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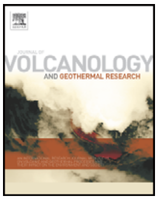

Generation and evolution of magma beneath the East Pacific Rise: Constraints from U-series disequilibrium and plagioclase-hosted melt inclusions

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A B S T R A C T

Mid-ocean ridge basalt (MORB) samples from the East Pacific Rise (EPR 12°50′N) were analyzed for U-series isotopes and compositions of plagioclase-hosted melt inclusions. The ^{226}Ra and ^{230}Th excesses are negatively correlated; the ^{226}Ra excess is positively correlated with Mg# and Sm/Nd, and is negatively correlated with La/Sm and Fe_8; the ^{230}Th excess is positively correlated with Fe_8 and La/Sm and is negatively correlated with Mg# and Sm/Nd. Interpretation of these correlations is critical for understanding the magmatic process. There are two models (the dynamic model and the "two-porosity" model) for interpreting these correlations, however, some crucial parameters used in these models are not ascertained. We propose instead a model to explain the U-series isotopic compositions based on the control of melt density variation. For melting either peridotite or the "marble-cake" mantle, the FeO_t content, ^{230}Th excess and La/Sm ratio increases and Sm/Nd decreases with increasing pressure. A deep melt will evolve to a higher density and lower Mg# than a shallow melt, the former corresponds to a long residence time, which lowers the ^{226}Ra excess significantly. This model is supported by the existence of low ^{226}Ra excesses and high ^{230}Th excesses in MORBs having a high Fe_8 content and high density. The positive correlation of ^{226}Ra excess and magma liquidus temperature implies that the shallow melt is cooled less than the deep melt due to its low density and short residence time. The correlations among Fe_8, Ti_8 and Ca_8/Al_8 in plagioclase-hosted melt inclusions further prove that MORBs are formed from melts having a negative correlation in melting depths and degrees. The negative correlation of ^{226}Ra excess vs. chemical diversity index (standard deviation of Fe_8, Ti_8 and Ca_8/Al_8) of the melt inclusions is in accordance with the influence of a density-controlled magma residence time. We conclude that the magma density variation exerts significant control on residence time and U-series isotopic compositions.

1. Introduction

Mid-ocean ridge basalts (MORBs) from new volcanic zones of mid-ocean ridges usually have ^{230}Th excesses ((^{230}Th/^{238}U) > 1) and ^{226}Ra excesses ((^{226}Ra/^{230}Th) > 1). ^{230}Th and ^{226}Ra excesses in MORBs are not controlled by their initial values in their mantle source, because U-series isotopes evolve into a state of secular equilibrium in which the decay rate of each intermediate nuclide equals its production rate due to the decay of its respective parent element in a closed system (Ivanovich and Harmon, 1982). Therefore, for the melting of a long-lived mantle, the ^{230}Th and ^{226}Ra excesses are controlled only by the melting process. In addition, because of the short half lives of ^{226}Ra (1600 yr) and ^{230}Th (75,200 yr), an interpretation of their excesses will provide good constraints on magma generation and evolution.

In general, the ^{230}Th and ^{226}Ra excesses of MORBs are generated by the mantle melting process. There are two models for the generation of ^{230}Th and ^{226}Ra excesses of MORBs. One is the "dynamic-melting" model (McKenzie, 1985), and the other is the "two-porosity" model (Spiegelman and Elliott, 1993; Lundstrom, 2000; Sims et al., 2002). The "dynamic-melting" model assumes a fractional melting in which once the critical porosity is reached, the melt is extracted and ascends rapidly maintaining the initial ^{226}Ra excess. In the "two-porosity" model, part of the melt ascends in a reactive porous flow in which the ^{226}Ra excess can be maintained despite the melt velocity, and the other parts ascend in a form similar to the "dynamic-melting" model.

These ^{230}Th and ^{226}Ra excesses may be influenced by the magma's evolution. The long magma residence time in the ridge crust will decrease ^{226}Ra excess. However, neither of the models above considers the influence of magma residence time on the U-series isotopic compositions. Many studies have proved that primary magmas reside in the crust for a certain amount of time before eruption, and the calculated magma residence time ranges from several decades to several thousand years (Lundstrom et al., 2000;

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Cooper et al., 2001; West et al., 2001; Sigmarsson et al., 2002; Turner et al., 2003; Streck and Wacaster, 2006). The magma residence time is most likely comparable to the half life of ^{226}Ra, and it probably affects the relationships of ^{238}U–^{230}Th–^{226}Ra.

Because the magma ascent and eruption dynamics are generally thought to be controlled by density-dominated buoyancy, we will discuss in this study the influence of magma density on residence time and U-series isotopic compositions. In addition, the compositions of melt inclusions hosted in phenocrysts of MORBs represent instant states of magma evolution, and the melt inclusions may have recorded the history of the magma's evolution in the magma chamber. Melt inclusions are used to investigate the density-controlled magma chamber processes.

2. Geological setting

The EPR is a narrow (1–2 km wide), roughly north–south trending zone of episodic neovolcanic activity (Fig. 1). The study area is located between the Orozco fracture zone and another small fracture zone (11°49′N). It is a fast ridge with a full spreading rate of 10–11 cm/yr (Choukroune et al., 1984). Choukroune et al. (1984) divided the study area into four main provinces based on tectonics and topography: (1) An active volcanic zone located in the central graben; (2) An active tectonic zone comprising the central graben and extending up to about 2 km from either side of the ridge axis; (3) An inactive tectonic zone starting 2 km away from the axis and formed by discontinuous horst- and graben-type of structures; and (4) Off-axis volcanoes (seamounts) located less than 20 km from either side of the ridge axis. The axial graben with many crannies is 200–600 m in width, 20–50 m in depth, 2630 m in average water depth, and is composed mostly of basalt (Ballard et al., 1984; Zeng et al., 2008). A sheeted and narrow magma chamber is situated in shallow crust (1–2 km). This chamber lies on a thick and wide mush zone and extends continuously along the axis (Detrick et al., 1987; Burnett et al., 1989).

3. Samples and methods

The MORB samples were dredged from the axial graben of the EPR 12º44′N–12º51′N. The sampling sites are E42-4X, E20-2B, E15-3B, E11-5X and E13-3X from South to North (Fig. 1). The samples are pillow basalts, except for E42-4X, which is lobate. Based on thin sections from the glassy margin, these samples contain 10–20% olivine and 80–90% plagioclase phenocrysts by volume. Most of the plagioclase phenocrysts are lathy and zoned, and they host melt inclusions. Clinopyroxene appears only as microlite. A few Cr-spinel phenocrysts appear in E20-2B and E15-3B as an accessory mineral (<1%). The groundmass of all samples contains abundant microlites of olivine, clinopyroxene and plagioclase, but these microlites are absent in the glassy margin.

The samples in this study have been previously studied. Therefore, data for major elements and some trace elements (except Ba, Cs, Pb, Rb, U and Th) were selected from Zhang et al. (2009). To obtain high precision data for ^{226}Ra radioactivity from the gamma-ray spectrometer, samples of 300–400 g were prepared. The alternated parts of these samples were removed. These samples were crushed to 2–3 mm particles, surged by ultrasonic wave in a 2.5 N HCl solution for 1 h (water changed every 15 min), left dry at 60 °C for 12 h, and were homogenized and milled to <60 μm. For analyses of Ba, Cs, Pb and Rb, 40 mg of sample powder was weighed precisely and transferred into Teflon beakers. Nest, 1.5 mL of HF and 0.5 mL of HNO_3 were added and heated at 150 °C for 24 h. The temperature was then lowered to 120 °C, and 0.2 mL of $HClO_4$ was added. When there was no white smoke, the residues were added at 1 mL of HNO_3 and 1 mL of H_2O and were then sealed and heated at 120 °C for 12 h. The solutions were diluted 1000 times using 2% distilled super-pure HNO_3, and were analyzed by ICP-MS (ELAN DRC II) using Re as an inner standard at the Institute of Oceanology, Chinese Academy of Sciences. The working parameters were as follows: oxide level of <3%, doubly charge of <3%, platinum sampler cone and skimmer cone, nebulizer gas flow of 0.88 L/min, auxiliary gas flow of 1.2 L/min, plasma gas flow of 15 L/min, lens voltage of 6 V, ICP RF power of 1200 W, pulse stage voltage of 1150 V, analog stage voltage of 1950 V. The standard solutions (American Lab Tech Company) were diluted to 1 μg/L, 10 μg/L, 50 μg/L and 100 μg/L to make the calibration curve, and their linear relativities were all above 0.9999. BCR-2, BHVO-2 and GSR-3 were run as external standards to evaluate the accuracy (Table 1), and we can see that the results were reproduced well.

The U and Th concentrations and isotopic ratios were determined on samples that were spiked with ^{236}U–^{229}Th tracers. These samples were dissolved using a HF–HNO_3–HCl mix, and measured using the dynamic mode of a Nu Instruments MC-ICP-MS at Macquarie University. The detailed procedure for sample pretreatment and

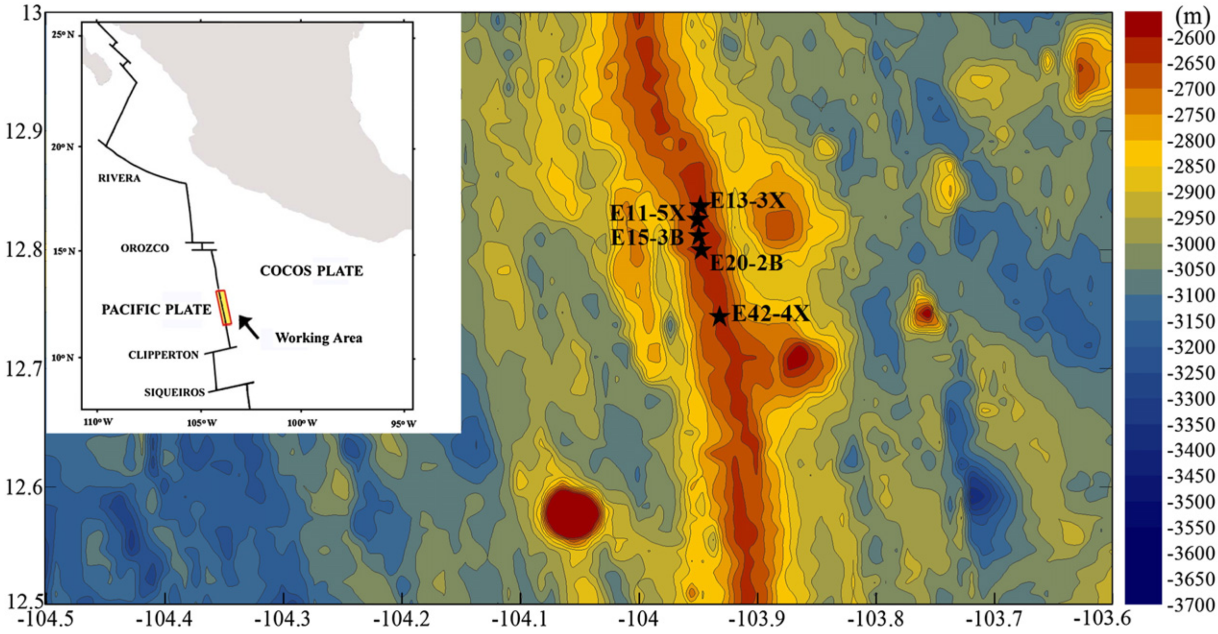

Fig. 1. Map of isobaths near EPR 12°50′N (data source: http://www.geomapapp.org) and sampling sites.