

Comparing the nature of the western and eastern Azores mantle

Felix S. Genske^{a,b,c,e,*}, Christoph Beier^{a,c}, Andreas Stracke^c, Simon P. Turner^a,
Norman J. Pearson^b, Folkmar Hauff^d, Bruce F. Schaefer^a,
Karsten M. Haase^c

^a Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia

^b ARC Centre of Excellence for Core to Crust Fluid Systems/GEMOC, Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia

^c GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg, Schlossgarten 5, 91054 Erlangen, Germany

^d GEOMAR, Helmholtz-Zentrum für Ozeanforschung Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany

^e Institut für Mineralogie, Westfälische Wilhelms-Universität Münster, Corrensstrasse 24, 48149 Münster, Germany

Received 11 March 2015; accepted in revised form 25 August 2015; available online 22 October 2015

Abstract

The Azores islands in the central North-Atlantic originate from a regional melting anomaly, probably created by melting hot, unusually hydrous and geochemically enriched mantle. Here, we present Hf, Pb and Os isotopic data in geochemically well-characterised primitive lavas from the islands Flores and Corvo that are located west of the Mid-Atlantic Ridge (MAR), as well as submarine samples from a subsided island west of Flores and from Deep Sea Drilling Project (DSDP) holes drilled in the western part of the Azores platform and beyond. These are compared to existing data from the Azores islands east of the MAR. The geodynamic origin of the two islands west of the ridge axis and furthest from the inferred plume centre in the central part of the plateau is enigmatic. The new data constrain the source compositions of the Flores and Corvo lavas and show that the western and eastern Azores mantle is isotopically similar, with the exception of an enriched component found exclusively on eastern São Miguel. Trace element ratios involving high field strength elements (HFSE) are distinctly different in the western islands (e.g. twofold higher Nb/Zr) compared to any of the islands east of the MAR. A similar signature is observed in MAR basalts to the south of the Azores platform and inferred to originate from (auto-) metasomatic enrichment of the sub-ridge mantle (Gale et al., 2011, 2013). In a similar fashion, low degree melts from an enriched source component may metasomatise the ambient plume mantle underneath the western Azores islands. Melting such a modified plume mantle can explain the chemical differences between lavas from the western and eastern Azores islands without the need for additional plume components. Recent re-enrichment and intra melting column modification of the upwelling mantle can cause local to regional scale geochemical differences in mantle-derived melts.

© 2015 Elsevier Ltd. All rights reserved.

1. INTRODUCTION

The Azores plateau is a bathymetric swell with a diameter of about 450 km divided by the Mid-Atlantic Ridge

(MAR) into a smaller western and larger eastern part (Fig. 1a). Altogether, there are nine volcanic islands, seven of which are located to the east (Pico, Faial, Terceira, São Miguel, Santa Maria, São Jorge, Graciosa) and two to the west of the MAR (Flores and Corvo; Fig. 1a). The lithospheric thickness increases from ca. 35–40 km under the western and central islands to ca. 70–80 km under the easternmost islands (Gente et al., 2003; Genske et al., 2012; Beier et al., 2013). Upwelling of unusually hot or

* Corresponding author at: Institut für Mineralogie, Westfälische Wilhelms-Universität Münster, Corrensstrasse 24, 48149 Münster, Germany.

E-mail address: felix.genske@uni-muenster.de (F.S. Genske).

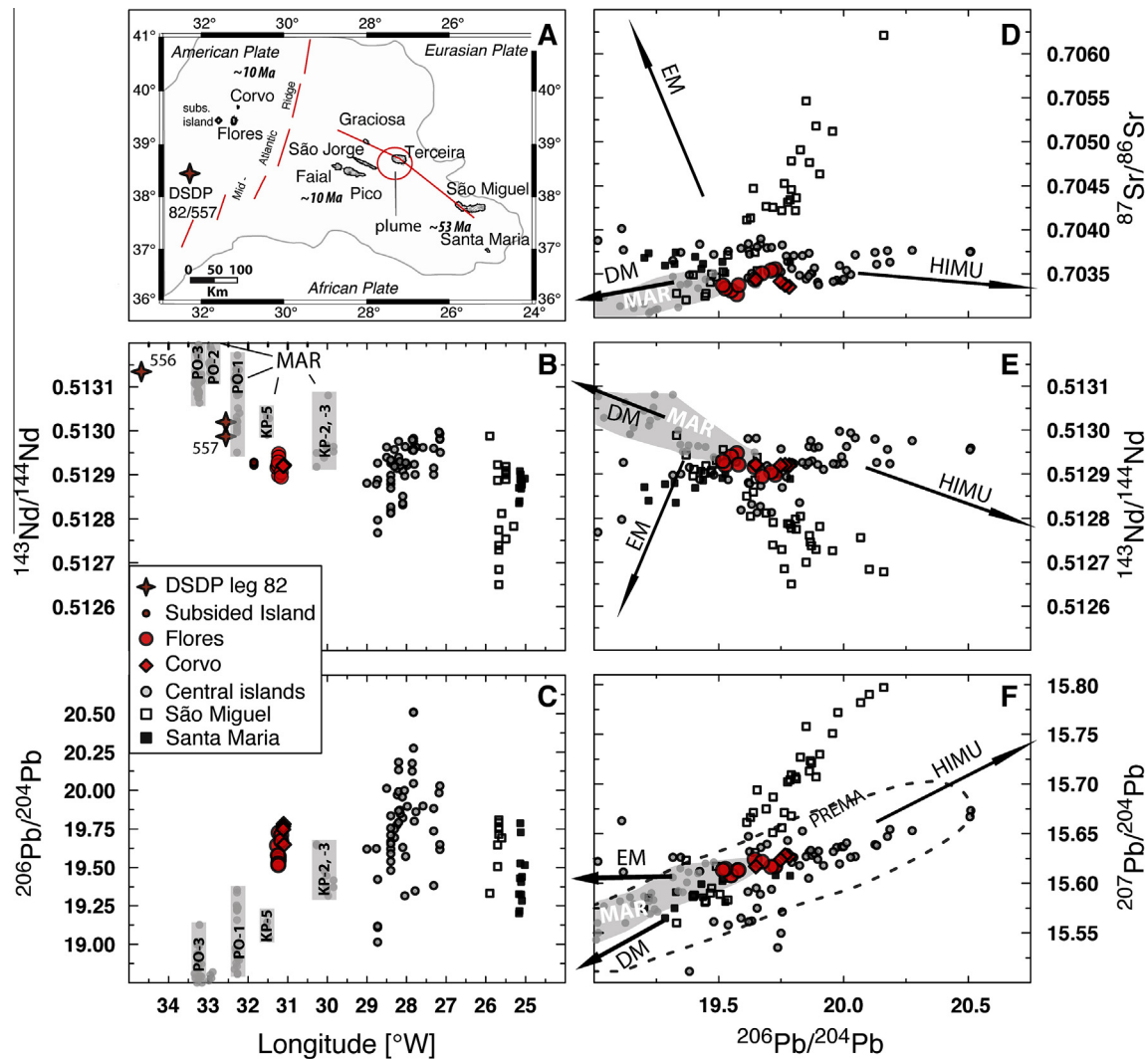


Fig. 1. (A) Map of the Azores plateau. The grey area reflects the bathymetric high of the plateau; red lines highlight the two spreading axes of the Mid-Atlantic ridge (MAR) and the Terceira rift, lithosphere age constraints are from [Searle \(1980\)](#) and [Cannat et al. \(1999\)](#). Submarine localities are Deep Sea Drilling Project Leg 82 Holes 556 and 557, where the off-plateau hole is not plotted on the map (refer to [Table 1](#) for coordinates). Samples west of Flores are from a subsided island described in more detail in [Ryall et al. \(1983\)](#). (B) Isotopic data of Nd and (C) Pb versus longitude for lavas across the Azores plateau, including MAR segment data (grey bars) towards the south of the Azores. Note the great variability in terms of the radiogenic isotope data observed on São Miguel is not seen on the other islands. (D) $^{87}\text{Sr}/^{86}\text{Sr}$, (E) $^{143}\text{Nd}/^{144}\text{Nd}$, and (F) $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ isotope ratios of the Azores lavas. Published data from Santa Maria, São Miguel, Terceira, Faial, Pico, São Jorge and Graciosa are from [Beier et al. \(2006, 2007, 2008, 2012, 2013\)](#), [Elliott et al. \(2007\)](#), [Millet et al. \(2009\)](#), [Schaefer et al. \(2002\)](#), [Turner et al. \(1997\)](#), [Widom et al. \(1997\)](#) and [Prytulak et al. \(2014\)](#). Published data from Flores and Corvo are from [Genske et al. \(2012\)](#), [França et al. \(2006a\)](#) and [Larrea et al. \(2012\)](#). New Pb isotope data from the latter two islands confirm the narrow range from Sr–Nd isotope space. Data from the MAR (grey fields) are taken from [Gale et al. \(2013, 2011\)](#). For further comparison, arrows towards different mantle end members (DM, EM and HIMU) are illustrated (*cf.* [Stracke, 2012](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

volatile-enriched mantle ([Schilling et al., 1980](#); [Bonatti, 1990](#); [Asimow et al., 2004](#); [Beier et al., 2012](#); [White and Schilling, 1978, 1983](#)) resulted in extensive melting and formation of this asymmetric oceanic plateau. The Azores mantle source is also geochemically more enriched than the local mid-ocean ridge mantle tapped at the MAR to the north and south of the Azores swell (e.g. [Schilling, 1975](#); [White et al., 1976, 1979](#)). Geochemical studies along the MAR have shown that the Azores plume influence extends far to the south of the islands and stops abruptly

just to the north of the bathymetric high of the plateau at around 41°N ([Bourdon et al., 1996](#); [Dosso et al., 1999](#); [Gale et al., 2011, 2013](#); [White and Schilling, 1978](#); [Schilling et al., 1983](#); [Laubier et al., 2012](#)). This observation may indicate a generally southward flow of the enriched Azores mantle material.

The available geochemical data for lavas from the Azores islands are mostly from the eastern islands, and indicate that their trace element and Sr–Nd–Hf–Pb isotope compositions are variable, both between and within individual islands (e.g.

Beier et al., 2008, 2010; Elliott et al., 2007; Prytulak and Elliott, 2009). Most of the across-plateau diversity, however, arises from the peculiar composition of some of the São Miguel lavas (Figs. 1 and 2), which are characteristic for basalts from the eastern part of this island. When excluding these unique signatures, the available data show relatively consistent enriched signatures that require only minor source heterogeneity. Previous studies have attributed the observed isotopic observation to several distinct sources within the Azores plume (Beier et al., 2008, 2007; Hawkesworth et al., 1979; Shirey et al., 1987; Widom and Shirey, 1996; Schaefer et al., 2002; Prytulak and Elliott, 2007; Turner et al., 2007). However, the mantle sources of basalts from the islands east of the MAR – Santa Maria, São Jorge, Faial, Graciosa, Terceira and Pico, and those from the Sete Cidades volcano on São Miguel – share common enriched isotope signatures (Beier et al., 2006, 2008, 2012, 2013), which straddle the field of enriched mid-ocean ridge basalts (MORB) and largely overlap with prevalent

mantle (PREMA) and its permutations (Zindler and Hart, 1986; Stracke, 2012; FOZO: Hart et al., 1992; “C”: Hanan and Graham, 1996; Figs. 1 and 2). Hence, it has been suggested that the Azores mantle plume contains a ubiquitous enriched end-member, the so-called common “Azores plume component” (Beier et al., 2008, 2013; Gale et al., 2011).

In recent years new data have become available for the central and easternmost Azores islands and the Azores-MAR (see above), which have placed constraints on the nature and extent of the Azores melting anomaly. Yet, very limited data are available for lavas from the islands west of the MAR. To further investigate the heterogeneity of the Azores mantle and to address the relationship between volcanism east and west of the MAR, we present new Pb–Hf–Os isotope data for rocks from the islands of Flores and Corvo, both located on the American plate (Fig. 1a). For enhanced spatial constraints, new major and trace element data along with radiogenic isotope compositions (Sr, Nd, Hf) from submarine samples to the west of the MAR are also included,

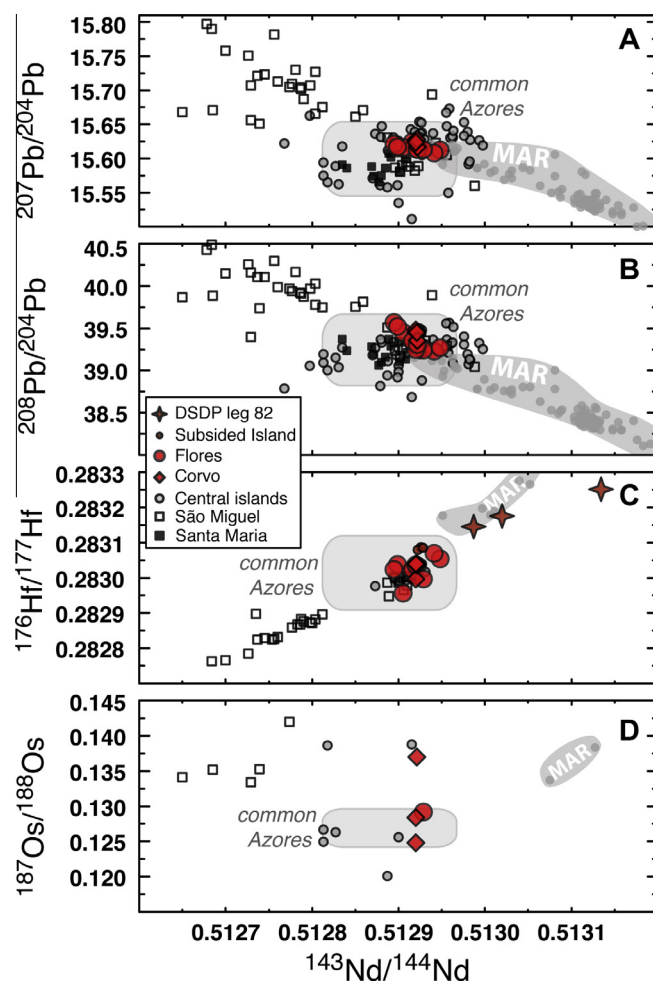


Fig. 2. Radiogenic isotope compositions of Pb (A, B), Hf (C) and Os (D) versus Nd isotope ratios. Compared to the eastern Azores islands, lavas from Corvo and Flores display a much narrower range and conform to a depleted end member relative to the other islands and slightly intersect the field of the MAR basalts, at least in Pb–Nd isotope space. Same sample set as previously shown (*cf.* Fig. 1), but on panel D the arrow points towards superchondritic, radiogenic Os isotope data from 4 Azores MAR samples, that are affected by seawater alteration (Table 1). MAR Hf and Nd isotope data from Hamelin et al. (2013), MAR Os isotope data from Gannoun et al. (2007).

extending into off-plateau MORB crust (i.e. Deep Sea Drilling Project (DSDP) Leg 82 Hole 556, [Table A.1](#)).

The new data show that the isotopic composition of the western lavas reflects the presence of an enriched (Sr–Nd–Pb–Hf isotope ratios) source component that is also common underneath the eastern Azores islands: the common “Azores plume component” ([Beier et al., 2008](#)). Hence there is no significant regional, across-ridge isotopic variation in the Azores mantle. In contrast, incompatible trace element ratios differ between the western and eastern lavas. Specifically, the high-field-strength elements Nb–Ta and Zr–Hf are more fractionated relative to similarly incompatible elements in lavas from Flores and Corvo when compared to lavas from the islands east of the MAR ([Genske et al., 2012](#)). Variability in incompatible element ratios for similar isotope compositions indicates that these signatures are likely related to the melting process. In this study we discuss how, in the absence of apparent source differences, the geochemical differences observed between the Azores islands west and east of the MAR could relate to the regional melting processes, which might be caused by differences in the regional geodynamic setting. We argue that parameters such as the lithospheric thickness cannot account for the observed disparities in the melting process. Melting underneath Flores and Corvo may be a two-step process similar to what has been proposed for the ridge segments to the south of the Azores MAR (i.e., in non-plume settings), where [Gale et al. \(2013, 2011\)](#) and [Wanless et al. \(2015\)](#) observed similar trace element enrichment in basalts from the Menez Gwen and Lucky Strike segments. It will be shown here that an (auto-) metasomatic model (e.g., [Roden et al., 1984](#)) can account for the distinct trace element variability observed in the western Azores lavas. Recent re-enrichment and intra melting column modification of the upwelling mantle could thus cause local to regional scale geochemical differences in mantle-derived melts in both plume and ridge-related settings, without the need for an additional source component.

2. SAMPLES AND ANALYTICAL TECHNIQUES

2.1. Sample selection

New Pb–Hf–Os isotope data for lavas from the western Azores islands Corvo and Flores are presented in [Table 1](#). Major element, trace element and Sr–Nd isotope data have been reported in [Genske et al. \(2012, 2014\)](#). In addition, Hf isotope ratios are presented for three samples from São Jorge and Pico that were previously analysed for Sr, Nd and Pb isotopes by [Turner et al. \(1997\)](#). We also measured Os isotope ratios for four samples from the Azores MAR (segments KP-2 and KP-3) and one MAR sample far to the south of the Azores (North Oceanographer segment). Sample localities, a detailed petrological description and major and trace element data for samples from Flores and Corvo along with Sr and Nd isotope data are given in [Genske et al. \(2012\)](#). Further data from Corvo, which are included here for comparison, are from [França et al. \(2006a\)](#) and [Larrea et al. \(2012\)](#). The oldest ages determined on Flores lavas are around 2 Ma ([Azevedo and Ferreira,](#)

[1999](#)) and the oldest lavas from Corvo are between 1.0 and 1.5 Ma ([França et al., 2006a](#)).

Three samples from a subsided island approximately 50 km west of Flores ([Fig. 1b](#); [Ryall et al., 1983](#)) were analysed for major and trace elements as well as Sr, Nd and Hf isotope ratios ([Table A.1](#)). Sample localities as well as the petrography of these three basalts are described in [Ryall et al. \(1983\)](#). These samples are described as subalkaline based on mineral chemical analyses. Three further samples were recovered from Deep Sea Drilling Project (DSDP) Holes 556 and 557, Leg 82 ([Fig. 1](#) and [Table A.1](#)). The former hole was drilled into normal MORB crust to the west of the Azores plateau, but the latter was attempted to recover enriched samples from the westernmost part of the Azores platform ([Bougault and Cande, 1985](#)). New major- and trace element data and Sr–Nd isotopic compositions were determined following the methods described in [Genske et al. \(2012\)](#).

Major element, trace element and Sr–Nd–Pb(–Hf)–Os data for the eastern islands (Pico, Faial, São Jorge, Graciosa, Terceira, São Miguel and Santa Maria) are from [Beier et al. \(2006, 2007, 2008, 2013\)](#), [Elliott et al. \(2007\)](#), [Schaefer et al. \(2002\)](#), [Turner et al. \(1997\)](#) and [Widom et al. \(1997\)](#) unless stated otherwise in the corresponding figure captions. A comprehensive compilation of all literature data used herein is given in [Table A.2](#).

2.2. Analytical techniques

2.2.1. Hf isotope analysis

Rock powders (ca. 140 mg), prepared using an agate mill, were digested in Savillex® Teflon vials with concentrated, distilled HF and HNO₃. Subsequent treatment involved HClO₄, 6 N HCl and H₂O₂. The samples were finally centrifuged to remove insoluble gels, if any. The chromatographic separation of Hf was done using anion and cation exchange columns following procedures reported by [Blichert-Toft \(2001\)](#). Hafnium isotope data were obtained on a Nu Plasma MC-ICP-MS at the Geochemical Analysis Unit (GAU), at Macquarie University, Sydney. Because all samples are much younger than 2 Ma, no age correction has been applied. Ratios were normalized to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ to correct for instrument mass fractionation. Repeated measurements of JMC-475 standard ($n = 24$) yielded $^{176}\text{Hf}/^{177}\text{Hf}$ of 0.282152 ± 0.000027 (2 S.D., not corrected for machine drift). All data were corrected to the bracketing standard JMC-475 $^{176}\text{Hf}/^{177}\text{Hf} = 0.282160$. Rock standard BHVO-2 was processed with the samples and repeated measurements ($n = 8$) gave values of $^{176}\text{Hf}/^{177}\text{Hf} = 0.283108 \pm 0.000018$ (2 S.D., corrected to JMC-475), which is in excellent agreement with accepted values for this standard (*cf.* [GeoReM, Jochum et al., 2005](#)). Duplicate analyses to verify the accuracy of the data are listed in [Table 1](#).

2.2.2. Pb isotope analysis

Double-spiked (DS) Pb isotope analyses were carried out at the GEOMAR Hemholtz Centre for Ocean Research Kiel (Germany), following procedures described in [Hoernle et al. \(2011\)](#) and references therein. Selected 1–2 mm-sized chips

were leached in warm (70 °C) 2 N HCl, rinsed three times in 18 MΩ H₂O thereafter and digested in a hot (150 °C) HF–HNO₃ mixture. Pb was separated using ion exchange procedures reported by Hoernle et al. (2008). The isotopic ratios were measured on a Finnigan MAT262 RPQ²⁺ thermal ionisation mass spectrometer (TIMS) operating in static multi-collection mode. Multiple analyses of NBS 981 resulted in DS corrected $^{206}\text{Pb}/^{204}\text{Pb} = 16.9419 \pm 0.0028$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4999 \pm 0.0026$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.7256 \pm 0.0067$ (2 S.D., $n = 99$). These values compare well with published double and triple spike data for NBS981 (Galer, 1999; Thirlwall, 2000, 2002; Baker et al., 2004). The total chemistry blank was <20 pg, and is thus negligible.

2.2.3. Os isotope analysis

For the determination of Os concentrations and isotopic composition, 4–5 g of powder per sample was spiked (^{190}Os spike, enriched to 96.583%) according to the expected Os contents in the lavas. The samples were then digested in inverse aqua regia by Carius tube dissolution followed by solvent extraction and micro distillation techniques, as described in detail elsewhere (Cohen, 1996; Birck et al., 1997). All samples were run on a Thermo Finnigan TRITON TIMS in negative-ionisation mode (N-TIMS) at the GAU at Macquarie University. Total procedural blank levels of typically 3 pg or better were achieved, resulting in blank contributions that were typically less than 1.1% on 5 g sample dissolutions. The WPR-1 reference material (Natural Resources Canada) was processed twice along with unknown samples to monitor chemical separation reproducibility and gave $^{187}\text{Os}/^{188}\text{Os} = 0.14449 \pm 0.00022$ and 0.14474 ± 0.00022 (2 S.D.) with Os (ppb) = 17.86 ± 0.02 and 18.08 ± 0.01 . These values are in good agreement with published values (e.g. Correia et al., 2007). A 5 ng solution of the JMC-2 standard run to monitor instrument performance during the course of this study was also measured twice and resulted in $^{187}\text{Os}/^{188}\text{Os} = 0.18345 \pm 0.00008$ (2 S.D.) and $^{187}\text{Os}/^{188}\text{Os} = 0.18333 \pm 0.00016$ (2 S.D.). The MAR sample far to the south of the Azores platform (AII-0127-D44-1), including a leached and an unleached fraction, was analysed at Scripps Institution of Oceanography, California, USA, to assess the effects of Mn crusts, following the analytical protocol by Day et al. (2013). The analytical results are given in Table 1.

3. RESULTS

3.1. Major elements

The samples discussed here are grouped according to their sample locality and geochemical composition. The following groups are distinguished: lavas from (a) Santa Maria (Beier et al., 2013), (b) São Miguel including the enriched eastern Nordeste volcano (Beier et al., 2006, 2007; Turner et al., 1997; Widom et al., 1997; Elliott et al., 2007), (c) the central islands Terceira, Faial, Pico, Graciosa and São Jorge (Beier et al., 2008, 2012; Turner et al., 1997; Elliott et al., 2007; Millet et al., 2009), (d) the western islands of Corvo and Flores (França et al., 2006a; Genske et al., 2012; Larrea et al., 2012; this study), and,

(e) submarine samples from the western plateau and beyond (Fig. 1 and (Ryall et al., 1983; Bougault and Cande, 1985, this study)). All of these data are compiled in Table A.2.

All Azores lavas discussed here are alkali basalts *sensu lato*. The major element systematics of samples from Flores and Corvo have been discussed in detail in Genske et al. (2012) and Larrea et al. (2012). The dataset used here is restricted to lavas with 5–12 wt.% MgO in order to minimise the effects of assimilation-fractional crystallisation (AFC)-derived imprints onto the lavas (Genske et al., 2013, 2014; Prytulak et al., 2014). We use only fresh samples with loss on ignition <2% and without petrographic signs of alteration, with the exception of the submarine samples.

The entire dataset across the central Azores plateau does not reveal any systematic major element trends with longitudinal distance from the proposed plume centre or lithospheric thickness (Beier et al., 2010, 2012), although the preservation of enriched trace-element signatures underneath eastern São Miguel and Santa Maria may relate to increased lithosphere thickness (Beier et al., 2013).

3.2. Trace elements

The trace element concentrations of lavas from Corvo and Flores are comparable to those of the eastern Azores islands (Genske et al., 2012; Larrea et al., 2012). However, lavas from Corvo and Flores and the samples from the nearby subsided island (samples 54B core, 58 core, 68 core) have distinctively higher, and more variable Nb/Zr, Nb/Yb (and Ta/Hf) owing to elevated Nb and Ta concentrations and lower Zr and Hf concentrations (Figs. 6–8, Fig. B.1), relative to similarly incompatible elements. Ratios of Nb over Zr are, on average, almost twice as high as the common Azores value, which is typical for OIB in general (Nb/Zr ~ 0.2 (cf. Willbold and Stracke (2006))), and lavas from the western margin of the Azores plateau (Figs. 3 and 6; DSDP 82/557) also conform to this value.

Hence, trace element ratios involving La, Sm, Nb and Zr can be used to distinguish basalts from the different localities (Fig. 4). Whereas the Azores MAR field is relatively restricted with low values for Zr/Sm and La/Nb, a larger compositional variation is observed across the islands, with the most extreme values in samples from São Miguel. Lavas from Flores and Corvo have comparable La/Nb to Santa Maria and the central islands, but Zr/Sm in lavas from the two western islands is similar to the MAR field (Fig. 4).

In order to correct the trace element abundances for the effects of fractional crystallisation, a least squares approach in the form of XLFrac (Stormer and Nicholls, 1978) has been applied to calculate the modal abundances of the fractionated mineral assemblage in each lava suite individually. These mineral modes were used to estimate the trace element concentrations of the parental melts (Fig. 6 and 7). The parental magmas in the Azores islands are assumed to have MgO contents of around 11.5 wt.%; values higher than 12 wt.% are interpreted to reflect accumulation of olivine and clinopyroxene crystals (cf. Beier et al., 2006; Genske et al., 2012; Larrea et al., 2012).

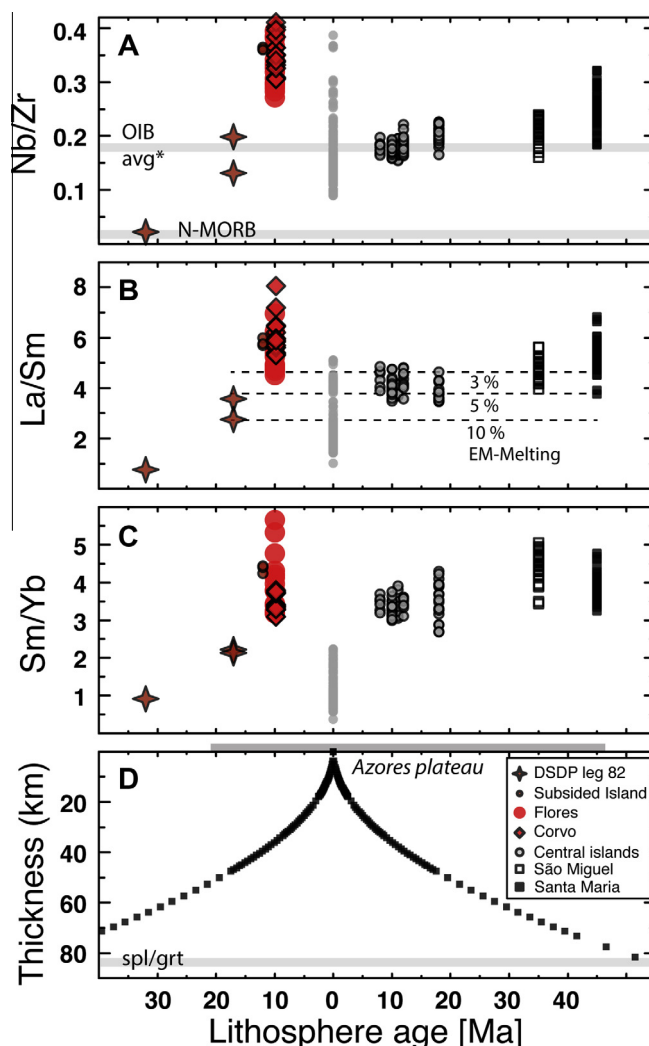


Fig. 3. Trace element ratios of Azores and MAR lavas versus lithosphere age (Searle, 1980; Cannat et al., 1999; Gente et al., 2003). Highest Nb/Zr values (panel A) are characteristic for the eastern (Santa Maria) and westernmost (Flores and Corvo) islands, but are also observed in samples from ridge segment centres of KP-4, KP-5 (Menez Gwen) and PO-1 (Lucky Strike). An across plateau symmetry in trace element enrichment is also observed in La/Sm (B), but is not pronounced in Sm/Yb (C). Different melting degrees using an EM-melting model as described in detail in Genske et al. (2012) are illustrated in (B). However, this model cannot explain elevated Nb/Zr values (A), as these are also observed in some ridge segment samples (Menez Gwen, Lucky Strike) that require comparatively higher degrees of partial melting (Gale et al., 2013). Same data sources as in Fig. 1.

3.3. (Sr–Nd)–Pb–Hf–Os isotopes

Lavas from Corvo and Flores cluster around $^{206}\text{Pb}/^{204}\text{Pb} = 19.50\text{--}19.90$ (Figs. 1 and 2), which is also common to lavas from the central island group, western São Miguel (Beier et al., 2008, 2012; Elliott et al., 2007) and Santa Maria (Beier et al., 2013). This compositional field intersects and extends that of the basalts from the MAR (Figs. 1d–f and 2). Samples from Corvo and Flores together with samples from the subsided island display a smaller Hf isotope range than lavas from São Miguel (Fig. 2) and overlap with the radiogenic end of the São Miguel rocks. Three samples from the central islands (i.e. two from Pico and one from São Jorge, Table 1) were also

analysed for Hf isotope ratios during the course of this study. Even though the available number of Hf isotope analyses from Pico and São Jorge likely does not represent the full range of the central group islands, it is striking that they display a very restricted range in $^{176}\text{Hf}/^{177}\text{Hf}$ (0.28298 to 0.28304), comparable that of Flores and Corvo ($^{176}\text{Hf}/^{177}\text{Hf} = 0.28296$ to 0.28309). Overall, the radiogenic isotope variability of lavas from the islands east of the MAR is larger than that of Corvo and Flores, but mostly as a result of the radiogenic isotope variability on São Miguel. The compositional field defined by the western lavas in Sr–Nd and Pb–Pb isotope spaces, but also in Hf isotope ratios, is consistent with PREMA-type signatures or its permutations, which are common to most OIBs

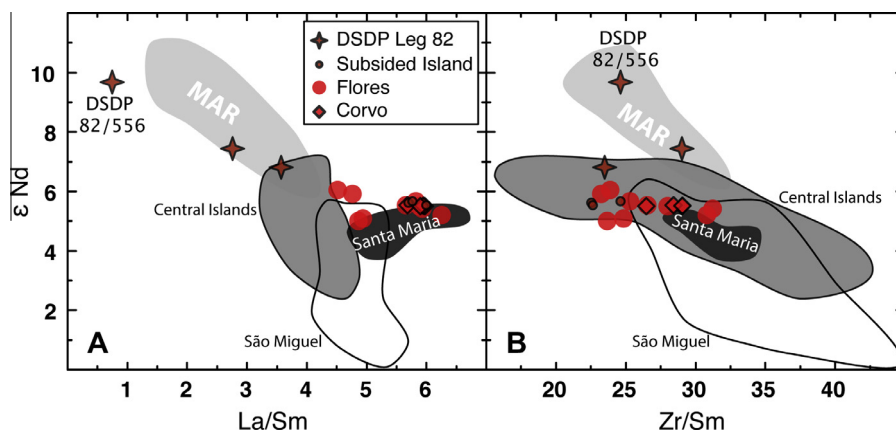


Fig. 4. Trace-element ratio plots of La/Sm and Zr/Sm versus ϵ Nd. Epsilon values represent normalisation of the radiogenic ratios to CHUR (Bouvier et al., 2008). The lack of a correlation between La/Sm and radiogenic isotope compositions in lavas from Flores, Corvo and Santa Maria (A) indicates that the same source is melted at somewhat lower degrees of partial melting compared to the central island lavas. Further, Zr/Sm also reveals no correlation with radiogenic isotope ratios (B) and appears comparable between Santa Maria and the western islands and perhaps São Miguel. Same data sources as in Fig. 1.

(e.g. Zindler and Hart, 1986; Hart et al., 1992; Stracke et al., 2005; Stracke, 2012), and similar to the inferred “Azores plume component” (Beier et al., 2008).

The new Os isotope data for Corvo and Flores lavas are supra- to slightly subchondritic and range in $^{187}\text{Os}/^{188}\text{Os}$ from 0.125 to 0.137. This is in agreement with Os isotope ratios reported by Schaefer et al. (2002) and Widom and Shirey (1996) on other Azores lavas (Fig. 2). There is no apparent correlation with radiogenic Sr, Nd or Pb isotopes. The Os contents of the new samples (Table 1) are systematically higher (Os = 0.05–0.12 ppb) than those reported for the central island group by Schaefer et al. (2002), but comparable to those of São Miguel (Widom and Shirey, 1996). In contrast, samples from the MAR with highly radiogenic $^{187}\text{Os}/^{188}\text{Os}$ (Table 1) are characterised by Os contents (Os = 0.004–0.011 ppb) commonly observed in the central islands or lower (Table 1).

4. DISCUSSION

4.1. An isotopically zoned Azores plume?

The Azores mantle plume is likely situated underneath the central island group (Cannat et al., 1999; Moreira et al., 1999; Gente et al., 2003; Saki et al., 2015), either below Terceira (Bourdon et al., 2005), Faial (Shorttle et al., 2010), or São Jorge (Millet et al., 2009; Beier et al., 2012). If plume material were to flow radially outward from the plume centre and mix with ambient mantle, any chemical or isotopic signature associated with the plume source should in principle vary systematically with distance from that centre (Shorttle et al., 2010). Such a simple pattern is not observed in the Azores (Fig. 1 b and c, Figs. 2 and 3, and e.g. Beier et al., 2010). Rather, the Azores melting anomaly appears to be heterogeneous on a variety of scales, both between and within individual islands.

Because the MAR intersects the Azores plateau (Fig. 1a), lavas from either side of the MAR, may sample compositionally distinct parts of the Azores mantle plume.

The few available geochemical and isotopic data on volcanic rocks from the two islands west of the MAR (França, 2008; Genske et al., 2014, 2012; Larrea et al., 2012), Flores and Corvo, however, have shown that their Sr–Nd isotope compositions overlap those of the eastern islands (Genske et al. (2012)). The new data presented here show that this is also the case for radiogenic Pb, Hf and Os isotope ratios (Figs. 1 and 2).

Temporal variations in mantle source composition are negligible, because the islands east and west of the MAR are of similar age (mostly K–Ar ages, cf. Azevedo and Ferreira, 2006; Feraud et al., 1980; Johnson et al., 1998, and references therein), are far younger than 10 Ma, and a clear age progression is not observed (Beier et al., 2015).

In summary, there is no systematic variation of the radiogenic isotope ratios with longitudinal distance from the plume centre (Fig. 1), with lithospheric thickness (cf. Figs. 1 and 3), or age. Hence unlike the Hawaiian plume (e.g. Tatsumoto, 1978; Hofmann and Farnetani, 2013; Xu et al., 2014), there is no obvious isotopic zonation within the Azores mantle plume.

4.2. The common Azores plume component

As discussed above, the Sr–Nd–Hf–Pb–Os isotope ratios are broadly uniform across the western, central and eastern Azores islands, with the exception of lavas from the eastern part of São Miguel (Figs. 1 and 2, Table A.2). The unique source composition of the latter has mostly been related to the presence of ancient recycled oceanic lithosphere or sediments (Beier et al., 2008, 2007; França et al., 2006b; Elliott et al., 2007; Hawkesworth et al., 1979; Prytulak and Elliott, 2007, 2009; Shirey et al., 1987; Widom and Shirey, 1996; Schaefer et al., 2002; Turner et al., 2007). Excluding these isotopically unique samples from São Miguel (i.e., restricting data to the Sete Cidades volcano, Beier et al., 2006) leaves a comparatively uniform field in Sr, Nd, Os, Hf, and Pb isotope space for all of the Azores islands (Fig. 2). On the basis of this observation, Beier et al.

(2008) proposed the existence of an “Azores plume component” that is common to the mantle sources of all the Azores islands (Beier et al., 2007). The “Azores plume component” has a PREMA-like isotope composition (Beier et al., 2007) and likely represents ancient recycled oceanic crust. Despite being arguably heterogeneous on a small scale (*cf.* Beier et al., 2008), the common Azores plume component is apparently sampled in a reproducible fashion by recurrent volcanism on the various islands, independent of their geographic position (see Section 4.1. above). As a result, a similar range in isotopic composition is observed across the archipelago, indicating that the Azores plume component is homogeneously distributed in the regional mantle.

4.3. Sampling the Azores mantle plume

Similar to the isotope ratios, most incompatible trace element ratios (e.g. Nb/Zr, La/Sm) are relatively uniform in lavas from the central islands, but those from the westernmost (Flores, Corvo) and easternmost islands (Santa Maria, São Miguel) have more variable and, on average, higher values (Fig. 3). Correlations between isotopic composition and trace element ratios are not observed (Figs. 4 and 6). Variable source compositions are therefore not the primary reason for the observed differences in incompatible trace element ratios. Another possibility to explain these would be changing melting conditions due to variable lithosphere thickness across the plateau, such that isotopically similar sources are sampled differently by partial melting.

The range and average values of Nb/Zr or La/Sm differ significantly between the central and the western islands, but both island groups are located on lithosphere of similar thickness (ca. 30–40 km; Fig. 3). In contrast, the two easternmost islands (São Miguel and Santa Maria) lie on thicker lithosphere (70–80 km) than their central counterparts, resulting in higher mean pressures and lower mean extents of melting (Beier et al., 2013). However, basalts

from São Miguel and Santa Maria in the east and Flores and Corvo in the west are characterised by a similar range in La/Sm, La/Nb or Sm/Yb (Figs. 3 and 4). This similarity between the eastern- and westernmost lavas suggests that they are produced by a similar degree of melting, despite the difference in lithospheric thickness. Hence no simple relationship between lithospheric thickness and incompatible trace element enrichment (and mean extent of melting) is apparent.

4.4. Unique HFSE signatures in the western Azores lavas

When specifically considering the HFSE abundances in the Azores basalts, it is evident that there are pronounced differences between islands west and east of the MAR (Figs. 3 and 6–8, Fig. B.1). Some similarly incompatible elements, such as Nb and Ta, appear to be slightly more enriched in basalts from the western islands compared to the islands east of the MAR (Genske et al., 2012; Beier et al., 2013). For instance, low La/Nb in Flores and Corvo is caused by slightly increased contents of Nb (Figs. 5 and B.1, Table A.2). In contrast, Zr and Hf in lavas from Flores and Corvo are slightly less enriched compared to the lavas east of the MAR (Fig. B.1). This distinct fractionation of the HFSE⁵⁺ from the HFSE⁴⁺, i.e. (Nb, Ta)/(Zr, Hf), in lavas from Corvo and Flores, appears to be a local feature, where Nb/Zr and Ta/Hf on Flores and Corvo yield average values of 0.33 and ~1, respectively, much higher than the global OIB averages of 0.2 and 0.6 (*cf.* Willbold and Stracke, 2006).

In contrast, the far-west on-plateau DSDP Drill Hole 82–557 yields common Azores or normal OIB values (Fig. 3), thus the elevated Nb/Zr is unlikely representative for the entire western plateau. The off-plateau drill hole sample from DSDP 82–556 has an N-MORB composition (*cf.* Gale et al., 2013; Arevalo and McDonough, 2010) and will be used to represent ambient MAR mantle in the modelling below.

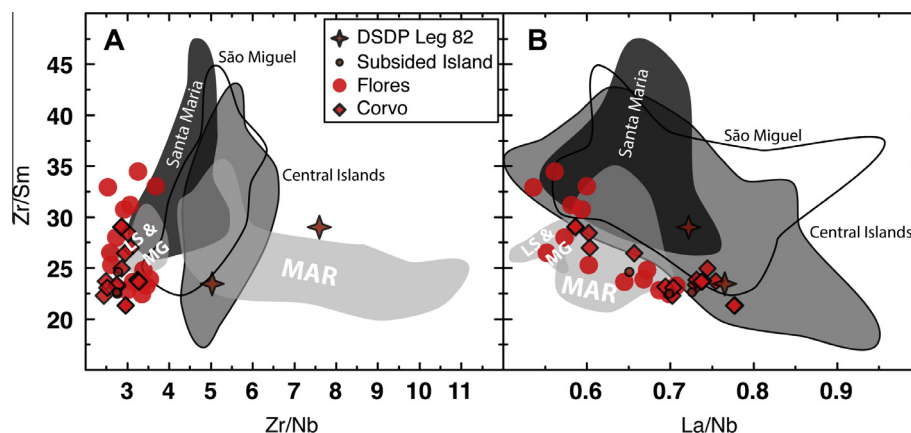


Fig. 5. Trace-element ratios of Zr–Sm are plotted against Zr/Nb (A) and La/Nb (B) to highlight the compositional differences amongst the Azores islands, including lavas from the MAR. Whereas MAR samples span a confined field in Zr/Sm and La/Nb space, much greater variability is observed on the islands, with greatest diversity observed on São Miguel. Distinct differences are evident in Zr/Sm versus Zr/Nb, where Lucky Strike and Menez Gwen plot in a similar range as Flores and Corvo, separated from the MAR field and the islands east of the MAR. Same data sources as in Fig. 1.

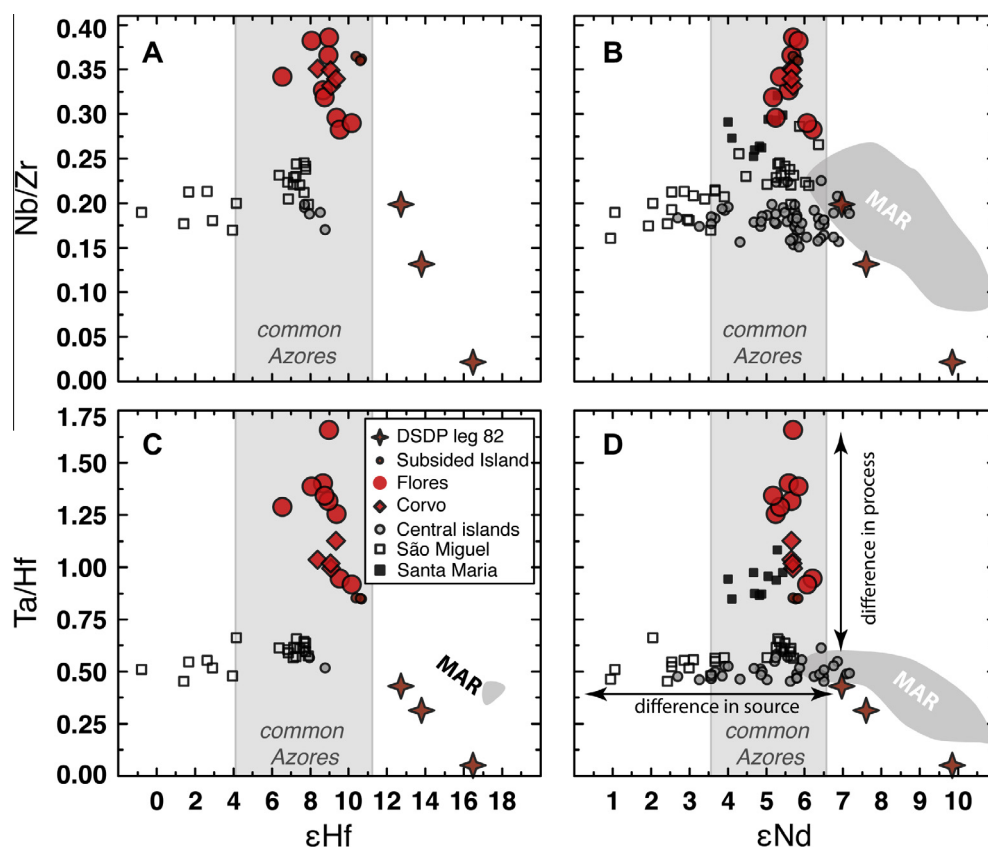


Fig. 6. Ratios of the HFSE versus Hf and Nd isotopes in epsilon notation (CHUR values from [Bouvier et al., 2008](#)). Whereas lavas from the central islands and São Miguel show invariable Nb/Zr and Ta/Hf at varying radiogenic isotopic compositions, the opposite is seen in lavas from Corvo, Flores and the subsided island west of Flores. This observation is consistent with the view of a common Azores component that is involved in different melting processes beneath the individual locations.

In summary, elevated Nb/Zr or Nb/Yb (e.g. [Figs. 7 and 8](#)) are most pronounced on Flores, Corvo and Santa Maria, but also occur in the Lucky Strike and Menez Gwen segments of the MAR. Thus, this peculiar trace element enrichment is not characteristic for plateau margin or plume edge lavas, but rather reflects a local feature of the Azores melting anomaly on a scale of less than 50 km (i.e. the longitudinal distance between São Miguel and Santa Maria, or between the subsided island west of Flores and DSDP-82/557). The differences in HFSE behaviour may be the result of unique (assimilation) fractional crystallisation processes, distinct melting conditions or source composition.

4.5. Origin of the unique HFSE signatures in the western Azores lavas

4.5.1. Assimilation or fractional crystallisation

Fractional crystallisation, with or without accompanying assimilation, cannot account for the distinct HFSE behaviour in lavas from Flores and Corvo. First, Nb/Zr and Ta/Hf do not vary with common differentiation indices such as Mg#, MgO or SiO₂ contents of the lavas. Second, the petrography and order of crystallisation is similar across the islands, such that clinopyroxene, which does

not significantly fractionate the HFSE from other similarly incompatible elements, dominates the crystallising assemblage on all islands (*cf.* [Beier et al., 2006](#); [Genske et al., 2012](#); [Larrea et al., 2012](#)). Minerals such as Fe–Ti oxides or amphibole, which might fractionate the HFSE during magma differentiation, have only been observed in strongly evolved rocks (MgO << 5 wt.%), which are not considered here (Section 3). Third, assimilation of crustal material is also unlikely to account for the higher Nb/Zr values, because the localised HFSE “anomaly” is in contrast to the ubiquitous assimilation inferred by [Genske et al. \(2013, 2014\)](#). Further, HFSE are unlikely affected by oceanic crustal assimilation. Lavas across the islands are arguably influenced by AFC processes involving hydrothermally altered crustal material. Hydrothermally altered materials from the oceanic crust, however, are not characterised by fractionated HFSE signatures ([Staudigel, 2014](#)) as are observed in the lavas from Flores and Corvo. In contrast, trace elements sensitive to hydrothermal alteration, such as Rb, Cs or U, are not unusually enriched in lavas from the western islands, as may be expected if hydrothermally altered materials ([Staudigel, 2014](#)) were assimilated in these lavas. Hence the differences in HFSE signatures observed in the most primitive samples between the islands must result from other processes.

The more comprehensive data set available now reveals that parental melts (and cumulates) of Flores and Corvo are characterised by about twofold higher Nb/Zr and Ta/Hf than observed in parental melts from the eastern islands (Figs. 6 and 7). Lavas from all islands fall on parallel sub-horizontal arrays in plots of Nb/Zr versus Nb, or Zr/Nb versus Zr (Fig. 6). Calculated vectors for fractional crystallisation and partial melting allow evaluation of the relative roles of crystallisation and melting processes (Allègre and Minster, 1978). The vectors presented in Fig. 7 show that lavas from different islands (or island groups) project to different parental values of Nb/Zr, which lie on a partial

melting trend. Therefore differences in trace element enrichment between the islands likely originate from differences in partial melting processes.

4.5.2. Source composition and melting conditions

A similarly enriched source across the islands is supported by the lack of correlations between trace element and radiogenic isotope ratios in the Azores samples (Figs. 4 and 6, see also discussion in Section 4.3.). Moreover, as illustrated in Fig. 5, ratios of trace elements such as La/Nb or Zr/Sm show considerable overlap between the islands. Because of their similar incompatibility (e.g. Salters and Longhi, 1999; Salters et al., 2002; Stracke et al., 2003a), La/Nb and Zr/Sm are difficult to fractionate by partial melting (cf. Table 2), and are thus potential source indicators. Consistent with the radiogenic isotopes, and also with the major element compositions, the uniform La/Nb and Zr/Sm imply a common source beneath all Azores islands (Fig. 4).

Figs. 3b and 7b show that the degree of partial melting varies in basalts from the Azores islands. Calculated partial melting vectors assume a similarly enriched source (i.e., EM from Donnelly et al. (2004)) with model parameters as given in Beier et al. (2013) and Genske et al. (2012). Apparent lower extents of melting are observed at the edges of the plateau on Flores and Corvo in the west, and São Miguel and Santa Maria in the east ($F = 2\text{--}3\%$; higher max. La/Sm values). Yet, islands with the same La/Sm have different Nb/Zr, even though the difference in bulk partition coefficients of La and Sm is comparable to that of Nb and Zr (cf. modelled partial melting trend in Fig. 7, Table 2). Hence, differences in extent of partial melting alone cannot explain the marked differences observed in Nb/Zr. This inference is supported by the observation that the major element and radiogenic isotope compositions of lavas from the Azores islands west of the MAR are similar to those from the central islands east of the MAR. Therefore, there is no local or regional systematic variation in degree of melting and sampling of enriched mantle components, contrary to what is observed in Iceland (e.g., Stracke et al., 2003b; Shorttle et al., 2013, 2014).

Beier et al. (2013) proposed melting of carbonated peridotite to explain the chemical composition of lavas from the easternmost island of Santa Maria. Carbonated peridotite may also influence HFSE systematics in melts from the Flores–Corvo region, but ratios involving major elements such as K/La and Ti/Sm, as well as the SiO_2 contents

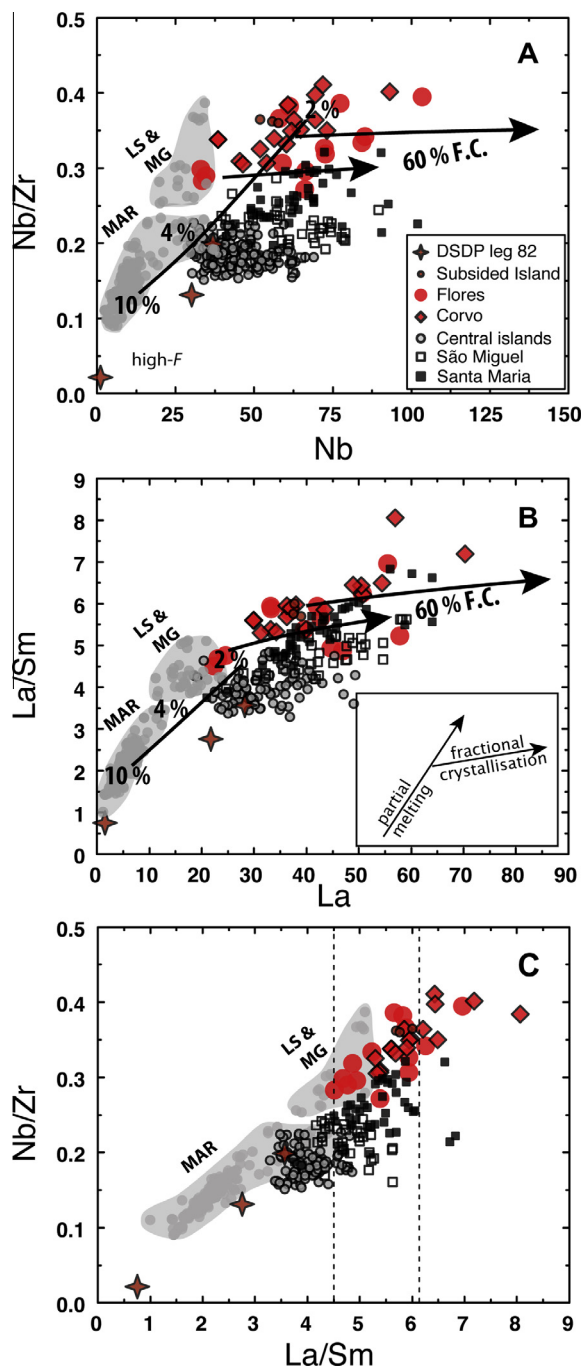


Fig. 7. Process evaluation plots (cf. Allègre and Minster, 1978), illustrating the HFSE and La/Sm systematics across the Azores highlight differences and similarities across the Azores islands. Calculated vectors of partial melting and fractional crystallisation on panels A and B indicate that partial melting alone is insufficient to explain high Nb/Zr, as a marked off-set to high values is observed in Flores and Corvo, which is absent in La/Sm (C). Further, the (on average) slightly lower Zr and slightly higher Nb contents observed in the western lavas produce the significantly different HFSE ratios. Data sources as in Fig. 1. Enriched MORB (i.e. Lucky Strike and Menez Gwen) represents data from Gale et al. (2011).

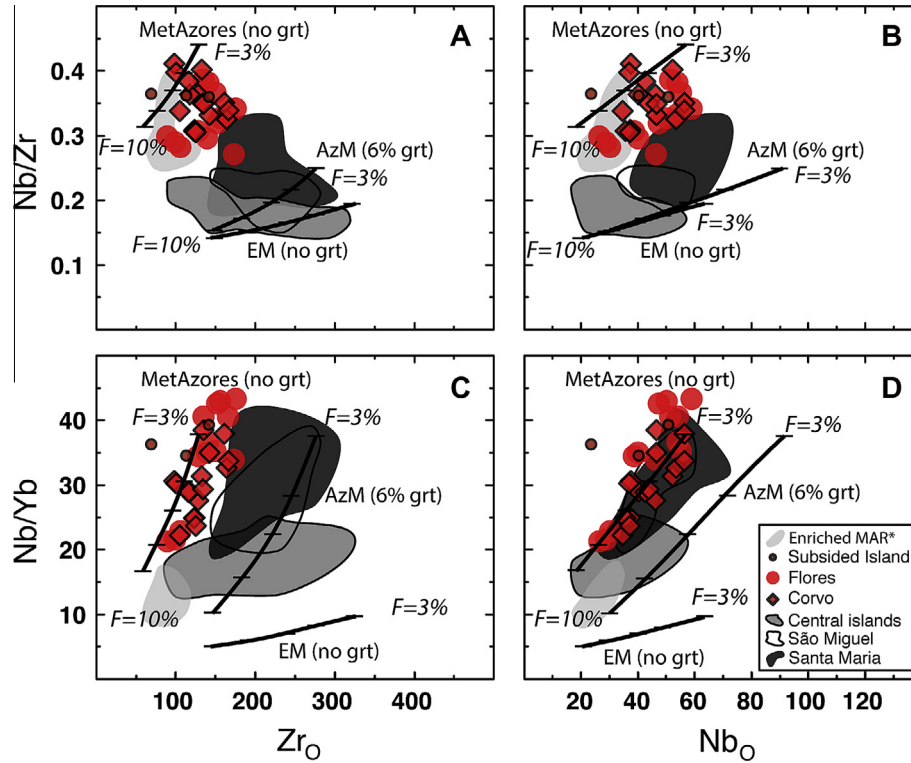


Fig. 8. Fractional crystallization corrected Nb₀ and Zr₀ concentrations are plotted against Nb/Zr (A, B) and Nb/Yb (A, B) for lavas across the Azores islands. Melting curves are plotted for enriched mantle (EM, Donnelly et al., 2004), a common Azores mantle source (AzM, Gale et al., 2011) and a melt-metasomatised source (MetAzores, after Gale et al. (2013, 2011)). Besides different sources, these models highlight the importance of different depths of melting. The data from Flores and Corvo can be reproduced by shallow melting (<80 km) of a source previously metasomatised at depth >80 km (cf. Gale et al., 2013), in a similar fashion as the enriched MAR samples (* refers to Lucky Strike and Menez Gwen samples, as shown in previous plots. Note that these data have not been corrected for fractional crystallisation and likely represent higher than parental Nb and Zr contents). The islands east of the MAR (Central islands, São Miguel and Santa Maria) are consistent with deep melting of an enriched source that is likely a common Azores component. Tick marks on all melting curves represent 3%, 4%, 5%, 7% and 10% partial melting. Melting parameters are summarized in the Appendix B. For details on the fractional crystallization correction scheme, the reader is referred to Tables B.1–3.

Table 2

Source compositions and bulk partition coefficients (*D*) for melting models of peridotite mantle. Azores plume mantle (AzM) and metasomatised mantle (MetAzores) taken from Gale et al. (2011); depleted mantle (DM) from Salters and Stracke (2004).

	AzM	<i>D</i>	DM	MetAzores	<i>D</i>
Zr	17.756	0.040	7.94	6.662	0.023
Sm	0.642	0.040	0.27	0.268	0.023
La	2.024	0.004	0.234	1.033	0.004
Nb	3.054	0.004	0.211	1.867	0.003
Yb	0.471	0.378	0.401	0.213	0.066
Nb/Zr	0.172	0.094	0.027	0.280	0.135
La/Sm	3.153	0.091	0.867	3.854	0.152
La/Nb	0.663	0.987	1.109	0.553	1.164
Sm/Zr	0.036	1.010	0.034	0.040	1.028
<i>AzM</i>					
Mineral mode		ol	opx	cpx	grt
Melting mode		0.60	0.19	0.15	0.06
		0.08	−0.19	0.81	0.30
<i>MetAzores & DM</i>					
Mineral mode		0.52	0.38	0.10	0.00
Melting mode		−0.10	0.35	0.75	0.00

of the western islands are difficult to reconcile with this metasomatic model. Prytulak and Elliott (2009) proposed a scenario in which melts from an isotopically enriched mafic component are dispersed into the surrounding peridotite, leading to partial melting of a metasomatised peridotite source. This model can reproduce most incompatible trace element and radiogenic isotope ratios observed across the islands to the east of the MAR, but it cannot explain the observed distinct trace element enrichments (most pronounced in Nb/Zr and Ta/Hf) in the Corvo and Flores region, which will be discussed below.

4.5.3. Does source mineralogy control HFSE fractionation?

During partial melting underneath Flores and Corvo, Nb and Ta apparently behave more incompatibly whereas Zr and Hf behave less incompatibly compared to lavas from the central island group and São Miguel (Figs. 6 and 8). Minerals such as amphibole or phlogopite, which are known to fractionate Nb, Ta, Zr and Hf from each other (e.g. Tiepolo et al., 2007) may account for this behaviour. However, these minerals are stable up to a maximum temperature of only 1160 °C at a pressure of 3 GPa in water

under-saturated conditions (e.g. Niida and Green, 1999; Green, 2015). These P – T conditions differ from those estimated for the Azores mantle (higher T and P of melting, e.g. Beier et al., 2012, 2013; Genske et al., 2012; Asimow and Langmuir, 2003, i.e. 3–4.5 GPa at 1450–1550 °C), making it unlikely that residual amphibole or phlogopite account for the observed depletion of Zr and Hf in the western lavas. Even considering that the Azores mantle may be unusually hydrous (e.g. Schilling et al., 1980; Bonatti, 1990; Asimow et al., 2004; Bourdon et al., 2005), phlogopite or amphibole are still only stable at pressures significantly lower (i.e. <3 GPa at maximum 1190 °C, cf. Green, 2015) than those calculated for the Azores mantle (Beier et al., 2012; Genske et al., 2012). Moreover, neither residual amphibole nor phlogopite can selectively produce Nb–Ta enrichment and concurrent Zr–Hf depletion (Tiepolo et al., 2007). Instead, concomitant depletion or enrichment in other elements such as Rb, Ba or K would be expected in the lava compositions (e.g. Class and Goldstein, 1997), which is not observed in the Azores (cf. Beier et al., 2013). Hence, source mineralogy is unlikely to cause this distinct behaviour of the HFSE during melting underneath the western Azores islands.

4.5.4. Autometasomatism explains the unique HFSE signatures in the western Azores lavas

The mantle source composition inferred from the Sr–Nd–Hf–Pb–Os isotope data is uniform across the entire Azores plateau (Fig. 2). Moreover, for each locality there is no correlation between radiogenic isotope and trace element ratios, as for example, Zr/Sm (Fig. 4). Hence no obvious first-order difference in the trace element composition of the mantle sources is evident, which could explain the HFSE systematics. Consequently, observed differences in HFSE are not related to isotopically distinct sources, but must be a consequence of the melting process. Similar trace element signatures of elevated Nb/Zr and Ta/Hf at common radiogenic isotopes (see above) are also noticeable in some enriched MORB from the Lucky Strike and Menez

Gwen ridge segments (cf. Gale et al., 2013, 2011). Gale et al. (2013, 2011) propose that low degree melts of an enriched source infiltrate and (auto-) metasomatise (e.g. Roden et al., 1984; Donnelly et al., 2004) the depleted MAR mantle. Subsequent melting of this metasomatised source in the shallower mantle gives rise to the enriched lavas that are observed locally at the MAR.

A similar model can also explain the geochemical signatures of western Azores lavas from the Flores–Corvo region, particularly the stronger HFSE fractionation. Mixing of low degree melts from the Azores plume component with the ambient depleted plume mantle produces a modified (re-) enriched source, which is largely similar to the common Azores plume source in terms of its radiogenic isotopic compositions, but different in its trace element budget. Source compositions used for the modelling, as well as mineral melting modes and partition coefficients are given in Table 2 and in Table B.4. Subsequent low-degree melting of the metasomatised source ($F < 7\%$; MetAzores, Fig. 8) in the shallower mantle (Table 2) produces melts with Nb/Zr and Nb/Yb similar to those of the western lavas. In this fashion, small differences in incompatibility of the HFSE relative to the lithophile elements are amplified by successive stages of low-degree partial melting, leading to comparatively high Nb/Zr for given La/Sm in the metasomatised source (cf. Table 2, Fig. 7c). The absence of this selective HFSE fractionation in melts with a similar range of La/Sm from islands east of the MAR (i.e. Santa Maria and São Miguel) suggests that either the proposed (auto-) metasomatism does not occur in these sources. The similar La/Sm in lavas from the easternmost islands (which possess lower average Nb/Zr than Flores and Corvo) must then be related to a comparatively lower extent of melting, which is probably related to the thicker lithosphere underneath these islands. Hence a metasomatic source likely contributes to the mantle underneath the western islands, whereas the “pure” Azores plume source dominates the mantle underneath the islands east of the MAR (Fig. 9).

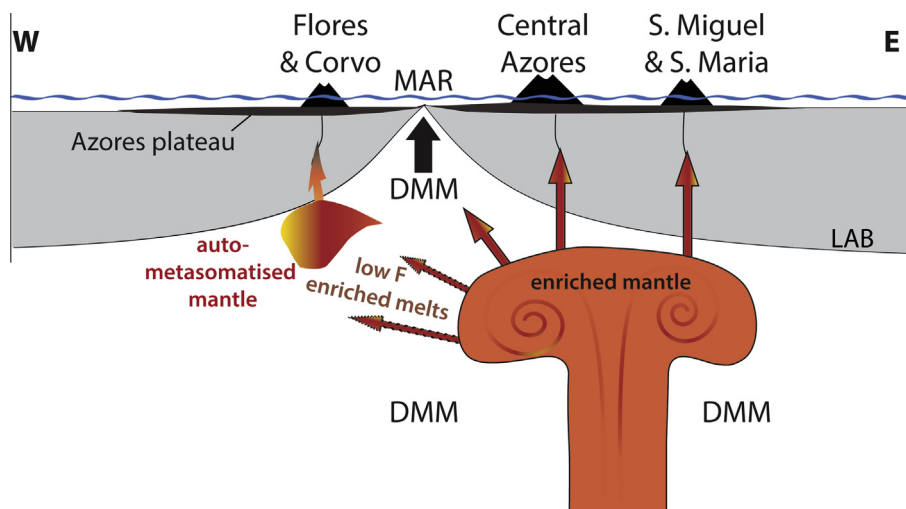


Fig. 9. Schematic cross section illustrating the melting processes involved in generating the Azores islands west and east of the MAR. Note that the metasomatised source dominates the lavas from Flores and Corvo, whereas pure Azores plume melts with little contribution (if any) from a metasomatised source feed the islands to the east of the MAR.

5. CONCLUSIONS

The Azores plume is not regionally zoned or stratified, because no systematic incompatible element or radiogenic isotope contrast is observed across the Azores islands. Instead, all Azores islands share a common enriched Azores plume component. However, local differences in incompatible trace element ratios, especially those involving the HFSE are observed. The localised feature of elevated and more variable Nb/Zr and Ta/Hf on Flores and Corvo to the west, on Santa Maria to the east, but also in the Lucky Strike and Menez Gwen segments to the south of the plume centre is decoupled from variation in radiogenic isotope ratios of Sr, Nd, Pb, Hf and Os. We have shown that this distinct behaviour of the HFSE is consistent with (auto-) metasomatism of the mantle source during the recent melting process. Lavas from the easternmost Azores island of Santa Maria might form by melting of carbonated peridotite (Beier et al., 2013). However, this scenario is unlikely for the Flores and Corvo system, because of discrepancies between major and trace element compositions of these lavas (*cf.* Section 4.5.2.). Instead a two-stage melting model is proposed for the westernmost Azores islands where low degree Azores plume melts metasomatise the ambient depleted mantle to create a metasomatised source, which contributes melt to the Flores–Corvo magmas.

The observed spatial difference in incompatible trace element compositions in melts from the western Azores mantle are not attributed to different plume materials, but relate to subtle differences in the regional melting processes, which are recorded in the trace- but not the major-element compositions. The distinct melting processes underneath Flores and Corvo are similar to those occurring at ridge segments to the south of the Azores MAR (*i.e.*, in non-plume settings). Recent re-enrichment and intra-column modification of the upwelling mantle may thus cause local to regional scale geochemical differences in mantle-derived melts in both plume and ridge-related settings in absence of isotopic source differences.

ACKNOWLEDGEMENTS

Victor H. Forjaz and the Observatório Vulcanológico e Geotérmico dos Açores are gratefully acknowledged for their assistance with the logistics of Flores and Corvo samples. We thank Alison Gale Soumen Mallick and an anonymous reviewer for their constructive reviews and Marc Norman and Shichun Huang for editorial support. Patrick J.C. Ryll is thanked for providing the samples from the subsided island west of Flores. We particularly thank Peter Wieland and Marek Locmelis for help during the Hf and Os isotope analytical work at Macquarie University. SPT thanks Charlie Langmuir and Bernard Bourdon for generously providing the MAR samples. James Day and Chris Waters at Scripps Institution of Oceanography, UC San Diego, USA, are gratefully acknowledged for the Os analyses on the far-field MAR sample. All other isotope data were obtained using instrumentation funded by DEST Systemic Infrastructure Grants, ARC LIEF, NCRIS, industry partners and Macquarie University. FSG acknowledges an iMQRES from Macquarie University, Sydney and ESSAC for an ECORD Research Grant to analyse the submarine lavas. This is contribution 665 from the ARC Centre of Excellence for Core to Crust Fluid Systems (<http://www.ccfscf>

[mq.edu.au](http://www.mq.edu.au)) and 1030 in the GEMOC Key Centre (<http://www.gemoc.mq.edu.au>).

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gca.2015.08.019>.

REFERENCES

- Allège C. J. and Minster J. F. (1978) Quantitative models of trace element behavior in magmatic processes. *Earth Planet. Sci. Lett.* **38**, 1–25.
- Arevalo, Jr, R. and McDonough W. F. (2010) Chemical variations and regional diversity observed in MORB. *Chem. Geol.* **271**, 70–85.
- Asimow P. D., Dixon J. E. and Langmuir C. H. (2004) A hydrous melting and fractionation model for mid-ocean ridge basalts: application to the Mid-Atlantic Ridge near the Azores. *Geochem. Geophys. Geosyst.* **5**(1). <http://dx.doi.org/10.1029/2003GC000568>.
- Asimow P. D. and Langmuir C. H. (2003) The importance of water to oceanic mantle melting regimes. *Nature* **421**, 815–820.
- Azevedo J. M. M. and Ferreira M. R. P. (1999) Volcanic gaps and subaerial records of palaeo-sea-levels on Flores Island (Azores): tectonic and morphological implications. *J. Geodyn.* **28**, 117–129.
- Azevedo J. M. M. and Ferreira M. R. P. (2006) The volcanotectonic evolution of Flores Island, Azores (Portugal). *J. Volcanol. Geoth. Res.* **156**, 90–102.
- Baker J., Peate D., Waight T. and Meyzen C. (2004) Pb isotopic analysis of standards and samples using a 207Pb–204Pb double spike and thallium to correct for mass bias with a double-focusing MC-ICP-MS. *Chem. Geol.* **211**, 275–303.
- Beier C., Haase K. M. and Hansteen T. H. (2006) Magma evolution of the Sete Cidades Volcano, São Miguel, Azores. *J. Petrol.* **47**, 1375–1411. <http://dx.doi.org/10.1093/petrology/egl014>.
- Beier C., Stracke A. and Haase K. M. (2007) The peculiar geochemical signatures of São Miguel (Azores) lavas: metasomatised or recycled mantle sources? *Earth Planet. Sci. Lett.* **259**, 186–199.
- Beier C., Haase K. M., Abouchami W., Krienitz M. S. and Hauff F. (2008) Magma genesis by rifting of oceanic lithosphere above anomalous mantle: Terceira Rift, Azores. *Geochem. Geophys. Geosyst.* **9**. <http://dx.doi.org/10.1029/2008GC002112>.
- Beier C., Turner S. P., Plank T. and White W. M. (2010) A preliminary assessment of the symmetry of source composition and melting dynamics across the Azores plume. *Geochem. Geophys. Geosyst.* **11**, Q02004. <http://dx.doi.org/10.1029/2009gc002833>.
- Beier C., Haase K. M. and Turner S. P. (2012) Conditions of melting beneath the Azores. *Lithos* **144–145**, 1–11. <http://dx.doi.org/10.1016/j.lithos.2012.02.019>.
- Beier C., Mata J., Stöckhert F., Mattioli N., Brandl P. A., Madureira P., Genske F. S., Martins S., Madeira J. and Haase K. M. (2013) Geochemical evidence for melting of carbonated peridotite on Santa Maria Island, Azores. *Contrib. Miner. Petrol.* **165**, 823–841. <http://dx.doi.org/10.1007/s00410-012-0837-2>.
- Beier, C., Haase, K.M., Abouchami, W., 2015. Geochemical and geochronological constraints on the evolution of the Azores Plateau. In: Neal, C.R., Sager, W., Erba, E., Sano, T., (Eds.),

- The Origin, Evolution, and Environmental Impact of Oceanic Large Igneous Provinces: Geological Society of America Special Paper 511, pp. 1–29, doi:[http://dx.doi.org/10.1130/2015.2511\(02\)](http://dx.doi.org/10.1130/2015.2511(02)).
- Birck J. L., Barman M. R. and Capmas F. (1997) Re–Os isotopic measurements at the femtomole level in natural samples. *Geostand. Geoanal. Res.* **21**, 19–27. <http://dx.doi.org/10.1111/j.1751-908X.1997.tb00528.x>.
- Blichert-Toft J. (2001) On the Lu–Hf isotope geochemistry of silicate rocks. *Geostand. Geoanal. Res.* **25**, 41–56. <http://dx.doi.org/10.1111/j.1751-908X.2001.tb00786.x>.
- Bonatti E. (1990) Not so hot “hot spots” in the oceanic mantle. *Science* **250**, 107–111. <http://dx.doi.org/10.1126/science.250.4977.107>.
- Bougault, H., Cande, S.C., 1985. Background, Objectives, and Summary of Principal Results: Deep Sea Drilling Project Sites 556–564, In: Initial Reports of the Deep Sea Drilling Project, Initial Reports of the Deep Sea Drilling Project. U.S. Government Printing Office. doi:<http://dx.doi.org/10.2973/dsdp.proc.82.101.1985>.
- Bourdon B., Langmuir C. H. and Zindler A. (1996) Ridge-hotspot interaction along the Mid-Atlantic Ridge between 37°30' and 40°30' N: the U–Th disequilibrium evidence. *Earth Planet. Sci. Lett.* **142**, 175–189.
- Bourdon B., Turner S. P. and Ribe N. M. (2005) Partial melting and upwelling rates beneath the Azores from a U-series isotope perspective. *Earth Planet. Sci. Lett.* **239**, 42–56.
- Bouvier A., Vervoort J. D. and Patchett P. J. (2008) The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth Planet. Sci. Lett.* **273**, 48–57. <http://dx.doi.org/10.1016/j.epsl.2008.06.010>.
- Cannat M., Briaies A., Deplus C., Escartín J., Georgen J. E., Lin J., Mercouriev S., Meyzen C., Muller M., Pouliquen G., Rabain A. and da Silva P. (1999) Mid-Atlantic Ridge-Azores hotspot interactions: along-axis migration of a hotspot-derived event of enhanced magmatism 10 to 4 Ma ago. *Earth Planet. Sci. Lett.* **173**, 257–269.
- Class C. and Goldstein S. L. (1997) Plume-lithosphere interactions in the ocean basins: constraints from the source mineralogy. *Earth Planet. Sci. Lett.* **150**, 245–260. [http://dx.doi.org/10.1016/S0012-821X\(97\)00089-7](http://dx.doi.org/10.1016/S0012-821X(97)00089-7).
- Cohen A. (1996) Separation of osmium from geological materials by solvent extraction for analysis by thermal ionisation mass spectrometry. *Anal. Chim. Acta* **332**, 269–275. [http://dx.doi.org/10.1016/0003-2670\(96\)00226-7](http://dx.doi.org/10.1016/0003-2670(96)00226-7).
- Correia C. T., Kirk J. D., Frick L. R., Petronilho L. A., Tassinari C. C. G. and Sato K. (2007) The Re–Os isotopic system: geochemistry and methodology at the Geochronological Research Center (CPGeo) of the University of São Paulo, Brazil. *Geologia USP. SÈrie Científica* **7**, 45–56.
- Day J. M. D., Pearson G. D. and Hulbert L. J. (2013) Highly siderophile element behaviour during flood basalt genesis and evidence for melts from intrusive chromitite formation in the Mackenzie large igneous province. *Lithos* **182–183**, 242–258. <http://dx.doi.org/10.1016/j.lithos.2013.10.011>.
- Donnelly K. E., Goldstein S. L., Langmuir C. H. and Spiegelman M. (2004) Origin of enriched ocean ridge basalts and implications for mantle dynamics. *Earth Planet. Sci. Lett.* **226**, 347–366. <http://dx.doi.org/10.1016/j.epsl.2004.07.019>.
- Dosso L., Bougault H., Langmuir C. H., Bollinger C., Bonnier O. and Etoubleau J. (1999) The age and distribution of mantle heterogeneity along the Mid-Atlantic Ridge (31–41°N). *Earth Planet. Sci. Lett.* **170**, 269–286.
- Elliott T., Blichert-Toft J., Heumann A., Koetsier G. and Forjaz V. H. (2007) The origin of enriched mantle beneath São Miguel, Azores. *Geochim. Cosmochim. Acta* **71**, 219–240. <http://dx.doi.org/10.1016/j.gca.2006.07.043>.
- Feraud G., Kaneoka I. and Allègre C. J. (1980) K/Ar ages and stress pattern in the Azores: geodynamic implications. *Earth Planet. Sci. Lett.* **46**, 275–286.
- França Z. T. M. (2008) Composition of Gabbroic Xenoliths in Flores Island (Azores, Portugal). *Rev. Soc. Esp. Mineral.* **9**, 103–104.
- França Z. T. M., Lago M., Nunes J. C., Gale C., Forjaz V. H., Pueyo O. and Arranz E. (2006a) Geochemistry of alkaline basalts of Corvo Island (Azores, Portugal): preliminary data. *Geogaceta* **40**.
- França Z. T. M., Tassinari C. C. G., Cruz J. V., Aparicio A. Y., Araújo V. and Rodrigues B. N. (2006b) Petrology, geochemistry and Sr–Nd–Pb isotopes of the volcanic rocks from Pico Island-Azores (Portugal). *J. Volcanol. Geoth. Res.* **156**, 71–89.
- Gale A., Escrig S., Gier E. J., Langmuir C. H. and Goldstein S. L. (2011) Enriched basalts at segment centers: the Lucky Strike (37°17'N) and Menez Gwen (37°50'N) segments of the Mid-Atlantic Ridge. *Geochim. Geophys. Geosyst.* **12**. <http://dx.doi.org/10.1029/2010GC003446>.
- Gale A., Laubier M., Escrig S. and Langmuir C. H. (2013) Constraints on melting processes and plume-ridge interaction from comprehensive study of the FAMOUS and North Famous segments, Mid-Atlantic Ridge. *Earth Planet. Sci. Lett.* **365**, 209–220. <http://dx.doi.org/10.1016/j.epsl.2013.01.022>.
- Galer S. J. G. (1999) Optimal double and triple spiking for high precision lead isotopic measurement. *Chem. Geol.* **157**, 255–274.
- Gannoun A., Burton K. W., Parkinson I. J. and Alard O. (2007) The scale and origin of the osmium isotope variations in mid-ocean ridge basalts. *Earth Planet. Sci. Lett.* <http://dx.doi.org/10.1016/j.epsl.2007.05.014>.
- Genske F. S., Turner S. P., Beier C. and Schaefer B. F. (2012) The Petrology and Geochemistry of Lavas from the Western Azores Islands of Flores and Corvo. *J. Petrol.* **53**, 1673–1708. <http://dx.doi.org/10.1093/petrology/egs029>.
- Genske F. S., Beier C., Haase K. M., Turner S. P., Krumm S. and Brandl P. A. (2013) Oxygen isotopes in the Azores islands: crustal assimilation recorded in olivine. *Geol.* **41**, 491–494. <http://dx.doi.org/10.1130/G33911.1>.
- Genske F. S., Turner S. P., Beier C., Chu M.-F., Tonarini S., Pearson N. J. and Haase K. M. (2014) Lithium and boron isotope systematics in lavas from the Azores islands reveal crustal assimilation. *Chem. Geol.* **373**, 27–36. <http://dx.doi.org/10.1016/j.chemgeo.2014.02.024>.
- Gente P., Dymant J., Maia M. and Goslin J. (2003) Interaction between the Mid-Atlantic Ridge and the Azores hot spot during the last 85 Myr: emplacement and rifting of the hot spot-derived plateaus. *Geochim. Geophys. Geosyst.* **4**. <http://dx.doi.org/10.1029/2003gc000527>.
- Green D. H. (2015) Experimental petrology of peridotites, including effects of water and carbon on melting in the Earth's upper mantle. *Phys. Chem. Miner.* **42**, 95–122. <http://dx.doi.org/10.1007/s00269-014-0729-2>.
- Hamelin C., Bezos A., Dosso L., Escartín J., Cannat M. and Mevel C. (2013) Atypically depleted upper mantle component revealed by Hf isotopes at Lucky Strike segment. *Chem. Geol.* **341**, 128–139. <http://dx.doi.org/10.1016/j.chemgeo.2013.01.013>.
- Hanan B. B. and Graham D. W. (1996) Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes. *Science* **272**, 991–995. <http://dx.doi.org/10.1126/science.272.5264.991>.
- Hart S. R., Hauri E. H., Oschmann L. A. and Whitehead J. A. (1992) Mantle plumes and entrainment: isotopic evidence. *Science* **256**, 517–520. <http://dx.doi.org/10.1126/science.256.5056.517>.

- Hawkesworth C. J., Norry M. J., Roddick J. C. and Vollmer R. (1979) $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from the Azores and their significance in LIL-element enriched mantle. *Nature* **280**, 28–31. <http://dx.doi.org/10.1038/280028a0>.
- Hoernle K. A., Abt D. L., Fischer K. M., Nichols H., Hauff F., Abers G. A., van den Bogaard P., Heydolph K., Alvarado G., Protti M. and Strauch W. (2008) Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. *Nature* **451**, 1094–1097. <http://dx.doi.org/10.1038/nature06550>.
- Hoernle K. A., Hauff F., Kokfelt T. F., Haase K. M., Garbe-Schönberg D. and Werner R. (2011) On- and off-axis chemical heterogeneities along the South Atlantic Mid-Ocean-Ridge (5–11°S): shallow or deep recycling of ocean crust and/or intraplate volcanism? *Earth Planet. Sci. Lett.* **306**, 86–97. <http://dx.doi.org/10.1016/j.epsl.2011.03.032>.
- Hofmann A. W. and Farnetani C. G. (2013) Two views of Hawaiian plume structure. *Geochem. Geophys. Geosyst.* **14**, 5308–5322. <http://dx.doi.org/10.1002/2013GC004942>.
- Jochum K. P., Nohl U., Herwig K., Lammel E., Stoll B. and Hofmann A. W. (2005) GeoReM: a new geochemical database for reference materials and isotopic standards. *Geostand. Geoanal. Res.* **29**, 333–338. <http://dx.doi.org/10.1111/j.1751-908X.2005.tb00904.x>.
- Johnson C. L., Wijbrans J. R., Constable C. G., Gee J., Staudigel H., Tauxe L., Forjaz V. H. and Salgueiro M. (1998) $^{40}\text{Ar}/^{39}\text{Ar}$ ages and paleomagnetism of São Miguel lavas, Azores. *Earth Planet. Sci. Lett.* **160**, 637–649.
- Larrea P., França Z. T. M., Lago M., Widom E., Galé C. and Ubide T. (2012) Magmatic Processes and the Role of Antecrysts in the Genesis of Corvo Island (Azores Archipelago, Portugal). *J. Petrol.* **54**, egs084–egs793.
- Laubier M., Gale A. and Langmuir C. H. (2012) Melting and crustal processes at the FAMOUS segment (Mid-Atlantic Ridge): new insights from olivine-hosted melt inclusions from multiple samples. *J. Petrol.* <http://dx.doi.org/10.1093/petrology/egr075>.
- Millet M.-A., Baker J. A., Doucelance R. and Schiano P. (2009) Reconsidering the origins of isotopic variations in Ocean Island Basalts: Insights from fine-scale study of São Jorge Island, Azores archipelago. *Chem. Geol.* **265**, 289–302.
- Moreira M., Doucelance R., Kurz M. D., Dupré B. and Allègre C. J. (1999) Helium and lead isotope geochemistry of the Azores Archipelago. *Earth Planet. Sci. Lett.* **169**, 189–205. [http://dx.doi.org/10.1016/S0012-821X\(99\)00071-0](http://dx.doi.org/10.1016/S0012-821X(99)00071-0).
- Niida K. and Green D. H. (1999) Stability and chemical composition of pargasitic amphibole in MORB pyroxene under upper mantle conditions. *Contrib. Miner. Petrol.* **135**, 18–40. <http://dx.doi.org/10.1007/s004100050495>.
- Prytulak J., Avanzinelli R., Koetsier G. and Kreissig K. (2014) Melting versus contamination effects on ^{238}U – ^{230}Th – ^{226}Ra and ^{235}U – ^{231}Pa disequilibria in lavas from São Miguel, Azores. *Chem. Geol.* **381**, 94–109. <http://dx.doi.org/10.1016/j.chemgeo.2014.04.030>.
- Prytulak J. and Elliott T. (2007) TiO_2 enrichment in ocean island basalts. *Earth Planet. Sci. Lett.* **263**, 388–403. <http://dx.doi.org/10.1016/j.epsl.2007.09.015>.
- Prytulak J. and Elliott T. (2009) Determining melt productivity of mantle sources from ^{238}U – ^{230}Th and ^{235}U – ^{231}Pa disequilibria; an example from Pico Island, Azores. *Geochim. Cosmochim. Acta* **73**, 2103–2122.
- Roden M. K., Hart S. R., Frey F. A. and Melson W. G. (1984) Sr, Nd and Pb isotopic and REE geochemistry of St. Paul's Rocks: the metamorphic and metasomatic development of an alkali basalt mantle source. *Contrib. Miner. Petrol.* **85**, 376–390. <http://dx.doi.org/10.1007/BF01150294>.
- Ryall P. J. C., Blanchard M.-C. and Medioli F. (1983) A subsided island west of Flores, Azores. *Can. J. Earth Sci.* **20**, 764–775.
- Saki M., Thomas C., Nippres S. E. J. and Lessing S. (2015) Topography of upper mantle seismic discontinuities beneath the North Atlantic: the Azores, Canary and Cape Verde plumes. *Earth Planet. Sci. Lett.* **409**, 193–202. <http://dx.doi.org/10.1016/j.epsl.2014.10.052>.
- Salteras V. J. M. and Longhi J. (1999) Trace element partitioning during the initial stages of melting beneath mid-ocean ridges. *Earth Planet. Sci. Lett.* **166**, 15–30. [http://dx.doi.org/10.1016/S0012-821X\(98\)00271-4](http://dx.doi.org/10.1016/S0012-821X(98)00271-4).
- Salteras V. J. M., Longhi J. E. and Bizimis M. (2002) Near mantle solidus trace element partitioning at pressures up to 3.4 GPa. *Geochem. Geophys. Geosyst.* **3**, 1–23. <http://dx.doi.org/10.1029/2001GC000148>.
- Salteras, V.J.M., Stracke, A., 2004. Composition of the depleted mantle 5, Q05B07. doi: <http://dx.doi.org/10.1029/2003GC000597>.
- Schaefer B. F., Turner S. P., Parkinson I. J., Rogers N. and Hawkesworth C. J. (2002) Evidence for recycled Archean oceanic mantle lithosphere in the Azores plume. *Nature* **420**, 304–307. <http://dx.doi.org/10.1038/nature01172>.
- Schilling J.-G. (1975) Azores mantle blob: Rare-earth evidence. *Earth Planet. Sci. Lett.* **25**, 103–115.
- Schilling J.-G., Bergeron M. B., Evans R. and Smith J. V. (1980) Halogens in the Mantle Beneath the North Atlantic [and Discussion]. *Philos. Trans. R. Soc. London, Ser. A* **297**, 147–178. <http://dx.doi.org/10.2307/36700>.
- Schilling, J.-G., Zajac, M., Evans, R., Johnston, T., White, W., Devine, J.D., Kingsley, R., 1983. Petrologic and geochemical variations along the Mid-Atlantic Ridge from 29°N to 73°N 283, 510–586. doi: <http://dx.doi.org/10.2475/ajs.283.6.510>.
- Searle R. (1980) Tectonic pattern of the Azores spreading centre and triple junction. *Earth Planet. Sci. Lett.* **51**, 415–434.
- Shirey S. B., Bender J. F. and Langmuir C. H. (1987) Three-component isotopic heterogeneity near the Oceanographer transform, Mid-Atlantic Ridge. *Nature*.
- Shorttle O., MacLennan J. and Jones S. M. (2010) Control of the symmetry of plume-ridge interaction by spreading ridge geometry. *Geochem. Geophys. Geosyst.* **11**. <http://dx.doi.org/10.1029/2009GC002986>.
- Shorttle O., MacLennan J. and Piotrowski A. M. (2013) Geochemical provincialism in the Iceland plume. *Geochim. Cosmochim. Acta* **122**, 363–397. <http://dx.doi.org/10.1016/j.gca.2013.08.032>.
- Shorttle O., MacLennan J. and Lambart S. (2014) Quantifying lithological variability in the mantle. *Earth Planet. Sci. Lett.* **395**, 24–40. <http://dx.doi.org/10.1016/j.epsl.2014.03.040>.
- Staudigel H. (2014) Chemical Fluxes from Hydrothermal Alteration of the Oceanic Crust. In *Treatise on Geochemistry* (ed. H. D. H. K. Turekian), Second ed. Elsevier, Oxford, pp. 583–606.
- Stormer, Jr., J. C. and Nicholls J. (1978) XLFRAC: a program for the interactive testing of magmatic differentiation models. *Comput. Geosci.* **4**, 143–159. [http://dx.doi.org/10.1016/0098-3004\(78\)90083-3](http://dx.doi.org/10.1016/0098-3004(78)90083-3).
- Stracke A. (2012) Earth's heterogeneous mantle: a product of convection-driven interaction between crust and mantle. *Chem. Geol.* **330–331**, 274–299.
- Stracke A., Bizimis M. and Salteras V. J. M. (2003a) Recycling oceanic crust: quantitative constraints. *Geochem. Geophys. Geosyst.* **4**. <http://dx.doi.org/10.1029/2001GC000223>.
- Stracke, A., Zindler, A., Salteras, V.J.M., McKenzie, D., Blichert-Toft, J., Albarède, F., Grönvold, K., 2003b. Theistareykir revisited 4. doi: <http://dx.doi.org/10.1029/2001GC000201>.
- Stracke A., Hofmann A. W. and Hart S. R. (2005) FOZO, HIMU, and the rest of the mantle zoo. *Geochem. Geophys. Geosyst.* **6**. <http://dx.doi.org/10.1029/2004GC000824>.

- Tatsumoto M. (1978) Isotopic composition of lead in oceanic basalt and its implication to mantle evolution. *Earth Planet. Sci. Lett.* **38**, 63–87.
- Thirlwall M. F. (2000) Inter-laboratory and other errors in Pb isotope analyses investigated using a 207Pb–204Pb double spike. *Chem. Geol.* **163**, 299–322.
- Thirlwall M. F. (2002) Multicollector ICP-MS analysis of Pb isotopes using a 207Pb–204Pb double spike demonstrates up to 400 ppm/amu systematic errors in Tl-normalization. *Chem. Geol.* **184**, 255–279.
- Tiepolo M., Oberti R., Zanetti A., Vannucci R. and Foley S. F. (2007) Trace-element partitioning between amphibole and silicate melt. *Rev. Mineral. Geochem.* **67**, 417–452.
- Turner S. P., Hawkesworth C. J., Rogers N. and King P. (1997) U–Th isotope disequilibria and ocean island basalt generation in the Azores. *Chem. Geol.* **139**, 145–164.
- Turner S. P., Tonarini S., Bindeman I. N., Leeman W. P. and Schaefer B. F. (2007) Boron and oxygen isotope evidence for recycling of subducted components over the past 2.5 Gyr. *Nature* **447**, 702–705.
- Wanless, V.D., Shaw, A.M., Behn, M.D., Soule, S.A., Escartín, J., Hamelin, C., 2015. Magmatic plumbing at Lucky Strike volcano based on olivine-hosted melt inclusion compositions. *Geochem. Geophys. Geosyst.* n/a–n/a. doi:<http://dx.doi.org/10.1002/2014GC005517>.
- White W. M. and Schilling J.-G. (1978) The nature and origin of geochemical variation in Mid-Atlantic Ridge basalts from the Central North Atlantic. *Geochim. Cosmochim. Acta* **42**, 1501–1516. [http://dx.doi.org/10.1016/0016-7037\(78\)90021-2](http://dx.doi.org/10.1016/0016-7037(78)90021-2).
- White W. M., Schilling J.-G. and Hart S. R. (1976) Evidence for the Azores mantle plume from strontium isotope geochemistry of the Central North Atlantic. *Nature* **263**, 659–663. <http://dx.doi.org/10.1038/263659a0>.
- White W. M., Tapia M. D. M. and Schilling J.-G. (1979) The petrology and geochemistry of the Azores Islands. *Contrib. Miner. Petrol.* **69**, 201–213. <http://dx.doi.org/10.1007/BF00372322>.
- Widom E., Carlson R. W., Gill J. B. and Schmincke H.-U. (1997) Th–Sr–Nd–Pb isotope and trace element evidence for the origin of the São Miguel, Azores, enriched mantle source. *Chem. Geol.* **140**, 49–68.
- Widom E. and Shirey S. B. (1996) Os isotope systematics in the Azores: implications for mantle plume sources. *Earth Planet. Sci. Lett.* **142**, 451–465.
- Willbold M. and Stracke A. (2006) Trace element composition of mantle end-members: implications for recycling of oceanic and upper and lower continental crust. *Geochem. Geophys. Geosyst.* **7**, Q04004. <http://dx.doi.org/10.1029/2005gc001005>.
- Xu G., Huang S., Frey F. A., Blichert-Toft J., Abouchami W., Clague D. A., Cousens B., Moore J. G. and Beeson M. H. (2014) The distribution of geochemical heterogeneities in the source of Hawaiian shield lavas as revealed by a transect across the strike of the Loa and Kea spatial trends: East Molokai to West Molokai to Penguin Bank. *Geochim. Cosmochim. Acta* **132**, 214–237. <http://dx.doi.org/10.1016/j.gca.2014.02.002>.
- Zindler A. and Hart S. (1986) Chemical geodynamics. *Annu. Rev. Earth Planet. Sci.* **14**, 493–571. <http://dx.doi.org/10.1146/annurev.ea.14.050186.002425>.

Associate editor: Shichun Huang