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# Initiation of a plume-ridge interaction in the South Pacific recorded by high-precision Pb isotopes along Hollister Ridge

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[1] The southern Pacific Ocean offers the rare possibility to study a situation where a spreading ridge (the Pacific-Antarctic Ridge (PAR)) migrates toward a fixed hot spot (the Louisville hot spot) (Small, 1995). Hollister Ridge is a 450 km long linear structure whose position, between the PAR axis and the most recent edifices of the Louisville hot spot trail, led some authors to suggest that the ridge is genetically related to the hot spot (Small, 1995; Wessel and Kroenke, 1997). Mapping and sampling of the ridge in 1996 revealed, however, that the contribution of the Louisville plume material to its mantle source is minor and suggested that it might be the result of intraplate deformation (Géli et al., 1998; Vlastélic et al., 1998). We report new, highly precise Pb isotopic data from Hollister Ridge, which (1) confirm that the maximal contribution of the Louisville plume, in the centrally, volcanic active part of the ridge, probably does not exceed 20% (15 and 35% for lower and upper limits) and (2) reveal through time an increasing plume influence. The initiation of the Louisville plume involvement in the source of Hollister Ridge is estimated to have occurred between 1.04 and 0.77 Myr ago. It thus followed closely the most recent volcanic activity reported along the Louisville trail (1.11 Ma (Koppers et al., 2004)). This suggests that Hollister Ridge has recorded the dispersion of the Louisville plume as the spreading ridge approached the hot spot. Assuming that the Louisville hot spot is located near the youngest seamount dredged along the Louisville seamount chain, Hollister Ridge lies along the shortest path of pressure release connecting the hot spot to the spreading axis. This path involves, first, an abrupt upwelling across the Eltanin fault system and, subsequently, a more progressive migration toward the spreading axis. Because Hollister Ridge is older than 2.5 Ma, the structure might not be the consequence of the plume-ridge flow. Instead, Hollister Ridge most likely emplaced through a lithospheric crack (Géli et al., 1998), which, subsequently, may have captured the plume-ridge flow.

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## 1. Introduction

[2] Because spreading ridges migrate in a fixed hot spot reference frame, it is common for ridges to encounter plumes. The effects of plume-ridge interactions have been extensively studied over the last decades because they give insights into the dynamics of the mantle. It has been shown that

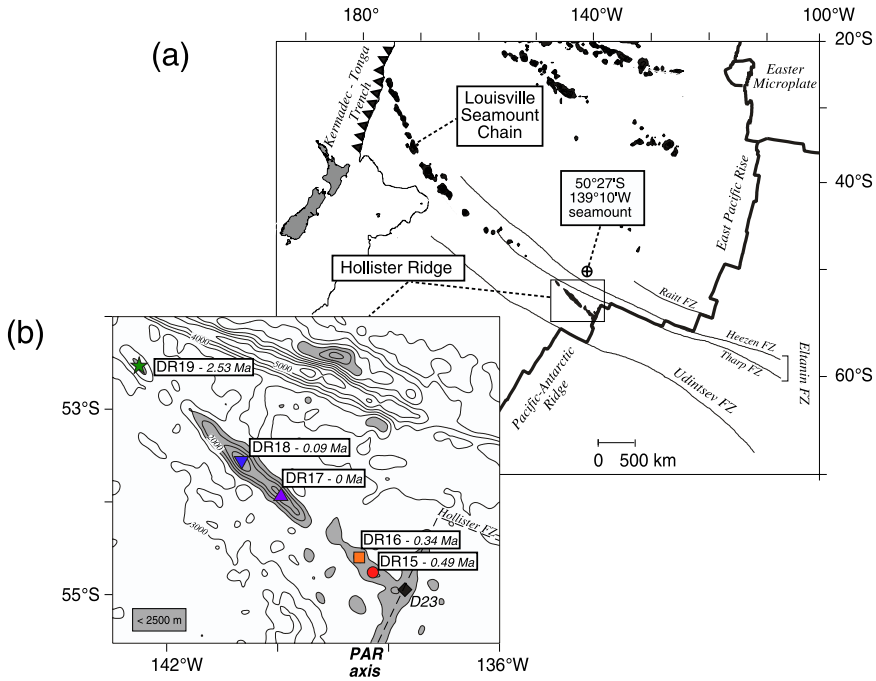


**Figure 1.** (a) Map showing the main structural features in the southern Pacific Ocean. The location of the youngest seamount (dated at 1.11 Ma by *Koppers et al.* [2004]) dredged along the Louisville Seamount Chain at 50°27′S–139°10′W is indicated. (b) Bathymetric map of the Hollister Ridge predicted from R/V *L'Atalante* multibeam data. Locations and ages [from *Vlastélic et al.*, 1998] of the five dredges collected during the PACANTARCIC cruise (1996) along the Hollister Ridge and dredge D23 from the PAR axis [*Castillo et al.*, 1998] are shown.

the effects of plume-ridge interactions depend on the position of the ridge relative to the plume. (1) When the ridge is over the plume, the excess of plume material is thought to flow along the spreading ridge axis, as in the Reykjanes Ridge case, south of Iceland [*Vogt*, 1971; *Schilling*, 1973]. (2) The most common situation is that of a ridge migrating away from a hot spot. In such a case, geophysical and geochemical data suggest that the ridge remains connected to the plume via subcrustal flow channels that drain plume material toward the ridge, which then acts as a sink [*Morgan*, 1978; *Schilling*, 1985; *Schilling et al.*, 1985]. Aseismic ridges or seamount chains linking the hot spot location to the spreading axis can be the surface expression of such a process. (3) The initiation of a plume-ridge interaction when a spreading ridge migrates toward a plume, is the most unusual case. It occurs between the Pacific-Antarctic Ridge and the Foundation hot spot. Despite the proximity between the hot spot and the ridge axis (35 km), the plume influence at the ridge axis is reported as being anomalously weak due to the rapid migration of the ridge toward the hot spot [*Maia et al.*, 2000].

[3] On the basis of satellite-derived marine gravity data, *Small* [1995] identified the Pacific-Antarctic Ridge–Louisville hot spot system as a key example of the initiation of a plume-ridge interaction. (1) The Pacific-Antarctic Ridge (PAR) is an intermediate spreading ridge, which is migrating very rapidly (52 mm/yr) toward the supposed location of the Louisville hot spot. A 15–20 km ridge jump in the direction of the hot spot occurred 3 to 4 Myr ago [*Small*, 1995]. (2) The Louisville Seamount Chain (LSC) extends for 4300 km in the Southern Pacific Ocean, from the Tonga Trench to the Eltanin Fault System (Figure 1). The chain shows a clear age progression since 70 Ma and a bend at 44 Ma [*Watts et al.*, 1988], which, together with morphological observations led *Lonsdale* [1988] to suggest that the LSC is the "South Pacific equivalent of the Hawaiian-Emperor Chain." But the volcanic activity declined drastically 20 Myr ago, which makes the Louisville hot spot difficult to locate [*Géli et al.*, 1998]. (3) Hollister Ridge is a 450 km long, 2.5 km high linear structure that extends from the PAR axis at 55°S toward the 10–12 Myr old volcanoes of the LSC. The oblique orientation of Hollister Ridge relative to the PAR but also to the current direction of Pacific plate motion, together with the supposed presence in the area of the Louisville hot spot led some authors to speculate on the origin of this structure. *Small*

[1995] proposed that Hollister Ridge is the surface expression of an asthenospheric flow from the Louisville hot spot to the PAR axis. On the basis of a new method for relocating hot spots, it has subsequently been proposed that the ridge could be the present-day location of the Louisville hot spot [*Wessel and Kroenke*, 1997]. Ridge sampling and mapping during the PACANTARCTIC cruise (1996) brought new constraints on the origin of the structure [*Géli et al.*, 1998; *Vlastélic et al.*, 1998]: (1) K-Ar ages suggest that the central part of the ridge is volcanically active. (2) Sr-Nd-Pb isotopes indicate that the Louisville plume material is not much present in the Hollister source (20% maximum), which makes it unlikely for the Louisville hot spot to be located somewhere along Hollister Ridge. (3) Geophysical observations suggest that Hollister Ridge results from intraplate deformation.

[4] Because Pb isotopes were the main argument to reject a major involvement of Louisville material in the Hollister source, we have reanalyzed Hollister Ridge samples for high-precision Pb isotopes with the new double spike technique in use in Brest [*Dosso et al.*, 2002]. These data help to better evaluate the involvement of the Louisville plume material in the Hollister Ridge source and its variation through time. It is shown that the Pb isotopic signatures of Hollister Ridge basalts have recorded the initiation of the interaction between the Louisville plume and the Pacific-Antarctic Ridge.

## 2. Sample Description and Analytical Technique

[5] The five dredges collected along the Hollister Ridge (Figure 1) brought tholeiites (DR15, DR16 and DR17), alkali basalts (DR16 and DR18) and a hawaiite (DR19). Sample description and preparation technique, as well as ages, major and trace element concentrations and Sr-Nd-Pb isotopic data were previously reported by *Vlastélic et al.* [1998]. Here we report high-precision U-Th-Pb concentration data and Pb isotopic compositions on the same powders.

[6] Concentrations were obtained by isotopic dilution. Optimal spiking for U and Th was achieved by using two mixed $^{230}$Th-, $^{235}$U- spikes with different concentrations and isotopic compositions. A single $^{206}$Pb- spike was used for Pb analysis. Spiked powders were dissolved in $HClO_4$-$HNO_3$-HF (1-1-4) and HBr-HF (1-4) mixtures for U-Th and Pb extraction, respectively. The Th-U fraction was extracted using the chemical procedure of *Condomines et al.* [1987]. Pb was purified following the procedure of *Manhès et al.* [1984]. Elements were loaded on rhenium filaments and isotopic ratios were measured in Brest with a Finnigan MAT 261 mass spectrometer (upgraded by Spectromat) using an ion counter to monitor beams of low-intensity. External errors for isotopic dilution data, are estimated from duplicate analyses (n = 6) to be less than 2% (2σ).

[7] For Pb isotope measurements, the powders were leached with 6N HCl for one hour at room temperature. Only sample DR16-2 consists in newly handpicked glass chips that were leached as powder. Because of their distinctive isotopic signatures, samples DR18-3 and DR19 were analyzed separately after a stronger leaching step (6N HCl at 180°C for one hour). Samples were dissolved in $HNO_3$-HF (1-4), and Pb was separated by anion exchange in HBr- $HNO_3$ mixed media, as described by *Lugmair and Galer* [1992]. During the study, the total procedural blank was <50 pg (n = 2) and thus negligible compared to the amount of extracted Pb (60–270 ng). Pb isotopes were measured on the same spectrometer as U-Th-Pb concentrations using a $^{207}$Pb-$^{204}$Pb spike (SBL74) to monitor mass fractionation [*Dosso et al.*, 2002; *Ishizuka et al.*, 2003; *Baker et al.*, 2004]. An aliquot of the sample was mixed with an optimal amount of SBL74 spike on a rhenium filament and run separately. Repeated analyses of NBS981 gave an average of 16.9432 ± 27, 15.5004 ± 29, 36.733 ± 9 (n = 115).

## 3. Results (Table 1)

[8] In agreement with conventional data, the new double spike Pb data indicate that the most radiogenic signatures are confined to the central, most recent edifice and to sample DR16-5. However, in contrast with the conventional data, most of the double spike data plot along a linear array in Pb isotope space (Figure 2). Only two samples (DR18-3 and DR19) plot significantly outside the array, an observation which is confirmed by duplicate analysis of these samples performed after hot leaching (see Table 1). A plot of the two data sets (high precision versus conventional) on the same diagram suggests that the difference essentially reflects the imperfect mass fractionation correction of conventional data. For sample DR16-2, the difference should be first ascribed to sample preparation mode (powder versus hand-picked glass).

**Table 1.** New Isotopic Compositions and Trace Element Concentrations of Hollister Ridge Basalts[a]

| Sample | Long., °W | Lat., °S | Depth, m | Age, ka | $^{206}Pb/^{204}Pb$ | $^{207}Pb/^{204}Pb$ | $^{208}Pb/^{204}Pb$ | $\kappa_{Pb}$ | U, ppm | Th, ppm | Pb, ppm | $^{4}He$, ccSTP/g | $^{3}He/^{4}He$, $R/R_A$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15-1g | 138.32 | 54.55 | 1645 | | 18.6079 | 15.5215 | 38.183 | 3.803 | | | | $2\ 10^{-7}$ | 7.5 ± 0.2 |
| 15-1 | | | | 487 | | | | | 0.0784 | 0.2408 | 0.4038 | | |
| 15-2g | | | | | 18.6149 | 15.5268 | 38.196 | 3.805 | | | | | |
| 15-2 | | | | | | | | | 0.0803 | 0.2473 | 0.3728 | | |
| 15-3 | | | | | 18.5889 | 15.5171 | 38.153 | 3.797 | 0.0599 | 0.1886 | 0.2999 | | |
| 16-2g-2 | 138.54 | 54.65 | 1964 | | 18.4169 | 15.4950 | 37.995 | 3.799 | | | | | |
| 16-2g-1 | | | | | | | | | 0.0338 | 0.1059 | 0.3462 | | |
| 16-3 | | | | 343 | 18.7153 | 15.5577 | 38.455 | 3.877 | 0.4717 | 1.6145 | 1.4028 | | |
| 16-5 | | | | | 18.8428 | 15.5734 | 38.597 | 3.885 | 0.7365 | 2.4112 | 1.8072 | | |
| 17-1 | 139.95 | 53.94 | 342 | | 18.8093 | 15.5598 | 38.516 | 3.864 | - | 0.4187 | 0.5666 | | |
| 17-1 dup | | | | | 18.8089 | 15.5601 | 38.515 | 3.864 | | | | | |
| 17-3 | | | | 0 | | | | | 0.1358 | 0.3924 | 0.5246 | | |
| 17-4 | | | | | 18.8180 | 15.5684 | 38.540 | 3.871 | | | | | |
| 18-1 | 140.65 | 53.58 | 165 | | 18.8107 | 15.5636 | 38.528 | 3.869 | 0.3392 | 1.1422 | 0.9907 | | |
| 18-2 | | | | 91 | 18.8055 | 15.5688 | 38.555 | 3.883 | 0.3378 | 1.1345 | 0.9209 | | |
| 18-3 | | | | | 18.6360 | 15.5540 | 38.484 | 3.922 | 0.0697 | 0.3443 | 0.4857 | | |
| 18-3 dup | | | | | | | | | 0.0692 | 0.3429 | - | | |
| 18-3 dup (*) | | | | | 18.6336 | 15.5499 | 38.477 | 3.920 | | | | | |
| 19 | 142.49 | 52.55 | 1958 | 2531 | 18.5471 | 15.5597 | 38.422 | 3.933 | 1.2865 | 4.8214 | 3.2903 | | |
| 19 dup | | | | | 18.5462 | 15.5590 | 38.421 | 3.933 | | | | | |
| 19 dup (*) | | | | | 18.5489 | 15.5567 | 38.421 | 3.932 | | | | | |

[a] New isotopic compositions are given for Pb and He, and trace element concentrations are given for U, Th, and Pb. Pb isotopic ratios were measured by TIMS in Brest. Mass fractionation was corrected by performing a second measurement on a sample aliquot to which a Pb double spike (SBL74) was added. Repeated analyses (n = 115) of the NBS981 standard using the same correction method yielded $^{206}Pb/^{204}Pb = 16.9432 \pm 27$ (2σ); $^{207}Pb/^{204}Pb = 15.5004 \pm 29$ (2σ); $^{208}Pb/^{204}Pb = 36.733 \pm 9$ (2σ). $\kappa_{Pb}$ represents the Th/U ratio integrated by $^{208}Pb/^{206}Pb$ since 4.55 Ga [*Allègre et al.*, 1986]. Pb isotopic compositions were measured in powders with the exception of sample 16-2g-2, for which glass chips were handpicked. All samples were leached (6N HCl −1 hour at room temperature) prior to dissolution. Stronger leaching (6N HCl −1 hour at 180°C) was applied to two samples (*). U,Th and Pb concentrations have been acquired by isotopic dilution. Age and Th data are from *Vlastélic et al.* [1998]. He data are from M. Moreira at IPGP/Paris (personal communication).

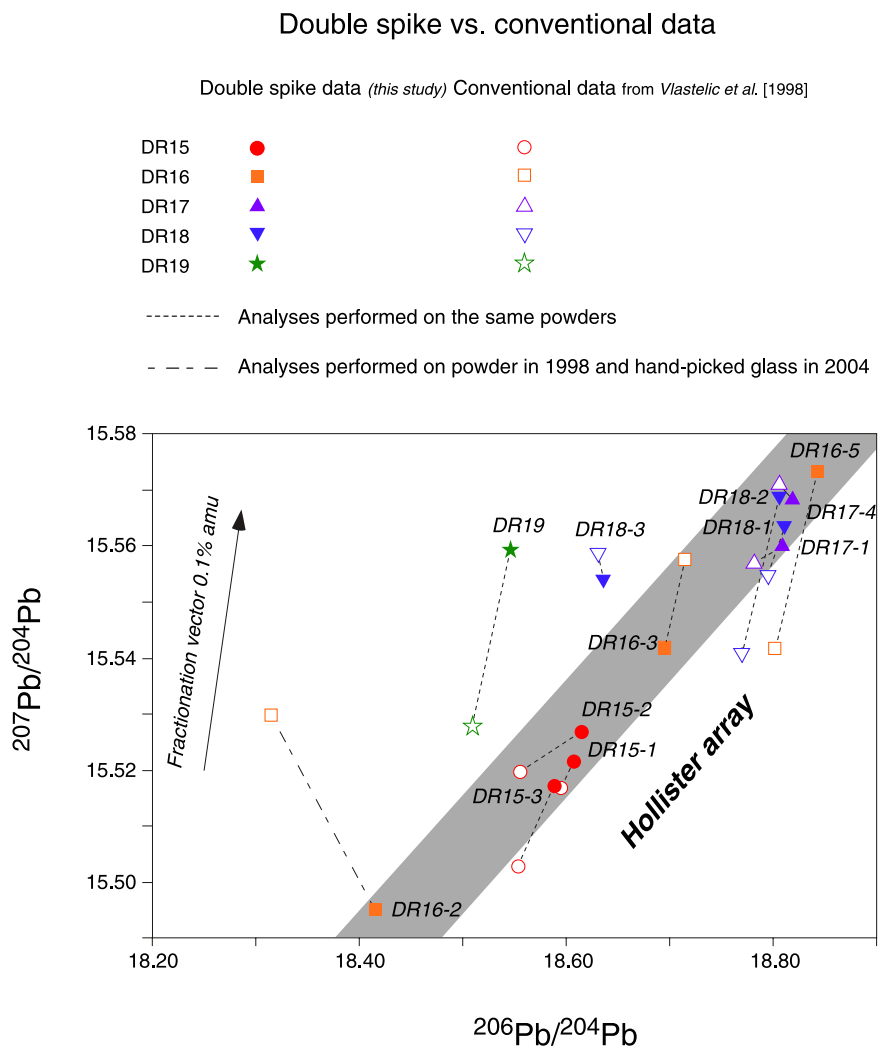


**Figure 2.** Comparison between double spike and conventional data. In order to show only the effect of precision, conventional data [from *Vlastélic et al.*, 1998] have been renormalized to the NBS981 values obtained with the SBL74 double spike (see Table 1) using a linear mass fractionation law: $R_{cor} = R_{conv}(1 + \varepsilon\delta m)$, where $R_{cor}$ and $R_{conv}$ are the corrected and conventional isotopic ratios, $\delta m$ is the mass difference between the two isotopes of the ratio, and $\varepsilon$ is the mass discrimination coefficient per mass unit. $\varepsilon$ is inferred from the same equation knowing the isotopic composition of the NBS981 each data set refers to. A mass fractionation vector of 0.1%/amu is shown. With the exceptions of samples DR18-3 and DR19, the new, highly precise data plot along a linear array (gray band).

Pb isotopes generally correlate with corresponding parent-daughter ratios (not shown). Samples plotting outside the correlations have also anomalously high Nb/U (80.8 for sample DR18-3) or low Nb/Th (11.1 for sample DR19), possibly reflecting U loss or Th gain during alteration of these samples. As for Mid-Ocean Ridge Basalts [*Galer and O'Nions*, 1985], Hollister samples have lower measured Th/U than time-integrated Th/U ($\kappa_{Pb}$ inferred from radiogenic $^{208}Pb/^{206}Pb$) (Table 1). The $^{3}He/^{4}He$ isotopic data obtained for sample DR15-1g (M. Moreira, IPG Paris) is also similar to MORB values.

[9] Only one sample per dredge has been previously dated [*Vlastélic et al.*, 1998]. Taking these sample ages as representative of the dredge ages, it appears that Pb isotopes become more radiogenic through time for dredges DR15 to DR18, whereas dredge DR19 clearly does not belong to this trend (Figure 3). Within dredge isotopic variations (DR16 and DR18) may indicate that the dredges sampled distinct lava flows having different ages.

[10] In Figure 4, the Pb double spike data from the Hollister Ridge are compared to the Pacific-Antarctic Ridge and the Louisville Seamount

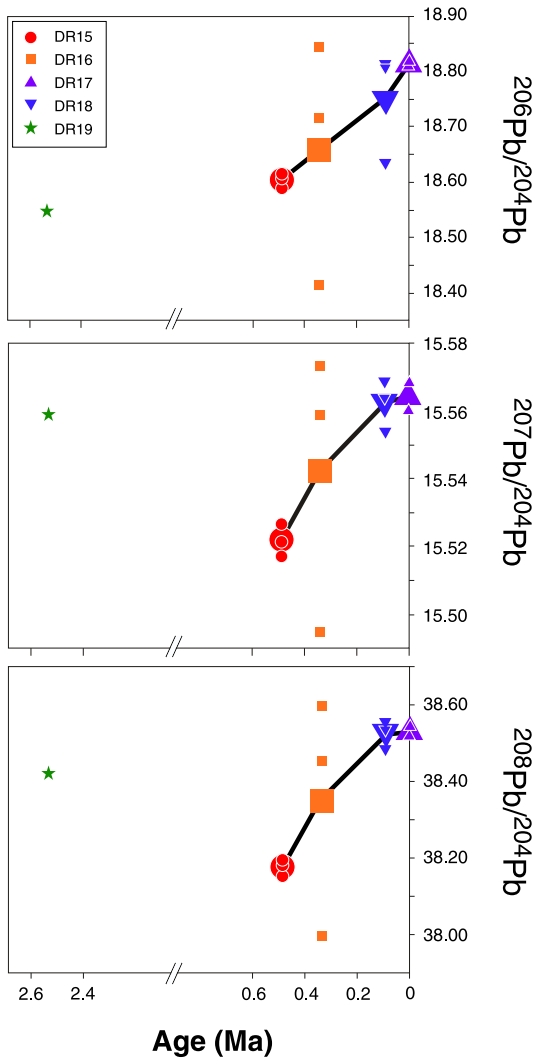


**Figure 3.** Pb isotope ratios plotted versus age. One sample per dredge was dated [*Vlastélic et al.*, 1998]. These ages are taken as representative of the dredges. Within dredge isotopic variation (DR16 and DR18) may reflect the sampling of distinct lava flows. The larger symbol represents the mean values of individual samples.

Chain conventional data. It can be seen that the Hollister array does not cross the Louisville field, which plots below the extension of the array. Additional observations can be made in the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ isotopic space (Figure 4b), where the variations of literature data are more clearly outside analytical error: (1) Most of Hollister data plot on the extension of the PAR array, as defined by normal-MORB from south of Udintsev fracture zone [*Vlastélic et al.*, 2000]. Exceptions are two samples from the distal part of the ridge (sample DR18-3 and DR19) that plot above the array, whereas the sample located at the intersection of the Hollister Ridge with the PAR axis (sample D23-3E from *Castillo et al.* [1998]) plots below the array. (2) The old (42–62 Ma) and young (1.1–35 Ma) seamounts from the LSC seem to define two distinct arrays. Samples DR18-3 and DR19 plot on the old LSC array, whereas the Hollister array is subparallel to the young LSC array.

## 4. Discussion

### 4.1. Three-Component Mixing Model

[11] Sr-Nd-Pb isotopes [*Vlastélic et al.*, 1998] as well as Pb-Pb relationships (this study) require the mixing of at least three distinct components in the Hollister Ridge magmatic source. Considering mixing between physical domains of the mantle that most likely contribute to the source of Hollister Ridge, two of these components are (1) the depleted mantle that feeds the nearby PAR and (2) the Louisville plume, both having well-defined, and relatively homogeneous isotopic signatures [*Cheng et al.*, 1987; *Vlastélic et al.*, 2000]. The third component involved in the mixing must be characterized by high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ [*Vlastélic et al.*, 1998], relatively low $^{206}Pb/^{204}Pb$ but high $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ (Figure 4), thus showing some resemblance to the mantle source of Indian plumes. Indeed such Indian mantle-type signatures have been identified along the nearby spreading system (within the Raitt transform and along the spreading segment bounded by Tharp and Hollister transforms) [*Castillo et al.*, 1998]. In our model, DR19 could be a sample of this third component of Indian mantle-type, and referred to as the "Hollister component." In the mixing model developed below, it is assumed that Louisville and Hollister components are equally enriched in Pb relative to the PAR component. As explained in the Figure 5 caption, the model does not require knowing the absolute concentration of Pb in the different mantle components, but only the enrichment factors of two components relative to the third. Enrichment factors of 2, 5 and 10 are considered for the lower limit, best estimate, and upper limit, respectively.

[12] The equations of the mixing model have been solved as explained in Appendix A, and the proportions of each component have been reported against the distance to the PAR axis (Figure 5a). The results agree well with previous quantification [*Vlastélic et al.*, 1998], showing (1) a decrease of

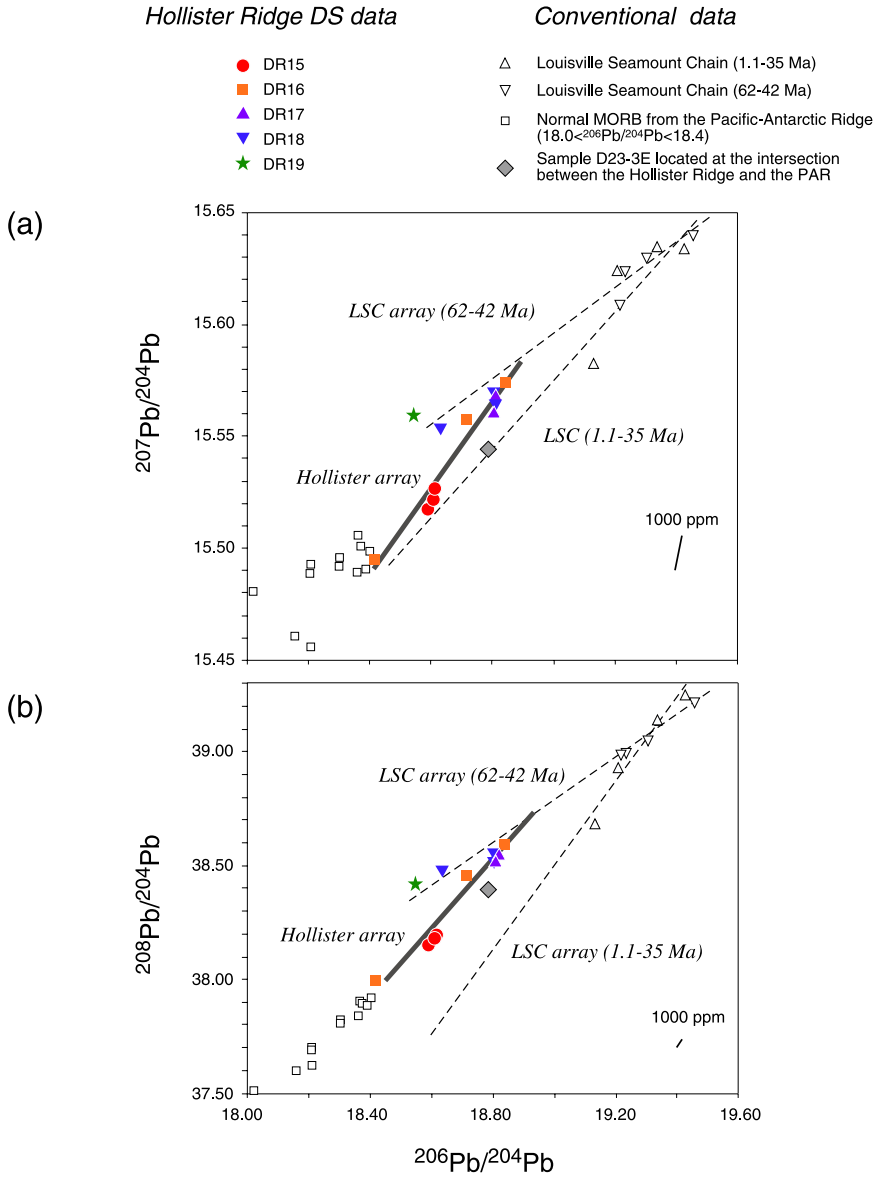


**Figure 4.** Comparison between the isotopic signature of Hollister Ridge and those of the Louisville Seamount Chain and the Pacific-Antarctic Ridge. Literature data [*Cheng et al.*, 1987; *Castillo et al.*, 1998; *Vlastélic et al.*, 2000] have been renormalized to the NBS981 values obtained with the SBL74 double spike (see Table 1), as explained in the Figure 2 caption. The error bars shown (1000 ppm) are the typical external error (2σ) of conventional data. Double spike data are about ten times more precise [*Dosso et al.*, 2002].

the PAR component together with an increase of the Hollister component with increasing distance to the PAR axis, and (2) a maximal contribution of the LSC component in the middle, shallowest and youngest part of the Hollister Ridge. The maximal contribution of the plume component is constrained to range between 15 and 35% with a most reasonable value of about 20%. Whereas the proportions of PAR and Hollister components do not show any simple relationship with sample age, the contribution of Louisville component clearly increased during the building history of the ridge (Figure 5b). This result is not model-dependent as it can be predicted from the evolution of Pb isotopes through time (Figure 3), Louisville plume having the most radiogenic Pb signature of the three components involved in the mixing. The extrapolation back in time of the linear trend of decreasing Louisville component with sample age yields an age ranging from 0.77 to 1.04 Ma (and a best estimate of 0.85 Ma) for the onset of Louisville plume input below the Hollister Ridge. Noteworthy, this age follows closely that of the most recent volcanic activity along the Louisville sea-

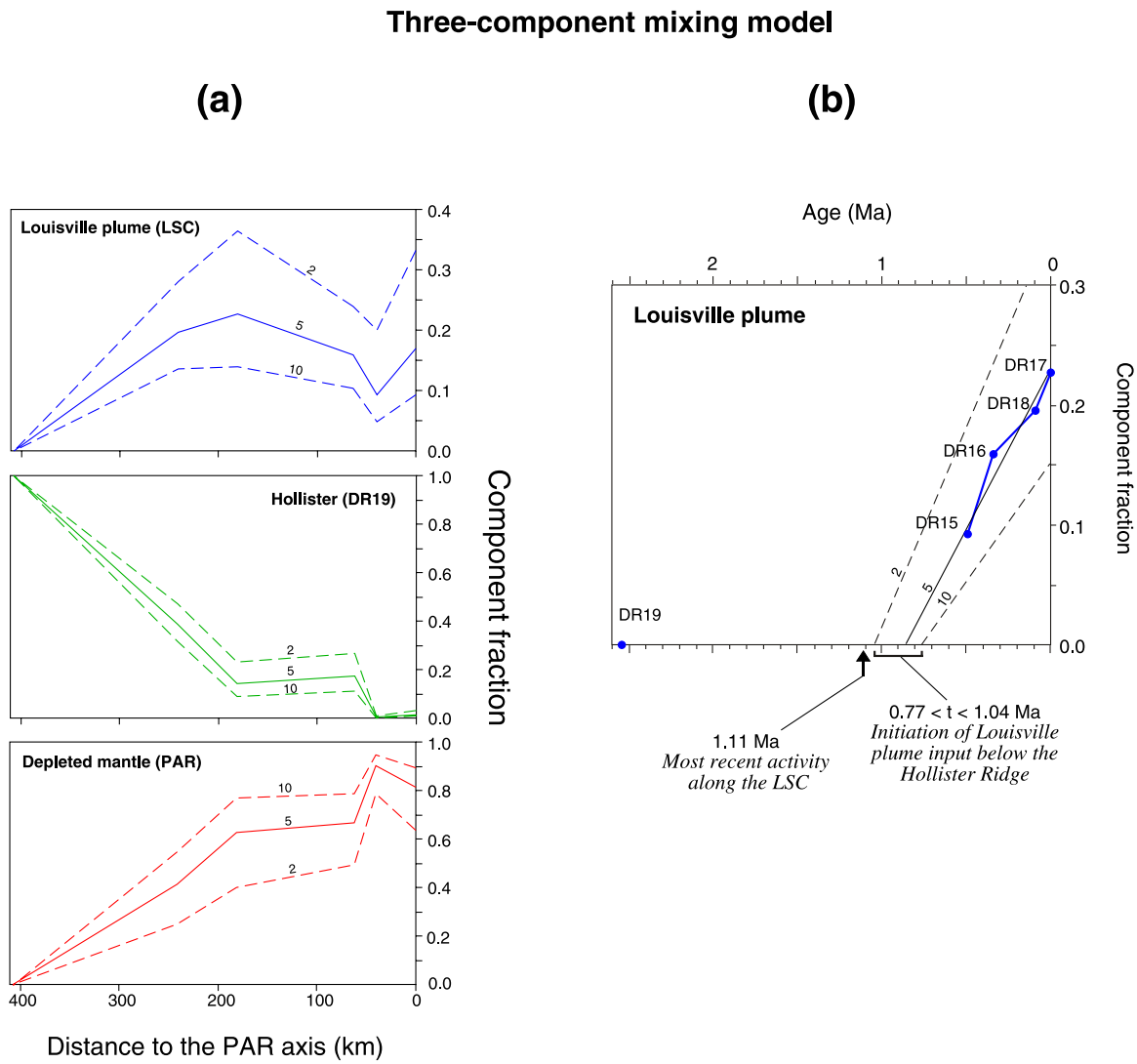


**Figure 5.** Three end-component mixing model. The three mantle components involved are (1) the Hollister component, the composition of which is best represented by sample DR19 (see Table 1); (2) the Louisville plume component, the composition of which ($^{206}Pb/^{204}Pb = 19.29$, $^{208}Pb/^{204}Pb = 39.032$) is taken from *Cheng et al.* [1987]; and (3) the PAR component, the isotopic composition of which ($^{206}Pb/^{204}Pb = 18.256$, $^{208}Pb/^{204}Pb = 37.737$) is that of unradiogenic MORB ($^{206}Pb/^{204}Pb < 18.40$) from south of the Udintsev fracture zone [*Vlastélic et al.*, 2000]. The model does not require knowing the absolute concentration of Pb in the different mantle components. Only the relative Pb enrichment has to be considered. The two "enriched" components (Louisville and Hollister) are assumed to have the same Pb concentration. These sources are enriched relative to the depleted mantle by a factor that is not known precisely. Factors of 2, 5, and 10 (numbers indicated on the lines) are considered for the lower limit, best estimate, and upper limit, respectively. (a) Component fractions plotted against the distance to the PAR axis. (b) Louisville plume fraction plotted against the age of the lavas. For clarity, data points are shown only for an enrichment factor of 5. However, regression lines are shown for the different enrichment factors and used to estimate the age of the initiation of Louisville plume contribution to the Hollister Ridge source. (a, b) Averaged values are used for each dredge location.

mount chain (1.11 Ma according to *Koppers et al.* [2004]).

## 4.2. Two-Stage Mixing Process

[13] The identification of binary mixing trends in the frame of a three-component mixing (often called pseudo-binary mixing arrays) has strong bearing on how mixing processes occur in the mantle [*Douglass and Schilling*, 2000]. According to Figure 4b, the Hollister array results from mixing unradiogenic material similar to that feeding the PAR south of Udintsev fracture zone with a radiogenic component that is not pure but results

from mixing between Louisville and Hollister components. A single stage mixing of the three components is possible but is however highly unlikely. Indeed, there is no simple physical model that can explain how the contribution of two components (Louisville and Hollister) remains constant, while the third component (PAR) varies during a single-stage mixing event. In other words, mixing three components simultaneously would produce clouds of data but not linear arrays, as actually observed in Figure 4b. A more plausible scenario is that two binary mixing processes occur successively. Pb-Pb relationships (Figure 4) require that the Louisville component first mixes with the Hollister component, and the resulting hybrid component subsequently mixes with the PAR component. The existence of two distinct binary mixing processes has been previously proposed as an alternate view to the three-component mixing model [*Vlastélic et al.*, 1998]. However, in the absence of further constraints (such as the resolution of pseudo-binary mixing arrays), it was suggested in this last study that the PAR and the Hollister components might mix independently with the LSC component.

[14] A likely interpretation of the two-stage mixing process is that the two processes take place in different geographical areas located along a mantle flow line. In this respect, two extreme scenarios can be proposed. (1) The first mixing process (Hollister + Louisville) takes place at great depth, and the resulting hybrid component subsequently mixes with the PAR component during its ascent to the surface. (2) The first mixing process (Hollister + Louisville) takes place away from the Hollister Ridge (possibly close to the Louisville hot spot), and the hybrid component mixes with the PAR component progressively toward the PAR axis. The reality could also be an intermediate scenario, similar to the two-stage plume-ridge melting model of *Morgan and Morgan* [1999].

[15] Through the resolution of pseudo-binary mixing arrays, the new highly precise Pb data suggest an early connection between Louisville plume and Hollister components. Although this should be reevaluated with high-precision data along the LSC, Figure 4b also raises the possibility that the Hollister component represents the unradiogenic source of Pb for the old (62–42 Ma) LSC array. *Castillo et al.* [1998] suggested that some Indian-type mantle could be entrained along with the Louisville plume. It is then possible that the Hollister component is represented by small-scale heterogeneities embedded within the Louisville plume reservoir. These small domains could be preferentially sampled by the low-melt fractions that prevail in a cold environment, such as the Raitt transform and, possibly the old, distal edifice of the Hollister Ridge.

### 4.3. Constraints on the Location and Dispersal of the Louisville Plume

[16] The decreasing volcanic activity of the Louisville hot spot after 20 Ma [*Lonsdale*, 1988], as the PAR gets closer to the plume, also raises the question of the location and dispersal of the Louisville plume. This question is part of an ongoing debate (see *Géli et al.* [1998] for a synthesis). The hot spot has been successively located along the anomalously shallow PAR segment that extends between Eltanin and Udintsev fracture zones [*Vogt*, 1976], near or within the Eltanin fault system [*Okal and Stewart*, 1982; *Stewart and Okal*, 1983; *Watts et al.*, 1988], near the youngest seamount sampled along the LSC [*Cheng et al.*, 1987; *Hawkins et al.*, 1987; *Lonsdale*, 1988; *Géli et al.*, 1998] and along Hollister Ridge [*Wessel and Kroenke*, 1997, 1998a]. On the basis of Sr, Nd and Pb ($^{206}Pb/^{204}Pb$) isotopic data, *Vlastélic et al.* [1998] estimated that the contribution of Louisville plume material to the Hollister Ridge mantle source does not exceed 20%, which estimate was used to infer that the hot spot cannot be located along Hollister Ridge. In this study, we confirm this result using a new isotopic space ($^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) and new highly precise data, and propose upper (35%) and lower (15%) limits.

[17] As pointed out by *Wessel and Kroenke* [1998b, 2001], extensive mixing in the Hollister Ridge mantle source is not surprising given the emplacement of the structure between a spreading ridge and a plume track, and a minor involvement of Louisville component cannot be used to reject the possibility that the hot spot is located along Hollister Ridge. In addition, the revised age of the most recent volcano sampled along the Louisville chain (1.11 Ma versus 0.5 Ma [*Koppers et al.*, 2004]) allows just enough time (see Figure 5b) for the Louisville hot spot to relocate along Hollister Ridge, or in its vicinity. However, it is difficult, if not impossible, to reconcile the high melt production of the Louisville plume ($3–4\ 10^3$ $km^3$/Myr according to *Lonsdale* [1988]) with the geochemical data in a model where the melt production of the Louisville hot spot is focused underneath Hollister Ridge. For example, it would imply a

very high growth rate of Hollister Ridge (>10 $10^3$ km$^3$/Myr). Such a rapid growth is not compatible with the volume of the main edifice of Hollister Ridge (3.3 $10^3$ km$^3$/Myr) and its probable age (2.5–3 Ma). These observations led us to suggest that only a separate limb of the Louisville plume feeds the Hollister source. Thus geochemical data together with plate kinematics constraints [*Géli et al.*, 1998; *Okal and Langenhorst*, 2000] do not support a Louisville hot spot centered on Hollister Ridge. In the rest of the paper we will consider that the hot spot is located near the youngest seamount sampled along the LSC (50°27′S; 139°10′W), a position that satisfies both geochemical and kinematic constraints [*Géli et al.*, 1998].

[18] The temporal increase of the Louisville plume component into the Hollister Ridge magmatic source is a new observation that deserves further attention. This may result (1) from the migration of the Pacific plate toward the plume, or (2) from the formation of an asthenospheric flow from the plume to the Hollister Ridge. Considering (1) a fixed plume with uniformly radial influence and (2) the motion of the Pacific plate (−64°, 85 km/Myr), it is difficult to explain the systematic decrease of the Louisville component with sample age from the distance that separated Hollister samples at the time of formation to the presumed location of the hot spot. For example, although samples DR19 and DR17 (or DR18) were formed at about the same location, their source contains variable amounts of Louisville plume material. Instead, the data suggest that an asthenospheric flow from the hot spot to the Hollister Ridge was established between 0.77 and 1.04 Myr ago (Figure 5b). Because the asthenospheric flow was initiated after the emplacement of Hollister Ridge (>2.5 Ma), the ridge may not be the consequence of the plume-ridge flow as proposed by *Small* [1995], but it might very well be the result of intraplate deformation [*Géli et al.*, 1998].

## 4.4. Louisville Hot Spot–Pacific-Antarctic Ridge Interaction Model

[19] The observations made above raise new questions. If Hollister Ridge results from intraplate deformation, why does this structure record an increasing plume contribution through time? How is Hollister Ridge connected to the Louisville plume and to the Pacific-Antarctic Ridge? Two key observations might help answer these questions.

[20] The first concerns the geological setting of the Louisville hot spot. A long distance (about 1300 km) separates the hot spot from the opposite spreading segment (Heezen-Raitt) of the southernmost East Pacific Rise. This distance is longer than that generally reported for plume-ridge interaction (<1100 km). This observation is consistent with the absence of a clear plume influence along the Heezen-Raitt segment [*Castillo et al.*, 1998]. On the other hand, the hot spot is located less than 150 km north of the Eltanin fault system, one of the longest (1000 km) fracture zone of the global spreading system. At the longitude of the hot spot, the oceanic crust is much older to the north than to the south of the Eltanin transform (about 45 Ma at the location of the hot spot against less than 10 Ma at the location of Hollister Ridge), indicating that the thickness of the oceanic lithosphere decreases sharply southward across the Eltanin fault system. Consequently, the buoyant plume material is expected to be entrained southward, as previously suggested by *Castillo et al.* [1998]. Supporting this idea, the upwelling of plume material within the Eltanin fault system has been proposed to explain the seismically silent coupling between the two adjacent plates [*Okal and Stewart*, 1982; *Stewart and Okal*, 1983]. In our model (illustrated in Figure 6), a limb of the Louisville plume is diverted to the south-southwest, following the direction of pressure release, and naturally reaches the location of Hollister Ridge. South of the closely spaced fracture zones, the direction of pressure release is then toward the east-southeast, and the plume material flows toward the spreading axis as suggested in common plume-ridge interaction models [*Small*, 1995]. According to this scenario, Hollister Ridge is located on the natural path of a plume limb going from the hot spot to the spreading ridge.

[21] The second key observation was also made by *Castillo et al.* [1998]. The authors observed that along the Pacific-Antarctic Ridge, the Louisville plume geochemical imprint is centered on the intersection with Hollister Ridge. At that location, according to the mixing model presented here, the Louisville plume contribution is slightly less than that expected in the center of Hollister Ridge (Figure 5). We interpret these observations as suggesting that Hollister Ridge (at least its central and eastern parts) is overlying the plume-ridge flow. In the intraplate deformation model of *Géli et al.* [1998], Hollister Ridge emplaced through a preexisting zone of weakness of the lithosphere. It is here suggested that such a lithospheric crack may have captured the flow and controlled its path toward the spreading axis (Figure 6). In addition, the PAR segment extending between Eltanin and Udintsev fracture zones shows a pronounced pos-

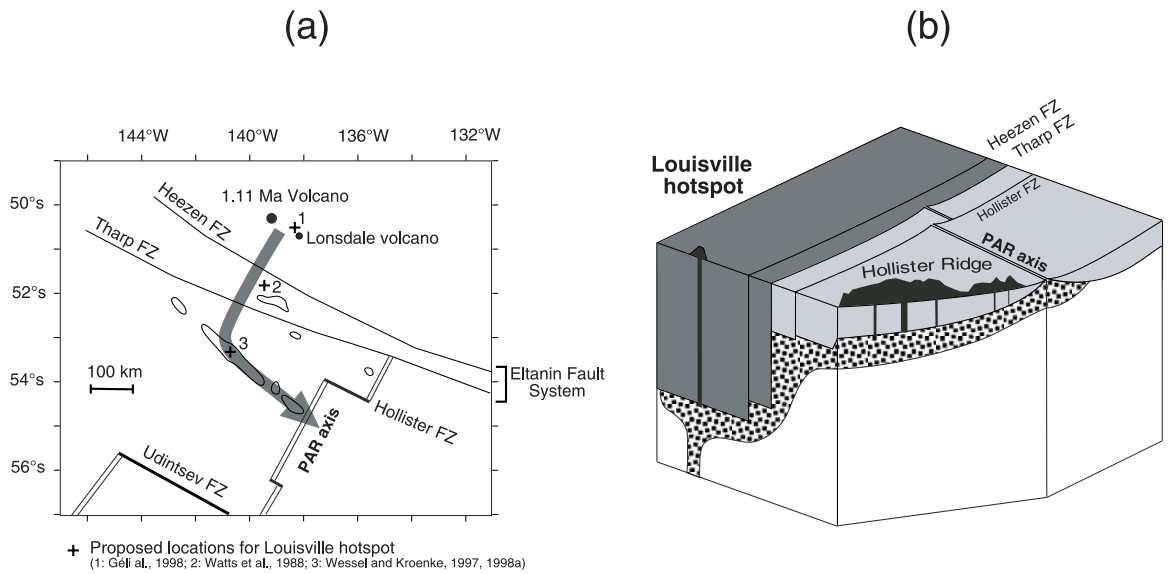


**Figure 6.** Louisville plume–Pacific-Antarctic Ridge interaction model. (a) Map showing the respective positions of the youngest volcanoes of the Louisville Seamount Chain (LSC), the Eltanin Fault System, Hollister Ridge, and the Pacific-Antarctic Ridge. The youngest seamount sampled along the LSC (50°27′S–139°10′W) is now dated at 1.11 ± 0.04 Ma [*Koppers et al.*, 2004]. Petrologic and isotopic data [*Hawkins et al.*, 1987; *Cheng et al.*, 1987] indicate unambiguously that this seamount originates from the Louisville hot spot. About 90 km southeast of the 139°10′W seamount, at 50°54′S–138°6′W, *Lonsdale* [1988] also mapped a volcano (named "Lonsdale volcano" in the map), which is also a candidate for the present site of the hot spot. Crosses indicate the location of the hot spot inferred from kinematic models. The location proposed by *Géli et al.* [1998], near "Lonsdale volcano," reconciles both geochemical and kinematics constraints and is used in this study to model the plume-ridge interaction. Because the hot spot is located at a great distance (1300 km) from the opposite spreading segment (Heezen-Raitt) of the East Pacific Rise, but only 120 km north of the Heezen FZ, a limb of the plume (gray arrow) may be diverted southward, where the lithosphere is much younger and thinner. Then, the plume material is expected to flow toward the nearby spreading axis, as suggested in common plume-ridge interaction models. During this last step, the flow may have been captured by the preexisting lithospheric crack through which Hollister Ridge most likely emplaced [*Géli et al.*, 1998]. This figure shows that Hollister Ridge lies along the shortest path of pressure release linking the Louisville hot spot to the Pacific-Antarctic ridge and explains why Hollister Ridge samples the plume-ridge flow. (b) Cartoon illustrating the shortest path of pressure release linking the Louisville hot spot to the Pacific-Antarctic ridge.

itive geoid anomaly [*Smith and Sandwell*, 1997], thus raising the possibility that the plume material accumulates beneath this spreading segment.

## 5. Conclusion and Perspectives

[22] Confirming previous results [*Vlastélic et al.*, 1998], the new highly precise Pb isotopic data from Hollister Ridge can be explained in a three-component mixing model (PAR-Louisville-Hollister) where the maximal contribution of the Louisville plume material, in the middle of the ridge, is constrained to range between 15 and 35% (with a best estimate of 20%). Two new, first-order observations are made: (1) Most of Hollister Pb isotopic analyses plot on a pseudo-binary mixing line that does not cross Louisville Seamount Chain isotopic field. It is suggested that two binary mixing processes occur successively along a mantle flow line, the Louisville component mixing first with the Hollister component, and the resulting hybrid component subsequently mixing with the PAR component. (2) The contribution from the Louisville plume has increased during the growth history of Hollister Ridge. Extrapolating the linear trend back through time, it can be estimated that the Louisville plume contribution initiated between 1.04 and 0.77 Myr ago and thus closely followed the most recent (known) volcanic activity along the Louisville trail (1.11 Ma according to *Koppers et al.* [2004]).

[23] These results suggest that Hollister Ridge has recorded the dispersal of the Louisville plume as the Pacific-Antarctic approached the hot spot. Assuming that the Louisville hot spot is located north of the Eltanin transform fault, near the youngest seamount dredged along the LSC [*Géli et al.*, 1998], we suggest that Hollister Ridge is located along the

shortest path of pressure release connecting the hot spot to the spreading ridge. Following the change in the direction of pressure release, the plume material flows first southward across the Eltanin fault system and subsequently migrates eastward toward the PAR axis. Because the asthenospheric flow was initiated after the emplacement of Hollister Ridge (>2.5 Ma), the ridge may not be a consequence of the flow as proposed by *Small* [1995]. Instead, the zone of weakness of the lithosphere through which Hollister Ridge emplaced [*Géli et al.*, 1998], may have captured the flow and controlled its path toward the spreading axis.

[24] The interaction between the Louisville-plume and the Pacific-Antarctic Ridge is thus more complex than previously thought and probably first involves an interaction with the Eltanin transform fault, as initially proposed by *Stewart and Okal* [1983]. Despite the considerable amount of work already done, the system is not fully understood and many questions remain unsolved, such as: what is the origin of the "Indian-like" component identified not only along Hollister Ridge but also along the PAR [*Castillo et al.*, 1998], and what is its relationship with the Louisville plume? Did the composition of the Louisville plume change between 35 and 42 Ma, as suggested by the conventional Pb data of *Cheng et al.* [1987]? Could the decrease of productivity along the Louisville seamount chain 20 Myr ago [*Lonsdale*, 1988] indicate an early dispersion of the plume?

## Appendix A: Three-Component Mixing Model

[25] As discussed in the text, Pb isotopic variations in Hollister Ridge samples (s) may be explained by mixing three end-member components: material from the Pacific-Antarctic Ridge (PAR) source, the Louisville Seamount Chain (LSC) source, and the Hollister Ridge (HR) source. The fractions of the three components are quantified in the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ space (which is less dependent on analytical error than $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ space) by solving the following three equations:

$$[Pb]_{PAR}.x_{PAR}.\left((64)_s-(64)_{PAR}\right)+[Pb]_{LSC}.x_{LSC}.\left((64)_s-(64)_{LSC}\right)+[Pb]_{HR}.x_{HR}.\left((64)_s-(64)_{HR}\right)=0, \quad (A1)$$

$$[Pb]_{PAR}.x_{PAR}.\left((84)_s-(84)_{PAR}\right)+[Pb]_{LSC}.x_{LSC}.\left((84)_s-(84)_{LSC}\right)+[Pb]_{HR}.x_{HR}.\left((84)_s-(84)_{HR}\right)=0, \quad (A2)$$

$$x_{PAR}+x_{LSC}+x_{HR}=1, \quad (A3)$$

where (64) and (84) are used in place of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, respectively; [Pb] is the concentration of lead in the different mantle sources; x is for component fraction (from 0 to 1). Note that these equations reflect simple barycentric relationships involving isotopic ratios weighted to concentrations. The system of three equations and three unknowns ($x_{PAR}$, $x_{LSC}$ and $x_{HR}$) can be written as the matrix product

$$\begin{pmatrix} [Pb]_{PAR}.\left((64)_s-(64)_{PAR}\right) & [Pb]_{LSC}.\left((64)_s-(64)_{LSC}\right) & [Pb]_{HR}.\left((64)_s-(64)_{HR}\right) \\ [Pb]_{PAR}.\left((84)_s-(84)_{PAR}\right) & [Pb]_{LSC}.\left((84)_s-(84)_{LSC}\right) & [Pb]_{HR}.\left((84)_s-(84)_{HR}\right) \\ 1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} x_{PAR} \\ x_{LSC} \\ x_{HR} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix},$$

or

$$A.B = C.$$

The solution is obtained from

$$B = A^{-1}.C,$$

where $A^{-1}$ is the inverse matrix of $A$.

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