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The influence of small-scale mantle heterogeneities on Mid-Ocean Ridge volcanism: Evidence from the southern Mid-Atlantic Ridge (7°30′S to 11°30′S) and Ascension Island

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ABSTRACT

Volcanism along Mid-Ocean Ridges is known to exhibit significant isotopic and elemental variations, traditionally regarded as reflecting global scale variations in mantle depletion history and refertilization processes. The ~400 km long Mid-Atlantic Ridge (MAR) between the Ascension and Bode Verde Fracture Zones (7°30′S to 11°30′S) has been sampled at high spatial resolution (c. 10 km along-axis scale) and large elemental and isotopic variations have been identified covering almost the entire compositional spectrum of MAR basalts. In this paper we employ a multi-isotope (Sr–Nd–Hf–Pb) and trace element approach in order to explore the geodynamic implications of along-ridge compositional variations and their relationship to off-axis volcanism on nearby Ascension Island, commonly regarded as plume-related.

The studied portion of the MAR consists of four major segments. Isotopic data from the deeply incised northern and southern segments A1 and A4 define a trend involving a high-εHf depleted mantle endmember. This isotopic signature is inferred to result from an ancient melting event in the garnet stability field, causing high time-integrated Lu/Hf and elevated $^{176}Hf/^{177}Hf$. In contrast, a low-εHf depleted mantle endmember is indicated by the compositional trend for samples from the topographically elevated central portion (segments A2 and A3). Both trends converge at a common enriched endmember with least diluted compositions represented by samples from the subaerial eruptive stage of nearby Ascension Island.

Because linear co-variations between isotope compositions and the respective parent–daughter ratios cannot be explained as representing "mantle isochrons" we infer that our data reflect arrays related to physical mixing of depleted and enriched mantle domains. This implies that distinctive mantle domains at kilometer scale may survive convection processes over time spans in the order of 1–2 Ga. This finding corroborates the results of recent Os-isotope studies of abyssal peridotite which returned similar conclusions.

The systematics of along-axis isotopic variations show that mantle upwelling is highly variable. A systematic decrease of the enriched isotopic signature from the central segment A3 toward the northern termination of the segment A2 suggests a northward flow of enriched mantle material. In marked contrast, the compositional variations along the marginal segments A1 and A4 are random indicating heterogeneous mixing of mantle domains at a spatial resolution of <50 km to 10 km (along-axis scale).

With regard to Ascension Island we show that the submarine volcanic stage, sampled by a 3216 m long drill hole, was fed by a distinctive enriched mantle source currently inaccessible to partial melting. We interpret this observation within the framework of recent local-scale geophysical investigations and infer an on-axis origin of the bulk of the Ascension volcanic edifice at around 5 to 6 Ma, synchronous with the surrounding oceanic crust. Off-axis partial melting of the current common enriched mantle endmember accounts for rejuvenation of volcanism on Ascension generating the volumetrically subordinate subaerial portion of the island.

1. Introduction

The geochemical and isotope characteristics of normal mid-ocean ridge basalt (N-MORB) indicate an origin from a depleted upper mantle reservoir. Compositional trends along the global ridge axis systems towards more enriched compositions have commonly been explained by

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interaction with mantle plume material rising from primitive or refertilized reservoirs (e.g., Andres et al., 2002; Blichert-Toft et al., 2005; Douglass et al., 1999; Haase et al., 1996; Hémond et al., 2006; Hofmann 1997, Humphris et al., 1985; Schilling, 1973, 1985). As alternatives to this traditional ridge–mantle plume interaction model, other scenarios have been proposed. For instance, the upper mantle may not be as homogeneous in composition as previously assumed and may resemble a "marble-cake" or "plum-pudding" rather than a stratified, "layer-cake" structure (e.g., Allègre et al., 1984; Allègre and Turcotte, 1986; Prinzhofer et al., 1989; recent review in Tackley, 2008). Moreover, some asthenospheric mantle domains show an increased volatile content (e.g., Bonatti, 1990; Ligi et al., 2005; Minshull et al., 1998). Hence, enriched geochemical signatures may be generated in the absence of any anomalous, plume-related temperature gradients.

To evaluate the alternative geodynamic interpretations, combined isotope studies are required (e.g., Allègre and Turcotte, 1986; Debaille et al., 2006; Hofmann, 1997; Niu et al., 1996; Pearce et al., 1999; Schiano et al., 1997; Stracke et al., 2005). The Lu–Hf system is a useful tool to elucidate the ancient depletion history of mantle domains due to the decoupling of Lu/Hf and Sm/Nd during peridotite partial melting in the garnet stability field (e.g., Andres et al., 2004; Chauvel and Blichert-Toft, 2001; Salters and Hart, 1991; Vervoort and Blichert-Toft, 1999). The preferential retention of Lu in residual garnet causes high time-integrated Lu/Hf and radiogenic $^{177}Hf/^{176}Hf$ signatures. In contrast to Lu–Hf, the bulk partition coefficients for Sm and Nd are similar for garnet and spinel peridotite and Nd isotope systematics largely remain unaffected by the two different melting regimes. As an alternative mechanism, it has been suggested that melts from garnet peridotite may selectively incorporate radiogenic Hf following disequilibrium melting during garnet breakdown (e.g., Blichert-Toft et al., 2005; Debaille et al., 2006). However, recent investigations suggest that melting of mantle peridotite occurs indeed under isotopic equilibrium conditions (Rampone et al., 2009).

The aim of this study is to examine the mantle dynamics of the southern Mid-Atlantic Ridge (MAR) between 7°30′S (Ascension Fracture Zone [AFZ]) and 11°30′S (Bode Verde Fracture Zone [BVFZ]), based on small-scale sampling along the ridge axis (Fig. 1). Furthermore, we sampled subaerial basalts at Ascension Island and from a 3126 m deep drill hole (ASI#1) that provide new geochemical constraints on the origin of the Ascension volcanic edifice.

Our data confirm that MORBs from this portion of the MAR are highly heterogeneous in trace element and isotopic composition, covering a large portion of the global MORB array. In particular, our Hf isotope measurements reveal the presence of at least three mantle components in the area. We consider the potential chronological significance of the observed isotope trends ("mantle isochrons" cf. Donnelly et al., 2004) and integrate the dataset in a geodynamic framework with respect to mantle convection models.

Moreover, the relationships between on-axis volcanism and volcanism on Ascension Island can be re-evaluated. Whereas previous investigations consider Ascension as plume-related, recent geophysical models call for an on-axis origin (Klingelhöfer et al., 2001). Our geochemical data indicate different mantle sources for the submarine and island stage volcanism of Ascension, in support of an on-axis origin of the Ascension volcanic edifice.

2. Geodynamic setting

2.1. The southern MAR (7°30′S to 11°30′S)

On an ocean basin scale, isotope compositions of southern Atlantic MORB become successively more radiogenic from the equator towards higher latitudes. This could reflect northward dispersal of

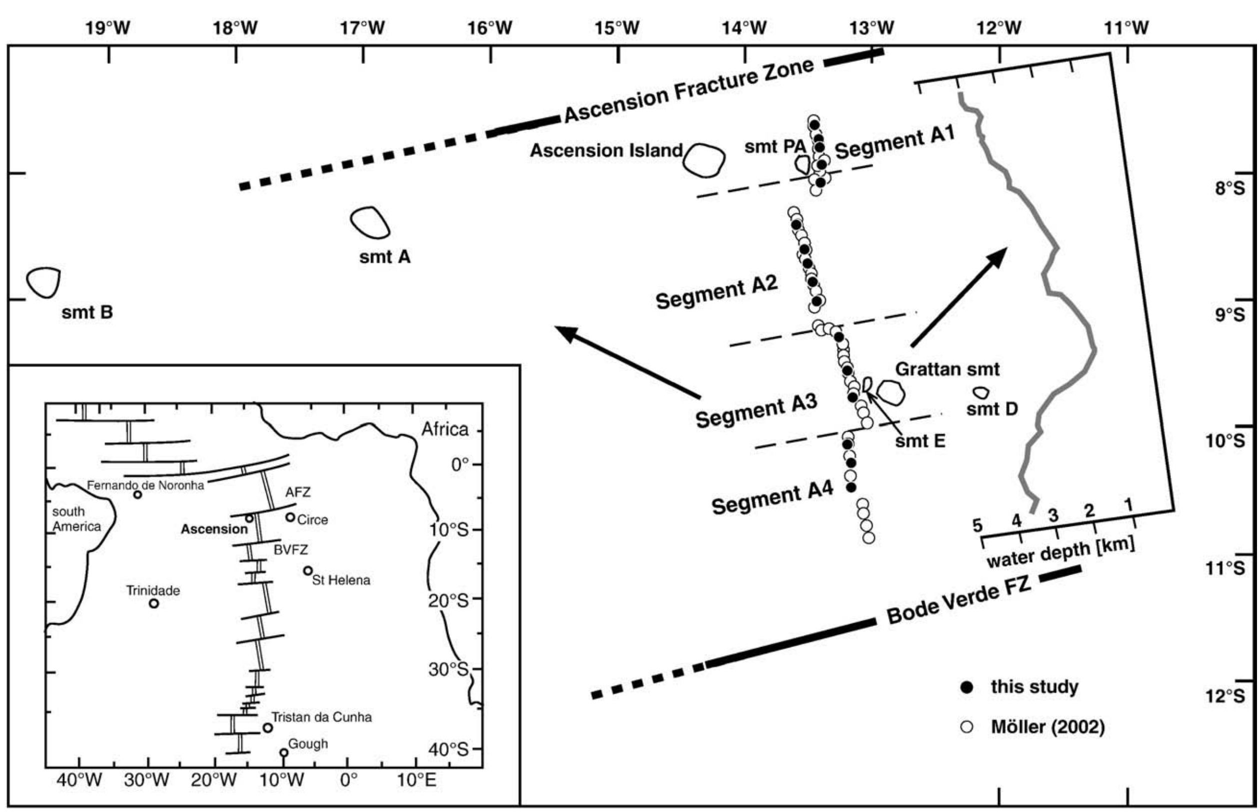

Fig. 1. Location of the study area at the southern Mid-Atlantic Ridge between 7°30′S and 11°30′S, Ascension Island, and major seamounts (after Almeev et al., 2008). Segmentation of the ridge axis is according to Bruguier et al. (2003). The inserted curve shows the bathymetry of the ridge axis, illustrating a substantial decrease in water depth towards the central segment A3. Black arrows show absolute plate motion vectors since 30 Ma (O'Connor and le Roex, 1992). Location of MAR samples previously examined by Möller (2002) is shown. A subset of these samples has been selected for this study as well as samples from the submarine and subaerial stage of Ascension Island. smt: seamount, PA: Proto-Ascension (Klingelhöfer et al., 2001).