceanic basalts—for example, from the Southwest Indian Ridge (La/Nb = 0.89 ± 0.2, excluding samples with ~2 ppm Nb, which is close to the detection limit for XRF; Le Roex et al., 1983) or from the Kerguelen Plateau—with the exception of the Cretaceous transitional tholeiites (La/Nb = 1.1–1.8; Davies et al., 1990). Conversely, a similar negative Nb spike has been reported for continental margin tholeiites (Fig. 3B)—for example, from the Faeroe Islands (Gariépy et al., 1983) or from Brazil (Fodor and Vener, 1984)—and for ultrapotassic rocks such as the Gaussberg leucitites (Fig. 3A, after Sheraton and Cundari, 1980). This anomaly, resulting from a preferential enrichment of the light REE/high field strength elements, is generally held as a crustal signature (Hofmann et al., 1986).

ISOTOPE DATA

The Sr, Nd, and Pb isotopic compositions of the sample depart from those of the recent (younger than 40 Ma) volcanic rocks of the Kerguelen and Heard islands (Dosso and Murthy, 1980; Hofmann and White, 1982; Barling et al., 1988; Storey et al., 1988; Gautier et al., 1989), as well as from those measured in Cretaceous samples dredged from between 50° and 59°S on the Kerguelen Plateau (Weis, 1987; Weis et al., 1988; Sevigny et al., 1989). With ⁸⁷Sr/⁸⁶Sr and εNd values of 0.7090 and –8.5, respectively (Fig. 4), the Site 738 basalt sample has the most enriched isotopic composition measured to date in oceanic areas,



A 200 μm



B 200 μm

Figure 2. Sample 119-738C-36R-1, 140–144 cm. **A.** The aphyric basalt has scattered plagioclase microphenocrysts and Fe-Ti oxides set in an intersertal to intergranular matrix of plagioclase-clinopyroxene and minor devitrified and altered glass. **B.** Millimeter-sized vesicles are filled by alternating celadonite and smectite-type clay minerals.

with the exception of some arc lavas from Martinique (Davidson, 1986). Pb isotope data (Fig. 5) show high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios in comparison with data reported for the Indian Ocean ridges and Kerguelen area. Age correction with plausible μ ($^{238}\text{U}/^{204}\text{Pb}$) values in the range of 10–20 corrected the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios by only 0.3 and 0.01, respectively. The position of Sample 119-738C-36R-1, 140–144 cm, to the left of the geochron in a $^{206}\text{Pb}/^{207}\text{Pb}$ isotope plot is rather unusual and indicates a multistage evolution of the mantle source of this lava, including an early high μ value.

DISCUSSION

The distinctive isotopic compositions obtained for Sample 119-738C-36R-1, 140–144 cm, are more extreme than those previously measured in aseismic ridges in general. They do not match any of the oceanic island-type mantle components (“plume” components) previously identified in the Indian Ocean. Conversely, the similarity of the isotope data, and also the incompatible element characteristics, such as a negative spike of Nb and a positive spike of Zr, between this tholeiitic basalt and the Holocene leucitites from Gaussberg, Antarctica (67°S, 89°E,

Table 2. Major (wt%) and trace element (ppm) analyses of basalt Sample 119-738C-36R-1, 140–144 cm, and REE content of vesicle-filling clay minerals.

	Basalt	Clays
SiO ₂	50.18	
TiO ₂	1.58	
Al ₂ O ₃	15.11	
Fe ₂ O ₃	5.00	
FeO	5.41	
MnO	0.19	
MgO	5.75	
CaO	9.24	
Na ₂ O	2.98	
K ₂ O	0.57	
P ₂ O ₅ ⁺	0.18	
H ₂ O ⁺	1.05	
H ₂ O ⁻	2.06	
CO ₂	0.32	
Total	99.62	
Ni	26	
Cr	91	
V	346	
Cu	51	
Ba	296	
Rb	7.08	
Sr	296	
La	14.7	
Ce	31.7	2.45
Nd	17.6	1.24
Sm	4.66	0.33
Eu	1.70	0.106
Gd	5.30	0.43
Dy	5.20	0.60
Er	2.88	0.45
Yb	2.52	0.47
Y	26	
Zr	153	
Nb	9	
CIPW norm		
Q	5.19	
Or	3.37	
Ab	25.2	
An	26.2	
Ne	—	
Di	14.7	
Hy	10.8	
Ol	—	
Mt	7.27	
Ilm	3.01	
Ap	0.42	

Fig. 1; Sheraton and Cundari, 1980; Collerson and McCulloch, 1983; after Nelson et al., 1986) is striking (Figs. 3–5). Although no tholeiitic basalt contemporaneous with the Kerguelen volcanic rocks has been observed in East Antarctica (R. Tingey, pers. comm., 1989), alkali lavas described from the Prince Charles Mountains area consist of alnoite sills, 110 Ma in age (Walker and Mond, 1971), and Eocene leucite tristanites (Sheraton, 1983). The Nd and Pb isotopic compositions of the latter rocks ($\epsilon\text{Nd} = -9$, $^{206}\text{Pb}/^{204}\text{Pb} = 17.749$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.729$; after Nelson, 1987) are very close to those of the Site 738 basalt. The restriction of these compositions to mafic volcanics erupted near the continental margin of East Antarctica suggests that the old subcontinental lithosphere is probably the source of both types of lavas. As a consequence, the nature of the underlying crust, in this part of the Kerguelen Plateau, could be transitional to continental crust (stretched continental crust?) or, possibly, some splinter of continental crust could still be present following the breakup of Gondwana.

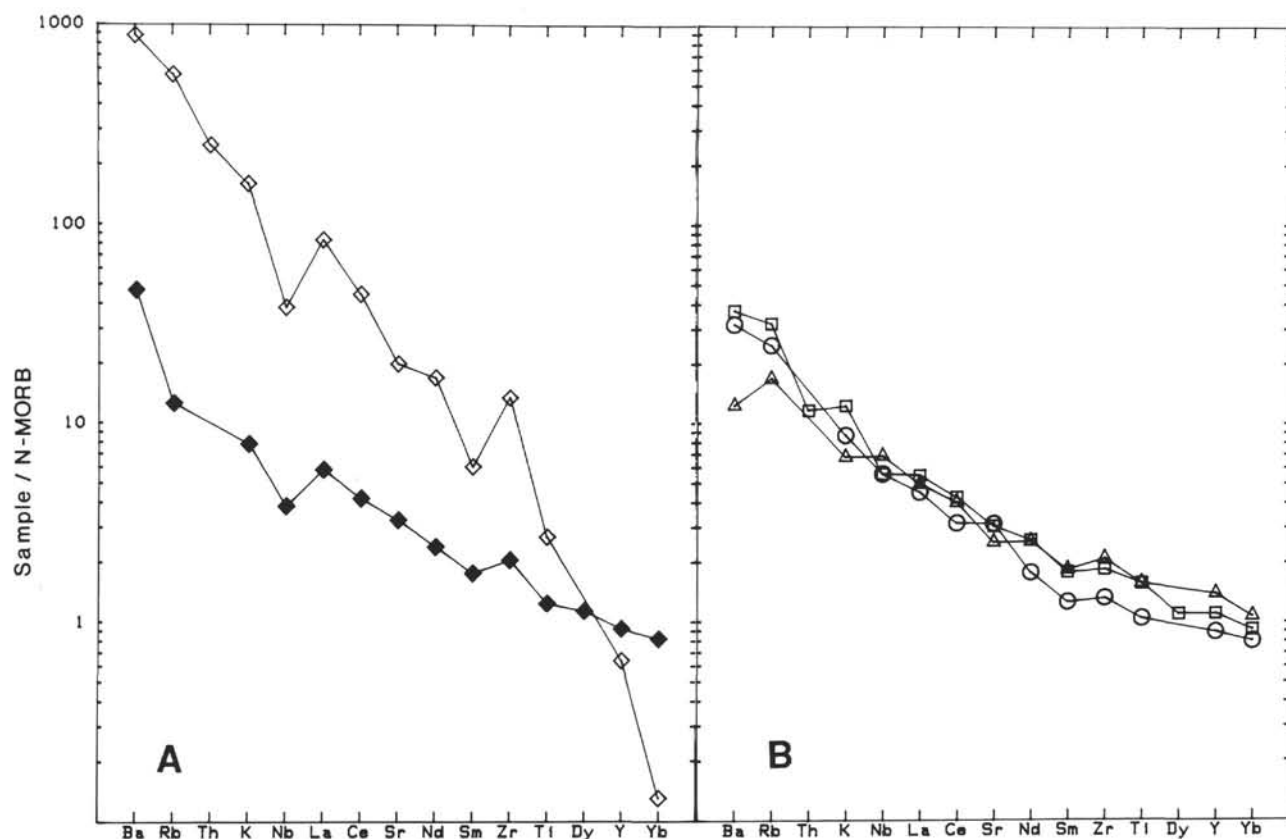


Figure 3. N-type MORB-normalized trace element distributions for basalt Sample 119-738C-36R-1, 140–144 cm (solid diamonds), compared with (A) Gaussberg leucitite (open diamond; Sheraton and Cundari, 1980) and (B) tholeiitic basalts from the Southwest Indian Ridge (triangle; 65–10 from Le Roex et al., 1983), Walvis Ridge (circle; 74–528 from Humphris and Thompson, 1983), and the Brazil margin (square; SPS-4A from Fodor and Vetter, 1984). Normalization values, from Sun and McDonough (1989), are as follows (ppm): Ba, 6.3; Rb, 0.56; Th, 0.12; K, 600; Nb, 2.33; La, 2.5; Ce, 7.5; Sr, 90; Nd, 7.3; Sm, 2.63; Zr, 74; Ti, 7600; Dy, 4.55; Y, 28; Yb, 3.05.

In the latter case, the possibility of some crustal contamination is difficult to assess. However, the previous comparison with the leucitites, which are unlikely to show any contamination effect because of their very high Nd and Pb contents, suggests that the unradiogenic Nd and high $^{207}\text{Pb}/^{204}\text{Pb}$ ratios measured in both rock types are characteristic of their mantle sources. A second implication of this comparison is that the degree of partial melting, expected to be much smaller for leucitites than for tholeiites on the basis of the Ce/Yb or Th/Yb ratios, had little influence on the isotopic composition of the melts ("seamount effect").

It remains unclear whether the continental margin, through which the tholeiites from Site 738 were erupted, was close to the Naturaliste Plateau (Western Australia) or to the continental extension area between Antarctica and Australia or even farther south along the present-day East Antarctica coast. A preliminary isotopic study of the Bunbury basalts, erupted at about 120–135 Ma in southwestern Australia, by N. McNaughton (pers. comm., 1989) shows that they are remarkably similar to the basalts from Site 738, which suggests that the enriched mantle component sampled by these lavas might be present in a large region of the Gondwana lithosphere.

The isotopic characteristics of this enriched mantle component are distinct from the end members previously identified in the Kerguelen "plume" (e.g., Weis et al., 1988) or in the Indian Ocean ridges in general. Only the recycled component of Michard et al. (1986), which is typical of the Dupal anomaly and reflects a long-term evolution in a source low in μ , Th/U, and

Sm/Nd and high in Rb/Sr, has some resemblance to the isotopic signature of the Site 738 basalt. However, the more negative ϵ_{Nd} and higher $^{207}\text{Pb}/^{206}\text{Pb}$ values found at Site 738 require the preservation, for a longer time, of chemical heterogeneities in a reservoir isolated from convection, probably in the subcontinental lithosphere.

This interpretation is consistent with the role generally attributed to the melting of the lithospheric mantle, triggered by a hot mantle plume, of producing continental margin tholeiites during the first stages of continental rifting.

In summary, the Site 738 basalt shows geochemical affinities with tholeiites from continental margins and is thought to have inherited its isotopic signature from the old lithospheric mantle underlying the East Antarctica and southwestern Australia continental margins, rather than from the Kerguelen hot spot.

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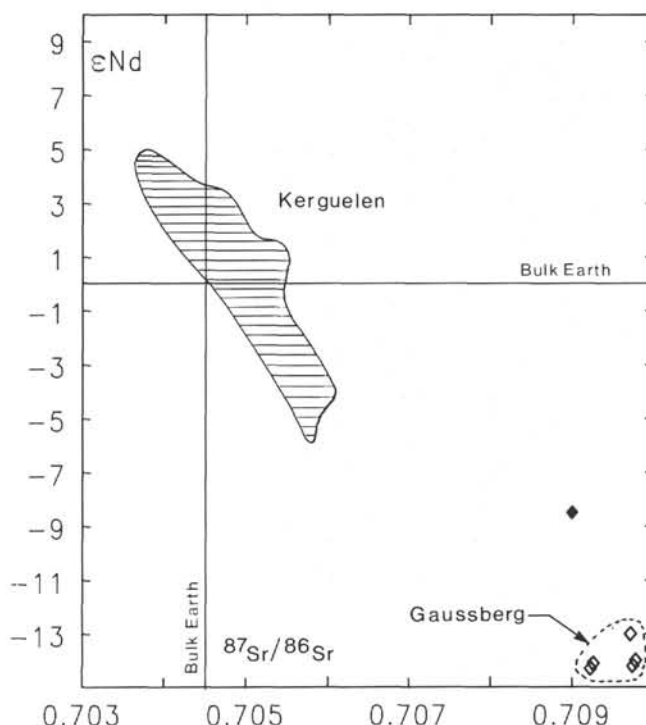


Figure 4. Sr and Nd isotopic compositions for basalt Sample 119-738C-36R-1, 140-144 cm, fall between those of the Kerguelen Island and Kerguelen Plateau basalts and the Gaussberg leucitites. See text for references.

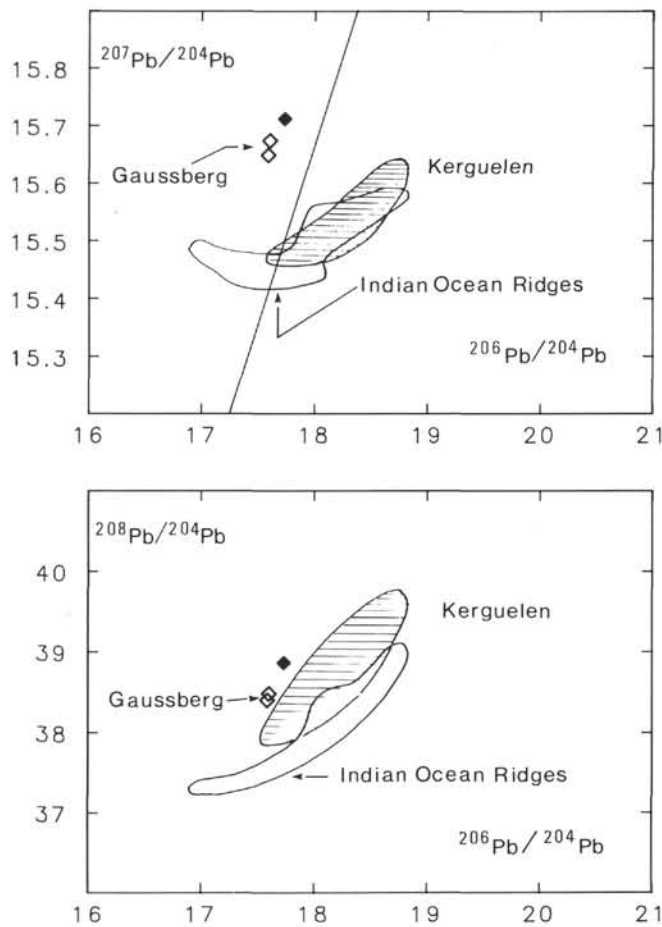


Figure 5. In Pb isotope systematics, basalt Sample 119-738C-36R-1, 140–144 cm (solid diamond), departs from those of both the Indian Ocean ridges and the Kerguelen area by high $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ relative to $^{206}\text{Pb}/^{204}\text{Pb}$. Such a composition is commonly reported for ultrapotassic rocks, including the Gaussberg leucitite (open diamond).

Table 3. Sr, Nd, and Pb isotopic composition of basalt Sample 119-738C-36R-1, 140–144 cm.

	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\epsilon\text{Sr}_{(90)}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon\text{Nd}_{(90)}$
Unleached	0.0695	0.709049 (34)	65			
Leached	0.0561	0.709017 (36)	65	0.184	0.512196 (27)	–8.5
		$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$		
Leached		17.735 (7)	15.712 (6)	38.86 (16)		

Note: Normalization values: $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Lead isotopic ratios were corrected for a mass fractionation of $0.5\text{‰} \pm 0.2\text{‰}$ per mass unit relative to NBS 981. (Error) = 2σ of the mean.