



The geochemical consequences of mixing melts from a heterogeneous mantle

John F. Rudge^{a,*}, John Maclennan^b, Andreas Stracke^c

^a Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Madingley Road, Cambridge CB3 0EZ, UK

^b Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

^c Westfälische Wilhelms Universität, Institut für Mineralogie, 48149 Münster, Germany

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Abstract

Binary mixing is one of the most common ways of describing the relationships between incompatible element concentrations and Sr–Nd–Pb isotopic ratios in oceanic basalts. Apparent binary mixing trends are seen in a wide variety of data sets, both at a local-scale and globally. Here we focus on data from Iceland where isotopic variations in whole-rock samples and olivine-hosted melt inclusions demonstrate the presence of high-amplitude, short lengthscale mantle heterogeneity. Binary mixing models fail to provide an adequate fit to data for moderately incompatible and compatible elements, which provides evidence that some of the variation in melt compositions arises from the fractional melting process itself. To explore the role of mixing in determining the geochemical systematics of oceanic basalts we have developed a new model of the mixing of fractional melts from a bi-lithological mantle source where small enriched fusible heterogeneities are embedded in a refractory depleted matrix. This model is a statistical model, based on the Dirichlet distribution, that allows us to determine the expected statistical distributions of melt compositions. The Icelandic data appears to provide evidence that the mixing process is not uniform with depth, and that the deepest melts appear to have undergone a greater degree of homogenisation than the shallower melts. The model most closely resembles the data when all melts beneath a depth corresponding to ~5% melting of the refractory lithology are homogenised. We speculate that this depth marks the transition between diffuse and channelised melt flow. This new statistical model of mixing challenges some of the conventional interpretations of trace element-isotope systematics. Notably, picking mantle end-members from apparent binary mixing arrays in isotope ratio plots is fraught with difficulty: in our models the apparent binary mixing arrays do not point towards the isotopic compositions of their mantle sources (with the exception of Pb–Pb).

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1. INTRODUCTION

Isotopic and trace element data from Mid-Ocean Ridge Basalt (MORB) and Ocean Island Basalt (OIB) samples are often interpreted in terms of binary mixing between two homogeneous materials. On the scale of individual ridge segments or ocean island volcanoes such binary mixing models often provide good fits to the observed isotopic

and incompatible trace element ratios (Stracke et al., 1999, 2003b; Abouchami et al., 2000, 2005; Tanaka et al., 2008; Blichert-Toft and Albarède, 2009; Hanano et al., 2010; Peate et al., 2009). It has long been recognised that the end-members of these binary mixing arrays need not correspond to globally significant mantle components, and that mixing of three components can lead to pseudo-binary mixing arrays when two of the components mix fully before mixing with a third component (Hamelin et al., 1986; Douglas and Schilling, 2000). Such regional-scale mixing is, however, consistent with the widely accepted assumption that the isotopic compositions of the end-members of mixing arrays, or even the individual samples themselves,

* Corresponding author. Tel.: +44 1223 765545; fax: +44 1223 360779.

E-mail address: rudge@esc.cam.ac.uk (J.F. Rudge).

correspond to those of substantial masses of mantle underneath oceanic volcanoes. This approach has arisen naturally from a view of the mantle where short-lengthscale isotopic and mineralogical variations are unimportant. Melts from such a mantle would have an isotopic composition identical to that of large volumes of the solid from which they are produced.

The study of small-scale variation in the compositions of the melts and mantle residues generated at spreading ridges has highlighted the importance of the melting process as an additional generator of geochemical diversity. The observation of substantial variation in the incompatible trace element contents and trace element ratios of olivine-hosted melt inclusions in individual MORB samples was accounted for by a model involving generation of extreme compositional variation during fractional melting (Sobolev and Shimizu, 1993). A similar model was used to account for the observation of residual clinopyroxene with depleted incompatible trace element contents in abyssal peridotites (Johnson et al., 1990). These models are consistent with a range of compositional and physical arguments for the separation of melts from the mantle at low porosities followed by rapid channelised flow towards the surface (McKenzie, 1985; Kelenen et al., 1997). The observations of extreme small-lengthscale variation in the trace element compositional record of mantle melts were believed to demonstrate that near-fractional melting was the primary cause of local-scale trace element variation, and provided evidence that the average trace element compositions of oceanic basalts is different from those of their mantle source regions (Johnson et al., 1990; Sobolev and Shimizu, 1993). These differences between melt and source extended even to the incompatible trace element ratios (Hofmann et al., 1986). A number of workers produced models of fractional melting of a single homogeneous mantle source composition, demonstrating the substantial range of trace element compositions that can be generated without any variation in the isotopic composition of the basalts (Gast, 1968; Shaw, 1970; Slater et al., 2001; MacLennan et al., 2003b). Since these models did not involve the generation of isotopic variability, they provided no challenge to the assumption that MORB and OIB isotopic arrays could be used to identify the compositions of solid material in the mantle rising under oceanic volcanoes.

More recent studies (Stracke et al., 2003b; Stracke and Bourdon, 2009; Peate et al., 2009; Cordier et al., 2010; Waters et al., 2011) have looked at a combination of trace element, major element, and isotopic data using samples from localities tightly constrained in space and time. These studies have found strong correlations in whole rock data between trace element ratios and isotopic ratios. Melt inclusion studies (MacLennan, 2008b) echo these strong correlations, at least for incompatible trace element concentrations and isotopes. The correlations suggest that heterogeneity in the mantle source has a key control on the observed trace element heterogeneity. Nevertheless, some part of the observed trace element heterogeneity must be generated by the melting process itself, as reflected in the systematics of REE variation in olivine-hosted melt inclusions (MacLennan et al., 2003a). Furthermore, the presence of U-series disequilibrium in young basalts from Iceland demonstrate

that highly incompatible elements can be fractionated from each other by the melting process (Condomines et al., 1981; Hémond et al., 1993; Stracke et al., 2003c; Kokfelt et al., 2006; Koornneef et al., 2012).

A further complication to understanding the isotopic systematics of oceanic basalts is that isotopic heterogeneity may be coupled with lithological heterogeneity and hence with fusibility (Hirschmann and Stolper, 1996; Stracke et al., 1999, 2003b,c; Phipps Morgan, 2001; Katz and Rudge, 2011; Shorttle and MacLennan, 2011). For example, recycled crustal material, which is often thought to be the carrier of the isotopically enriched signature, may be more pyroxenitic and thus more fusible than the rest of the depleted peridotitic mantle. The isotopic composition of a sample formed by melting of a multi-lithology source will be biased from that of the mean mantle source, and will be a function of the degree of melting. As a result, a number of studies have explained the correlations between isotopes and trace elements as arising naturally from varying degrees of melting of a lithologically heterogeneous source (Phipps Morgan, 1999; Ito and Mahoney, 2005a,b; Stracke and Bourdon, 2009; Ingle et al., 2010).

The present manuscript seeks to address the following key question: Why do binary mixing models work so well if the generation of melt in the mantle is dominated by fractional melting? This question becomes even more pressing when it is understood that fractional melting of a heterogeneous mantle can fill a huge volume in isotope and trace-element compositional space. We believe the answer lies in understanding precisely how the fractional melts are mixed to form the samples we see at the surface. To this end we have developed a new model of melting and the mixing of melts from a bi-lithological source, building on the previous studies by MacLennan (2008b) and Stracke and Bourdon (2009). The manuscript is organised as follows: the next section describes the main observational constraints, and is followed by a description of a new statistical model. Subsequent sections discuss the application of the model to trace element and isotopic data for whole rocks and melt inclusions. Detailed mathematical derivations are provided in an appendix at the end of the manuscript.

The data used in the examples throughout this manuscript come from Iceland, but the modelling techniques and ideas we develop are relevant for understanding melt mixing more generally. Iceland provides one of the best windows into the melt mixing process: On Iceland it is possible to constrain the origin of basalts tightly in space and time; spatially because it is possible to make detailed maps of volcanic flows in the field; and temporally because one can distinguish easily between subglacial and postglacial eruptions through their geomorphology, and use tephrochronology to bracket the ages of postglacial flows (Smundsson, 1991). There is a large quantity of high quality data available from Iceland which has a wide spread of different geochemical measurements (majors, traces, and isotopes) made on exactly the same set of samples, both whole-rock samples and olivine-hosted melt inclusions. Having all the measurements on the same samples is particularly important for understanding melt mixing because of the information it provides on the correlations between different observables.

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