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Melt extraction in the Earth's mantle: Constraints from U–Th–Pa–Ra studies in oceanic basalts

Andreas Stracke [a,*], Bernard Bourdon [b,1], Dan McKenzie [c]

[a] Max-Planck-Institut für Chemie, Postfach 3060, 55020 Mainz, Germany
[b] Laboratoire de Géochimie et Cosmochimie IPGP-CNRS UMR7579, 4 Place Jussieu, 75252 Paris Cedex 05, France
[c] Bullard Laboratories, Department of Earth Sciences, Cambridge University, Madingley Road, Cambridge, CB3 0EZ, UK

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Abstract

U-series studies in oceanic basalts are critical for understanding melting and melt extraction in the Earth's mantle. The combined results of a detailed geochemical study of melting and melt extraction at Theistareykir, northern Iceland, provide a strong case for melt extraction via channeled melt flow at an active spreading ridge. It has often been argued, however, that widely used melting and melt extraction models, which simulate channeled melt extraction (i.e. fractional and/or dynamic melting), can only partially explain the global U-series systematics in oceanic basalts. As a consequence, more complicated models have been invoked, which suggest different styles of melt extraction at different depths/pressures in the mantle, so-called "two-porosity models". Alternatively, diffusion-controlled mechanisms have been proposed. Here we show that U–Th–Pa–Ra systematics in oceanic basalts can indeed be explained by models where melt transport occurs without chemical equilibrium between melt and solid when variations in all three critical melting parameters (residual porosity, upwelling rate of the solid mantle and melt velocity) are taken into account. Melting at ridges requires systematic variation of at least two critical melting parameters, most likely upwelling and melt extraction rate. Melts generated with increasing lateral distance to the ridge axis are generated with slower upwelling rates and are extracted with lower velocities than melts created closer to the ridge axis. Melting at ocean islands, on the other hand, can successfully be explained by variations in upwelling rate only. Global U-series systematics in OIB originate from superimposed global variations in upwelling velocity due to different buoyancy fluxes and from local variation in upwelling velocity as a function of radial distance to the plume center. The model proposed here is consistent with other geochemical data for oceanic basalts and strongly supports melt extraction via high-porosity channels as a general means of melt extraction from the Earth's upper mantle.

Keywords: U-series; MORB; OIB; melt extraction; dynamic melting

1. Introduction

Despite numerous geophysical and geochemical studies, our knowledge about mantle melting and melt extraction remains limited. The fluid dynamical process of melt movement is theoretically described by two-

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[*] Corresponding author. Fax: +49 6131 371051.
E-mail address: stracke@mpch-mainz.mpg.de (A. Stracke).

[1] Now at: Institut für Isotopengeologie und Mineralische Rohstoffe, Department of Earth Sciences, ETH-Zürich, CH-8092, Zürich, Switzerland.

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phase flow [1,2]. These equations require melt to move in chemical equilibrium with the solid and support solitary waves in one, two, or three dimensions. Only three-dimensional solitary waves are stable [3–5], however, and there is, as of yet, no evidence for the existence of such waves in the melting regions in the Earth's upper mantle. Moreover, time scales of melt transport of about 1000 years or less are incompatible with solitary wave transport and require melt to move in channels with a minimum dimension of a few millimeters [6]. Such channels may be formed by chemical [7,8] or mechanical processes. Since direct observations of the physical process of melting and melt movement in the mantle are unavailable and geophysical studies lack the necessary resolution, geochemical and petrological tools appear, at this time, to be most promising for studying melting and melt extraction.

The comprehensive study of basaltic melt generation, melt movement and source composition at Theistareykir, northern Iceland [9–17], has shown that melting at Theistareykir occurs as a result of passive decompression melting at shallow depths ($<$about 80 km) with a possible component of active upwelling at greater depths [18,19]. Slater et al. [15] showed that mixing of instantaneous fractional melts reproduces the chemical composition of the melt inclusions and the erupted melts by incomplete mixing of instantaneous fractional melts from different depths of the melting region [11,12,15]. Erupted melts at Theistareykir, even those from a single flow, also preserve considerable compositional variability [11,15,16]. Decreasing compositional variability in melt inclusions with decreasing fosterite content in olivine phenocrysts indicate that mixing and crystallization occur concurrently at Moho depths or deeper [11]. Thus melts entering major sites of melt pooling and mixing (magma chambers?) must have preserved considerable compositional heterogeneity, indicating that melt mixing during transport from the source region to the surface is incomplete.

A detailed isotopic and geochemical investigation of the Theistarykir melts [16] showed that erupted melts also preserve considerable isotopic heterogeneity, indicating that the source region is composed of at least two isotopically heterogeneous components. Isotopic variation in the Theistareykir melts is well-correlated with major element and trace element variability [16]. Thus the erupted lavas represent variable mixtures of melts from different depths and regions with different isotopic compositions. The combined geochemical results from Theistareykir show that melts must be able to move to magma chambers with little interaction with the material through which they pass and retain correlations between different isotopes, trace elements and major elements right through to eruption as lavas on the surface. This behavior is most readily explained if melt transport occurs in a channeled network and not by porous flow.

Simple porous flow cannot produce extraction velocities greater than 2 m/yr [8]. The rates of melt transport therefore provide another important constraint on melt transport mechanisms (e.g. [6]). Maclennan et al. [10] argue that a peak in eruption rates occurred immediately after the end of the last glacial period with concurrent melt extraction velocities greater than 50 m/yr. Such high velocities cannot be generated by porous flow and require melt flow to be in channels or along fractures. Potential variations in either mantle upwelling rate and/or melt extraction velocities have also been discussed as a potential explanation for the variation in excess ^{230}Th in the Theistareykir lavas [17]. Taken together, the observations discussed above provide a strong case for channeled melt transport at Theistareykir.

Here, we use new U–Pa data from Theistareykir in combination with global U–Th–Pa–Ra data from MORB and OIB to put further constraints on melting and melt extraction mechanisms beneath Theistareykir, and mid-ocean ridges and ocean islands in general. In particular, we address the following questions: 1) Does the new Pa data complement the existing picture of melting and melt extraction at Theistareykir? 2) Can U–Th–Pa–Ra data in oceanic basalts in general be explained by melting models that simulate channeled melt flow (fractional or dynamic melting), or are more complicated models required? 3) What are the mechanisms and timescales of melt extraction beneath ridges and ocean islands?

2. Modeling U-series disequilibria with dynamic melting

The maximum melt extraction time is constrained by the half-life of the shortest-lived radioactive isotope out of isotopic equilibrium [20]. U-series data can therefore provide important model-independent order of magnitude constraints on the timescales of melt extraction. More precise absolute estimates of the critical melting parameters, upwelling rate of the solid mantle (W), melt extraction velocity (v), and residual porosity (ϕ), however, depend on model calculations. While the relative variations between these model-derived parameters are robust, the accuracy of absolute estimates relies on how well the applied model approximates the natural system.