

Th–Sr–Nd–Pb isotope and trace element evidence for the origin of the São Miguel, Azores, enriched mantle source

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Abstract

A suite of young alkali basalts from across the island of São Miguel has been analyzed for major and trace element concentrations and Sr, Nd, Pb and Th isotopic compositions in order to document the intra-island variation, and to constrain the processes involved in the formation of the enriched mantle sources of these lavas.

As shown in previous studies, large isotopic and trace element variations correlate with geographic location across São Miguel. New Th isotope data show a similar correlation, with $(^{230}\text{Th})/(^{232}\text{Th})$ varying from 1.094 to 0.877. These variations are attributed to two-component mixing, where the western end of the island is similar to the source of the Azores Platform tholeiites, and the eastern end of the island has a more enriched, EMII-type source. Trace element systematics indicate that the São Miguel enriched mantle source is enriched relative to the predominant Azores plume source in elements including K, Rb, Th, U, Pb and Zr, but not Ba, Nb or Ti.

Incorporation into the Azores plume of approximately 5% subduction-processed terrigenous sediment can explain many of the trace element and isotopic characteristics of the São Miguel enriched mantle source. However, this mechanism cannot easily explain the constant Cs/Rb ratios across the island, the concave downward trend of Ba/Th vs. Ti/Zr, and the recent decrease in Th/U of the São Miguel enriched mantle source documented by Th and Pb isotope systematics.

An alternative model is that the São Miguel enriched mantle source is subcontinental lithospheric mantle. This is supported by the similarity of the trace element signatures of the São Miguel enriched mantle source to those of hydrous metasomatized mantle xenoliths. In particular, the low Ba/Rb signature of the São Miguel enriched mantle, which is unusual for oceanic basalts, is a characteristic of many hydrous metasomatized mantle xenoliths and magmas believed to be derived from such sources. We propose that this subcontinental lithospheric mantle resided originally beneath northwestern Africa or Iberia but was delaminated during rifting upon the opening of the Atlantic Ocean basin, and that it is presently a shallow, localized contaminant that is melted due to an influx of heat from the Azores plume. © 1997 Elsevier Science B.V.

Keywords: Th; Sr; Nd; Pb; trace element; São Miguel; Azores; mantle source

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1. Introduction

Isotopic differences among oceanic basalts have provided unequivocal evidence of mantle source heterogeneity. During the past 30 years, a vast data base has grown that reveals systematic variations of Sr–Nd–Pb isotopic compositions within oceanic basalt suites. From this observation emerged a classification of mantle source compositions consisting of at least four end-member components that, when mixed, can produce the global isotopic variations (Zindler and Hart, 1986). These include a depleted, low $^{87}\text{Sr}/^{86}\text{Sr}$, low $^{206}\text{Pb}/^{204}\text{Pb}$ component (DMM), a low $^{87}\text{Sr}/^{86}\text{Sr}$, high $^{206}\text{Pb}/^{204}\text{Pb}$ component (HIMU), and two enriched components (EMI and EMII) which have low $^{143}\text{Nd}/^{144}\text{Nd}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ with relatively low and high $^{206}\text{Pb}/^{204}\text{Pb}$, respectively.

Despite the near-global coverage of Sr, Nd and Pb isotope data for oceanic basalts, the identity and location within the Earth of the isotopically distinct mantle sources remain elusive. The origins of the enriched sources EMI and EMII are the most contentious. These components appear to have both isotopic and trace element affinities with continental material, the main debate revolving around whether the signatures are due to metasomatic processes (Menzies, 1983), delaminated subcontinental lithosphere (McKenzie and O'Nions, 1983), or sediment recycling into the mantle (Weaver et al., 1986). The EM components are of special interest in that they are largely restricted to a narrow band in the Southern Hemisphere, termed the Dupal anomaly (Hart, 1984). This perhaps can be explained by extensive recycling of either sediment or delaminated subcontinental lithosphere during the formation or breakup of Pangea (Hart, 1988).

In this paper we investigate the isotopic and trace element systematics of São Miguel, Azores, the sole example of a strong EMII signature in the Northern Hemisphere (Hart, 1988). Trace element systematics and U-series disequilibria are used to distinguish the effects of partial melting vs. those of mantle source heterogeneity, and to infer the style of mantle source enrichments. Sr, Nd, Pb and Th isotope systematics are used to constrain the time-integrated history of the source enrichments.

2. Tectonic and geochemical setting

The Azores Archipelago, a group of nine islands straddling the Mid-Atlantic Ridge (MAR) between 37 and 40°N (Fig. 1), has long been recognized as an area unusual and complex in tectonic setting as well as in trace element and isotopic signatures. The islands emerge from the Azores Platform, a topographic high located at the triple junction of the African, Eurasian and North American plates. The formation of the Azores Platform was originally attributed to plume activity based on the observation that tholeiitic basalts from the MAR along the Azores Platform (henceforth platform tholeiites) exhibit a greater degree of light rare earth element (LREE) enrichment than tholeiites from normal ridge segments, and that there is a progressive increase in LREE enrichment as the platform is approached (Schilling, 1975). The platform tholeiites have since been found to have correspondingly high concentrations of large-ion-lithophile elements (LILE) and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (White et al., 1976; White and Schilling, 1978), as well as high Pb- and low Nd-isotopic ratios (Dupré and Allègre, 1980, 1984; Ito et al., 1987). These geochemical enrichments correlate with a topographic high and a positive gravity anomaly, suggestive of mantle upwelling beneath the Azores, and consistent with a hotspot origin (Schilling, 1975).

The alkali basalts of the Azores islands also are characterized by the elemental and isotopic enrichments observed in the platform tholeiites. São Miguel in particular is distinguished among the Azores islands by the extremity of its geochemical enrichments. Of the nine islands, São Miguel is the most potassic (Schmincke and Weibel, 1972; Schmincke, 1973), displays the most radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (White et al., 1979), and is among the most LREE-enriched (Flower et al., 1976). Another unusual feature of São Miguel is the strong intra-island heterogeneity, exhibited by large variations across the island in Sr, Nd, Pb and He isotopic signatures (Hawkesworth et al., 1979; Davies et al., 1989; Kurz, 1991; Kurz et al., submitted).

In addition to being unique in its geochemical characteristics, the island of São Miguel is tectonically unusual in that it is severed by a plate bound-

ary. The active Terceira Rift, which is thought to be the locus of the present-day Eurasian–African plate boundary, passes through the western side of the island. In detail, the rift is thought to pass through the ‘waist zone’ (Fig. 1), an area of NW–SE trending fissures (Booth et al., 1978) that has been the most volcanically active part of São Miguel during the Holocene (Moore, 1990). Most of the isotopic variation on São Miguel occurs within the western two-thirds of the island, and largely within the waist zone.

3. Sampling and analytical techniques

The suite of alkali basalts discussed in this paper include samples from the western end of São Miguel to within 25 km of the eastern end. The majority of the samples are from the waist zone that lies between the trachytic stratovolcanoes of Sete Cidades and Fumas. Approximate sample locations are

illustrated in Fig. 1, and corresponding ages listed in Table 1.

Major and trace element data (Table 1), with the exception of Rb, Sr, Sm, Nd, Pb, Th and U concentrations, were obtained on a Philips PW 1400 X-ray spectrometer with a Rh X-ray tube in Bochum. Measurements of both major and trace elements were made on glass fusion pellets with a 1:4 ratio of rock powder to lithium metaborate/dilithium tetraborate flux. Details of the analytical procedures and precision have been discussed elsewhere (Feraud et al., 1981; Flower et al., 1983).

Sr, Nd and Pb isotopic compositions and Rb, Sr, Sm, Nd, Th, U and Pb concentrations by isotope dilution (Table 1) were measured at DTM using procedures described previously (Walker et al., 1989). Th-isotope ratios were measured at UCSC using a VG Sector 54-30 thermal ionization mass-spectrometer. The method of Williams et al. (1992) was used, except that the Daly/Faraday gain (DFG) was measured before and after each run. The DFG was stable within individual runs to a few per mil.

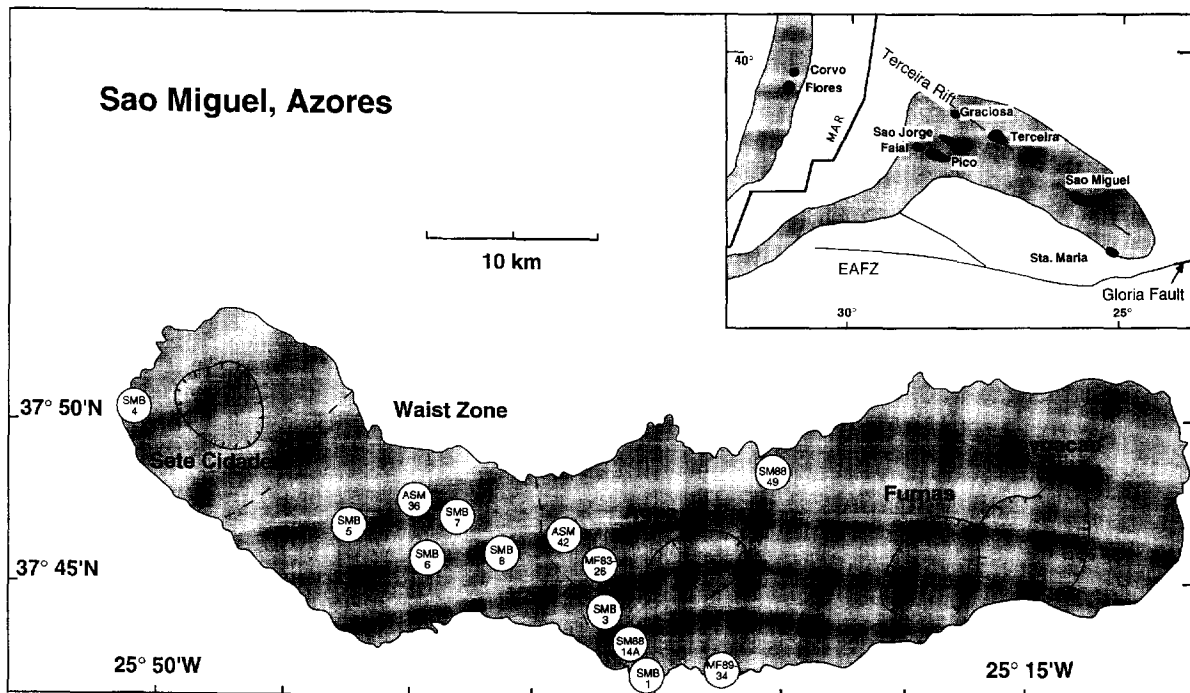


Fig. 1. Map of São Miguel, showing sample locations. Trachytic stratovolcanoes and ‘waist zone’ are identified for reference (after Kurz et al., submitted). Inset illustrates the Azores Archipelago and associated tectonic features.

Table 1
Major and trace element and isotopic compositions of São Miguel basalts

Sample	SMB-4	SMB-5	ASM36	SMB-6	SMB-7	SMB-8	ASM42	MF83-26	SMB-3	SM88-14A	SMB-1	MF89-34	SM88-49
SiO ₂	47.5	46.0	47.3	45.9	45.2	46.2	47.7		46.1		45.6		
TiO ₂	3.35	3.38	2.42	3.07	3.62	3.79	3.15		3.44		3.81		
Al ₂ O ₃	15.50	13.48	12.51	12.06	12.37	14.68	13.31		13.08		13.30		
Fe ₂ O ₃	10.5	11.0	10.5	11.0	12.0	12.0	12.3		11.5		12.0		
MnO	0.18	0.17	0.17	0.17	0.18	0.18	0.17		0.17		0.17		
MgO	6.39	9.12	11.48	11.88	10.14	7.37	8.80	8.6	9.58	11.4	8.91	10.3	5.5
CaO	9.64	11.88	11.69	11.11	11.94	9.58	9.29		10.22		9.78		
Na ₂ O	3.15	2.28	2.37	2.14	2.25	2.84	3.07		2.27		2.40		
K ₂ O	1.91	1.23	1.12	1.18	1.37	1.87	2.34		1.81		2.24		
P ₂ O ₅	0.73	0.53	0.38	0.48	0.44	0.64	0.45		0.54		0.63		
V	268	311		288	320	291	270		287		289		
Cr	134	447	727	751	440	298	336		400		338		
Ni	66	156	255	275	223	111	164		414		304		
Rb	49.7	29.8	30.6	28.5	38.4	44.7	53.9		56.7	44.1	51.1		40.9
Sr	844.4	667.3	495.4	581.6	575.6	804.9	500.5		628.7	544.8	738.4		943.2
Y	33	28	25	27	30	35	28		31		32		
Zr	328	199	162	188	223	300	314		298		281		
Nb	72	57	43	42	57	69	57		61		49		
Ba	627	477	399	441	528	621	431		530		616		
Nd	55.3	38.4	28.4	34.5	39.4	53.1	40.5		46.7	43.1			53.6
Sm	10.3	7.8	6.1	7.1	8.2	10.5	7.9		9.0	8.3	9.5		10.4
Pb	3.2	1.9	1.7	2.1	2.3	3.1	3.3		3.3	2.9	3.9		2.8
Th	6.396	3.722	2.973	3.345	3.866	5.059	5.914		5.801	6.071	5.243		5.313
U	1.780	1.036	0.817	0.913	1.058	1.388	1.617		1.554	1.485	1.393		1.359

$^{206}\text{Pb}/^{204}\text{Pb}$	19.368	19.489	19.518	19.653	19.612	19.638	19.905	19.775	19.827	20.040	19.890	19.777	19.977
$^{207}\text{Pb}/^{204}\text{Pb}$	15.623	15.617	15.605	15.694	15.661	15.671	15.730	15.662	15.727	15.795	15.707	15.643	15.748
$^{208}\text{Pb}/^{204}\text{Pb}$	39.254	39.352	39.291	39.893	39.753	39.816	40.162	39.644	40.029	40.583	40.157	39.840	40.236
$^{87}\text{Sr}/^{86}\text{Sr}$	0.703202	0.703464	0.703522	0.703532	0.704112	0.70447	0.704633		0.704911	0.705475	0.705181		0.705114
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512943	0.512931	0.512956	0.512939	0.512850	0.512859	0.512781		0.512804	0.512667	0.512729		0.512756
$(^{230}\text{Th})/(^{232}\text{Th})_{\text{ms}}$	1.0935	1.0294	1.0513	1.0565	0.9366	0.9677	0.9125		0.8910	0.8771	0.9098		0.9592
2- σ error	0.0044	0.0061	0.0101	0.0090	0.0046	0.0030	0.0042		0.0043	0.0176	0.0042		0.0033
$(^{230}\text{Th})/(^{232}\text{Th})_{\alpha}$	1.094	1.075	1.055	1.075	0.986	0.982	0.942		0.886	0.889	0.938		0.975
2- σ error	0.050	0.044	0.042	0.056	0.052	0.030	0.036		0.036	0.023	0.038		0.029
$(^{238}\text{U})/(^{232}\text{Th})$	0.844	0.845	0.834	0.828	0.830	0.832	0.830		0.813	0.742	0.806		0.776
$(^{230}\text{Th})/(^{238}\text{U})$	1.295	1.219	1.261	1.276	1.128	1.162	1.100		1.096	1.182	1.129		1.236
K_{Th}	2.867	3.046	2.982	2.968	3.348	3.240	3.436		3.519	3.575	3.446		3.269
$^{208}\text{Pb}^*/^{206}\text{Pb}^*$	0.972	0.970	0.961	1.007	0.997	1.001	1.008	0.971	1.003	1.035	1.009	0.990	1.008
K_{Pb}	3.948	3.940	3.904	4.090	4.051	4.065	4.096	3.945	4.075	4.203	4.100	4.021	4.096
Eruption date	< 5 ka	< 5 ka	< 5 ka	< 5 ka	< 5 ka	< 5 ka	1563 AD	8.7 ka	< 5 ka	6.5 ka	< 5 ka	< 15.2, > 5 ka	26.5 ka

Samples are listed according to geographic location across the island from west to east. Oxide concentrations are in wt.%, element concentrations in ppm. MgO data for samples SM88-14A, MF83-26, MF89-34 and SM88-49 courtesy of R.B. Moore (SM88-14A, MF83-26 and MF89-34 by XRF, J.S. Meen and D.F. Siems, USGS; SM88-49 by the Rapid Rock wet chemistry technique, D. Kay, USGS). $^{87}\text{Sr}/^{86}\text{Sr}$ measurements were corrected for fractionation using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and are normalized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for NBS 987. $^{143}\text{Nd}/^{144}\text{Nd}$ measurements were corrected for fractionation using $^{144}\text{Nd}/^{146}\text{Nd} = 0.72190$ and normalized to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for La Jolla. $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ measurements were corrected for fractionation by 1.3, 1.2 and 1.45‰ per amu, respectively, based on NBS 981. External analytical errors determined as 2σ of the population of many (> 100) standard runs are approximately $^{87}\text{Sr}/^{86}\text{Sr} = \pm 0.000025$, $^{143}\text{Nd}/^{144}\text{Nd} = \pm 0.000020$, $^{206}\text{Pb}/^{204}\text{Pb} = \pm 0.02$, $^{207}\text{Pb}/^{204}\text{Pb} = \pm 0.02$, $^{208}\text{Pb}/^{204}\text{Pb} = \pm 0.08$. $(^{230}\text{Th})/(^{232}\text{Th})_{\text{ms}}$ denotes Th isotope ratios measured by mass-spectrometry and converted to activity ratios. $(^{230}\text{Th})/(^{232}\text{Th})_{\alpha}$ denotes Th isotope activity ratios measured by α -spectrometry.

Abundance sensitivity at mass 231 relative to mass 232 was approximately 0.3 ppm. The Th-isotope ratios were measured statically, with mass 230 measured on a pulse counting Daly. With one exception, within-run precision on the $(^{230}\text{Th})/(^{232}\text{Th})$ ratios ranged from 0.3 to 1%. No age corrections were applied due to the young age of all samples.

4. Results

4.1. Major and minor element systematics

The samples discussed in this paper are all mildly ($< 5\%$) nepheline-normative alkali basalts with MgO

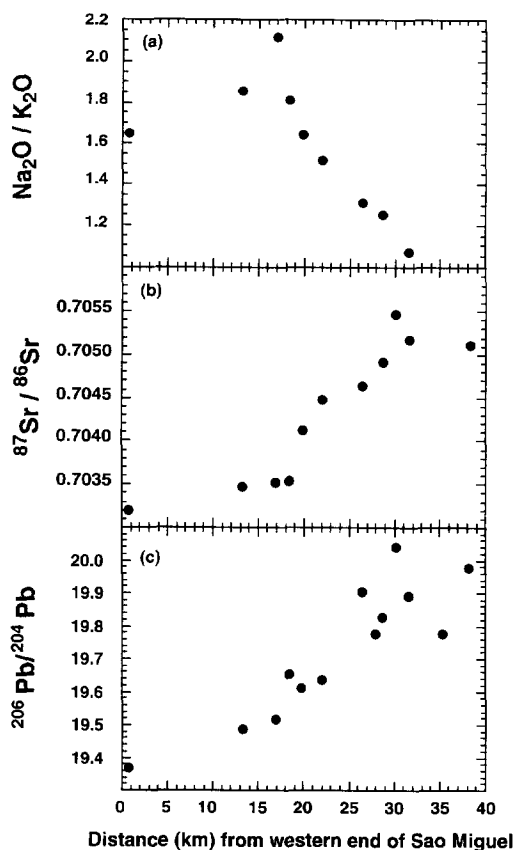


Fig. 2. Variations in: (a) $\text{Na}_2\text{O}/\text{K}_2\text{O}$, (b) $^{87}\text{Sr}/^{86}\text{Sr}$, and (c) $^{206}\text{Pb}/^{204}\text{Pb}$, as a function of distance from the western end of São Miguel. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios vary greatly over a 40 km distance, increasing from west to east. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios remain relatively constant east of the 'waist zone' (Hawkesworth et al., 1979). Sample SMB-4 at 0.25 km, plots off the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ trend due to syenite assimilation.

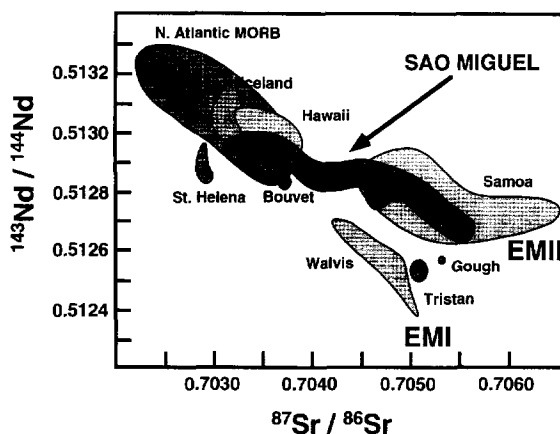


Fig. 3. Nd vs. Sr isotope correlation showing that São Miguel plots on a trend shallower than the original mantle array, extending from values similar to enriched North Atlantic MORB towards the EMII mantle component. North Atlantic MORB and ocean island fields from Dupré and Allègre (1980), Ito et al. (1987), and Shirey et al. (1987) and Zindler and Hart (1986) and references therein, respectively.

ranging from 5 to 12%. Fractionation trends have been summarized previously (Flower et al., 1976; White et al., 1979; Moore, 1991), and show that in general, as MgO decreases, SiO_2 , Al_2O_3 , K_2O , Na_2O , TiO_2 and P_2O_5 increase, while FeO and CaO decrease, consistent with a fractionating assemblage dominated by olivine and clinopyroxene. One sample (SMB-4, which was erupted through the flanks of the trachytic stratovolcano Sete Cidades) shows petrographic evidence of having assimilated crustal material in the form of alkali syenite xenoliths. The other basalts appear to be xenolith-free.

Ratios of $\text{Na}_2\text{O}/\text{K}_2\text{O}$ show a two-fold variation from 1.07 to 2.12, and are independent of MgO content. Rather, they are correlated with geographic location such that the basalts become more potassic from west to east (Fig. 2a). The increasingly potassic nature of basalts towards the east is also reflected in an eastward increase in $\text{K}_2\text{O}/\text{TiO}_2$. Sample SMB-4, the western-most basalt sample, has anomalously low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (and high $\text{K}_2\text{O}/\text{TiO}_2$) given its geographic location. Relatively low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and high $\text{K}_2\text{O}/\text{TiO}_2$ are both expected to result from contamination with K-feldspar-rich alkali syenite (Widom et al., 1992, 1993).

4.2. Sr, Nd, Pb and Th isotope systematics

Hawkesworth et al. (1979) were the first to report the striking correlation between isotopic composition and geographic location on São Miguel. Fig. 2b illustrates the eastward increase in $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7032 at the western end of the island, to 0.7055 on the east side of Agua de Pao. From this point eastward, the $^{87}\text{Sr}/^{86}\text{Sr}$ value remains roughly constant (Hawkesworth et al., 1979). Similar geographically correlated trends are observed in both Nd and Pb isotopic composition (Figs. 2 and 3). The less enriched end of the island (hereafter referred to as the São Miguel depleted source) overlaps with the Azores Platform tholeiites in Sr, Nd and Pb isotopic composition, but the São Miguel trend deviates from the main oceanic trend in Sr vs. Nd and both $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams (Figs. 3 and 4).

(^{230}Th)/(^{232}Th) ratios (expressed as activity ratios) range from 1.094 to 0.877, decreasing from west to east across the island. The good correlations with Sr, Nd and Pb isotope composition (Fig. 5) indicate that the Th isotope ratios in the São Miguel basalts are representative of their mantle source regions and are not dominated by effects of variable melting regimes, magma ascent rates or shallow-level contamination.

Fig. 5a illustrates that relative to the Th–Sr ‘mantle array’ (Condomines et al., 1981b, 1988), São Miguel plots on a shallow trend with the most enriched São Miguel basalts extending to higher Th isotope ratios for a given $^{87}\text{Sr}/^{86}\text{Sr}$. Interestingly, other EMII-rich OIBs including Heard and the Society Islands also plot above the Th–Sr mantle array. Mantle sources of basalts which lie in this region of the diagram can be produced either by an old increase in Rb/Sr relative to Th/U, or by an enrichment in U relative to Th at any time greater than a few hundred thousand years ago.

4.3. Trace element and U-series systematics

Incompatible trace element concentrations in alkali basalts from the Azores islands are generally twice those of the tholeiites from the Azores Platform, consistent with lower degrees of partial melting involved in the production of the alkali basalts

(White et al., 1979). However, inter-island variations in trace element concentrations have been noted, and São Miguel basalts appear to be enriched relative to other islands in the alkalis K, Rb, and Cs, and the light REE (White et al., 1979). Our results show further that the concentrations of several elements

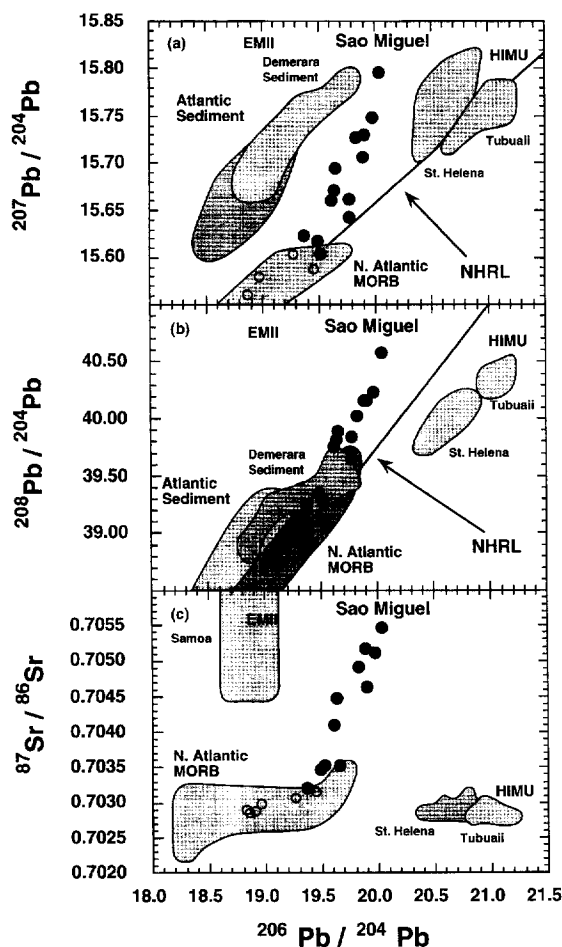


Fig. 4. (a) $^{207}\text{Pb}/^{204}\text{Pb}$, (b) $^{208}\text{Pb}/^{204}\text{Pb}$, and (c) $^{87}\text{Sr}/^{86}\text{Sr}$, vs. $^{206}\text{Pb}/^{204}\text{Pb}$. São Miguel basalts display linear mixing trends involving a component which falls within the enriched end of the MORB field, similar to the Azores Platform tholeiites (open circles), and an enriched component which plots above the NHRL at high values of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$. The São Miguel enriched mantle source has characteristics intermediate between EMII and HIMU. Data for MORB, including Azores Platform tholeiites, from Dupré and Allègre (1980), Ito et al. (1987), and Shirey et al. (1987); data for OIB from Vidal et al. (1984), Zindler and Hart (1986), Chaffey et al. (1989), Hauri and Hart (1993), and Reisberg et al. (1993); and data for sediment from White et al. (1985), and Ben Othman et al. (1989).

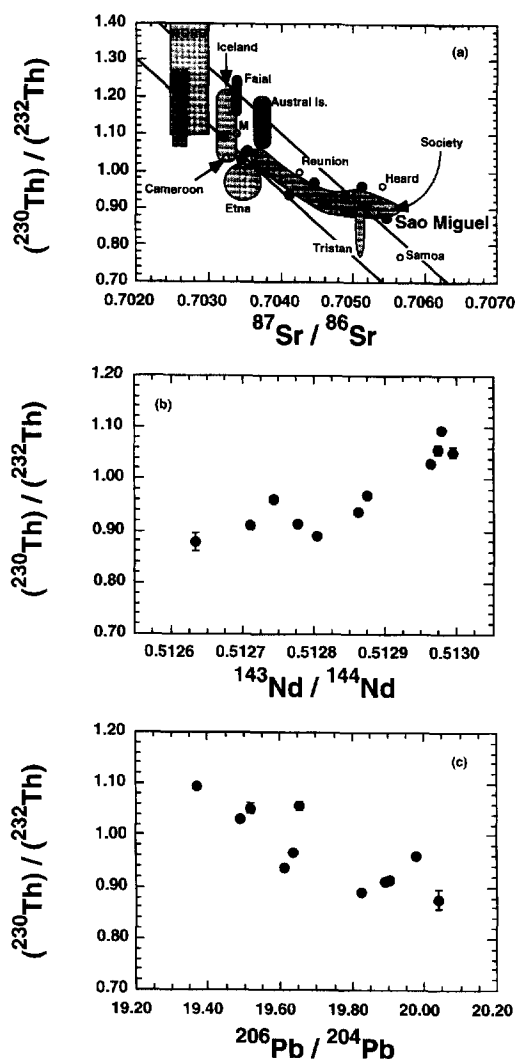


Fig. 5. (a) Correlations of $(^{230}\text{Th})/(^{232}\text{Th})$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$. The São Miguel basalts display a negative trend of Th vs. Sr isotopes which is shallower than the 'mantle array' (Condomines et al., 1988) denoted by the parallel lines. EMII islands of Heard and the Societies also plot above the mantle array. Note that the Society Islands data field is nearly identical to that of São Miguel (dots). M denotes Marion Island. Literature data from Oversby and Gast (1968), Condomines et al. (1981a,b, 1988, 1995), Newman et al. (1983, 1984), Ben Othman and Allègre (1990), Sigmarsson and Condomines (1991), Williams and Gill (1992), Rubin and Macdougall (1992), Hemond et al. (1994). (b) Correlations of $(^{230}\text{Th})/(^{232}\text{Th})$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$, illustrating the negative trend of the São Miguel basalts. (c) Correlations of $(^{230}\text{Th})/(^{232}\text{Th})$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$, showing the positive, approximately linear trend of the São Miguel basalts. Th-isotope data for São Miguel basalts plotted in this and subsequent figures are those measured by mass-spectrometry (Table 1).

vary systematically across the island of São Miguel. Fig. 6 illustrates variations of trace element concentrations (normalized to 9.0 wt.% MgO following Plank and Langmuir, 1988) as a function of $^{206}\text{Pb}/^{204}\text{Pb}$. Note that concentrations of several elements including Th, U, Pb and Zr increase with increasing $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 6a–d). In contrast, concentrations of Ba and Nb are relatively constant across the island (Fig. 6e,f).

Differences in trace element concentrations in basalts can be caused by a variety of petrogenetic processes including degree of differentiation from a parental magma, degree of partial melting, or variations in mantle source composition. Because the São Miguel basalts show variable trace element abundances even after normalization to a fixed MgO content (Fig. 6), the variations in trace element concentration with geographic location must be dominated by either variations in degree of partial melting or differences in source composition.

Evidence from U-series disequilibria can be used to investigate relative degrees of partial melting based on the enrichment of ^{230}Th relative to ^{238}U . The São Miguel basalts are generally Th-enriched, and therefore plot to the left of the equiline on a Th-isochron diagram (Fig. 7), with enrichments of ^{230}Th over ^{238}U ranging from 10 to 30%. Basalts from the enriched end of the island are generally less enriched in ^{230}Th over ^{238}U than basalts from the depleted end, indicating that the enriched source melted to a somewhat greater degree than the depleted source. The higher degree of melting of the enriched source relative to the depleted source results in a limited variation in $(^{232}\text{Th})/(^{238}\text{U})$, or melt Th/U, relative to the variation in $(^{230}\text{Th})/(^{232}\text{Th})$, or source Th/U ratios (approximately 14% vs. 25%, respectively).

A higher degree of melting in the São Miguel enriched source relative to the depleted source would be expected to produce lower concentrations of incompatible trace elements on the enriched end of the island if the source composition were uniform, but this is opposite to the observed relationships. We can conclude, therefore, that the concentrations of Th, U, Pb and Zr are higher in the enriched São Miguel source, and that the concentrations of Ba and Nb are similar in the depleted and enriched sources.

Another perspective on variation in degree of partial melting across the island may be gained from

variations in Th/Pb and U/Pb, and to a lesser extent Th/U ratios, all of which show a complex correlation with $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 8). Th/Pb and

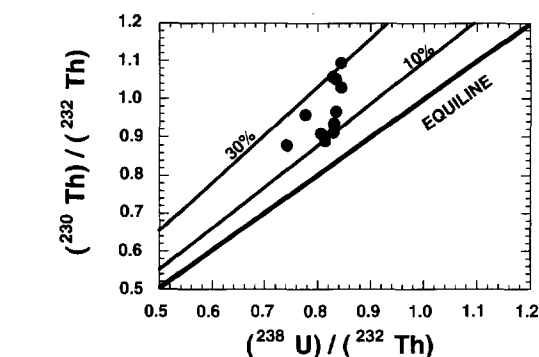
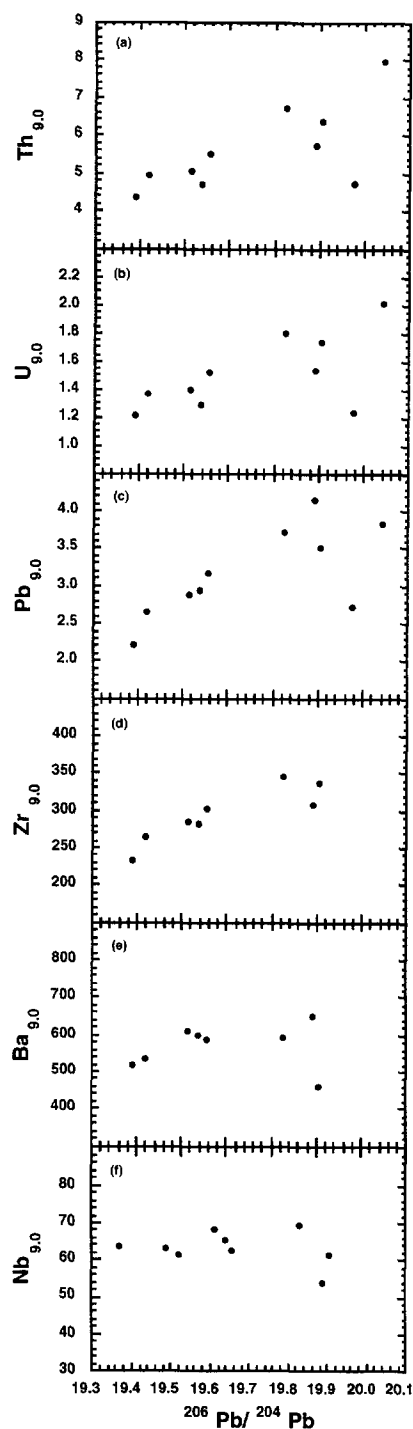


Fig. 7. $(^{230}\text{Th})/(^{232}\text{Th})$ vs. $(^{238}\text{U})/(^{232}\text{Th})$ with the equiline for reference. Lines of constant Th-enrichment of 10% and 30% are illustrated, which bracket the enrichments observed in the São Miguel basalts. The variation in Th/U of the basaltic melts (14%) is less than the variation in Th/U of their mantle sources as inferred by $(^{230}\text{Th})/(^{232}\text{Th})$ ratios (25%).

U/Pb show minima on plots vs. $^{206}\text{Pb}/^{204}\text{Pb}$, with the low ratios occurring in the middle of the island, and increasing to either side. It is impossible to produce such correlations with two-component mixing, as required by the linear isotope ratio–isotope ratio diagrams, unless there is a variation in degree of partial melting involved. Because Th and U are more incompatible than Pb, the minima imply that a region of higher degree of melting exists beneath the middle of the island, indeed at the eastern edge of the waist zone depicted in Fig. 1. Interestingly, the inferred higher degree of partial melting within the waist region corresponds with the high output of Holocene basalts in this area.

Several other incompatible trace element ratios

Fig. 6. Normalized element concentrations (relative to 9.0% MgO) vs. $^{206}\text{Pb}/^{204}\text{Pb}$. Normalizations are based on regression to a best-fit line through the São Miguel data on plots of element vs. MgO, following the procedure of Plank and Langmuir (1988). Several incompatible elements in the São Miguel basalts, including (a) Th, (b) U, (c) Pb, and (d) Zr, increase with increasing $^{206}\text{Pb}/^{204}\text{Pb}$ (sample SM88-49 behaves anomalously in a–c, perhaps due to the Rapid Rock technique which was used to analyze MgO in this sample only). In contrast, concentrations of (e) Ba, and (f) Nb, appear to be relatively constant across São Miguel. Note that all plots show a 3-fold range of element concentration on the y-axis for purposes of comparison. Sample SMB-4 has been omitted from this figure as well as Fig. 8Fig. 9Fig. 10 because syenite assimilation has altered its trace element systematics, as illustrated in Fig. 2a.

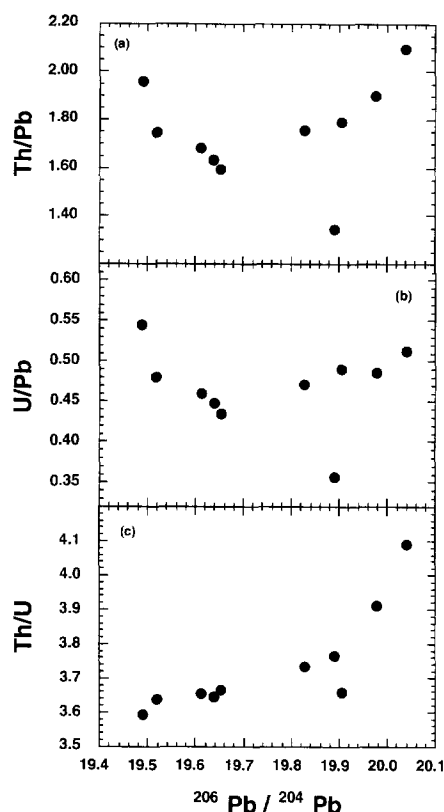


Fig. 8. (a) Th/Pb, (b) U/Pb, and (c) Th/U, vs. $^{206}\text{Pb}/^{204}\text{Pb}$. The V-shaped patterns on (a) and (b) are difficult to reconcile with a two-component mixing model unless variations in partial melting are affecting these ratios. Degree of partial melting appears to increase from low to intermediate $^{206}\text{Pb}/^{204}\text{Pb}$ values, and then to decrease again toward higher values. The inferred point of maximum melting ($^{206}\text{Pb}/^{204}\text{Pb}$ approximately 19.64) corresponds to the east end of the waist region of São Miguel. Th/Pb and U/Pb ratios in the basalts are lowest where degree of partial melting is highest, and are controlled by both source differences and variation in degree of partial melting. The curved as opposed to linear trend of Th/U vs. $^{206}\text{Pb}/^{204}\text{Pb}$ (c) also attests to variation in degree of partial melting, but the lack of a V-shaped pattern indicates that variations in Th/U ratios are dominated by source differences.

show pronounced variation across São Miguel and display correlations with isotopic ratios. This suggests that these element pairs have distribution coefficients similar enough to one another or that there are large enough differences in these element ratios between the enriched and depleted São Miguel sources, that these ratios are relatively unaffected by variation in degree of partial melting. Nb/U, Nb/Zr,

Ti/Zr, Ba/Pb, Ba/Th and Ba/Rb ratios all decrease by approximately a factor of 2 with increasing $^{206}\text{Pb}/^{204}\text{Pb}$ ratio (Fig. 9a–f). These trends are consistent with the observation from the trace element concentration variations that Th, Pb and Zr are relatively more abundant in the enriched source, and furthermore indicate that U and Rb are enriched. Fairly constant $\text{K}_2\text{O}/\text{Rb}$ ratios in the São Miguel basalts indicate a similar enrichment of the respective alkalis.

The decreasing ratios of Ba/Pb, Ba/Th and Ba/Rb with increasing $^{206}\text{Pb}/^{204}\text{Pb}$ are quite surprising given that Ba is generally thought to be the most incompatible of these elements. This and the lack of correlation of Ba/Nb with $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 9g), again emphasizes the previous conclusion that neither Ba nor Nb is enriched in the São Miguel enriched mantle source. The lack of correlation between Ba/Ti and $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 9h) also argues that Ti is not enriched in the São Miguel enriched mantle. In summary, the São Miguel enriched mantle appears to have higher abundances of K, Rb, Th, U, Pb and Zr than the São Miguel depleted mantle, but comparable abundances of Nb, Ba and Ti.

5. Discussion

The isotopic variations on São Miguel require long-term trace element differences between the enriched and depleted mantle sources. In particular, the extremely high $^{207}\text{Pb}/^{204}\text{Pb}$ ratios in the São Miguel enriched mantle require that the source of the radiogenic Pb had a high U/Pb in the early part of Earth's history. The continental crust and the subcontinental lithospheric mantle are two reservoirs where enriched material may have formed early and remained isolated for long enough periods of time to develop the radiogenic Pb and Sr isotope ratios and unradiogenic Nd isotope ratios displayed by the São Miguel enriched mantle source. While fairly radiogenic Sr and Pb isotope ratios are characteristic features of continental crust, terrigenous sediment, and many arcs in which sediment is being subducted (Gill, 1981; Taylor and McLennan, 1985), similar isotope signatures are also known from xenolith studies to exist in the subcontinental lithospheric mantle (Kramers et al., 1983; Stolz and Davies,

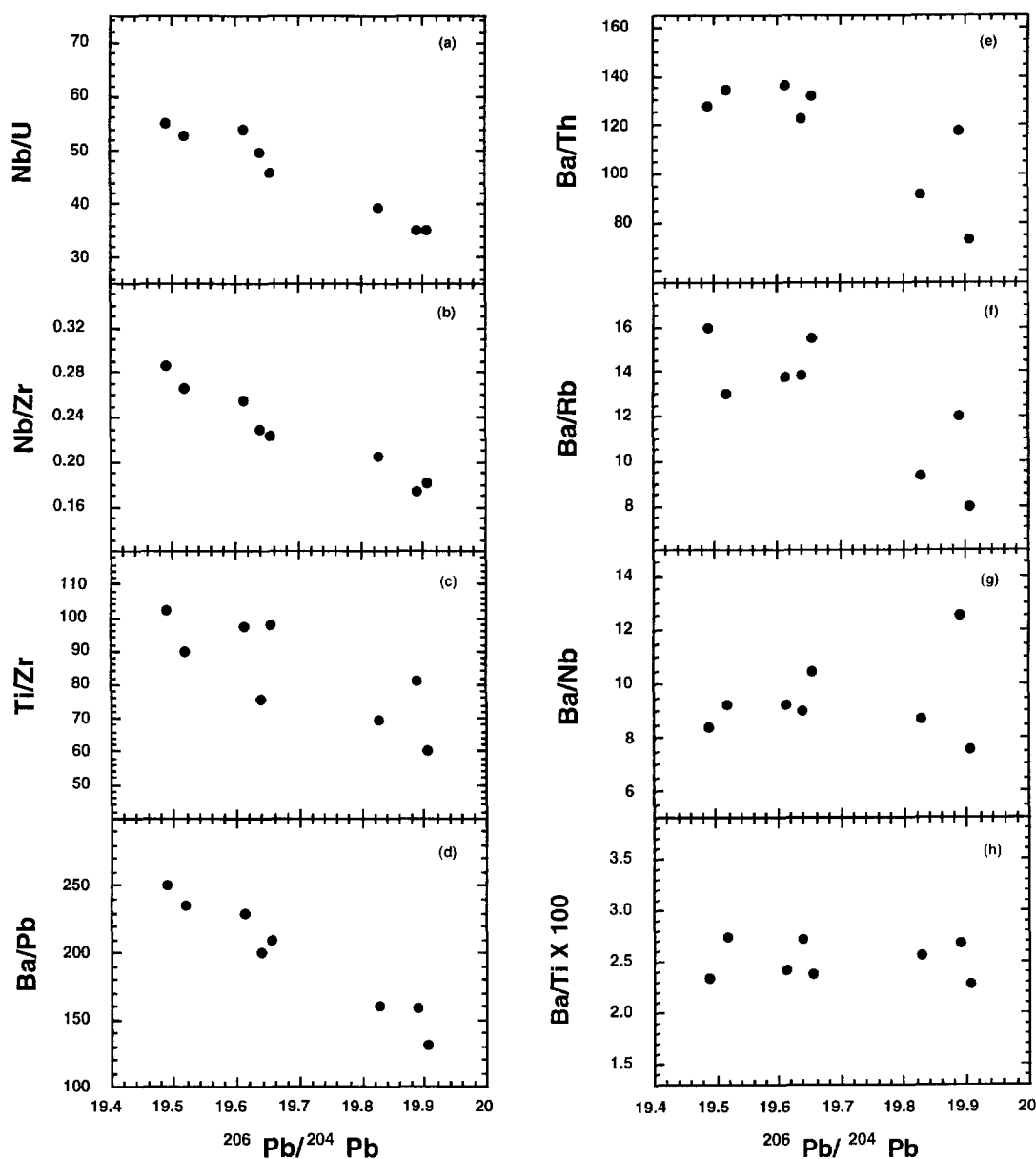


Fig. 9. Incompatible trace element ratios plotted against $^{206}\text{Pb}/^{204}\text{Pb}$: (a) Nb/U, (b) Nb/Zr, (c) Ti/Zr, (d) Ba/Pb, (e) Ba/Th, (f) Ba/Rb all correlate closely with $^{206}\text{Pb}/^{204}\text{Pb}$, decreasing by factors of 1.5 to 2 as $^{206}\text{Pb}/^{204}\text{Pb}$ increases. In contrast, (g) Ba/Nb, and (h) Ba/Ti, appear to be essentially the same in the São Miguel enriched and relatively depleted mantle sources. Because concentrations of Ba and Nb have been shown to be similar in the basalts from the two sources (Fig. 6), this indicates that Ti concentration is also similar in the two sources. As in Fig. 6, all plots show a 3-fold range of element ratio values on the y-axis for purposes of comparison.

1988; Zindler and Jagoutz, 1988; Tatsumoto et al., 1992). Thus, either recycling of sediment or delamination of mantle lithosphere could plausibly account for the origin of such signatures in the oceanic

mantle. In the following discussion we show that, in detail, neither bulk sediment nor subduction processed sediment can produce the trace element and isotopic signatures observed in the São Miguel en-

riched mantle source. The São Miguel enriched mantle source is more likely hydrous subcontinental lithospheric mantle.

5.1. Sediment recycling

The elemental enrichment characteristics of the São Miguel enriched mantle source, namely enrichment in K, Rb, Th, U, Pb and Zr relative to Ba, Nb and Ti are qualitatively compatible with a terrigenous sediment component. For example, the Nb/U ratio in the São Miguel enriched mantle (Fig. 9a) is below the relatively constant Nb/U ratio of 47 ± 10 (Hofmann et al., 1986) found in MORB and most non-EMII OIB, consistent with the suggestion that the sources of EMII OIB may have a minor sediment component (Hofmann, 1993).

The possibility of a sediment component in the São Miguel enriched mantle source can be investigated quantitatively by calculating expected mixing curves on element ratio–element ratio diagrams. The composition of the São Miguel depleted mantle source was estimated by assuming that it has concentrations of K₂O, TiO₂, Rb, Sr, Cs and Ba which are approximately 10% of the values measured in the least-fractionated Azores Platform tholeiites (Schilling et al., 1983), assuming in effect 10% equilibrium batch melting. Concentrations of other incompatible elements in the São Miguel depleted mantle source were calculated from observed ratios to K₂O, TiO₂, Rb, Sr, Cs and Ba in the least radiogenic São Miguel basalts. An internally consistent set of element concentrations for the São Miguel depleted mantle was obtained by this method (Table 2).

The approach to calculating the São Miguel depleted mantle source composition is justified in that the Sr–Nd–Pb isotope signatures of basalts from the depleted end of São Miguel indicate that it taps the same mantle source as the Azores Platform tholeiites on the MAR. Furthermore, the fact that many incompatible trace element ratios are the same in alkali basalts from the São Miguel depleted mantle source as in the Azores Platform tholeiites indicates that these incompatible trace elements are not greatly fractionated from one another during melting. Least well justified is the absolute concentration of elements in the calculated mantle source. However, the only effect that the absolute element concentrations

of the mantle source have on the modeling which follows is the net amount of sediment addition required to produce the enriched source composition. Importantly, the curvature on the mixing diagrams is controlled only by the element ratios in the mixing

Table 2
Calculated compositions of the São Miguel depleted and enriched mantle sources

Element concentration in ppm	São Miguel depleted mantle	São Miguel enriched mantle
K	415	830
Ti	726	726
Rb	1.12	2.24
Sr	24.4	24.4
Zr	7.14	12.18
Nb	2.07	2.07
Cs	0.01	0.02
Ba	18.25	18.25
Nd	1.31	2.01
Sm	0.275	0.38
Pb	0.073	0.118
Th	0.104	0.212
U	0.037	0.059
μ	31.3	30.9
ω	90.5	115
κ	2.89	3.72
$(^{230}\text{Th})/(^{232}\text{Th})$	1.094	0.877
$^{87}\text{Sr}/^{86}\text{Sr}$	0.7032	0.7055
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51297	0.51267
$^{206}\text{Pb}/^{204}\text{Pb}$	19.37	20.04
$^{207}\text{Pb}/^{204}\text{Pb}$	15.58	15.80
$^{208}\text{Pb}/^{204}\text{Pb}$	39.0	40.58

The calculation of the composition of the São Miguel depleted mantle source is outlined in detail in the main text. The composition of the São Miguel enriched mantle source was calculated based on the calculated composition of the São Miguel depleted mantle source as follows. The relative enrichment of U was determined by the variation of U_{9.0} in Fig. 6b. The Th/U ratio of the enriched source was then fixed to be consistent with that implied by its Th-isotope signature, and the Pb content assigned such that Th/Pb and U/Pb were consistent with the respective ratios in Fig. 8a,b. Other element concentrations were determined by the variations in element concentrations and element ratios in Fig. 6Fig. 9Fig. 10. The relative enrichments in the São Miguel enriched mantle source relative to the depleted source are considered to be minima, in that basalts from the enriched source may have melted to a somewhat higher degree than those from the depleted source, thus minimizing the element enrichments in the basalts from the enriched source.

end-members, and is unaffected by the absolute concentrations of elements attributed to either mixing end-member.

Results of mixing a terrigenous sediment compo-

nent into the São Miguel depleted mantle source are shown in Fig. 10. Element concentrations of the terrigenous sediment are based on estimates of average post-Archaean shale (Krauskopf, 1967; Taylor and McLennan, 1985). Note that high ratios of Th/U and corresponding low ratios of Ti/Zr in the São Miguel enriched mantle source could be explained by bulk addition of approximately 5% terrigenous sediment. Pelagic sediment, however, appears to have a Th/U ratio too high to explain the São Miguel data trend (Fig. 10a). Furthermore, because U is more mobile than Th (Bailey and Ragnarsdottir, 1994), the Th/U ratio of recycled sediment would only be expected to increase during subduction zone dewatering. Terrigenous sediment would therefore be the more viable enrichment agent for the São Miguel enriched mantle source.

In contrast to Th/U and Ti/Zr, other trace element systematics of the São Miguel basalts would require significant mobilization of some elements during subduction zone dewatering in order to accommodate a recycled terrigenous sediment component. The variations in Rb/Nb ratio, for example, would require loss of approximately 75% of the sediment Rb, assuming that Nb is relatively immobile (Fig. 10b). This is somewhat higher than the mobility estimated for Rb during dewatering of serpentinite (Tatsumi et al., 1986), but not inconceiv-

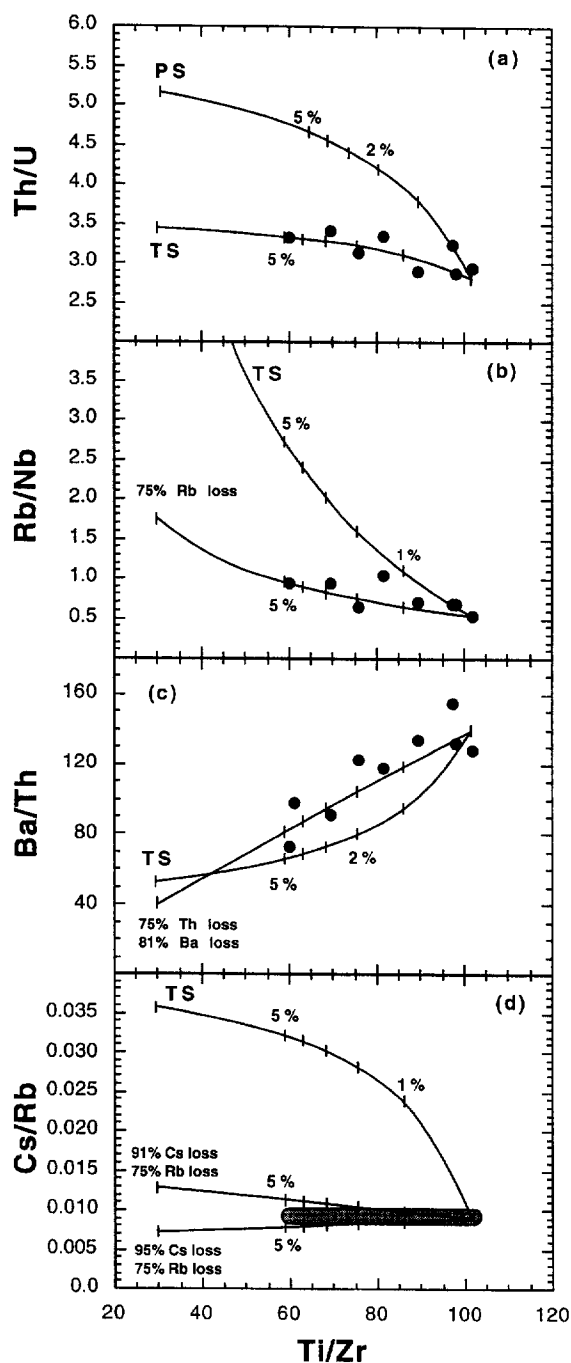


Fig. 10. Mixing diagrams illustrating the effect of mixing terrigenous sediment into the São Miguel depleted mantle source. The composition of the São Miguel depleted mantle source is from Table 2, and the sediment composition is average post-Archaean shale (Krauskopf, 1967; Taylor and McLennan, 1985). (a) Th/U (mantle source values based on $(^{230}\text{Th})/(^{232}\text{Th})$ ratios) vs. Ti/Zr. Recycling of approximately 5% bulk terrigenous sediment could explain the variations in the São Miguel basalts of Th/U and Ti/Zr. (b) Rb/Nb vs. Ti/Zr, indicating that loss of 75% of the sediment Rb during subduction zone dewatering of the sediment would be required. (c) Ba/Th vs. Ti/Zr. The Ba/Th systematics cannot be reconciled with sediment recycling unless subduction zone dewatering mobilized $\sim 80\%$ of the Ba and 75% of the sediment Th. Such a large loss of Th is unlikely. (d) Cs/Rb (data from White et al., 1979) vs. Ti/Zr. The low and constant Cs/Rb ratios in the São Miguel basalts would require the unlikely situation in which subduction zone dewatering of the sediment component resulted in a recycled sediment with precisely the same Cs/Rb ratio as the São Miguel depleted mantle source.

able. Ba/Th systematics, however, are difficult to reconcile with a recycled terrigenous sediment component in the São Miguel enriched mantle source. Incorporation of bulk terrigenous sediment would induce a low Ba/Th and low Ti/Zr signature, but the mixing curve would be concave upward, in contrast to the slightly concave downward trend of the São Miguel basalts (Fig. 10c). In fact, the only way to produce a mixing trend which is remotely consistent with the São Miguel data is by invoking major losses of both Th and Ba during subduction zone dewatering of the sediment (75% and ~80%, respectively). Although Ba is known to be very mobile (Tatsumi et al., 1986), Th is generally believed to be quite immobile (Bailey and Ragnarsdottir, 1994), and such a large loss of Th from the sediment during subduction zone dewatering is therefore highly unlikely.

Also problematic for a sediment recycling model for the São Miguel enriched mantle source is the Cs/Rb signature of the São Miguel basalts. Cs/Rb is one of the most sensitive indicators of sediment contribution to mantle sources (Ben Othman et al., 1989). Cs/Rb ratios in MORB and many OIB are known to be relatively constant at about 0.012 ± 0.002 (Hofmann and White, 1983), whereas Cs/Rb ratios in sediment, upper continental crust and island arc basalts are significantly higher and more variable (Hofmann and White, 1983; Ben Othman et al., 1989). However, basalts from across the island of São Miguel, representing the full range of isotopic variation, all have relatively low and constant Cs/Rb ratios (average 0.0094 ± 0.0014 ; White et al., 1979), despite the large variation in isotopic composition. This low and fairly uniform Cs/Rb ratio places a severe constraint on the mobility of Cs during subduction zone dehydration if sediment recycling is the cause of the São Miguel enriched mantle source. Assuming a 75% loss of Rb, as required by the Rb/Nb systematics (Fig. 10b), the São Miguel basalt data would be reproduced only with a 91–95% loss of Cs (Fig. 10d). Either a greater or lesser loss of Cs would produce a variability in the Cs/Rb ratio of the São Miguel basalts. Indeed, the only way to explain the constant Cs/Rb ratios in the São Miguel basalts by sediment recycling is if the relative loss of Cs and Rb during subduction zone dewatering produced a sediment with precisely the Cs/Rb ratio of the São

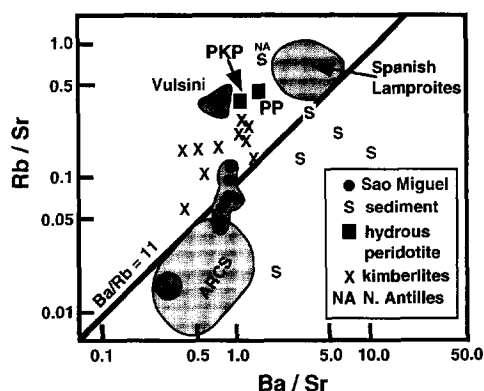


Fig. 11. Rb/Sr vs. Ba/Sr after Hawkesworth et al. (1985). The São Miguel enriched mantle source has low Ba/Rb relative to average oceanic basalts, and falls within a field dominated by continentally derived magmas and hydrous peridotites from the subcontinental lithospheric mantle. Fields for island arc basalts and their respective sediment inputs from Plank and Langmuir (1993). Field for Spanish lamproites from Venturelli et al. (1984). PKP and PP are average compositions from Hawkesworth et al. (1990).

Miguel depleted mantle source, a rather unlikely scenario.

Further evidence against recycled sediment is the very high K_{pb} signature of the São Miguel enriched mantle source. The São Miguel enriched mantle source has a K_{pb} value of 4.2 (Table 1), which requires that the sediment component would have to have had a long-term, time-integrated Th/U ratio of greater than 4.2. The Th-isotope and trace element systematics of the São Miguel basalts, however, indicate that the sediment component would have to have a present-day Th/U ratio close to 3.5 (Fig. 10a). In order for a sediment component to have a time-integrated Th/U ratio greater than 4.2, but a present-day Th/U ratio of approximately 3.5, it would have to have undergone a substantial decrease in Th/U during subduction. This is highly unlikely, as U is by far the more mobile of the two elements (Bailey and Ragnarsdottir, 1994).

5.2. Recycling of subcontinental lithospheric mantle

Given these difficulties with a recycled sediment origin for the São Miguel enriched mantle source, an alternate origin to consider is recycling of enriched, subcontinental lithospheric mantle. Several aspects

of the trace element and isotopic signatures of the São Miguel enriched mantle source are similar to signatures found in the subcontinental lithospheric mantle. One of the most distinctive characteristics of the São Miguel enriched mantle source is the lack of an enrichment in Ba relative to other large ion lithophile elements, which manifests itself as low Ba/Rb. Ba/Rb ratios in MORB and most OIB display limited variation (11.6 ± 0.2) with an average value close to the primitive ratio of 11.3 (Hofmann and White, 1983), whereas the São Miguel enriched mantle source has a Ba/Rb ratio of ≤ 8 . Low Ba/Rb ratios are also a characteristic of some continental potassic volcanic rocks (Hawkesworth et al., 1985), including many kimberlites, potassic basalts from Vulsini (Rogers et al., 1985), and Spanish lamproites (Venturelli et al., 1984) (Fig. 11). Also plotting in the distinctive low Ba/Rb field (Fig. 11) are hydrous metasomatized phlogopite and phlogopite-potassium richterite peridotites (PP and PKP, respectively) and some MARID (mica, amphibole, rutile, ilmenite and diopside-rich) xenoliths from the Kimberly pipes in South Africa (Hawkesworth et al., 1985; Erlank et al., 1987).

Although low Ba/Rb appears to be a characteristic of some hydrous metasomatized subcontinental lithospheric mantle as well as a variety of continental magma types, the origin of the low Ba/Rb is not well understood. Both the Spanish lamproites and the Vulsini potassic lavas are thought to owe their distinctive trace element signatures to mantle sources that have been previously metasomatized by subduction-related fluids (Holm and Munksgaard, 1982; Rogers et al., 1985; Hertogen et al., 1988). However, attributing the low Ba/Rb signatures to subduction related fluids is not straightforward in that most island arc basalts do not exhibit a low Ba/Rb signature (Fig. 11) (Plank and Langmuir, 1993). Altered oceanic crust, which has distinctly low Ba/Rb ratios of roughly 1–10 (Hofmann and White, 1983), could in some cases be the primary contributor of Ba and Rb to slab-derived fluids which rise to metasomatize the overlying mantle wedge.

The lack of Ba enrichment relative to other highly incompatible trace elements in the São Miguel enriched mantle source also manifests itself in terms of low and relatively uniform Ba/Nb ratios of approximately 9. Low Ba/Nb ratios are characteristics of

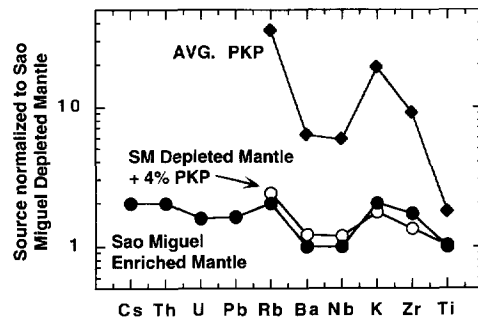


Fig. 12. Compositions of the São Miguel enriched mantle source and average hydrous PKP peridotite xenoliths relative to the São Miguel depleted mantle source (data for PKP xenoliths from Hawkesworth et al. (1990)). Both the São Miguel enriched mantle source and the PKP xenoliths are enriched in Rb, K and Zr over Ba, Nb and Ti relative to the São Miguel depleted mantle. The trace element pattern of the São Miguel enriched mantle source is well matched by addition of approximately 4% PKP-type peridotite to the São Miguel depleted mantle source.

both the Vulsini potassic volcanic rocks and many of the hydrous Kimberly xenoliths, although the Vulsini volcanic rocks (Rogers et al., 1985) have Ba/Nb ratios substantially lower than the São Miguel enriched mantle source. The compiled average Ba/Nb of PKP xenoliths (Hawkesworth et al., 1990), however, is close to 9, as is the Ba/Nb ratio of one MARID xenolith (Erlank et al., 1987), and these metasomatized continental mantle xenoliths are therefore similar to the São Miguel enriched mantle source in terms of both Ba/Rb and Ba/Nb ratios.

Fig. 12 illustrates that the PKP mantle xenoliths share many of the trace element signatures which characterize the São Miguel enriched mantle source, including pronounced enrichments of Rb, K and Zr relative to Ba, Nb and Ti. Indeed, addition of 4% of an average PKP component to the São Miguel depleted mantle produces a mantle source with abundances of Rb, Ba, Nb, K, Zr and Ti that closely match those estimated for the São Miguel enriched mantle (Table 2, Fig. 12). The major and trace element composition of the São Miguel enriched mantle source is therefore consistent with a similar style of enrichment to that of the PKP hydrous metasomatized continental mantle xenoliths.

The São Miguel enriched mantle source also shares some isotopic characteristics with the PKP xenoliths. Although the latter display a large range in

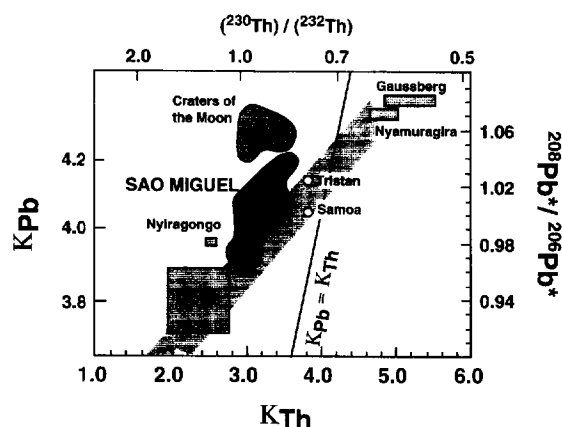


Fig. 13. K_{Pb} vs. K_{Th} showing variation of São Miguel basalts relative to the oceanic mantle array (shaded) along which MORB and most OIB plot (Allègre et al., 1986). The São Miguel enriched mantle source plots to the left of the mantle array, at a relatively high K_{Pb} of 4.2, greater or equal to bulk earth. High K_{Pb} values are also a feature of many continentally derived magmas including those from Craters of the Moon (Reid, 1995) with $K_{Th} < K_{Pb}$ and Gauseberg and Nyamuragira (Williams et al., 1992) with $K_{Th} > K_{Pb}$.

$^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$, they overlap in composition with the enriched São Miguel mantle in all three isotopic systems. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios in the PKP xenoliths (Erlank et al., 1987; Hawkesworth et al., 1990), however, are substantially less radiogenic than the São Miguel enriched mantle source, indicating that the São Miguel enriched mantle source has undergone more ancient enrichment events than the PKP xenolith source. This is supported by the very high K_{Pb} of the São Miguel enriched mantle, which indicates that it evolved with a time-integrated Th/U ratio of 4.2 (Fig. 13), greater than or equal to bulk earth (Allègre et al., 1986; Williams and Gill, 1992). The early high U/Pb and high Th/U signatures are consistent with a source which has been metasomatized by a small-degree silicate melt, where $K_{d_{Th}} < K_{d_U} < K_{d_{Pb}}$.

K_{Th} signatures, on the other hand, indicate that the present-day Th/U ratio of the São Miguel enriched mantle source is only 3.6 (Fig. 13). The combined K_{Pb} – K_{Th} systematics therefore require that the São Miguel enriched mantle source has undergone a decrease in Th/U ratio at some point in time greater than on the order of 10^5 years, in order that it be registered by the $(^{230}\text{Th})/(^{232}\text{Th})$ ratio.

This relatively recent metasomatic event must either have involved a low Th/U fluid or caused a low Th/U phase to be stabilized in the metasomatized mantle source. The high present-day U/Pb and Th/Pb signature of the São Miguel enriched mantle source inferred from the respective ratios in the basalts (Table 2), indicates that the process responsible for decreasing the Th/U ratio also produced or maintained relatively high source U/Pb and Th/Pb.

Unfortunately, the μ ($^{238}\text{U}/^{204}\text{Pb}$), ω ($^{232}\text{Th}/^{204}\text{Pb}$) and κ ($^{232}\text{Th}/^{238}\text{U}$) signatures of hydrous mantle phases such as phlogopite and K-richterite are poorly constrained, due both to limited analyses and to great variability in the existing analyses (Kramers et al., 1983; Stolz and Davies, 1988; McDermott and Hawkesworth, 1991; Tatsumoto et al., 1992; Rosenbaum, 1993; Ionov and Hofmann, 1995). However, if we consider only the PKP xenoliths, some likely have high μ values in order to produce $^{206}\text{Pb}/^{204}\text{Pb}$ ratios as high as 21.2 (Hawkesworth et al., 1990). Although no κ values have been measured in whole-rock PKP xenoliths, the one analysis of a hydrous phase (K-richterite) from a PKP xenolith produced a relatively low κ value of 2.5 (McDermott and Hawkesworth, 1991). Based on these limited data, the recent metasomatism of the São Miguel enriched mantle which produced a high μ but relatively low κ signature, is consistent with metasomatism by a hydrous fluid phase which stabilized phlogopite and K-richterite, similar to the formation of the PKP xenoliths. In the case of the São Miguel enriched mantle, the source of the hydrous fluid is unlikely to be related to subduction-zone dewatering, as this would be expected to impart on the metasomatized mantle a relatively low K_{Pb} signature inherited from sediment (McDermott and Hawkesworth, 1991; Reid, 1995). Rather, the metasomatizing fluid might have been generated from melting deeper within the mantle.

The proposed model, in which the trace element and Sr–Nd–Pb–Th isotopic signatures of the São Miguel enriched mantle source are due to a 4% component of PKP-type subcontinental lithospheric mantle, is also consistent with Os isotopic signatures in the São Miguel basalts. $^{187}\text{Os}/^{188}\text{Os}$ isotope ratios have been shown previously to be relatively uniform across the island, with typical plume signatures of approximately 0.132 (Widom and Shirey,

1996). PKP-type subcontinental lithospheric mantle is unradiogenic in Os relative to most mantle plume sources due to early Re-depletion events (Pearson et al., 1995), but the incorporation of only 4% of such material into the São Miguel enriched mantle source would have little effect ($\leq 0.5\%$) on the net Os isotope signature of the resulting mixed source composition. In contrast, due to the very high concentrations in PKP xenoliths of many incompatible trace elements, 4% incorporation of PKP-type mantle would dominate the incompatible trace element and Sr, Nd, Pb and Th isotope signatures of the resulting mixture (Fig. 12).

We propose that the São Miguel enriched mantle source was formed by multiple enrichments of the subcontinental lithospheric mantle beneath northwestern Africa or Iberia. The opening of the Atlantic Ocean basin beginning about 200 Ma may have caused this enriched material from the base of the continental lithosphere to delaminate and remain close to the present-day plate boundary, where it now resides as a shallow, low-density contaminant at the base of the oceanic lithosphere beneath the eastern end of São Miguel. Upon heating by the Azores plume, this recycled hydrous mantle would melt and contribute its distinctive isotopic and trace element signatures. The hydrous subcontinental lithospheric mantle would be expected to melt to a higher degree than the bulk of the plume mantle, which would explain the apparent higher degree of melting of the basalts from the São Miguel enriched mantle relative to those from the São Miguel depleted mantle. This is in contrast to a 'plum pudding' model in which the enriched component dominates basalt signatures during lower degrees of melting, when less of the surrounding depleted mantle is melted.

6. Conclusions

The São Miguel enriched mantle source is enriched relative to the predominant Azores plume source in K, Rb, Th, U, Pb and Zr, but not Ba, Nb and Ti. These elemental variations as well as variations across the island in many incompatible trace element ratios, are qualitatively consistent with a recycled terrigenous sediment origin for the São Miguel enriched mantle. However, a quantitative

assessment of sediment recycling indicates that the Ba/Th and Cs/Rb systematics as well as the $K_{\text{Pb}}-K_{\text{Th}}$ relationship of the São Miguel basalts are incompatible with this model.

The similarity of the trace element signature of the São Miguel enriched mantle with hydrous metasomatized mantle peridotites leads us to prefer an origin due to recycling of subcontinental lithospheric mantle. At least two metasomatic events are required to produce the Th and Pb isotopic signatures of the São Miguel enriched mantle: an early small-degree silicate melt metasomatism, and a more recent hydrous metasomatism. Shallowly residing lithospheric mantle from northwestern Africa or Iberia, left behind during the opening of the Atlantic, may be tapped by ascending Azores plume melts, producing the enriched trace element and isotopic signatures observed on São Miguel.

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