The peculiar geochemical signatures of São Miguel (Azores) lavas: metasomatised or recycled mantle sources?

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1. Introduction

This webpage summarises our recent paper published in Earth and Planetary Science Letters discussing and modelling the source composition of São Miguel (Azores) lavas (*Beier et al.*, 2007). Among OIB, the lavas erupted on São Miguel (Figure 1) are in many respects geochemically unusual. We present new major element, trace element and Sr, Nd, Pb and Hf isotope data that cover the entire compositional spectrum. The mechanism most often invoked to explain the enriched mantle signatures of OIB is recycling of oceanic crust (*e.g., Weaver et al.*, 1986; *Zindler & Hart*, 1986). However, the geological, physical and chemical processes involved in creation and recycling of continental and oceanic crust, and/or melt-rock interaction processes, are complex and the range of plausible input parameters for quantitative estimates of the chemical and isotopic composition is large (*Hart & Zindler*, 1989; *Kelley et al.*, 2005; *Stracke et al.*, 2003; *Workman et al.*, 2004). Although the large compositional range and unusual isotopic composition of the São Miguel lavas provides relatively tight constraints on source composition, they do not allow conclusions regarding where and when the Azores melting anomaly formed and what the the physical reasons for this melting anomaly are. This is, to some extent, the subject of two papers in preparation.

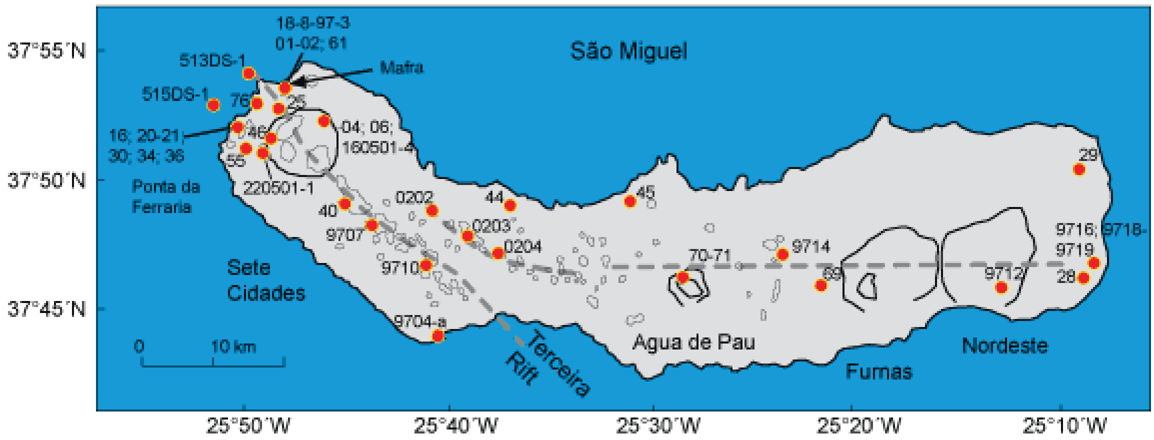

Figure 1: Map of São Miguel with main tectonic features (grey dotted lines) and sample locations. Click here or on Figure for enlargement.

2. Melt composition and evolution

The São Miguel samples are mostly alkali basalts with MgO concentrations up to 14.1 wt. % but range to more evolved rocks (~0.2 wt. %). Samples from each volcanic system lie on a single liquid line of descent indicating progressive fractionation. Syenite assimilation has previously been invoked to influence the major and trace element composition of the São Miguel lavas (*Elliott et al.*, 2007; *Storey et al.,* 1989; *Widom et al.,* 1993). We found no physical and/or geochemical evidence for such assimilation at Nordeste. Similar Na_2O, FeO^2, SiO_2, TiO_2, La/Sm and Sm/Yb ratios for all São Miguel lavas suggest a comparable extent and pressure of partial melting (see also *Elliott et al.*, 2007) for the western and eastern lavas.

3. Inter-island compositional differences and mantle source characteristics

Comparison of the average trace element composition of the primitive Nordeste and Sete Cidades samples shows that the Nordeste lavas are generally enriched relative to the Sete Cidades lavas. A gradual increase in the relative enrichment in some incompatible element concentrations from the west to east is also observed in previous studies (*Elliott et al.*, 2007; *Turner et al.,* 1997; *Widom et al.*, 1997). The Nordeste lavas are more enriched in Cs, Rb, Th, U and Pb but more depleted in Sr, Ba, Ti and, to a lesser degree, in Eu relative to the Sete Cidades lavas. Compared to other OIB, the average trace element concentrations of both the Nordeste and especially the Sete Cidades are similar to those in HIMU basalts (*e.g.,* St. Helena, Tubuaii) but have slightly higher alkali (Cs, Rb, K, Ba) and Th concentrations.

The Sr, Nd, Pb and Hf isotope ratios of the São Miguel samples (Figure 2) display a large range of linearly correlated isotope ratios with progressively higher Sr and Pb, and lower Nd and Hf isotope ratios from west (Sete Cidades) to east (Nordeste; *e.g. Elliott et al.*, 2007; *Turner et al.,* 1997; *Widom et al.,* 1997). The Sete Cidades lavas are similar to some enriched MORB and lavas from other Atlantic ocean islands, whereas lavas from Nordeste have unusual isotopic compositions with highly radiogenic Pb and Sr isotope ratios and low Nd and Hf isotope ratios, unlike any of the previously defined mantle end-members (*Zindler & Hart*, 1986). Despite the similarity of the trace element concentrations and Pb isotope ratios to those found in typical HIMU lavas, for example, the Sr isotope ratios of the Nordeste samples are clearly unlike those in typical HIMU islands, which are characterised by low and relatively constant Sr isotope ratios (Figure 2).

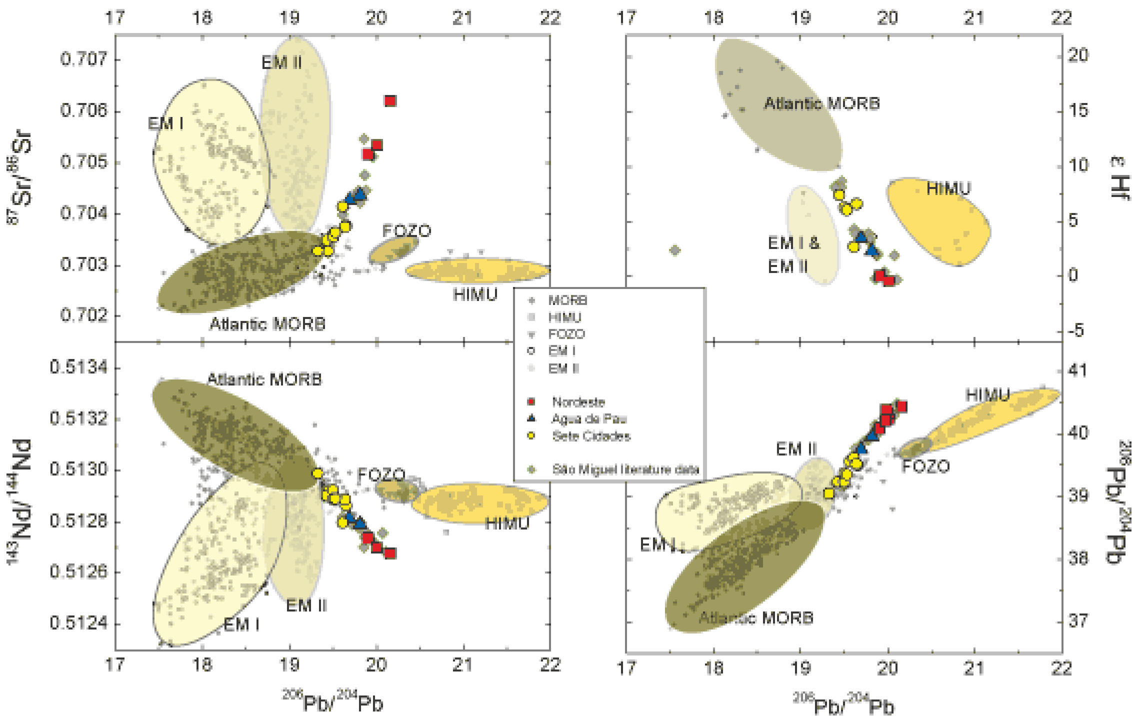

Figure 2: ^{206}Pb/^{204}Pb versus Sr, εHf, Nd and ^{208}Pb/^{204}Pb isotope data of the São Miguel volcanoes Sete Cidades, Agua de Pau and Nordeste. The overlapping isotopic trends of Agua de Pau and Sete Cidades mainly reflect samples from from a a zone of scoria cones between the two volcanoes, with two overlapping rift zones, each connected to one of the two systems (Haase & Beier, 2003). The HIMU, MORB, FOZO and EM (Enriched Mantle) compositions are referenced in detail in Stracke et al. (2003; 2005). Click here or on Figure for enlargement.

Generally, most of the trace element ratios (LILE and HFSE) that differ between the two volcanic centres correlate with differences in isotopic compositions (*Beier et al.*, 2007). Lack of evidence for syenite accumulation and concurrent enrichment of the trace element and isotope ratios observed in this study, however, suggest that trace elements and isotopes are enriched by the same process and imply a close genetic relationship between the two mantle sources.

4. Discussion

4.1 The São Miguel mantle source

Our data support the conclusion of *Elliott et al.* (2007) that previously proposed models involving enrichment by sediments or subcontinental lithospheric mantle are unlikely to explain the enrichment of the Nordeste mantle source.

The coupled high Sr and Pb, and low Nd and Hf isotope ratios require a source with a long-term evolution with high Rb/Sr, U/Pb, Th/Pb, Th/U and low Sm/Nd and Lu/Hf parent daughter ratios. The coupled enrichment of Rb/Sr, U/Pb and Th/Pb argues against the presence of sediments, because even minute amounts of sediment significantly increase the Pb concentrations and Th/Pb and U/Pb ratios, which leads, with time, to relatively unradiogenic Pb isotope ratios. As a result of previous melt extraction events, refractory lithospheric mantle is generally characterised by high ^{176}Hf/^{177}Hf and low ^{187}Re/^{188}Os isotope ratios (*Bizimis et al.*, 2003; *Jung et al.*, 2005; *Salters et al.*, 2006) leading to very radiogenic Hf and Os isotope ratios (*Ionov et al.*, 2005; *Salters & Zindler,* 1995; *Schmidberger et al.*, 2002). This is contrary to the ratios observed at Nordeste. While published $^{187}Re/^{188}Os$ isotope data (*Schaefer et al.*, 2002; *Widom & Shirey*, 1996) from several Azorean islands including São Miguel do have relatively low $^{187}Os/^{188}Os$ isotope ratios, they also have very low $^{176}Hf/^{177}Hf$ isotope ratios. Recycled subcontinental lithosphere therefore seems unlikely to account for the enriched Nordeste signature.

4.1.1 Metasomatic interaction

Infiltration or metasomatism of the sub-oceanic mantle by small-degree metasomatic melts leads to enrichment in incompatible elements proportional to the enrichment and relative proportion of the melts involved. The calculated composition of a small degree (0.5-1% degree of partial melting) melt generated from a depleted upper mantle source (*Salters & Stracke*, 2004) in the garnet stability field shows a melt composition that is even more enriched than most OIB. Infiltration and mixing of small amounts (1-2%) of these melts with depleted upper mantle generates enriched peridotite sources which can develop isotopic compositions comparable to those of Nordeste, provided there is enough time (~2.5 Ga) for the evolution of isotopic signatures (Figure 3).

Compared to Nordeste, the Sete Cidades isotope ratios require the infiltration of a smaller amount (1%) of slightly higher degree melts (3-5% degree of partial melting) to be consistent with the observed isotopic compositions. Although the metasomatic interaction scenario reproduces the isotopic composition of both the Nordeste and Sete Cidades lavas, the small-degree partial melts imprint their highly enriched trace element signature on the metasomatised mantle, often generating sources that have even more enriched trace element signatures than most OIB (see also [Workman et al., 2004](#)). For the specific case of São Miguel, the Nordeste lavas have lower Nb/Zr than the Sete Cidades basalts. If Nordeste's lavas are produced by metasomatic melts generated with smaller degrees of partial melting than those metasomatising the Sete Cidades source, as required by the isotopes, then Nordeste would be expected to have higher Nb/Zr ratios.

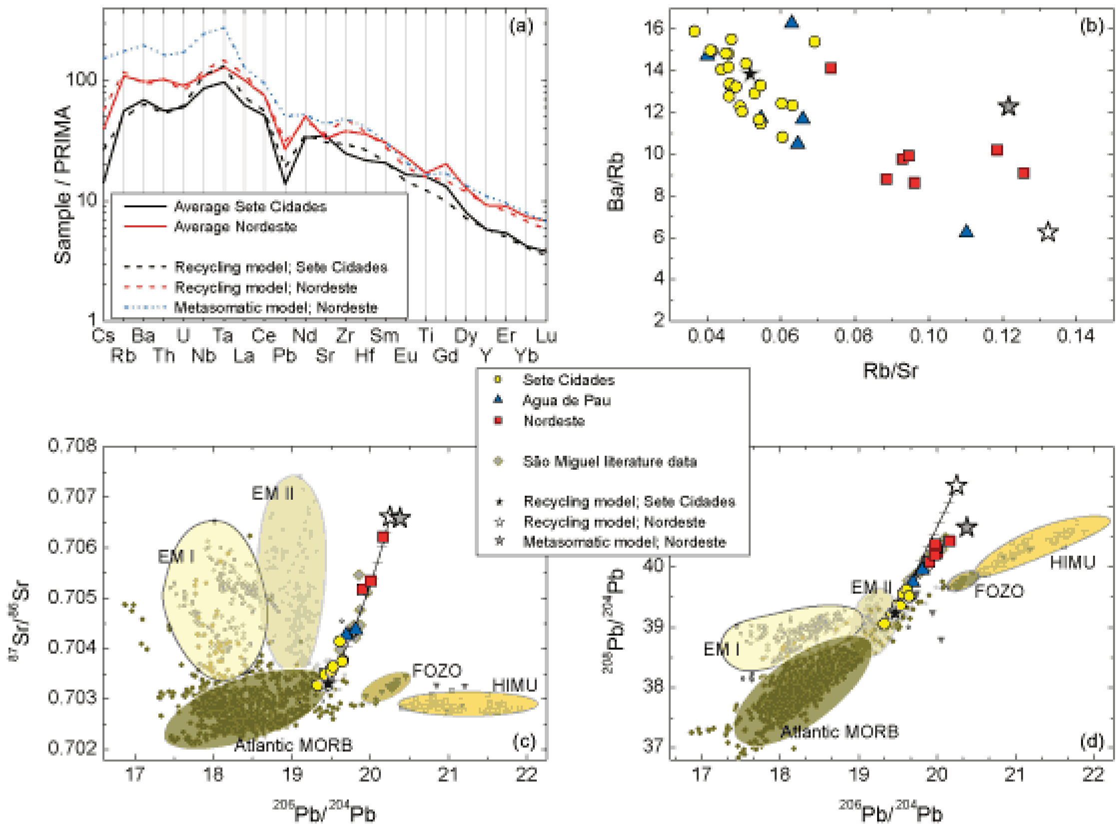

Figure 3: Calculated trace element and isotopic composition of the recycling (Sete Cidades, Nordeste) and melt metasomatism models. Tick marks of the mixing array represent 10% steps of the mixing array between the calculated Sete Cidades and Nordeste recycling models. Trace element and isotope ratios of the metasomatic model (grey star) also proposed by Elliott et al. (2007) and the proposed recycling model (white star) of ancient, altered recycled oceanic crust with evolved seamount lavas, are in agreement with the Nordeste trace element and isotope signatures. For detailed model parameters see Beier et al. (2007). HIMU, MORB, FOZO and EM compositions are referenced in detail in Stracke et al. (2003; 2005). The HIMU data (St. Helena) were compiled from the GEOROC database and Willbold & Stracke (2005). Click here or on Figure for enlargement.

4.1.2 Recycling

The correlation between Sr and Pb isotope ratios requires long-term evolution with coupled high parent-daughter ratios. Basaltic crust that is significantly affected by sub-arc alteration develops, with time, relatively low Sr and high Pb isotope ratios similar to those observed in HIMU basalts (*Stracke et al.*, 2005; *Willbold & Stracke*, 2005; *Zindler & Hart*, 1986). As a consequence, recycled basaltic crust is only compatible with the isotopic signatures of the São Miguel lavas when it has not been influenced by extensive sub-arc alteration.

The average isotopic composition of Sete Cidades overlaps with the compositional range defined by the depleted ends of many OIB arrays (FOZO; *Hart et al.*, 1992; *Stracke et al.*, 2005). Recycled oceanic crust must be relatively enriched with high Rb/Sr, U/Pb and Th/Pb in order to be compatible with the moderately enriched Sr and Pb isotope ratios of the FOZO/Sete Cidades lavas. Since Pb is probably the most mobile element during sub-arc alteration (*Kogiso et al.*, 1997), Pb concentrations are most easily affected during sub-arc alteration resulting in elevated Ce/Pb, U/Pb and Th/Pb . It seems conceptually plausible, therefore, that the Sete Cidades (FOZO) mantle source includes ancient recycled oceanic crust that has experienced some Pb loss during sub-arc alteration (*Stracke et al.*, 2005), but that other elements remained relatively little affected by sub-arc alteration processes.

The Nordeste lavas have lower Ce/Pb, U/Pb and Ba/Rb and higher Rb/Sr, Th/U and Sr isotope ratios compared to both Sete Cidades and HIMU lavas. Thus, if both the Sete Cidades and Nordeste sources are explained by recycled oceanic crust, the larger extent of sub-arc alteration inferred for Sete Cidades is incompatible with the trace element and isotopic differences between the two volcanoes. The Nordeste lavas are generally more enriched in incompatible elements but depleted in Sr (relative to Nd), Eu, Ti (relative to Gd) and Ba relative to Rb compared to Sete Cidades lavas. These depletions could be explained if the precursor rock of the Nordeste source originated from a melt that had previously undergone extensive fractionation of K-feldspar and Fe-Ti oxides. A ubiquitous source of evolved and chemically and isotopically enriched lavas on the ocean floor are seamounts (*McKenzie et al.*, 2004). Adding a small amount of trachyte to the modelled composition of the Sete Cidades mantle source quantitatively reproduces the Nordeste trace element pattern and isotopic composition.

The recycling of both slightly altered basaltic and evolved melts therefore significantly increases the Rb/Sr, U/Pb, Th/Pb and Th/U ratios, and is able to explain both the trace element and isotope systematics of the Nordeste lavas. It can also account for the correlation between trace element concentrations and isotope ratios between the Sete Cidades and Nordeste lavas.

5. Conclusions

The long-term evolution of trace element and isotopic enrichment of the Nordeste lavas suggested by the coherent correlation of isotope and trace element ratios requires involvement of a basaltic melt, either by melt metasomatism or recycling of oceanic crust. Although the metasomatic scenario is compatible with the isotope ratios (*Elliott et al.*, 2007), it fails to reproduce successfully the trace element signatures, a conclusion that is to a large extent independent of the exact input parameters (*e.g.* initial starting composition, partition coefficients).

The trace element and isotopic composition of São Miguel suggest that subduction and recycling of enriched evolved rocks may in some cases be detectable via the trace element and isotopic composition of OIB and may contribute to the evolution of mantle heterogeneities. The sparse occurrence of enriched source signatures comparable to Nordeste may be taken as circumstantial evidence that, at least in some cases, stirring and homogenisation processes in Earth's mantle cannot homogenise material the size of seamounts over relevant timescales.

Acknowledgments

We acknowledge the invitation of Gillian Foulger to present a summary of our paper in this webpage.

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last updated 6th August, 2007

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