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Madagascar basalts: tracking oceanic and continental sources

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ABSTRACT

Extensive Upper Cretaceous volcanism in southern Madagascar was fed in part by mantle sources resembling those expressed today in the Indian Ocean at Marion and Prince Edward islands and on the central Southwest Indian Ridge. In addition, very low $\epsilon_{Nd}(T)$ (to -17.4), high $(^{87}Sr/^{86}Sr)_T$ (to 0.72126) tholeiites in southwestern Madagascar were variably but highly contaminated by ancient continental material broadly like that affecting the Bushe and Poladpur Formations of the later Deccan Traps in India. Alkalic dikes in southwestern Madagascar have a rough analogue in the Mahabaleshwar Formation of the Deccan, in that they document the influence of a low $^{206}Pb/^{204}Pb$, negative ϵ_{Nd}, relatively low $^{87}Sr/^{86}Sr$ reservoir. A very similar reservoir is manifested at present in mid-ocean ridge basalts on the central Southwest Indian Ridge near 40°E. The original location of this end-member appears likely to have been in the Madagascan lithospheric mantle, a portion of which may have been removed in the Middle Cretaceous by the action of the Marion hotspot or the rifting of Indo-Madagascar. An origin within the hotspot itself also may be possible; however, recent products of the hotspot appear to lack completely the necessary low $^{206}Pb/^{204}Pb$, low ϵ_{Nd} signatures.

1. Introduction

Between the main phase of Karoo volcanism (roughly 190 Myr) in what is now southern Africa and the Deccan Traps episode in Greater India (about 65 Myr), extensive basalts were erupted in Madagascar. Originally they may have blanketed most of the island [1] (the fourth largest in the world, with an area greater than that of France) but now remain principally along the east and west coasts and offshore, with only isolated outliers inland (Fig. 1). Their age is not known precisely, for no $^{40}Ar/^{39}Ar$ work has been done; however, some flows in the north are intercalated with Turonian (~ 88.5–91 Myr [2]) sediments, whereas lavas in the southwest rest upon Turonian and are interbedded with sparse Campanian (~ 73–83 Myr [2]) sediments [1,3,4]. In the southeast, the basalts lie directly upon Precambrian basement. Despite being recognized as an important link in the succession of massive flood volcanism associated with the breakup of Gondwana, very little geochemical or petrological attention has been paid to the Madagascan lavas, and no isotopic study has been undertaken. The reason, in large part, is that for many years there have been formidable legal difficulties in removing geological specimens from the island. Recently, however, Dostal et al. [5] carried out a major and trace element, and K-Ar study of flows and dikes from the southwestern and southeastern regions. Here we present the results of a Nd, Pb, and Sr isotopic investigation of the same sample suite.

Strong spatial and temporal connections between flood basalt volcanism and continental rifting in the vicinity of hotspots have been noted for many years ([6–8], and many more recent works). The precise role of hotspots in furnishing material, as opposed to only heat, to fuel flood activity has been difficult to establish, because (1) there commonly are significant elemental contributions from continental crust or lithospheric mantle which obscure sublithospheric geochemical signals; and (2) the isotopic and chemical composition of a given hotspot may change somewhat over time, so that its present-day magmatic products (which generally provide most available samples) may not be directly comparable to earlier ones.

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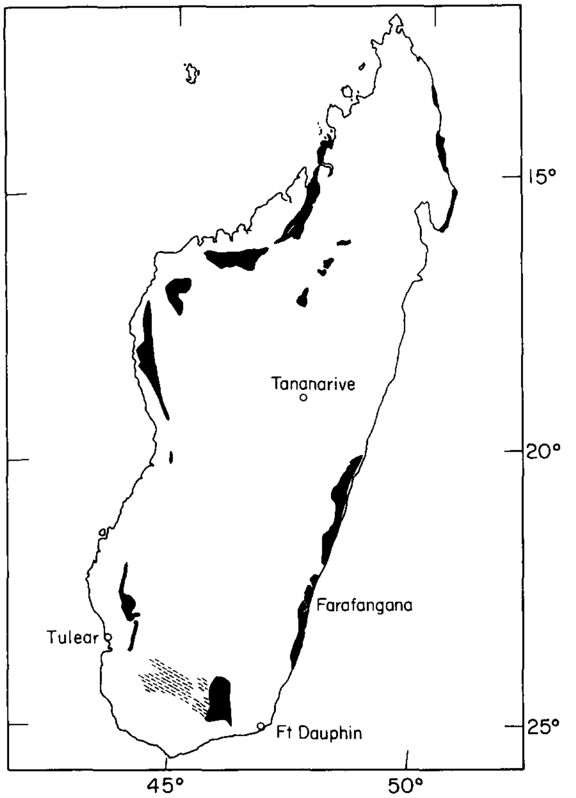

Fig. 1. Map of Madagascar with main locations of Upper Cretaceous basalts (and associated rhyolites) in black. Southern dike swarm is indicated by stippled pattern (after [1,5]). Samples in this study are from flows and dikes east and southeast of Tulear and along the southeast coast north of Farafangana, as described in Dostal et al. [5].

Recent work in the western Deccan Traps, however, has shown that the lavas least affected by continental lithosphere (Ambenali Formation) reflect a mantle source that appears to be a relatively uniform mixture of present-day Reunion hotspot and MORB (mid-ocean ridge basalt) isotopic and chemical characteristics [9,10]. Following Deccan volcanism and the rifting of the Seychelles Platform from Greater India soon thereafter, the proportion of the MORB-like component gradually declined in lavas erupted along the oceanic trace of the Reunion hotspot, the Chagos-Laccadive Ridge [11]. This composite (MORB plus Reunion) character of Deccan parental magmas and the subsequent domination of the Reunion end-member can be accommodated conceptually in a recent hypothesis [12,13] that flood basalts, and often continental rifting, are triggered by the arrival of inflated plume "heads" at the base of the lithosphere. As a nascent plume head rises through the convecting mantle, it should entrain substantial quantities of the surrounding material, whereas the narrow plume "tail" that follows will entrain a much smaller fraction of non-plume mantle (e.g. [11,13]).

Plate reconstructions place Madagascar, then the westernmost portion of Indo-Madagascar, over the Marion or Crozet hotspot in the interval between about 120–80 Myr (see Fig. 2) [7,14]. By 80 Myr the hotspot was off the southern end of Indo-Madagascar, similar to the disposition of western India near the Reunion hotspot at 65 Myr. Around the same time, Madagascar rifted from Greater India, much as the Seychelles Block would do 15 Myr later with the waning of Deccan volcanism (e.g. [7,15]). Given these plate-tectonic similarities between the two provinces, plus the fact that their basement crusts were originally contiguous, geochemical parallels might be expected as well. The principal objectives of the present work were to assess for the first time the geochemical importance of Marion or Crozet hotspot and MORB mantle sources in the basalts of southern Madagascar, and to evaluate the nature and influence of continental lithosphere in their genesis.

2. Samples and methods

The samples analyzed here include both tholeiitic and alkalic lavas and dikes, chosen to cover the range of chemical compositions reported by Dostal et al. [5]. Two of the tholeiites are from flows in the southeastern coastal exposures (samples 58, 60), one (59) is from a dike in the same region; six others are from flows and dikes in the southwest. All of the alkalic samples, which include two basanites (7, 52), are from a major NW-oriented dike swarm in the southwest (see Fig. 1, and [5]).

Preparation for mass spectrometric analysis involved a sequential, three-step ion-exchange column procedure used routinely at the Hawaii Institute of Geophysics. Following dissolution of 20–40 mg, each sample was split, and one aliquant spiked with ^{206}Pb, ^{146}Nd, ^{149}Sm, ^{84}Sr, and ^{87}Rb tracers. Pb was then separated from both spiked and unspiked splits in a two-step elution with

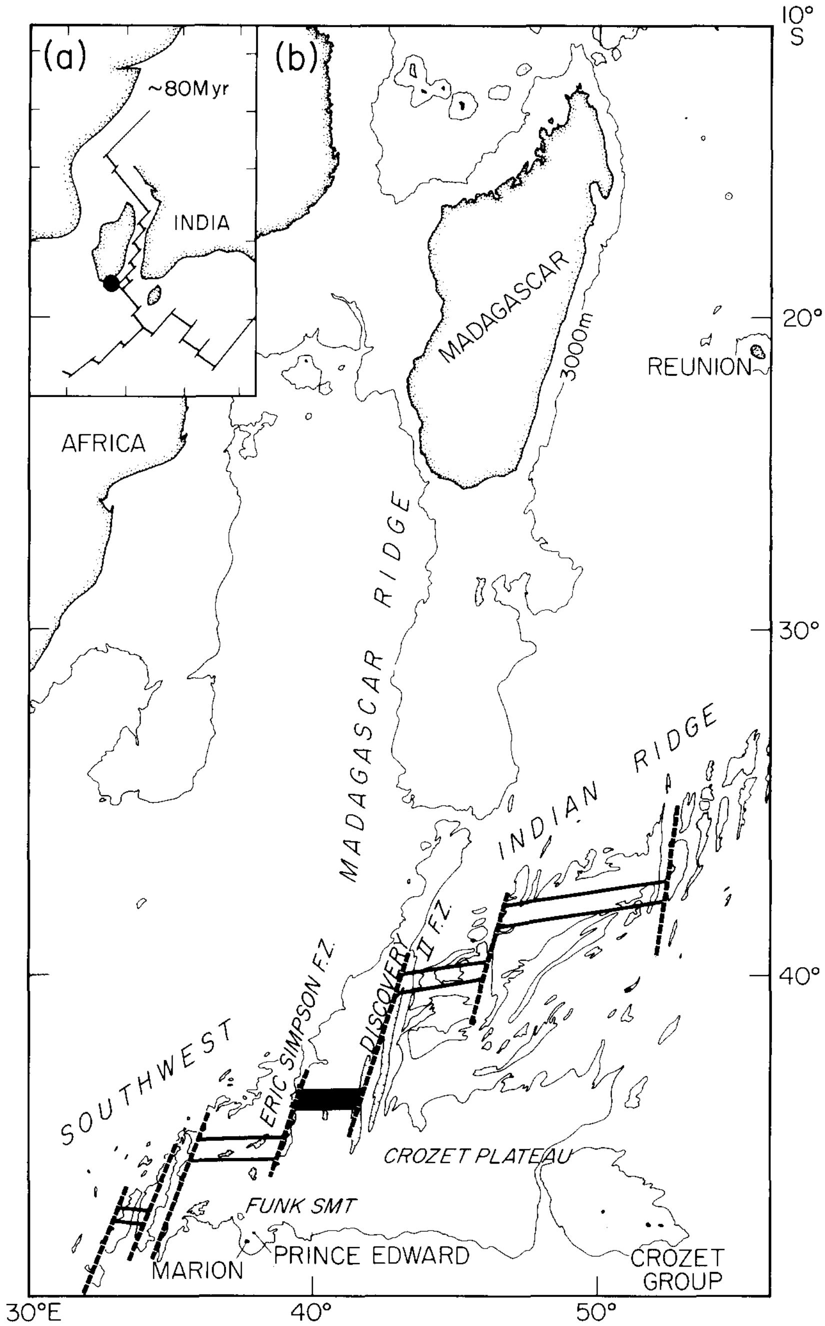

Fig. 2. (a) Inset: reconstruction at 80 Myr showing location of southern Madagascar near the Marion hotspot (black dot) and the incipient splitting of Indo-Madagscar [37]. (b) Present configuration of Madagascar, the Madagascar Ridge, Marion, Prince Edward, and the Crozet islands, Funk seamount, and the central Southwest Indian Ridge (ridge segment locations taken from le Roex et al. [21]). The low 6/4 ridge segment is indicated by a black bar. Contour shown is the 3000 m isobath.

mixed HBr-HNO_3 solutions on 50-μl anion exchange columns [16]. The wash from the spiked split was loaded onto a 0.6 × 20 cm cation exchange column; Rb and Sr were eluted with 2*N* HCl, followed by the rare earth elements as a group in 4*N* HCl (e.g. [17]). Finally, Sm and Nd were separated from the other rare earth elements with an α-hydroxy-isobutyric acid elution on a 0.2×20 cm cation column (e.g. [18]). Total blanks, listed in Table 1, are negligible in all cases.

Mass spectrometric measurements were performed on the VG Sector multicollector instrument at the Hawaii Institute of Geophysics. Nd and Sr were analyzed in the dynamic multicollector mode, Nd (typically 100–150 ng) as the oxide on single Re filaments (e.g. [18]), Sr (about 600–800 ng) on Ta single filaments with Ta_2O_5 substrate (e.g. [19]). Pb was run on single Re filaments with silica gel evaporator and H_3PO_4 (e.g. [20]); the spiked fraction was analyzed first to determine concentration, then 4–8 ng of the unspiked aliquant were loaded and measured for isotopic composition either in single collector or static multicollector mode. Two such runs were made for many of the samples here. Standard reference values, estimated uncertainties, and fractionation corrections are given in Table 1, along with the isotopic data. Isotope dilution results are presented in Table 2.

The Nd and Sr isotopic values in Table 1 have been age-corrected to 75 Myr using measured parent/daughter ratios. This age represents a probable minimum based on biostratigraphic controls in southwestern Madagascar (e.g. [1,3]); many of the K-Ar dates reported by Dostal et al. [5] are in this range as well. An adjustment also has been applied to the Pb isotopic data by using our measured Pb abundances, the Th concentrations for the same samples given by Dostal et al. [5], and assuming Th/U = 4.0. This is an approximate correction because magmatic Th/U can be somewhat less or greater than 4.0; thus the adjusted

TABLE 1

Isotopic data for Madagascar lavas

Sample	$\epsilon_{Nd}(T)$ [a]	$(^{87}Sr/^{86}Sr)_T$	$(^{206}Pb/^{204}Pb)_t$	$(^{207}Pb/^{204}Pb)_t$	$(^{208}Pb/^{204}Pb)_t$
Tholeiites					
39	−17.4 (−18.0)	0.72126 (0.72158)	18.832 (19.003)	15.879 (15.887)	40.728 (40.945)
46	−6.5 (−7.1)	0.71185 (0.71257)	18.639 (18.856)	15.862 (15.872)	41.037 (41.313)
47	−11.2 (−11.8)	0.71776 (0.71813)	18.215 (18.373)	15.773 (15.870)	40.690 (40.890)
50	−7.6 (−8.2)	0.71540 (0.71567)	18.224 (18.392)	15.744 (15.752)	40.623 (40.836)
55	−5.0 (−5.5)	0.71135 (0.71201)	18.302 (18.480)	15.776 (15.783)	39.927 (40.115)
1	−8.9 (−9.5)	0.71752 (0.71787)	18.427 (18.594)	15.784 (15.792)	40.634 (40.847)
58	+5.8 (+5.7)	0.70317 (0.70322)	17.904 (18.108)	15.523 (15.533)	37.751 (38.011)
59	+3.3 (+2.9)	0.70439 (0.70442)	(17.011)	(15.150)	(37.980)
60	+5.6 (+5.3)	0.70326 (0.70328)	17.751 (17.912)	15.518 (15.526)	38.897 (38.102)
Alkalic lavas					
2	+4.7 (+4.2)	0.70392 (0.70403)	18.113 (18.306)	15.536 (15.545)	37.885 (38.130)
8	+2.5 (+2.0)	0.70410 (0.70431)	17.735 (17.869)	15.487 (15.493)	37.588 (37.758)
10	−1.5 (−2.2)	0.70458 (0.70468)	17.429 (17.600)	15.478 (15.486)	37.693 (37.910)
43	+3.3 (+2.9)	0.70440 (0.70444)			
44	+3.7 (+3.2)	0.70459 (0.70470)	17.935 (18.206)	15.505 (15.518)	37.949 (38.294)
45	+4.8 (+4.4)	0.70371 (0.70385)	17.945 (18.197)	15.507 (15.519)	37.872 (38.192)
7	+1.3 (+0.4)	0.70440 (0.70446)	17.962 (18.540)	15.539 (15.566)	38.069 (38.803)
52	−2.5 (−3.4)	0.70566 (0.70575)	17.550 (18.098)	15.608 (15.634)	39.071 (39.767)

Values for Nd, Sr, and Pb isotopic ratios are age-corrected to 75 Myr as described in text. Adjacent values in parentheses are present-day ratios.

Isotopic fractionation corrections are $^{148}Nd/^{144}Nd = 0.241572$, $^{86}Sr/^{88}Sr = 0.1194$. Data are reported relative to Hawaii Institute of Geophysics standard values: for La Jolla Nd, $^{143}Nd/^{144}Nd = 0.511855$; for BCR-1, $^{143}Nd/^{144}Nd = 0.512630$; for NBS 987 Sr, $^{87}Sr/^{86}Sr = 0.71025$; for E&A Sr, $^{87}Sr/^{86}Sr = 0.70803$. The total range measured for La Jolla Nd is ± 0.000012 (0.2 ϵ units); for NBS 987 it is ± 0.000022. Pb isotopic ratios are corrected for fractionation using the NBS 981 standard values of [47]; the total ranges measured are ± 0.008 for $^{206}Pb/^{204}Pb$, ± 0.008 for $^{207}Pb/^{204}Pb$, and ± 0.030 for $^{208}Pb/^{204}Pb$. Within-run errors on individual sample measurements are less than or equal to the above external uncertainties on the La Jolla, NBS 987, and NBS 981 standards in all cases.

Total procedural blanks are 10–40 pg for Pb, < 20 pg for Nd, and < 200 pg for Sr; all are negligible.

[a] Present-day $\epsilon_{Nd}(0) = 0$ corresponds to $^{143}Nd/^{144}Nd = 0.51264$; $\epsilon_{Nd}(T) = 0$ at 75 Myr corresponds to $(^{143}Nd/^{144}Nd)_T = 0.51254$, for $^{147}Sm/^{144}Nd = 0.1967$.

TABLE 2

Elemental abundance data for Madagascar lavas

Sample	Nd (ppm)	Sm	Sr	Rb	Th [a]	Pb
Tholeiites						
39	24.75	5.56	299.8	31.3	6.70	8.80
46	33.51	7.52	275.4	64 [b]	7.40	7.68
47	43.38	9.37	462.5	55.4	5.80	8.21
50	37.60	8.49	399.9	34.6	5.20	6.89
55	35.61	8.56	295.4	63.4	4.90	7.29
1	37.66	8.39	382.9	44.0	6.70	8.93
58	15.67	4.61	243.9	3.61	0.80	0.83
59	23.88	5.86	533.9	4.70		1.69
60	5.431	1.50	372.2	2.41	0.35	0.46
Alkalic lavas						
2	18.09	4.42	335.6	11.4	1.30	1.44
8	25.12	6.08	313.5	20.6	2.10	3.31
10	34.47	6.91	615.4	20.2	3.40	4.19
43	14.01	3.69	377.9	4.94	0.90	
44	15.86	3.92	376.3	13.6	1.30	1.02
45	24.32	6.13	372.2	17 [b]	1.80	1.53
7	57.28	9.41	1100	21.9	10.50	3.93
52	34.04	6.03	598.1	16.3	4.80	1.91

Nd, Sm, Sr, Pb, and Rb were measured by isotope dilution; uncertainties are estimated respectively at 0.2%, 0.2%, 0.4%, 1%, and 1% or better.

[a] Th data are INAA results from Dostal et al. [5].

[b] Measured by XRF [5].

$(^{206}Pb/^{204}Pb)_t$ values in some cases may be under- or over-corrected slightly. The effect of the Pb correction is major, however, only for the basanites, which have very high Th/Pb ratios.

3. Results

Isotopic data are depicted in Figs. 3–6, along with fields for Marion (Marion and Prince Edward islands and nearby Funk seamount) and Crozet; for normal MORB (N-MORB) from the central Southwest Indian Ridge, 17–50°E (SWIR); for a Southwest Indian Ridge segment south of Madagascar near 40°E, between the Eric Simpson and Discovery II fracture zones, which displays the lowest $^{206}Pb/^{204}Pb$ and ϵ_{Nd} values of any known spreading center (henceforth called the "40°E" or "low 6/4" Southwest Indian Ridge segment); and for Pacific and/or Atlantic N-MORB.

The Madagascan rocks define two strikingly different distributions, which are best discussed in terms of Dostal et al.'s [5] basic division (made on petrographic and major element grounds) into tholeiitic and alkalic types. One isotopic group is composed entirely of tholeiites from the southwestern part of the island, the other of the alkalic rocks and the tholeiites from the east coast. The southwestern tholeiites span a wide range of isotopic values, all having markedly negative $\epsilon_{Nd}(T)$ (-5.0 to -17.4), and very high $(^{87}Sr/^{86}Sr)_T$ (0.71135 to 0.72126) and $(^{208}Pb/^{204}Pb)_t$ (39.93 to 41.04). In contrast, the second group exhibits a more restricted overall range of variation; it describes a steep, relatively low $(^{87}Sr/^{86}Sr)_T$ trend in Fig. 3, which extends toward low $(^{206}Pb/^{204}Pb)_t$ in Figures 4 and 5. The two samples with the highest $\epsilon_{Nd}(T)$ of $+5.8$ and $+5.6$, similar to more radiogenic oceanic island mantle values, are from the tholeiitic flows along the east coast. Note that the $(^{206}Pb/^{204}Pb)_t$ values of these two specimens (58, 60; see Figs. 4, 5) are within or very close to the field of present central Southwest Indian Ridge N-MORB but are much lower than for Marion today (by about 0.6–0.7); the difference with Crozet is even more pronounced, based on the very limited data available for the Crozet archipelago. The Sr isotopic ratios of samples 58 and

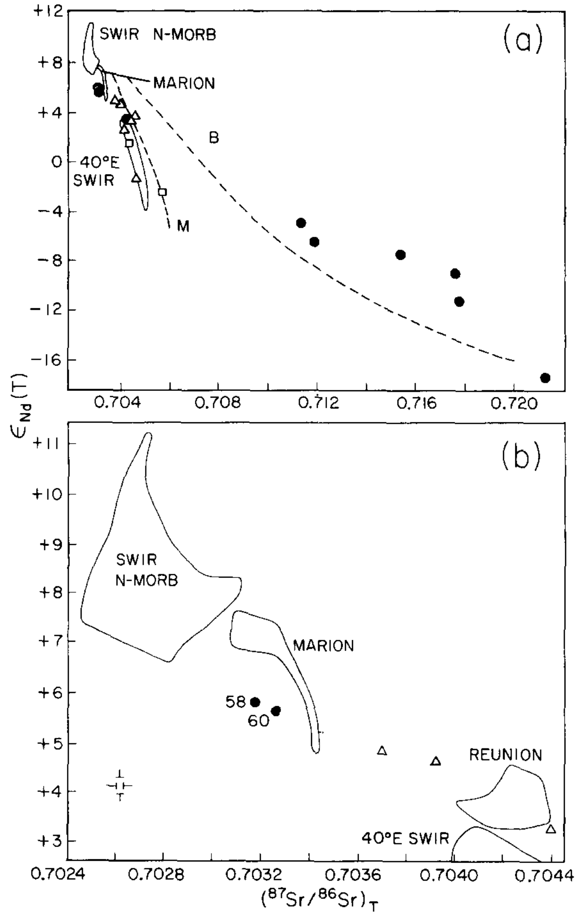

Fig. 3. (a) Initial ϵ_{Nd} and Sr isotopic ratios for southern Madagascan lavas. Solid circles represent tholeiites, hollow triangles alkalic basalts, and hollow squares basanites. Dashed curves indicate Ambenali-Poladpur-Bushe (*B*) and Ambenali-Mahabaleshwar (*M*) trends in the western Deccan Traps. Note the general similarity between Madagascan and Deccan trends. (b) High ϵ_{Nd} end of (a) showing positions of tholeiites 58 and 60 well to the left of Marion field at comparable ϵ_{Nd}. Data for normal and low 6/4 MORB from the central Southwest Indian Ridge, 17–50°E (SWIR N-MORB and 40°E SWIR) are from [27,29,40]. Fields for Marion (Marion and Prince Edward islands, and Funk seamount) and Reunion are from [27,41,21,42].

60 also are less than for Marion at a given value of ϵ_{Nd} (Fig. 3b), and much less than for Crozet (Fig. 4). Of course, even assuming no changes in hotspot chemical compositions, the positions of the Marion and Crozet fields on the figures would have changed slightly during the last 75 Myr simply because of continued decay of ^{87}Rb, ^{147}Sm, U, and Th in the source mantle. Pb isotopic ratios would have changed the most owing to the comparatively short half-lives of U and Th. However, it is highly unlikely that ^{206}Pb/^{204}Pb, for example, has increased for either Marion or Crozet by this mechanism by more than about 0.2 (corresponding to a ^{238}U/^{204}Pb value of 20 typically assumed for oceanic island sources). Likewise, based on Rb/Sr values of high-Mg Marion and Prince Edward island alkalic basalts ($\sim$ 0.02–0.03; A. le Roex, unpublished data, 1989), Marion ^{87}Sr/^{86}Sr would have increased less than $6-9 \times 10^{-5}$.

Data for several alkalic rocks approach—but do not attain—the high $\epsilon_{Nd}(T)$ and low $(^{87}Sr/^{86}Sr)_T$ values of the east coast tholeiitic flows (Fig. 3), with which Dostal et al. [5] have noted they have similarities in several incompatible element ratios (e.g., Nb/La, Th/La, Zr/Hf). Pb isotopic ratios for the alkalic samples lie mostly between the fields of Marion and the low 6/4 Southwest Indian Ridge segment; that is, mostly within the field encompassed by central Southwest Indian Ridge N-MORB (Fig. 5a, b), but their Nd and Sr

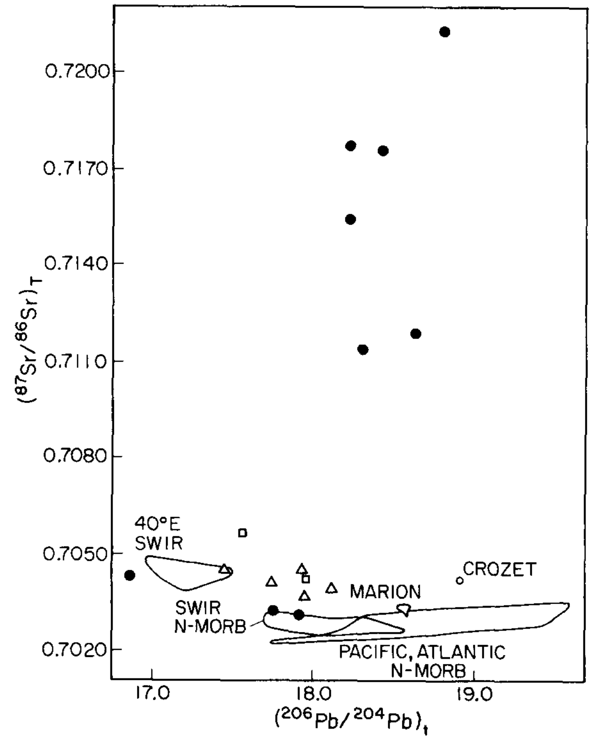

Fig. 4. $(^{87}Sr/^{86}Sr)_T$ versus $(^{206}Pb/^{204}Pb)_t$ for southern Madagascan samples. Symbols and sources as in Fig. 3, plus data for Crozet from [43]. Note that Pb isotopic ratios for sample 59 are present-day values.

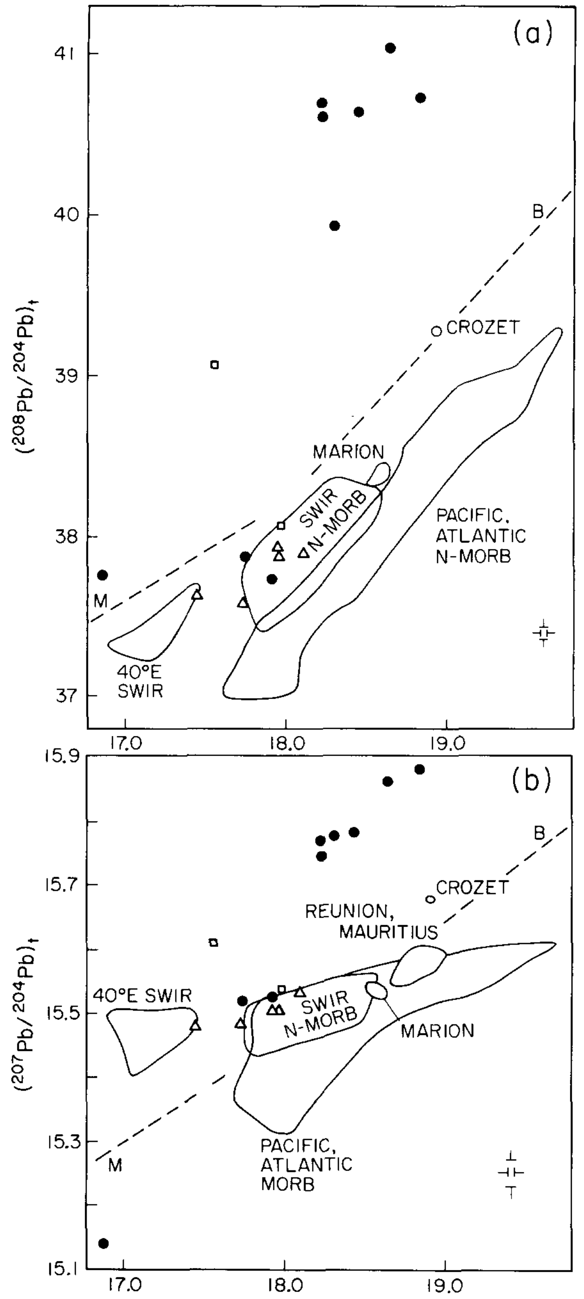

Fig. 5. (a) (^{208}Pb/ ^{204}Pb)$_t$ versus (^{206}Pb/^{204}Pb)$_t$ and (b) (^{207}Pb/^{204}Pb)$_t$ versus (^{206}Pb/^{204}Pb)$_t$. Symbols and data sources as in Figs. 3 and 4. Note the difference between southwest Madagascan tholeiites and the dashed Poladpur-Bushe trend of the Deccan (B). Mahabaleshwar trend of the Deccan is summarized by dashed line M (from data in [10]).

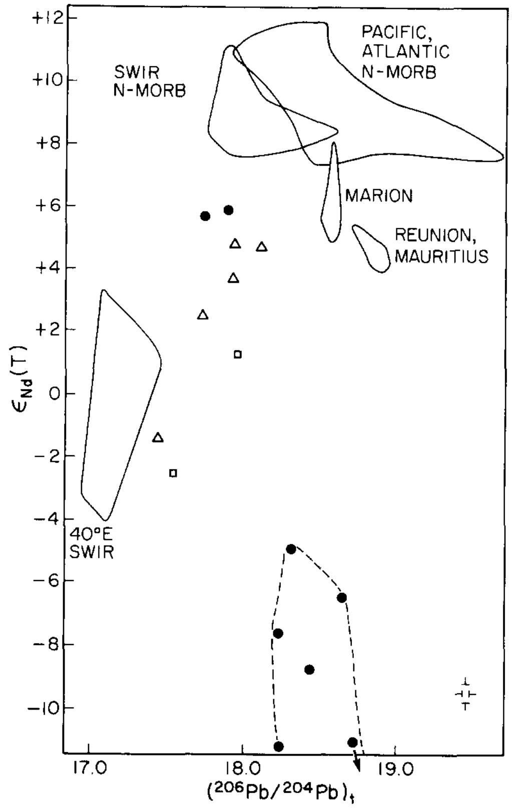

Fig. 6. $\epsilon_{Nd}(T)$ versus (^{206}Pb/^{204}Pb)$_t$. Symbols and data sources as in Fig. 3. Note the trend of alkalic basalts toward the low 6/4 40°E Southwest Indian Ridge field.

isotopic values, respectively, fall well below and above this field (Figs. 4, 6). One sample (10) is isotopically almost identical to the unusual low 6/4 Southwest Indian Ridge basalts near 40°E. Sample 52 (a basanite) also has low (^{206}Pb/^{204}Pb)$_t$, but stands out in the figures because of its markedly higher (^{208}Pb/^{204}Pb)$_t$, (^{207}Pb/^{204}Pb)$_t$, and (^{87}Sr/^{86}Sr)$_T$ than the other alkalic rocks. As with the east coast tholeiitic flows, none of the data for the alkalic lavas actually overlap the fields for Marion or Crozet. Lastly, the tholeiitic dike from the east coast of Madagascar (59) is unique among all the samples studied in that it possesses unusually low ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb, yet relatively high ^{208}Pb/^{204}Pb.

Isotopic results for the eastern and southwestern tholeiites as a group correlate relatively well with certain incompatible element ratios such as Ba/Nb and Th/Nb (Fig. 7). In contrast, the alkalic lavas, which range from basalts to basanites,

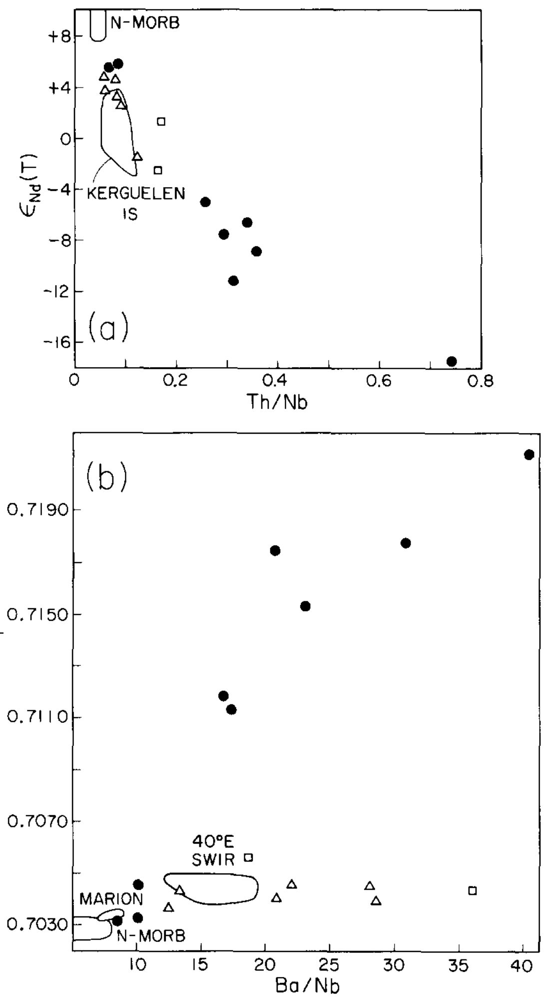

Fig. 7. (a) Th/Nb versus $\epsilon_{Nd}(T)$ and (b) Ba/Nb versus initial Sr isotopic ratios for southern Madagascar lavas. Symbols as in Fig. 3. Th/Nb and Ba/Nb data are from [5] for Madagascar rocks; Marion, N-MORB, and 40°E Southwest Indian Ridge fields are from [21,27]. Kerguelen Islands field in (a) is from [44].

generally show poorer correlations between isotopic and incompatible element ratios, possibly as a result of variable degrees of partial melting. Also, their Ba/Nb ratios extend to greater values (from 12 up to 36 [5]) than have yet been found on any oceanic ridges or islands, even such high Ba/Nb examples as the low 6/4 Southwest Indian Ridge segment at 40°E, Kerguelen, Tristan, or Gough (all of which have Ba/Nb < 19; e.g. [21]). The higher values may largely be a consequence of Ba mobilization during low-temperature alteration; several alkalic samples with low H_2O loss on ignition (< 0.6% [5]), for example, have Ba/Nb between 12 and 15 (still higher than most oceanic lavas, however).

4. Discussion

A rather remarkable resemblance exists in Nd and Sr isotopes between the Madagascan basalts and the upper-level formations of the Deccan Traps. Like the Madagascan rocks, the upper Deccan lavas define two distinct groupings (summarized by dashed curves in Fig. 3a) (e.g. [10,22,23]). Specifically, the Bushe, Poladpur and Ambenali Formations of the Deccan describe an elongate array which extends from values typical of oceanic rocks (the Ambenali at $+7\ \epsilon_{Nd}(T)$) to $\epsilon_{Nd}(T)$ as low as -16 and $(^{87}Sr/^{86}Sr)_T$ as great as 0.7200 (Bushe). The Madagascan tholeiites follow a roughly parallel trend and attain even higher $(^{87}Sr/^{86}Sr)_T$ and lower $\epsilon_{Nd}(T)$. Likewise, the Mahabaleshwar Formation overlying the Ambenali in the Deccan defines a steep, low $^{87}Sr/^{86}Sr$ array (anchored at its high $\epsilon_{Nd}(T)$ end by the Ambenali data), which is superficially very similar to that of the Madagascan alkalic dikes.

The Bushe–Poladpur–Ambenali sequence represents one of the best-documented cases of contamination of flood basalt magmas by Precambrian, broadly granitic crust (e.g. [10,22–24]). Going upward in the section, the level of contamination gradually decreases (from a Bushe high of perhaps 20%), such that the Ambenali flows are virtually uncontaminated. The latter are superseded by the Mahabaleshwar lavas which, although tholeiitic, possess elevated contents of incompatible elements, including Nb. This formation records the advent of a continental lithospheric end-member toward the end of Deccan volcanism, which acted either as a new contaminant or as a direct source of magmas (e.g. [9,10,22–24]).

4.1. Southwestern Madagascan tholeiites

The southwestern Madagascan tholeiites appear to be the products of variable contamination by a continental end-member not unlike that involved in the Bushe and Poladpur Formations of the Deccan. Incompatible element data support this interpretation, particularly in the telltale negative primitive-mantle-normalized Nb anomalies, high Th/Nb, Ba/Nb [5], and strongly positive Pb anomalies typical of many crustal rocks (see Figs. 7, 8a). Their highly elevated $(^{208}Pb/^{204}Pb)_t$ and $(^{207}Pb/^{204}Pb)_t$ also indicate substantial contamination by continental material, probably crust. Despite these important similarities, however, the contaminant of the Madagascar tholeiites was clearly different than that of the Bushe Formation (see Fig. 5), for the former all possess relatively low $(^{206}Pb/^{204}Pb)_t$ (less than 18.8), whereas the Bushe data extend to much higher values (19.7–22.5) at comparable $(^{207}Pb/^{204}Pb)_t$ and $(^{208}Pb/^{204}Pb)_t$) [10]. Moreover, the Bushe flows exhibit much more pronounced negative primitive-mantle-normalized Sr anomalies than the Madagascan lavas, consistent with contamination by very low-Sr crust. Basalts in the southern Karoo which also have somewhat similar incompatible element patterns to those of the southwestern Madagascar tholeiites have been interpreted in terms of lithospheric mantle influences, but they have much higher Nd and much lower Sr isotopic values [25,26].

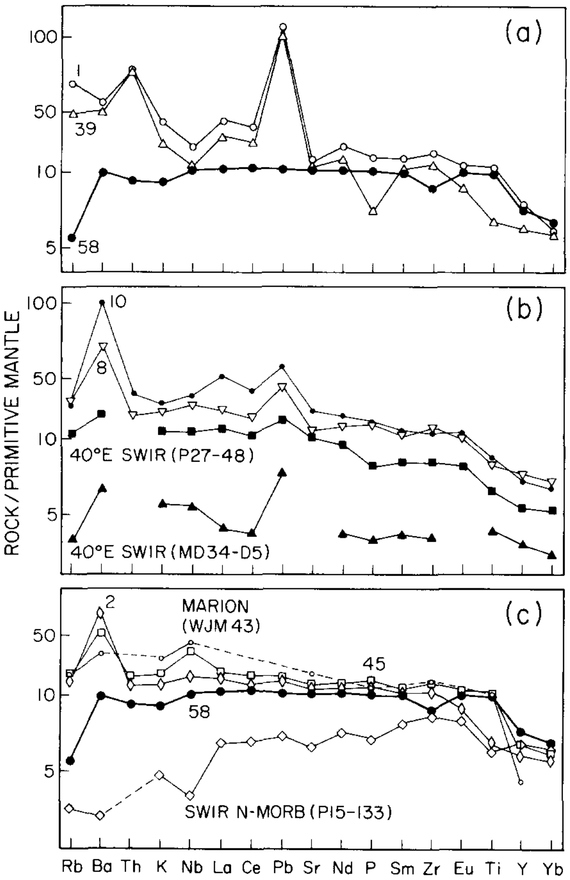

Fig. 8. (a) Primitive-mantle-normalized incompatible element patterns of two high $(^{87}Sr/^{86}Sr)_T$ southwestern tholeiites (39, 1) and an east coast tholeiite (58). Note the prominent, positive Pb and negative Nb peaks on the former. (b) Patterns for alkalic basalts 8 and 10, and two samples from the low 6/4 40°E Southwest Indian Ridge segment (P27-48, MD34-D5. Note: Sr and Eu data have been left off the pattern for MD34-D5, as the sample analyzed contains abundant plagioclase phenocrysts which have elevated Sr and Eu abundances over those in a pure liquid composition.) (c) Patterns for east coast tholeiite 58, high ϵ_{Nd} alkalic basalts 2 and 45, and a N-MORB (P15-133) from the central Southwest Indian Ridge, plus a partial pattern for a Marion island basalt (WJM 43). Data for Madagascan basalts from Table 2 and [5]; for Southwest Indian Ridge and Marion basalts from [21,27,45]. Normalizing values used are those of [46].

Another important difference between the western Deccan and Madagascan tholeiites is that in the Bushe–Ambenali sequence the most contaminated flows tend to be the least evolved in terms of Ni, Cr, and Mg-number, counter to expectations based on conventional notions of coupled assimilation and fractional crystallization (e.g. [22–24]). All the contaminated Madagascan tholeiites are quite evolved, however, with low Mg-number (0.38–0.43), Ni (27–39 ppm) and Cr (6–43 ppm) [5], at least superficially consistent with coupled fractionation and assimilation. Also, unlike the Deccan, voluminous rhyolites were extruded more or less contemporaneously with the basalts in southern Madagascar [1,4]; this suggests the possibility of mixing of rhyolitic magmas into basaltic magmas as an alternate contamination mechanism. A more detailed analysis is precluded at present by the large isotopic gap between the southwestern and east coast tholeiites in the existing sample collection, the lack of knowledge of flow stratigraphy, and of data on rhyolite compositions.

4.2. *East coast tholeiites*

On the east coast, the dike represented by sample 59 provides evidence for the existence of very low $^{206}Pb/^{204}Pb$ material, probably ancient, lower continental crust or lithospheric mantle, but its extremely low $^{207}Pb/^{204}Pb$ indicates that such material was not particularly important in the genesis of the other samples studied (see Fig. 5b).

The two high $\epsilon_{Nd}(T)$ tholeiitic flows from the east coast (58, 60) show little or no sign of contamination (they lack Nb and Pb anomalies, for example) and thus provide important insights into the nature of their mantle source. Their isotopic values are neither consistently MORB-like nor like those of Marion or Crozet. By analogy with the Ambenali Formation of the Deccan, they might be expected to reflect a mixed MORB and Marion—or Crozet—parentage; and indeed, their incompatible element patterns and ratios are generally transitional between those of N-MORB and oceanic island basalts [5] (see Fig. 8c, for example). However, the combined isotopic results indicate that the situation is not so simple. For instance, Fig. 6 shows that the data for these two lavas do not lie strictly between (or within) the fields for Marion and either Atlantic or central Southwest Indian Ridge N-MORB. Nor do they fall along plausible mixing curves between a mixed Marion–MORB source and the relatively high $^{206}Pb/^{204}Pb$ contaminant of the southwestern tholeiites. Instead, they plot directly *beneath* the Southwest Indian Ridge N-MORB field. If they do result from N-MORB and Marion mixtures, then the isotopic data appear to require the addition of small amounts of low 6/4 material similar to that now beneath 40°E on the Southwest Indian Ridge. Alternatively, the results also can be accounted for by admixture of Southwest Indian Ridge or Atlantic-type N-MORB mantle with small amounts of the low 6/4 component. Thus, the presently available data certainly are compatible with a Marion hotspot contribution to the Madagascan tholeiites but they do not absolutely require it. Significantly, there is no evidence for a magmatic influence from material with modern Crozet isotopic characteristics.

4.3. Alkalic suite

With one exception (see below), the alkalic samples lack the high $(^{208}Pb/^{204}Pb)_t$, $(^{207}Pb/^{204}Pb)_t$ signature of the contaminated southwestern tholeiites. On the whole, they exhibit Pb, Nd, and Sr isotopic ratios intermediate between those of modern Marion and the low 6/4 section of the Southwest Indian Ridge. As noted earlier, their Pb isotopic values for the most part fall within the field of N-MORB from the central Southwest Indian Ridge. However, their Nd and Sr isotope ratios are respectively lesser and greater than for either Atlantic or central Southwest Indian Ridge N-MORB, for Marion, or for the little-contaminated east coast tholeiitic flows. Unlike the east coast tholeiites, they appear as a group to record variable but more significant interaction of a comparatively high ϵ_{Nd} end-member with a low $^{206}Pb/^{204}Pb$, low ϵ_{Nd}, relatively low $^{87}Sr/^{86}Sr$ reservoir similar to that now beneath the Southwest Indian Ridge at 40°E (see Fig. 6, for example).

Whether their high ϵ_{Nd} mantle end-member was equivalent to that of modern Marion or was a mixture of Marion and N-MORB-type mantle cannot be ascertained with the present set of samples; but a pure N-MORB end-member appears unsuitable given the location of the alkalic basalt data array well above the central Southwest Indian Ridge N-MORB field in Fig. 4. Dostal et al. [5] noted that several alkalic samples are not drastically different in many of their incompatible element ratios than the high $\epsilon_{Nd}(T)$ tholeiites (see Fig. 8c, for example), and suggested that they may have shared a common mantle source. The isotopic results confirm that the source for the higher $\epsilon_{Nd}(T)$ alkalic basalts was at least similar to that of the two east coast tholeiitic flows, despite their bulk chemical differences and spatial separation.

Only one of the alkalic samples analyzed for isotopes (52, a basanite) appears to have been contaminated appreciably by high $^{208}Pb/^{204}Pb$ continental material like that affecting the southwestern tholeiites (Fig. 5a; also 5b, 4, 3a), although both types are present in the same general area. This is perhaps surprising given that the Nd, Sr, and Pb contents of several of the alkalic lavas are only a factor of two or less greater than for the east coast tholeiites (Fig. 8c, Table 2, and [5]). However, the alkalic samples are generally much less evolved than the southwestern tholeiites [5], suggesting that most may have migrated to the surface quickly, without residing at length in crustal or subcrustal magma reservoirs or conduits.

4.4. Low 6/4 end-member

Several factors may be relevant for deciphering the origin of the low 6/4 end-member manifested in the alkalic basalts. Understanding its nature is important not just for the Madagascan province, but also because material with the same general characteristics is in large part responsible for the unique isotopic composition of Indian Ocean MORB today. Its expression along the Indian Ocean ridge crests is highly variable, but by far the strongest signature in the entire Indian Ocean (to date) is found south of Madagascar on the Southwest Indian Ridge segment near 40°E; isotopic and chemical data, in fact, permit only a small fraction of normal MORB-type mantle to be present beneath this segment at the depth of magma generation [21,27]. The location of this ridge segment is precisely the same (in the hotspot reference frame) as that occupied by Madagascar around the time of flood basalt volcanism, a relationship that is unlikely to be coincidental. This segment also lies at the southern end of the submarine Madagascar Ridge, the presumed post-80 Myr oceanic trace of the Marion hotspot on the African plate (e.g. [14,28]). Significantly, however, the distinctive low $^{206}Pb/^{204}Pb$, low ϵ_{Nd} isotopic signature appears to be completely *absent* at the Marion hotspot today. Moreover, where somewhat similar low 6/4 signals are observed elsewhere on the Indian Ocean spreading centers, most notably at the triple junction and on the northern Carlsberg Ridge south of the Owen Fracture Zone, they are not associated in any simple way with hotspots [27,29].

In Madagascar, dikes of the southwestern swarm from which the alkalic samples were taken are strongly oriented in a NW–SE direction [1,5]. Such oriented intrusions, indicative of lithospheric extension, slightly postdate the main tholeiitic phase in several flood basalt provinces, wherein the bulk of eruptive activity appears to have transpired under regimes of little or no extension [30]. If pertinent to the Madagascan province also, then the implication is that major expression of the low 6/4 end-member was contingent upon lithospheric extension.

In conjunction with the above considerations, the most plausible original location of the low 6/4 end-member would appear to be in the continental lithosphere of Madagascar. Indeed, the required isotopic signature appears to be quite common in old continental lithosphere in general (e.g. [31]). Dostal et al. [5] also concluded on the basis of high Th/Nb, Ba/Nb and other incompatible element ratios that a continental lithospheric component was involved in the generation of some of the alkalic rocks. Removal of this type of material into the shallow convecting mantle now beneath the Southwest Indian Ridge at 40°E would be a consequence of continued extensional thinning and hotspot-driven thermal erosion of the Madagascan lithosphere. That a low 6/4 signal remains so pronounced today beneath the ridge at 40°E implies limited dispersal of material in an along-axis direction [27], and may largely reflect the rate and direction of shallow mantle flow beneath the region and the extremely slow spreading on the Southwest Indian Ridge since the Late Cretaceous (e.g. [32]). Somewhat similar scenarios of lithospheric detachment have been proposed for other areas by Hawkesworth et al. [33], Mahoney et al. [29], and Storey et al. [34].

An altogether different view is that the low 6/4 reservoir intrinsically belongs to the Marion hotspot, which then must be seen as being composed of two very different isotopic components. In this case, both the Madagascan alkalic rocks and the low 6/4 Southwest Indian Ridge basalts at 40°E would owe their distinctive compositions solely to hotspot mantle (cf. [35]), at 40°E presumably by a hotspot source-ridge sink interaction (e.g. [36]). The critical requirement of this hypothesis is that the low $^{206}Pb/^{204}Pb$, low ϵ_{Nd} component currently must be entirely dormant in the hotspot; that is, that it fortuitously happens not to have been involved in generating hotspot magmas on Marion or Prince Edward islands or Funk seamount in the recent past, as none shows any evidence for its presence. Such a possibility probably should not be discarded outright, because these volcanoes provide only a recent "snapshot" of the long geologic history of the Marion hotspot. Presently, its volcanic output is quite low and it appears to be in a period of much-reduced intensity. Drilling or dredging along the trace of the hotspot, particularly on the Antarctic plate, would provide information on temporal variation in hotspot composition. For the present, we note that no oceanic island in the world has yet been found to have the extremely low $^{206}Pb/^{204}Pb$ (to 16.87 [27]) displayed by the ridge basalts at 40°E.

Interestingly, a broadly analogous situation can be found among the early Cretaceous HPT (high phosphorous and titanium) flood basalts of the Parana province of Brazil, available mid-Cretaceous samples from the Rio Grande Rise and Walvis Ridge (on the paleo-track of the Tristan hotspot), and the recent products of the Tristan hotspot at Tristan da Cunha and Gough islands. The latter have restricted $^{206}Pb/^{204}Pb$ values similar to those of Marion (though with much lesser ϵ_{Nd} and greater $^{87}Sr/^{86}Sr$), whereas the analyzed HPT, Walvis Ridge, and Rio Grande Rise lavas display a range of substantially lower $^{206}Pb/^{204}Pb$ (to 17.1 in the HPT basalts) [33,37,38].

5. Summary and conclusions

The sources of Upper Cretaceous tholeiitic and related alkalic basalts in southern Madagascar can be explained as combinations of three different mantle components, all of which are expressed today in the Indian Ocean in or near the region that was overlain by Madagascar (hotspot reference frame) at the time of major volcanism. They are: (1) Marion hotspot, (2) normal MORB, and (3) unusually low $^{206}Pb/^{204}Pb$, low ϵ_{Nd} mantle similar to that now located beneath the Southwest Indian Ridge segment near 40°E. There is no evidence for a contribution by material of Crozet isotopic composition, based on the very limited data available for the Crozet Islands.

The low $^{206}Pb/^{204}Pb$ end-member is important mainly in the (possibly late stage) alkalic dike rocks. It originally could have been situated in the lithospheric mantle of Madagascar, a portion of which subsequently would have been stranded in the shallow convecting mantle by the erosive action of the Marion hotspot or lithospheric thinning associated with the separation of Madagascar and Greater India. Alternatively, it could have been a component of the Marion hotspot itself; however, recent products of the hotspot, which completely lack low $^{206}Pb/^{204}Pb$, low ϵ_{Nd} signatures, do not support this idea.

In southwestern Madagascar, the tholeiitic basalts were highly, though variably, contaminated by ancient, low ϵ_{Nd}, high $^{87}Sr/^{86}Sr$ continental material, most probably crust. Its composition was broadly similar to that which contaminated the Bushe and Poladpur Formations of the later Deccan Traps in western India, but was significantly lower in $^{206}Pb/^{204}Pb$ at comparable $^{208}Pb/^{204}Pb$. An east coast tholeiite dike records contamination by a very low $^{207}Pb/^{204}Pb$, low $^{206}Pb/^{204}Pb$ end-member different than the low $^{206}Pb/^{204}Pb$ material affecting the alkalic rocks.

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