Beyond EM-1: Lavas from Afanasy-Nikitin Rise and the Crozet Archipelago, Indian Ocean

J. J. Mahoney School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96826
W. M. White Department of Geological Sciences, Cornell University, Ithaca, New York 14853
B. G. J. Upton Department of Geology and Geophysics, University of Edinburgh, Edinburgh EH9 3JW, United Kingdom
C. R. Neal Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, Indiana 46556
R. A. Scrutton Department of Geology and Geophysics, University of Edinburgh, Edinburgh EH9 3JW, United Kingdom

ABSTRACT

Lavas from Afanasy-Nikitin Rise, possibly the Late Cretaceous product of the Crozet hotspot, cover a wide range of isotopic compositions that includes the lowest $(^{206}Pb/^{204}Pb)_t$ (to 16.77) and $\varepsilon_{Nd}(t)$ (to −8) values yet found among oceanic islands or spreading centers worldwide, as well as high $(^{87}Sr/^{86}Sr)_t$ (to 0.7066). In contrast, young basalts from the Crozet Archipelago exhibit a narrow range of variation around $\varepsilon_{Nd} \sim +4$, $^{87}Sr/^{86}Sr \sim 0.7040$, and $^{206}Pb/^{204}Pb \sim 19.0$, closely resembling that of shield lavas of the Réunion hotspot. The Afanasy-Nikitin rocks also have much higher Ba/Nb, Ba/Th, and Pb/Ce than modern oceanic island or ridge lavas, as well as high La/Nb. The data do not obviously support the Crozet plume model but, assuming the model to be plate tectonically correct, would indicate that the plume-source composition either changed dramatically or that Afanasy-Nikitin magmatism involved significant amounts of nonplume mantle. The low $^{206}Pb/^{204}Pb$, low ε_{Nd} lavas provide the best evidence to date of the sort of material that, by variably contaminating much of the Indian mid-ocean-ridge basalt (MORB) source asthenosphere, may be responsible for the isotopic difference between most Indian MORB and Pacific or North Atlantic MORB. The combined isotopic and trace element results suggest an ultimate origin in the continental crust or mantle lithosphere for this material, although whether it was cycled through the deep mantle or resided at shallow levels in the convecting mantle cannot currently be determined.

INTRODUCTION

Low $^{206}Pb/^{204}Pb$ values between about 17.5 and 18.0 are characteristic of "EM-1 type" oceanic island and seamount volcanoes such as Lanai, Koolau, and the Pitcairn group (e.g., West et al., 1987; Woodhead and Devey, 1993; Roden et al., 1994); these volcanoes also have high $^{208}Pb/^{204}Pb$ relative to their $^{206}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$ between ~0.7040 and ~0.7050, and low ε_{Nd} between about +4 and −4. Still lower $^{206}Pb/^{204}Pb$ values are found in mid-ocean-ridge basalts (MORB) in the Indian Ocean, particularly along the 39–41°E section of the Southwest Indian Ridge, where $^{206}Pb/^{204}Pb$ = 16.9–17.4, with corresponding ε_{Nd} = +3 to −4 and $^{87}Sr/^{86}Sr$ = 0.7040–0.7049 (Mahoney et al., 1992). The origin of such isotopic signatures is controversial, having been attributed in various instances to fairly recent intramantle derivation from near-primitive lower mantle (e.g., Roden et al., 1994); to recycling, via mantle plumes, of deeply subducted, aged pelagic sediments (e.g., White, 1985; Ito et al., 1987; le Roex et al., 1989); and to the introduction into the shallow convecting mantle of old, thermally mobilized or shallowly subducted continental lithospheric material (e.g., Hawkesworth et al., 1986; Storey et al., 1992; Mahoney et al., 1992). Here we report the lowest $^{206}Pb/^{204}Pb$ signatures yet observed among oceanic mantle-derived rocks, in lavas from Afanasy-Nikitin Seamount in the Indian Ocean.

Afanasy-Nikitin Seamount is the principal peak of Afanasy-Nikitin Rise (~300 km × 100 km at 4500 m water depth), reaching a minimum water depth of 1549 m at 3°01′S, 83°05′E (Fig. 1). Curray and Munasinghe (1991) concluded that the rise lies near the southern terminus and is one of the most prominent edifices of the aseismic 85°E Ridge, which they interpreted to be the ~115–80 Ma track of the Crozet hotspot on the Indian plate. In their model, the hotspot formed the Rajmahal Traps of eastern India prior to creating the 85°E Ridge on the northward moving Indian plate; Afanasy-Nikitin Rise was constructed around 80 Ma when the hotspot was situated near the spreading axis of the paleo-Southeast Indian Ridge. Soon thereafter, migration or a jump of the spreading center placed the hotspot beneath the Antarctic plate, where it subsequently formed the Crozet Plateau and modern Crozet Archipelago. An alternative model by Müller et al. (1993) suggests that Afanasy-Nikitin Rise and the southern part of the 85°E Ridge (south of ~10°N) were produced by another hotspot, now probably long dead, located ~800 km south of the Crozet Archipelago. In this paper we present isotopic data for lavas from the Crozet Archipelago for comparison with results for Afanasy-Nikitin.

SAMPLES AND RESULTS

A dredge haul on Afanasy-Nikitin Seamount in 1987 by the R.S.S. *Charles Darwin* (CD28) recovered several pillow-lava fragments from depths of 2000 to 3000 m. Microfossils in chalk recovered in the dredge are of Maastrichtian to Paleocene age (~73–60 Ma) and provide a lower limit on the age of the lavas. We have determined Sr-Pb-Nd isotopic ratios and major and trace element abundances for two of the best-preserved lava samples (see Tables 1

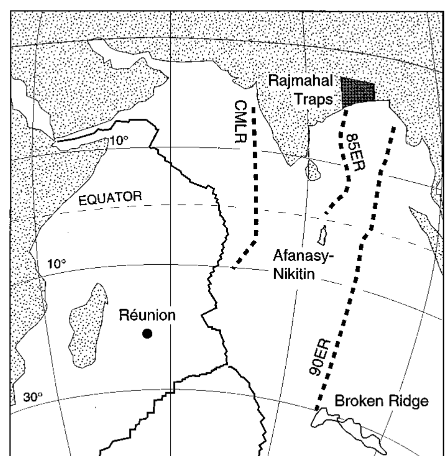

Figure 1. Simplified map (after Curray and Munasinghe, 1991) of part of Indian Ocean showing Afanasy-Nikitin Rise and other locations discussed in text. CMLR = Chagos-Maldive-Laccadive Ridge; 90ER = Ninetyeast Ridge; 85ER = 85°E Ridge.

Data Repository item 9632 contains additional material related to this article.

and 2[1]) In addition, Russian investigators recently have reported major element analyses (Mateenkov et al., 1991) as well as isotopic and some trace element data (Sushchevskaya et al., 1996) for samples dredged from several locations on Afanasy-Nikitin Rise. The Crozet Archipelago samples we analyzed isotopically (see Table 2, footnote 1) are for nine lavas from East and Possession islands, obtained from the collection of N. Watkins.

The Afanasy-Nikitin Seamount samples are of fast-quenched, amygdaloidal lavas, carrying phenocrysts (20–30 vol%) of relatively fresh, K-rich plagioclase (An_{51-55}, with Or = 3.75–5.01 mol%), altered olivine, and Ca-rich augitic clinopyroxene ($Ca_{46}Mg_{41}Fe_{13}$–$Ca_{43}Mg_{42}Fe_{15}$). The matrices, originally glassy, are largely devitrified; the amygdules are mostly $<$2 mm across and calcite filled, with subordinate phosphate. Plagioclase is the dominant phenocryst phase; some of the larger plagioclase crystals (up to 1 cm across) may be xenocrysts, because they display jagged terminations and tend to be intensely resorbed. A fairly early crystallization of magnesian ilmenite (with up to 6.4 wt% MgO) is indicated by the presence of rounded ilmenite microphenocrysts and ilmenite inclusions in plagioclase and pyroxene. The lavas are rich in K_2O, having contents of 3.37 and 3.85 wt%. They are evolved, with $MgO/Fe_2O_3^*$ of 0.17 and 0.20 (where $Fe_2O_3^*$ = total Fe as Fe_2O_3) at SiO_2 = 47.20 and 50.09 wt%, and are probably best classified as hawaiites; however, the abundant phenocrysts preclude precise estimation of liquid major element compositions from whole-rock compositions. Mateenkov et al. (1991) reported a wider range of rock types from the rise: subalkalic olivine-phyric and tholeiitic basalt, trachybasalt, and trachyte; our samples appear to correspond roughly to their trachybasalts.

Primitive-mantle-normalized incompatible element patterns of our samples (Fig. 2) reveal an overall enrichment in highly incompatible elements relative to less incompatible ones; in this respect they resemble most oceanic island basalts (OIB). However, they are quite distinct in having prominent peaks at Ba, K, and Pb (Rb also is elevated relative to Th and U), a positive slope from Nb to La, and low Ti. Thus, the samples display much higher ratios of, for example, Ba/Nb, La/Nb, and Ba/Th (respectively, 30–36, 1.3–1.4, 253–264) than modern oceanic hotspot volcanoes (e.g., 7.3, 0.77, and 88 for average OIB [Sun and McDonough, 1989]), including EM-1 type volcanoes (which also differ among each other; cf. averages of 7.8, 0.89, and 87 for the Pitcairn Seamounts [Woodhead and Devey, 1993] and 11, 1.3, and 205 for the Koolau shield of Hawaii [Frey et al., 1994; Roden et al., 1994]). The samples also possess significantly lower Nb/U (27–28), Nb/Th (7.3–8.5), Ce/Pb (7–13), Nd/Pb (3–6), and Ti/Y (307–360) values (cf 47, 12, 25, 12, and 593, respectively, for average OIB or 34–51, 9–12, 19–22, 9–16, and 665–800 for the Pitcairn Seamounts basalts). Although the rocks have been affected by moderate levels of low-temperature seawater alteration, alteration alone is unlikely to be the cause of their distinctive trace element signatures, particularly for alteration-resistant ratios such as Nd/Pb, La/Nb, and Nb/Th, but also for the very high Ba and K abundances. Limited trace element data for three trachybasalts and two olivine-phyric basalts analyzed by Sushchevskaya et al. (1996) suggest generally similar characteristics, including low Ti relative to Y and Zr in the comparatively unevolved basalts.

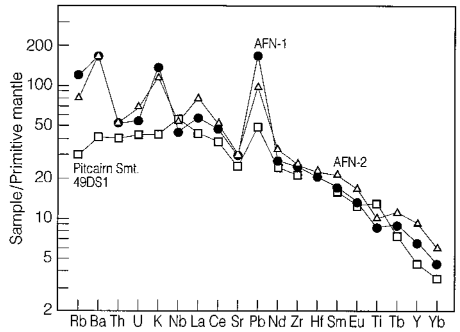

Figure 2. Primitive-mantle-normalized incompatible element patterns of samples AFN-1, AFN-2, and low $^{206}Pb/^{204}Pb$ (17.62) Pitcairn Seamounts basalt 49DS-1 (Woodhead and Devey, 1993). Normalizing values used are Sun and McDonough's (1989).

The high Ba, K, and Pb and low relative Nb and Ti of the Afanasy-Nikitin patterns in Figure 2 qualitatively resemble patterns of continental crustal averages and averages of pelagic clay (e.g., Taylor and McLennan, 1985; Rudnick and Fountain, 1995); most features of the Afanasy-Nikitin patterns can be reproduced crudely by calculated batch melts of mixtures of average OIB mantle with several percent of average pelagic sediment. However, their low Th and U (relative to Ba and K) are not reproduced by many such mixtures. Broadly similar enrichment patterns are found in minettes, believed by many workers to originate in metasomatized continental lithospheric mantle (e.g., Thompson et al., 1990), and Saunders et al. (1992) argued that similarly low relative Th and U levels may be characteristic of parts of the continental lithospheric mantle involved in the production of some continental flood basalts. At Afanasy-Nikitin, however, the likelihood of intact continental lithosphere being present appears remote, as the rise was emplaced on very young oceanic lithosphere in a location far from continents (e.g., Curray and Munasinghe, 1991; Müller et al., 1993). In this respect, Afanasy-Nikitin contrasts with the Naturaliste and southern Kerguelen plateaus in the eastern Indian Ocean, which formed much closer to continental margins and may contain blocks of continental lithosphere (Storey et al., 1992; Mahoney et al., 1995; Charvis and Operto, 1995).

Isotopically, the Afanasy-Nikitin Seamount lavas are remarkable in possessing very low initial $(^{206}Pb/^{204}Pb)_t$ (= 16.77 and 16.80), very low $\varepsilon_{Nd}(t)$ (= -7.6 and -8.0), high $(^{87}Sr/^{86}Sr)_t$ (= 0.70641 and 0.70662), and high $(^{208}Pb/^{204}Pb)_t$ (37.06, 37.08) and $(^{207}Pb/^{204}Pb)_t$ (15.41, 15.42) relative to their $(^{206}Pb/^{204}Pb)_t$ (see Fig. 3; here, t = 80 Ma, but the age corrections are small and the values do not change significantly if the lower age limit of 60 Ma is used: e.g., $[^{206}Pb/^{204}Pb]_t$ only by 0.016 and 0.042, $\varepsilon_{Nd}[t]$ by only 0.2). Although broadly similar and often more extreme compositions are found in some continental flood basalts, this combination of values is unique (to date) among oceanic island, seamount, and ridge basalts worldwide, the closest isotopic analogues being the 39–41°E mid-ocean-ridge basalt (MORB) from the Southwest Indian Ridge. Acid-leached splits of several trachybasalts and subalkalic olivine-phyric basalts from Afanasy-Nikitin Rise analyzed by Sushchevskaya et al. (1996) range to higher $(^{206}Pb/^{204}Pb)_t$ (16.85–17.70) and $\varepsilon_{Nd}(t)$ (-3.6 to -7.3) values than our samples, and to lower $(^{87}Sr/^{86}Sr)_t$ (0.70565–0.70611), with quite variable and in several cases markedly higher $(^{207}Pb/^{204}Pb)_t$ (15.45–15.61). However, a leached plagioclase phenocryst separate has isotopic values very similar to our analyses, which were made on phenocryst-free portions of sample. Three leached tholeiitic basalts have significantly higher $(^{206}Pb/^{204}Pb)_t$ (17.83–18.12), positive $\varepsilon_{Nd}(t)$ (+3 to +5.5), and lower $(^{87}Sr/^{86}Sr)_t$ (0.70368–0.70440) (Sushchevskaya et al., 1996). Thus, the combined isotopic data for Afanasy-Nikitin Rise cover a considerable spread of values.

In contrast, the nine samples from the Crozet Archipelago exhibit a very restricted range of isotopic ratios: $^{206}Pb/^{204}Pb$ = 18.79–19.18, ε_{Nd} = +3.5 to +4.3, and $^{87}Sr/^{86}Sr$ = 0.70396–0.70408 (Fig. 3). These values closely resemble those of several other hotspot islands in the Indian Ocean; in fact,

[1]GSA Data Repository item 9632, Tables 1 and 2, Supporting Data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

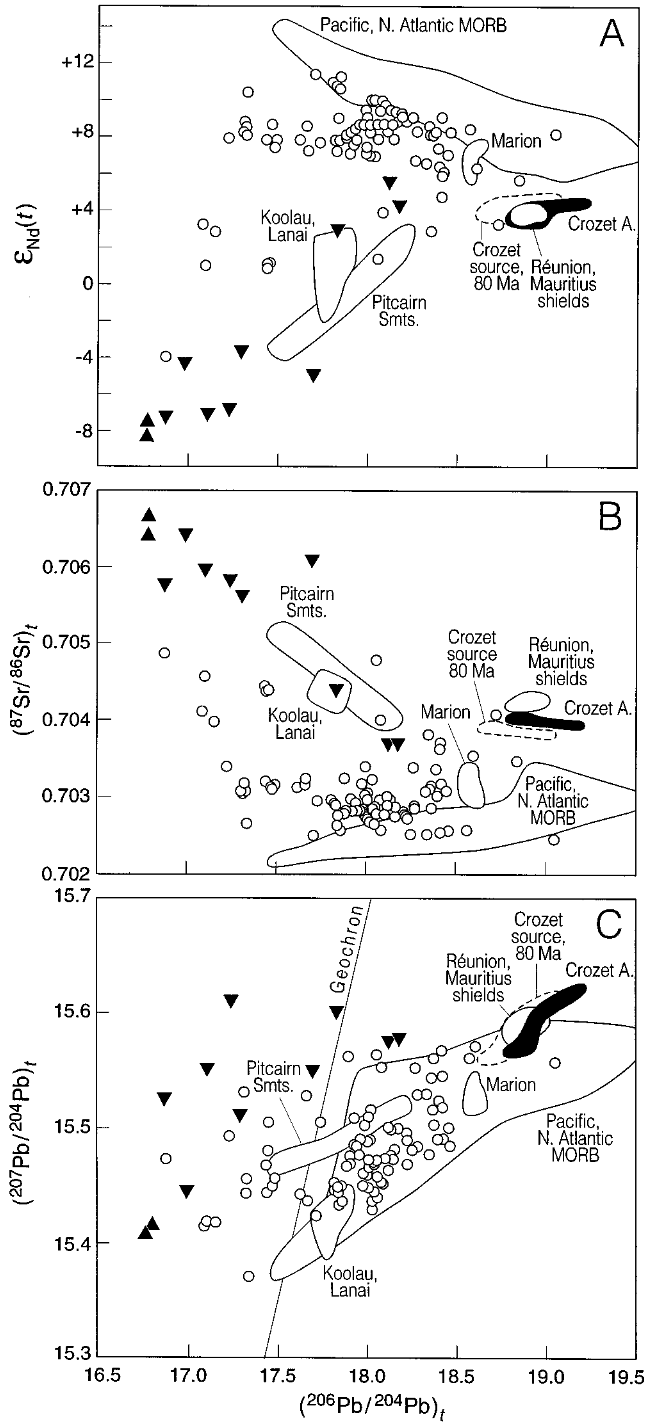

Figure 3. (A) $\varepsilon_{Nd}(t)$, (B) $(^{87}Sr/^{86}Sr)_t$, (C) $(^{207}Pb/^{204}Pb)_t$ vs. $(^{206}Pb/^{204}Pb)_t$ for Afanasy-Nikitin Seamount lavas of this study (up-pointing triangles), leached rock powders of Sushchevskaya et al. (1996) (down-pointing triangles), and Crozet Archipelago (A.) basalts (shaded field). Data for Indian mid-ocean-ridge basalt (MORB) (circles) and fields for Pacific and North Atlantic MORB and Marion hotspot (see Mahoney et al., 1992; Dosso et al., 1993, and references therein), Réunion and Mauritius shields (data of W. M. White; Peng and Mahoney, 1995), Pitcairn Seamounts (Smts.; Woodhead and Devey, 1993), and Koolau and Lanai (West et al., 1987; Roden et al., 1994) are shown for comparison. 80 Ma Crozet source field assumes source parent-daughter ratios estimated by Peng and Mahoney (1995) for Réunion source.

they are nearly identical to data for the recent (<7 Ma) shield volcanoes of the Réunion hotspot, which lies 25° north of Crozet at a similar longitude. Note that the broad isotopic array defined by the Afanasy-Nikitin samples does not point unambiguously toward the present-day or estimated 80 Ma Crozet field.

DISCUSSION

The low $^{206}Pb/^{204}Pb$ Afanasy-Nikitin lavas provide the most extreme examples yet found of the type of material hypothesized to have variably (but generally only slightly) contaminated much of the Indian MORB mantle (see Mahoney et al., 1992, and references therein). No evidence exists from Indian MORB that this material was isotopically homogeneous, and the broad Afanasy-Nikitin field in Figure 3 requires either the involvement of more than two mantle end members or an isotopically heterogeneous low $^{206}Pb/^{204}Pb$ end member; note in particular the wide range of $(^{207}Pb/^{204}Pb)_t$ at low $(^{206}Pb/^{204}Pb)_t$. Comprehensive incompatible element data are limited for Indian MORB but, like our Afanasy-Nikitin samples, the low $^{206}Pb/^{204}Pb$ Southwest Indian Ridge lavas are significantly elevated in Ba and Pb (e.g., Ba/Nb = 9–22 and Nd/Pb = 10–15 [le Roex et al., 1989; Mahoney et al., 1992] vs. 2.7 and 24 for average normal MORB [e.g., Sun and McDonough, 1989]). They do not have markedly high K, however. Outside the Indian Ocean, EM-1 type OIB show substantial differences in key incompatible element ratios from the Afanasy-Nikitin Seamount lavas and from each other (e.g., see Fig. 2 and results section). As a group, such OIB also display considerable heterogeneity in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (e.g., West et al., 1987; Woodhead and Devey, 1993; Roden et al., 1994), albeit at much higher $^{206}Pb/^{204}Pb$ than the low $^{206}Pb/^{204}Pb$ Afanasy-Nikitin lavas, indicating different ages, modes of formation, and/or histories of their sources (Mahoney et al., 1995). Thus, on a global basis, more than one low $^{206}Pb/^{204}Pb$ end member appears to be required.

Because the isotopic results show most of the Afanasy-Nikitin samples to be dramatically different from the recent products of the Crozet hotspot, and because the Afanasy-Nikitin isotopic field does not overlap with or necessarily converge toward the Crozet field in Figure 3, the data do not support the Crozet plume model for the formation of Afanasy-Nikitin Rise. However, they do not rule it out. The Crozet Archipelago lavas are isotopically quite distinct from nearly all Indian MORB, and their very close similarity to the 0–7 Ma shield volcanoes of the Réunion hotspot at Réunion and Mauritius islands (Fig. 3) suggests that they are likely to reflect the present isotopic signature of the plume. If so, and assuming the Crozet plume model for Afanasy-Nikitin Rise is geodynamically correct, then the composition of material feeding the plume at its base (e.g., near the core-mantle boundary) could have changed dramatically, becoming much more homogeneous and Réunion-like over time. However, in the much-better-studied Réunion case, the isotopic signature of the main component in the source appears to have changed relatively little in at least 66 m.y. (White et al., 1990; Peng and Mahoney, 1995). An alternative and perhaps more likely possibility is that the low $^{206}Pb/^{204}Pb$ signatures at Afanasy-Nikitin could reflect nonplume material that became entrained into the plume either at depth or at relatively shallow levels, but which no longer contributes to Crozet-plume-related volcanism. Possible parallels exist in the Tristan hotspot and Marion hotspot systems (e.g., Hawkesworth et al., 1986; Mahoney et al., 1992; S. C. Milner and A. P. le Roex, 1996).

The alternative plume model ascribing Afanasy-Nikitin Rise to a now-dead hotspot south of the Crozet Archipelago (Müller et al., 1993) is likely to be subject to the same geochemical restrictions as the Crozet plume model, given that isotopic and incompatible element ratios as extreme as those observed for Afanasy-Nikitin have not been found in any modern oceanic hotspots. Unfortunately for both models, no igneous rock samples of the 85°E Ridge (or of the pre-Crozet-Archipelago portions of the Crozet Plateau) have been collected, to our knowledge, so it is not yet possible to track the composition of lavas, particularly the variation of low $^{206}Pb/^{204}Pb$ contributions, through time. Data for the Rajmahal Traps, presumed to be the initial product of the plume in the Crozet model, are inconclusive because the Rajmahal lavas are variably affected by continental crust (e.g., Kent al., 1996); furthermore, the Rajmahal Traps have been attributed to the early Kerguelen hotspot, rather than the Crozet hotspot, by several workers (e.g., Storey et al., 1992; Baksi, 1995; Kent et al., 1996). Available $^{206}Pb/^{204}Pb$ values for Rajmahal lavas are mostly in the 17.9–18.1 range, and the least-contaminated samples have ($^{87}Sr/^{86}Sr$), ~0.7040 and $\varepsilon_{Nd}(t)$ ~+3, roughly similar to values of the tholeiitic Afanasy-Nikitin basalts analyzed by Sushchevskaya et al. (1996). A large, Rajmahal-related basaltic dike and several lamprophyres interpreted to reflect melting in the continental lithospheric mantle have $^{206}Pb/^{204}Pb$ as low as 17.1 (Kent et al., 1996).

With the current limitations, it is not possible to evaluate whether the low $^{206}Pb/^{204}Pb$, low ε_{Nd} material affecting Afanasy-Nikitin volcanism was situated in the shallow mantle or deep mantle prior to formation of the rise. However, an origin by a relatively recent extraction from deep primitive mantle, as proposed by Roden et al. (1994) for the Koolau source, can be ruled out conclusively in the Afanasy-Nikitin case. If the Afanasy-Nikitin data with $(^{206}Pb/^{204}Pb)_t < 17.3$ were interpreted as defining a rough secondary Pb-Pb isochron, it would correspond to an age of $\sim 4 \times 10^9$ yr; more generally, the Nd, Sr, and Pb isotopic compositions of the lowest ε_{Nd} lavas are far removed from plausible primitive mantle values (e.g., $\varepsilon_{Nd} \sim 0$, Pb isotope ratios near the geochron). Rather, the combined isotopic and incompatible element data strongly imply some type of continental crustal or lithospheric mantle origin. That the most extreme Indian Ocean isotopic compositions found thus far are in old, rather than young, sea floor is consistent with the hypothesis (e.g., Storey et al., 1992; Mahoney et al., 1992) that the major introduction of low $^{206}Pb/^{204}Pb$ material into the Indian Ocean source mantle occurred prior to and during the breakup of Gondwana, and that subsequently this material has been dispersed and diluted within the asthenosphere. In view of the very sparse present sampling of Indian Ocean sea floor, lavas with even more unusual compositions than those of Afanasy-Nikitin may well exist in other regions of old Indian Ocean crust.

ACKNOWLEDGMENTS

Supported by the National Science Foundation and Natural Environment Research Council. We thank J. Jain, P. Hill, S. Kearns, J. G. Fitton, and D. James for help with the analytical work, N. Sushchevskaya for her data and preprint, and L. Danyushevsky and B. Salov for help in translation. J. R. Curray and R. A. Duncan provided helpful reviews.

REFERENCES CITED

Baksi, A. K., 1995, Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, northeastern India: Chemical Geology, v. 121, p. 73–89.

Charvis, P., and Operto, S., 1995, Deep structure of the Kerguelen Plateau (southern Indian Ocean): LIP Reader (Newsletter of Commission on Large-Volume Basaltic Provinces, International Association of Volcanology and Chemistry of Earth's Interior), no. 5, p. 3.

Curray, J. R., and Munasinghe, T., 1991, Origin of the Rajmahal Traps and 85°E Ridge: Preliminary reconstructions of the trace of the Crozet hotspot: Geology, v. 19, p. 1237–1240.

Dosso, L., Bougault, H., and Joron, J.-L., 1993, Geochemical morphology of the north Mid-Atlantic Ridge, 10°–24°N: Trace element-isotope complementarity: Earth and Planetary Science Letters, v. 120, p. 443–462.

Frey, F. A., Garcia, M. O., and Roden, M. F., 1994, Geochemical characteristics of Koolau Volcano: Implications of intershield geochemical differences among Hawaiian volcanoes: Geochimica et Cosmochimica Acta, v. 58, p. 1441–1462.

Hawkesworth, C. J., Mantovani, M. S. M., Taylor, P. N., and Palacz, Z., 1986, Evidence from the Paraná of south Brazil for a continental contribution to Dupal basalts: Nature, v. 322, p. 356–359.

Ito, E., White, W. M., and Göpel, C., 1987, The O, Sr, Nd and Pb isotope geochemistry of MORB: Chemical Geology, v. 62, p. 157–176.

Kent, R. W., Saunders, A. D., Kempton, P. D., and Ghose, N. C., 1996, Ramjahal basalts: Mantle sources and melt distribution at a volcanic rifted margin, *in* Mahoney, J. J., and Coffin, M. F., eds., Large igneous provinces: Washington, D. C., American Geophysical Union (in press).

le Roex, A. P., Dick, H. J. B., and Fisher, R. L., 1989, Petrology and geochemistry of MORB from 25°E to 46°E along the Southwest Indian Ridge: Evidence for contrasting styles of mantle enrichment: Journal of Petrology, v. 30, p. 947–986.

Mahoney, J. J., le Roex, A. P., Peng, Z., Fisher, R. L., and Natland, J. H., 1992, Southwestern limits of Indian Ocean ridge mantle and the origin of low $^{206}Pb/^{204}Pb$ mid-ocean ridge basalt: Isotope systematics of the central Southwest Indian Ridge (17°–50°E): Journal of Geophysical Research, v. 97, p. 19771–19790.

Mahoney, J. J., Jones, W. B., Frey, F. A., Salters, V. J. M., Pyle, D. G., and Davies, H. L., 1995, Geochemical characteristics of lavas from Broken Ridge, the Naturaliste Plateau and southernmost Kerguelen Plateau: Cretaceous plateau volcanism in the southeast Indian Ocean: Chemical Geology, v. 120, p. 315–345.

Mateenkov, V. V., Kashintsev, G. L., and Almuchamedov, A. I., 1991, The composition of basalts of the Aphanasy-Nikitin Rise (in Russian): Doklady Akademii Nauk SSSR, v. 317, no. 5, p. 1183–1188.

Milner, S. C., and le Roex, A. P., 1996, Isotope characteristics of the Okenyenya igneous complex, northwestern Namibia: Constraints on the composition of the early Tristan plume and the origin of the EM 1 mantle component: Earth and Planetary Science Letters (in press).

Müller, R. D., Royer, J.-Y., and Lawver, L. A., 1993, Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks: Geology, v. 21, p. 275–278.

Peng, Z. X., and Mahoney, J. J., 1995, Drillhole lavas from the northwestern Deccan Traps, and the evolution of Réunion hot spot mantle: Earth and Planetary Science Letters, v. 134, p. 169–185.

Roden, M. F., Trull, T., Hart, S. R., and Frey, F. A., 1994, New He, Nd, Pb, and Sr isotopic constraints on the constitution of the Hawaiian plume: Results from Koolau Volcano, Oahu, Hawaii, USA: Geochimica et Cosmochimica Acta, v. 58, p. 1431–1440.

Rudnick, R. L., and Fountain, D. M., 1995, Nature and composition of the continental crust: A lower crustal perspective: Reviews of Geophysics, v. 33, p. 267–309.

Saunders, A. D., Storey, M., Kent, R. W., and Norry, M. J., 1992, Consequences of plume-lithosphere interactions, *in* Storey, B. C., et al., eds., Magmatism and the consequences of continental break-up: Geological Society of London Special Publication 68, p. 41–60.

Storey, M., and 10 others, 1992, Lower Cretaceous volcanic rocks on continental margins and their relationship to the Kerguelen Plateau: Proceedings of the Ocean Drilling Program, Scientific results, Volume 120: College Station, Texas, Ocean Drilling Program, p. 33–54.

Sun, S.-S., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, *in* Saunders, A. D., and Norry, M. J., eds., Magmatism in the ocean basins: Geological Society of London Special Publication 42, p. 313–345.

Sushchevskaya, N. M., Ofchinnikova, G. V., Borisova, A. Y., Belyaszsky, B. V., Vasilyeva, J. M., and Levsky, L. K., 1996, Geochemical heterogeneity of Afanasy-Nikitin Rise magmatism, Northeast Indian Ocean (in Russian): Petrologia (in press).

Taylor, S. R., and McLennan, S. M., 1985, The continental crust: Its composition and evolution: Cambridge, Massachusetts, Blackwell, 312 p.

Thompson, R. N., Leat, P. T., Dickin, A. P., Morrison, M. A., Hendry, G. L., and Gibson, S. A., 1990, Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: Earth and Planetary Science Letters, v. 98, p. 139–153.

West, H. B., Gerlach, D. C., Leeman, W. P., and Garcia, M. O., 1987, Isotopic constraints on the origin of Hawaiian lavas from the Maui Volcanic Complex, Hawaii: Nature, v. 330, p. 216–220.

White, W. M., 1985, Sources of oceanic basalts: Radiogenic isotopic evidence: Geology, v. 13, p. 115–118.

White, W. M., Cheatham, M. M., and Duncan, R. A., 1990, Isotope geochemistry of Leg 115 basalts and inferences on the history of the Réunion mantle plume, *in* Proceedings of the Ocean Drilling Program, Scientific results, Volume 115: College Station, Texas, Ocean Drilling Program, p. 53–62.

Woodhead, J. D., and Devey, C. W., 1993, Geochemistry of the Pitcairn seamounts, I: Source character and temporal trends: Earth and Planetary Science Letters, v. 116, p. 81–99.

Manuscript received November 9, 1995
Revised manuscript received March 25, 1996
Manuscript accepted April 4, 1996