Hafnium Isotopic Constraints on the Source of Kerguelen Plateau Lavas (Leg 183 Sites 1140 and 1137)

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Introduction

The formation of Kerguelen Plateau and Archipelago basalts is attributed to partial melting of the long-lived (115 myr) Kerguelen mantle plume.
Kerguelen Plateau and Archipelago lavas show a very large range of isotopic compositions that reflect:
(1) a main origin from the Kerguelen Plume;
(2) some interaction with the depleted upper mantle, especially when close to a ridge;
(3) geochemical evidence for continental contamination for some Kerguelen Plateau lavas.
Detailed Hf isotopic characterization of Kerguelen lavas should provide a better understanding of the evolution of the Kerguelen Plume, the formation of the Kerguelen-Broken Ridge LIP, the spatial and temporal evolution of the role of continental contamination and the interaction between the plume and the depleted upper mantle.
We analyzed Hf isotopes in basement lavas for Sites 1140 and 1137 from ODP Leg 183 on the Kerguelen Plateau, as this isotopic system should provide additional constraints to model the evolution and interactions of the Kerguelen Plume.

Site 1140 lies ~270 km north of the Kerguelen Archipelago on the northernmost Kerguelen Plateau; Site 1140 lavas have been dated at 34 Ma (Pringle & Duncan, Spring AGU 2000) (Fig. 1).
Site 1137 lies on Elan Bank, a salient of the Kerguelen Plateau, extending westward from the boundary between the Central Kerguelen Plateau (CKP) and the Southern Kerguelen Plateau (SKP). Elan Bank formed at 108 Ma (Pringle & Duncan, Spring AGU 2000), i.e. contemporaneous to the rest of the plateau (CKP and SKP) (Fig. 1).
The two sites clearly are distinctive in location, age and lithology: most of the Site 1137 basement basaltic flows erupted in a subaerial environment. The interbedded volcaniclastic conglomerate containing clasts of trachyte, rhyolite, granitoids and garnet-biotite gneiss, in addition to many basalts, provides direct evidence for felsic crustal rocks in the upper lithosphere at this south Indian Ocean location. In contrast, the igneous basement from Site 1140 consists exclusively of submarine basaltic pillows and flows, separated by thin layers of sediments.

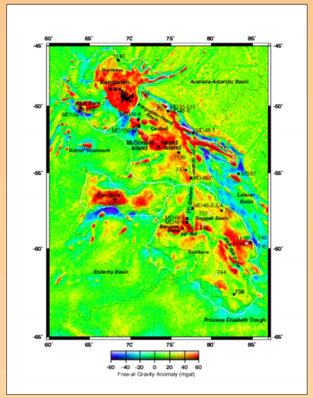

Figure 1

Site 1140

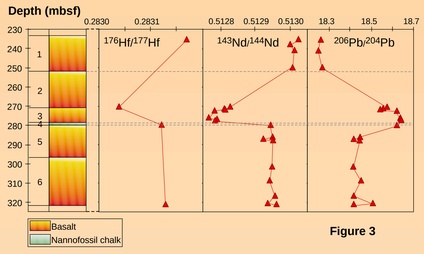

Figure 3

Site 1140

Site 1140 is the northernmost site on the Northern Kerguelen Plateau (NKP). This site is particularly interesting to compare the submarine NKP to its emerged part constituting the Kerguelen Archipelago.
Drilling at Site 1140 penetrated ~87 m of basement rocks, divided into 6 units: five units of tholeiitic basalt flows and one unit of dolomitized nannofossil chalk. We selected representative samples from four basement flow units: 1, 2, 5 and 6 (Fig. 3).

Site 1140 basalts have the most depleted isotopic signature ($^{176}Hf/^{177}Hf$ = 0.28304-0.28317; $^{143}Nd/^{144}Nd$ = 0.51283-0.51302; $^{87}Sr/^{86}Sr$ = 0.70428-0.70343) amongst all Kerguelen lavas. In isotopic diagrams, in particular ε_{Hf}versus ε_{Nd} and/or $^{87}Sr/^{86}Sr$ or Pb-Pb , all the data from Site 1140 are systematically distributed along a straight line (Fig. 4-5). Of all Kerguelen Plateau lavas, only Site 749, from the Southern Kerguelen Plateau, is comparable to Site 1140, having high Hf isotopic ratios and relatively low incompatible element ratios, such as Nb/Y, Zr/Y and Zr/Ti (Fig. 4, 6a).

Site 1140 basaltic flows form distinctive geochemical groups.
Units 2-3: Units 2 (and 3) stands out by lower ε_{Hf} and ε_{Nd} and higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ from the other Units 1, 5 and 6 (Fig. 4-5). This distinction is consistent with the enrichment in highly incompatible elements, such as P, Zr and Nb (by a factor of 2 to 5) for Units 2 and 3, relative to Units 1, 5 and 6 (Fig. 6a). Units 2 and 3 are the only basaltic flows from Site 1140 with Hf (0.28304), Nd (0.51277-0.51283), Sr (0.70447-0.70423) and Pb ($^{206}Pb/^{204}Pb$=18.493-18.592) isotopic compositions overlapping those of Kerguelen archipelago lavas that had interacted with a depleted component (Group-D, Yang et al., 1998) (Fig. 4-6).

Those archipelago lavas have higher MgO contents (6 – 13 wt%) relative to all other volcanic series on the archipelago that represent 80% of collected samples and show an MgO content ~5 wt%. Except for Site 749, the basalts at Site 1140 range to higher MgO (8.3 wt%) contents than basalts at other locations on the Kerguelen Plateau.
Units 1 and 5-6: Site 1140 lavas (Units 1, 5 and 6) show the highest Hf isotopic ratios that overlap the composition field of Indian Ridges. Pb isotopic data for those units are also overlapping the Indian Ridge field (Fig. 4-5); in detail, Unit 1 data are included in the Southeast Indian Ridge (SEIR) field in a plot $^{208}Pb^*/^{206}Pb^*$ versus $^{176}Hf/^{177}Hf$. Units 1, 5 and 6 have near chondritic Nb/Zr, Nb/Y and Zr/Y and they plot close to the SEIR field (Fig. 6a, b).

The linear Hf-Nd isotope correlation for Site 1140 lavas can be modelled in terms of mixing between the average Indian MORB (high Hf-Nd end-member) and the average composition of Mt Crozier lavas (Kerguelen Archipelago), taken as representative of the isotopic signature of the Kerguelen Plume source (low Hf-Nd endmember) (Fig. 4). The contribution of a depleted component is supported by all isotopic data of Site 1140 basalts that range from within the Indian Ridge field to the Kerguelen Archipelago field (Fig. 4-5). In a Nb/Y vs. Zr/Y designed by Fitton et al. (1997) to discriminate Iceland basalts from plume related to MOR related, Site 1140 basalts plot in three distinct fields: Unit 1 within the Indian Ridge data field, Units 5 & 6 at the limit between the ridge and plume fields and Units 2 & 3 within the Kerguelen Archipelago field (Fig. 6a). Trace element ratio variations are correlated with the isotopic variations (Fig.6b,c).
We conclude that each flow unit of basalts at Site 1140 results from a distinct proportion of mixing between the Kerguelen Plume and the SEIR depleted reservoir (from up to ~92% of the depleted component in Unit 1 to ~70% in Unit 2) (Fig. 4).

The parameter $^{208}Pb^*/^{206}Pb^*$ is the ratio of the radiogenic additions to the initial terrestrial lead, defined as ($^{208}Pb/^{204}Pb$)-29.476)/($^{206}Pb/^{204}Pb$)-9.307) (Hofmann, 1997).

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Kerguelen Plateau and Archipelago: General Features in Hf Isotopic Compositions

The Kerguelen Plume is the most isotopically enriched plume (i.e. low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$) on Earth. The Kerguelen basalts are therefore key oceanic lavas to study for delimiting the enriched Hf-Nd (Sr-Pb) endmember(s) of Oceanic Island Basalts (OIBs).

The Kerguelen Archipelago and Plateau lavas have an extremely wide range in $^{176}Hf/^{177}Hf$ that is mirrored by $^{143}Nd/^{144}Nd$ (Fig. 2). $^{176}Hf/^{177}Hf$ varies from 0.28267 to 0.28317, corresponding to 14 units of ε_{Hf} for the archipelago and 18 units for the plateau (the OIB field covers 21 units; Vervoort et al., 1999).

Hf-Nd isotopic data for all Kerguelen lavas (61 samples) fall along a general linear trend. The regression line (ε_{Hf}= 1.56 x ε_{Nd} + 2.58) has a slightly steeper slope than those of the mantle array (ε_{Hf} = 1.33 x ε_{Nd} + 3.19) and the terrestrial array (ε_{Hf}= 1.36 x ε_{Nd} + 2.95) (Vervoort et al., 1999). Individual oceanic island arrays (Salters & White, 1998; Blichert-Toft et al. 1999; Kempton et al., 2000) usually show a flatter slope (~1) (Hawaiian basalt data field yields a slope of 1.00±0.03 (with an intercept of +5.22±0.17); Samoa: 0.72 ; St. Helena: 0.71; Comores: 1.25), only those for Walvis Ridge, Pitcairn and Kerguelen have a slope > 1.5 (Fig. 2).

Hf-Nd data field for Site 1137 lavas lies on the non-radiogenic end ($^{176}Hf/^{177}Hf$ = 0.28274 – 0.28267) of the Kerguelen array and constitutes the unradiogenic endmember of the OIB array. In contrast, Site 1140 lavas have the most radiogenic isotopic compositions ($^{176}Hf/^{177}Hf$ = 0.28317 – 0.28304) of the Kerguelen array. Age corrections at 34 Ma and 108 Ma (Ar-Ar dates; Pringle & Duncan, Spring AGU 2000) for Sites 1140 and 1137 lavas, respectively, are relatively small (maximum 16 ppm) and do not modify the overall isotopic data distribution.
An important result of our Hf study is that basalts from each drilling site are geochemically distinct; such differences emphasize the compositional diversity of the huge Kerguelen Plateau and result from the interactions of the Kerguelen Plume with various components, continental crust for Site 1137 and depleted upper mantle for Site 1140.

All the initial ε_{Hf} were calculated with values of $(^{176}Hf/^{177}Hf)_{CHUR(0)}$ = 0.282772 and $(^{176}Lu/^{177}Hf)_{CHUR(0)}$ = 0.0332. For calculations of initial ε_{Nd}, we used $(^{143}Nd/^{144}Nd)_{CHUR(0)}$ = 0.512638 and $(^{147}Sm/^{144}Nd)_{CHUR(0)}$ = 0.1966. For 1140 and 1137 basalts, we used only $\varepsilon_{Nd(0)}$.

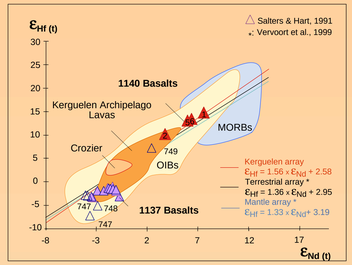

Figure 2

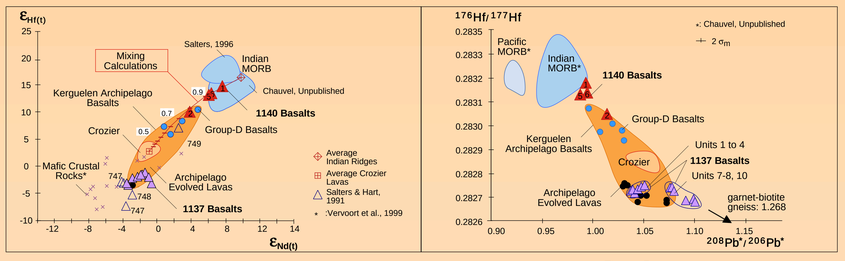

Figure 4

Figure 5

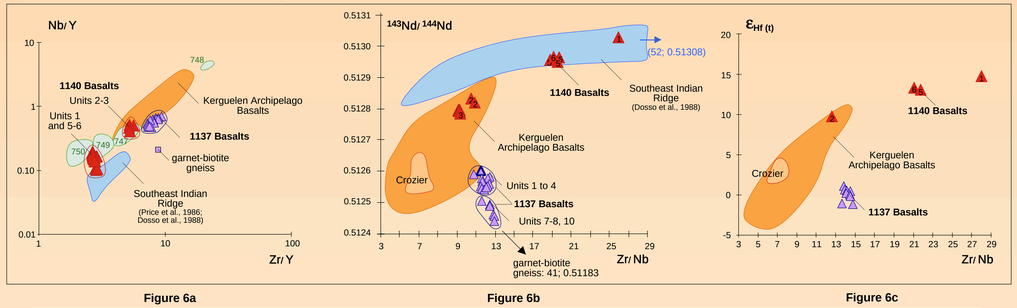

Figure 6a

Figure 6b

Figure 6c

Conclusions

●Kerguelen Plume origin
The genesis of the Kerguelen Plateau is attributed to partial melting of the Kerguelen Plume. However, Hf isotope systematics for Site 1140 and 1137 lavas emphasize the geochemical specificities of each drilling site and outline the additional role of interaction of the plume with various other components.

●NKP: Site 1140
Site 1140 basalts result from the interaction between the Kerguelen Plume and a depleted component in various proportions for each flow unit of that site from the NKP. Units 1, 5 and 6 of Site 1140 show isotopic compositions that overlap the Southeast Indian Ridge (SEIR) field. 1140 basalts erupted in late Eocene time, when the SEIR was <50 km away from the NKP (Royer & Coffin, 1992).
Units 2 and 3 of Site 1140 show similarities in isotopic compositions, trace element abundances and MgO contents with Group-D archipelago lavas that have also incorporated a depleted component. The archipelago lies on the Northern Kerguelen Plateau (NKP) about ~270 km south of Site 1140; the early stages of magmatism on the archipelago (maximum 40 Ma; Nicolaysen et al., 2000) are contemporaneous with the genesis of Site 1140 lavas.

●Elan Bank: Site 1137
Sr-Nd-Pb-Hf isotopic data of Site 1137 basalts require the Kerguelen Plume as the basaltic source with continental crust contamination decreasing with time. The lower units (7-8) in between the volcaniclastic conglomerate (unit 6) and the felsic tuff (unit 9) are the most contaminated.
The isotopic similarities between the upper units (1 to 4) from Site 1137 and the evolved archipelago lavas (< 10 Ma) suggest that the latter have interacted with the Kerguelen Plateau.

●Continental contamination
There is no compelling evidence for the presence of a continental component in more recent manifestations of the Kerguelen Plume activity, i.e. in the <39 Ma lavas forming the Kerguelen Archipelago, despite the fact that over 150 samples have been analyzed (Weis et al., 1998; unpublished). Similarly, there is no evidence of continental crust contamination in the northernmost site on the NKP (Site 1140). In contrast, 1137 basalts reflect shallow interaction of the plume-derived magmas with continental crust fragments associated with Gondwanaland break-up.

Site 1137

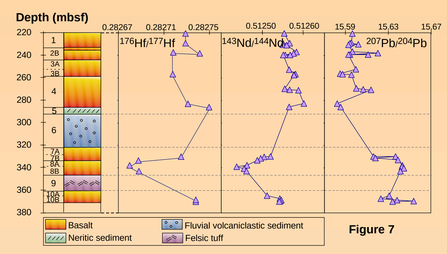

Figure 7

Site 1137

Elan Bank formed at 108 Ma (Pringle & Duncan, Spring AGU 2000) within the embryonic Indian Ocean ~20 Ma after separation of Greater India from Australia-Antarctica (Royer & Coffin, 1992). Elan Bank is contemporaneous to most of the SKP.

The drillcore penetrated the basement complex for a total thickness of 151.7 meters. The basement was composed of seven tholeiitic basalt flow units (90 meters) with three interbedded volcaniclastic sedimentary rock units. The fluvial conglomerate (Unit 6) and the felsic tuff (Unit 9) containing e.g. clasts of granitoids and garnet-biotite gneiss together with basalts, provide the first direct evidence for the presence of continental crust material within the Kerguelen Plateau.
Representative samples from all the basaltic flow units (1 to 4, 7, 8 and 10) of Site 1137 were selected for Hf analyzes (Fig. 7).

Site 1137 lavas display the lowest $^{176}Hf/^{177}Hf$ (down to 0.28267) and $^{143}Nd/^{144}Nd$ (down to 0.51246) of the Kerguelen array (Fig. 4).
The isotopic compositions of 1137 lavas, especially in Units 1 to 4, overlap the Hf-Nd and Sr-Nd fields of the evolved Kerguelen Archipelago lavas (Weis et al., 1993, 1998). For Pb isotopic compositions, the comparisons are more subtle as Units 1 to 4 plot at the low $^{206}Pb/^{204}Pb$ end of the evolved Kerguelen Archipelago lavas while Units 7-8, 10 have distinctly higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (Fig. 5). The isotopic similarities between the upper units (1 to 4) of Site 1137 and the evolved archipelago lavas (< 10 Ma) suggest that the latter may have interacted with the plateau. This interpretation is consistent with the lower $^{206}Pb/^{204}Pb$ of units 1 to 4 relative to those of the archipelago flood basalts (30-24 Ma).
Units 7 and 8 basalts systematically have the most enriched isotopic signature (the highest $^{207}Pb/^{204}Pb$ (≤ 15.65), and the lowest $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ (down to 0.51244 and 0.28267)). In contrast, basalts from units 1 to 4 have the lowest $^{87}Sr/^{86}Sr$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ (down to 0.70496, 15.58 and 38.47), and the highest $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ (>0.51255 and 0.28271) of all Site 1137 lavas. Overall, the downhole variations describe a general decrease in Hf and Nd, and increase in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, for a "low" and nearly uniform, almost within error $^{206}Pb/^{204}Pb$ (Ingle et al., Spring AGU 2000).

Geochemical characteristics of Site 1137 basalts clearly reflect contamination by a continental component.
Hf-Nd and Hf-Pb isotopic trends defined by Site 1137 basalts point toward the composition of mafic continental crust (Vervoort et al., 1999) (Fig. 4). The low values in $^{176}Hf/^{177}Hf$ of 1137 basalts result from low $^{176}Lu/^{177}Hf$ (0.0062 – 0.0075); low Lu-Hf ratios are observed in upper continental crust ($^{176}Lu/^{177}Hf$ =0.0078, calculated from concentrations reported in Rudnick & Fountain, 1995). Relative to other Kerguelen Plateau basement lavas, Site 1137 basalts are more enriched in incompatible elements and depleted in Nb, with high $(La/Nb)_{PM}$ (1.4-1.8) and Zr/Ti, and low Nb/Ce, Nb/Zr (Fig. 6). These characteristics have been interpreted as indicative of continental crust contamination in other Kerguelen Plateau sites (Mahoney et al., 1995), together with high $^{207}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ coupled with low $^{143}Nd/^{144}Nd$, as observed in Site 1137 basalts. The overlapping in Sr-Nd-Pb isotopes for 1137 basalts with Rajmahal Group II lavas (Kent et al., 1997) that have interacted with continental crust , supports this interpretation (Ingle et al., Spring AGU 2000; Weis et al., submitted).
Downhole variations in incompatible element abundances are correlated with isotopic variations (e.g. inverse correlation between $^{87}Sr/^{86}Sr$ and Nb/Y). Overall downhole variations reflect an increase of a continental contamination with depth. Units 7 and 8 are the most contaminated; they are in contact with Units 6 and 9 (volcaniclastic conglomerate and felsic tuff, respectively) (Fig. 7).
Only one garnet-biotite gneiss sample has been analyzed yet (others in progress). This sample does not have the specific $^{206}Pb/^{204}Pb$ necessary to account for the trend observed in 1137 basalts. However, one could expect Proterozoic (Nicolaysen et al., submitted) upper continental crust to cover a range of $^{206}Pb/^{204}Pb$ that extend at least from the field of 738 (extreme Southern Kerguelen Plateau) to the most radiogenic pebble of 1137 (Weis et al., submitted). In diagrams $^{176}Hf/^{177}Hf$ or $^{143}Nd/^{144}Nd$ versus $^{208}Pb^*/^{206}Pb^*$, Units 7, 8 & 10 basalts show a systematic shift to higher $^{208}Pb^*/^{206}Pb^*$ relative to Units 1-4 and plot toward the value of the garnet-biotite gneiss (Fig. 5-6b).