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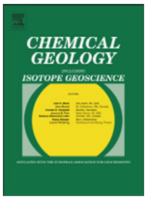

Research paper

Volcanism on the flanks of the East Pacific Rise: Quantitative constraints on mantle heterogeneity and melting processes

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ABSTRACT

We present major and trace element and Sr, Nd and triple-spike Pb isotope data for 17 fresh volcanic glasses from Seamount 6, a 10-km diameter seamount located 140 km east of the East Pacific Rise at 12°45′N. Geological and geochronological evidence show that magma compositions evolved from tholeiitic basalts to alkalic basalts and basaltic trachyandesites during the 1–2 Ma active lifetime of the seamount. Major and trace element compositions in Seamount 6 lavas vary systematically with isotope ratios; the youngest lavas with the highest incompatible trace element concentrations have the highest La/Yb, Nb/Zr, K_2O/TiO_2, $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$ and the lowest $^{143}Nd/^{144}Nd$, MgO and CaO. The range in element concentrations, incompatible element ratios, and isotope compositions in Seamount 6 lavas exceeds that observed in lavas erupted at the adjacent ridge axis, and is comparable to the range in lava compositions reported from all near-ridge seamounts studied to date. The observed range in lava compositions is consistent with mixing between enriched and depleted melts at shallow levels in the crust. The inferred difference in composition between these mixing endmembers cannot be explained by variable degrees of melting of a single source composition, and requires that the upper mantle is extremely heterogeneous on the scale of the melting region beneath a single seamount.

We can show that the range in composition of EPR seamount lavas cannot be generated by melting of variably heterogeneous mantle in which enriched and depleted materials contribute equally to melting (source mixing). Instead, the trace element and isotope compositions of seamount lavas can be reproduced by melting models in which more enriched, fertile mantle lithologies are preferentially melted during mantle upwelling. At progressively lower degrees of melting, erupted lavas are thus more enriched in incompatible trace elements, have higher La/Yb, K/Ti, $^{87}Sr/^{86}Sr$ ratios and lower $^{143}Nd/^{144}Nd$. If this is a common process, then mantle-derived magmas are unlikely to inherit the average incompatible trace element and isotope composition of their mantle source, which is likely to be significantly more depleted, nor will they display the full range of compositions present in the mantle melting region. These results have implications for the way in which oceanic basalts can be used to infer the composition of the upper mantle.

1. Introduction

At mid-ocean ridges, plate separation and mantle upwelling result in mantle melting and eruption of approximately 3 km^3 mid-ocean ridge basalt (MORB) per year (Crisp, 1984). The chemical and isotopic compositions of MORB are commonly used to infer the composition of the upper mantle, and the processes of mantle melting, melt transport and crystallisation. Numerous geochemical studies of MORB (e.g. Allègre and Turcotte, 1986; Arevalo and McDonough, 2010; Donnelly et al., 2004; Hirschmann and Stolper, 1996; Niu et al., 1999; Phipps Morgan and Morgan, 1999; Schilling et al., 1983; Zindler and Hart, 1986) have shown that even in the absence of nearby hotspots, the upper mantle is chemically and isotopically heterogeneous. The ultimate origin of this heterogeneity is unclear, but likely results from subduction and 'recycling' of oceanic crust, sediment, metasomatised oceanic lithosphere, mantle wedge material, or oceanic island chains and plateaus (Donnelly et al., 2004; Niu and O'Hara, 2003; Pilet et al., 2005; White and Hofmann, 1982).

Most MORB are apparently derived from mantle that is depleted in highly incompatible trace elements and has time-integrated low Rb/Sr, Nd/Sm compared to the source of intraplate oceanic islands (e.g. Hofmann, 1997). However, several studies (e.g. Ito and Mahoney,

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2005b; Meibom and Anderson, 2004) have argued that preferential melting of incompatible element enriched, relatively fertile mantle lithologies at small degrees of mantle melting could be at least partly responsible for the trace element and isotopic differences between MORB and oceanic intraplate basalts (OIB). If this is the case, then inversion of basalt compositions to infer mantle composition and melting processes will not be straightforward (e.g. Stracke and Bourdon, 2009). Evidence for this kind of melting behaviour is seen in the ^{143}Nd/^{144}Nd isotope compositions of clinopyroxenes from abyssal peridotites, which extend to more radiogenic values than MORB from the same ridge segment, suggesting that more enriched components are preferentially sampled during melting and that the Nd isotope composition of the mantle may be more radiogenic than that inferred from analysis of MORB alone (Salters and Dick, 2002; Snow et al., 1994; Stracke et al., 2011; Warren et al., 2009).

At mid-ocean ridges, relatively high degrees of melting of a large volume of mantle, together with magma mixing during melt migration within the mantle and crustal magma chambers have the effect of homogenising the magma compositions that are erupted at the surface (e.g. Bryan, 1983; Dungan and Rhodes, 1978; Rhodes et al., 1979; Rubin and Sinton, 2007; Sinton and Detrick, 1992; Walker et al., 1979). As a result, MORB are unlikely to preserve an accurate picture of the degree of heterogeneity of the upper mantle beneath spreading ridges. In contrast, magmas erupted on small off-axis seamounts apparently result from melting of smaller volumes of mantle. Most seamounts form within 5–15 km of the ridge axis (Scheirer and Macdonald, 1995), whereas the width of the melt lens beneath the EPR is on average about 0.5 km, meaning that most seamount magmas by-pass the main axial magma chamber system beneath spreading ridges. Seamount lavas therefore undergo less mixing during melting and melt migration, and should more faithfully record the heterogeneity of the upper mantle. Previous studies have shown that the lavas erupted on seamounts on the flanks of Pacific spreading ridges have far more variable trace element and isotope compositions than MORB erupted at the adjacent ridge (Batiza and Vanko, 1984; Graham et al., 1988; Niu and Batiza, 1997; Niu et al., 2002; Zindler et al., 1984). Seamount lavas therefore offer an opportunity to study the degree of mantle heterogeneity in much greater detail.

Most previous studies have analysed only a few samples from individual seamounts. In order to determine more precisely the compositional contrast between mantle heterogeneities, their length scale and origin, and how these are sampled during mantle melting, more detailed geochemical studies of individual seamounts are required. Here, we present new major and trace element and Sr, Nd and Pb isotope data for a suite of lavas from Seamount 6, a small seamount located 140 km east of the East Pacific Rise at about 13°N. The range of lava compositions on this single seamount is comparable to that observed in the NE Pacific seamount lava dataset. Our new data provide insights into the nature and scale of upper mantle heterogeneity, and its influence on mantle melting processes.

2. Geological setting

Seamount 6 is located in the eastern Pacific on the Cocos Plate at 12° 45′N, 102° 35′W (Fig. 1). Although the seamount has recently been renamed ‘Baja A’ (see seamount catalogue; http://earthref.org/SBN/), we use the name Seamount 6 in this manuscript to ensure consistency with earlier publications. Seamount 6 is situated some 140 km east of the East Pacific Rise (EPR) on a plate segment bordered by the Orozco Fracture Zone to the north and Clipperton Fracture Zone to the south (see Fig. 1). The full spreading rate along this segment of the EPR is about 10–11 cm a^{-1}, but spreading is asymmetric with a spreading rate of 6.5 cm a^{-1} to the west and 4.5 cm a^{-1} to the east (Choukroune et al., 1984).

Seamount 6 consists of three coalesced volcanic edifices, termed 6W, 6C, and 6E (from west to east) that are aligned parallel to the relative motion of the Cocos Plate. The largest of the three cones is 6C with a basal diameter of 9.6 km, a volume of about 52 km^3 and an elevation of ~1300 m above the seafloor (Batiza et al., 1989; Batiza and Vanko, 1984). The eastern and western edifices are significantly smaller with volumes of about 21 km^3 and 22 km^3, and elevations of 750 m and 420 m above the seafloor, respectively (Batiza et al., 1989). Cone 6C has a prominent rift zone on its north side that is oriented subparallel to the trend of the East Pacific Rise (340°; Batiza et al., 1989). Lavas from Seamount 6 were dredged during cruise RISE III Leg 3 of R/V New Horizon in 1979 and also during Leg 3 of the CERES expedition in 1982. A detailed photographic and submersible study (with submarine Alvin) followed during cruise AII-112-18 with R/V Atlantis II in 1984, and cruise A132-17 in 1995. As a result of submersible observations and analysis of samples collected during these cruises, the geological structure and petrological evolution of Seamount 6 is relatively well known (Fig. 2; e.g. Aggrey et al., 1988; Batiza, 1980; Batiza et al., 1989; Batiza and Vanko, 1984; Graham et al., 1987, 1988; Honda et al., 1987; Zindler et al., 1984).

Seamount 6 is situated on oceanic crust that formed approximately 3.0 Ma ago during magnetic anomaly 2′, which represents an upper limit on the age of the oldest lavas. The seamount is composed entirely of normally polarised lavas, and is partly built on negatively magnetised seafloor, indicating that the seamount was not formed directly at the EPR axis. The magnetic data indicate that Seamount 6 formed within magnetic anomaly 2′, no further than about 45 km from the EPR axis, on seafloor that was less than about 1 Ma old (McNutt and Batiza, 1981; McNutt, 1986). An ^{40}Ar/^{39}Ar analysis of a sample of alkali basalt (19–23) from Seamount 6 yielded a ‘model age’ of <2 Ma (Honda et al., 1987). The same sample was dated at 500 ± 500 ka using the ^{3}He/^{4}He disequilibrium dating method (Graham et al., 1987). Other ^{3}He/^{4}He disequilibrium ages for alkalic lavas from Seamount 6 range from 3 to 900 ka (Graham et al., 1987). Based on the thickness of Fe–Mn coatings and degree of sediment cover, the three volcanic edifices of Seamount 6 are approximately the same age, and lavas from the summit region of Seamount 6 are younger than those from the lower flanks (Batiza et al., 1989).

On Seamount 6, a relationship between lava composition, morphology and stratigraphy has been documented by combined submersible, geophysical and geochemical studies (Fig. 2a; Batiza et al., 1989; Batiza and Vanko, 1983; 1984; Graham et al., 1987; 1988; Honda et al., 1987; Maicher et al., 2000; McNutt, 1986; Zindler et al., 1984). Intensely weathered pillow lavas composed of incompatible trace element depleted tholeiites (N-MORB) with thick Fe–Mn coatings make up the lower slopes of 6C (below about 2300 m water depth), and probably also much of the main edifices of 6E and 6W. The summit regions of 6C and 6E are built of visibly younger hyaloclastites, sheet flows, pahoehoe lava and lobate pillows, and on 6C most of these consist of alkalic lavas of enriched MORB (E-MORB) type.

Previous geochemical studies of Seamount 6 lavas (e.g. Batiza et al., 1989; Batiza and Vanko, 1984; Zindler et al., 1984) have shown that their chemical and isotopic variability is far greater than that of MORB erupted at the adjacent northern EPR axis. Many Seamount 6 lavas have higher concentrations of incompatible trace elements and higher ^{87}Sr/^{86}Sr and lower ^{143}Nd/^{144}Nd than most East Pacific Rise MORB. In this study, we analysed 17 fresh volcanic glass samples that extend the known compositional range of Seamount 6 lavas in order to better constrain the melting dynamics in this seamount.

3. Samples and methods

The samples analysed in this study were collected on dives 3009 to 3017 of submarine Alvin during research cruise A132-17 of R/V Atlantis II in 1995. Most of these dives were located at the upper, younger section of the southern slope of Seamount 6 (Fig. 1). The terraced summit of Seamount 6 is predominantly characterized by pillow lavas, but also hyaloclastites and sheet flows, which cap a