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Geochemical variability in MORB controlled by concurrent mixing and crystallisation

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ABSTRACT

The isotopic and elemental diversity in mid-ocean ridge basalts (MORB) traces the history of mantle differentiation, recycling and convective stirring. However, to interpret this record it is critical to account for the magma transport and storage processes modifying the primary geochemical variability of mantle derived melts. Magma mixing during low pressure differentiation is a key petrological process that controls the chemical variability of basalts throughout the global mid-ocean ridge system. Mixing occurs concurrent with crystallisation and must in general be dominant over any assimilatory processes in controlling the chemical evolution of basalts with MgO concentrations >5 wt% MgO. The effect of this mixing is to collapse the diversity of melt compositions leaving the mantle into the narrow range expressed in most mid-ocean ridge settings. In this context magma mixing can be viewed as contaminating the variance structure of primitive mantle melts, which leads to irreversible information loss on the sources and processes involved in melt generation unless primitive, unmixed, liquids and crystal phases are erupted. However, where we can track magma mixing, the homogenisation itself offers the potential to be an important petrological tool, which constrains the storage and transport processes magma experiences during its ascent through the mantle and crust. In the global dataset interrogated here systematic mixing trends are visible up to the length scales of first order ridge segmentation (∼300 km), indicating the possible links between surface tectonics and the record of mantle heterogeneity in basalts. The importance of magma mixing at mid-ocean ridges hints at the need to reevaluate the MORB-ocean island basalt chemical dichotomy, given the poorly understood mixing processes operating during intraplate magma transport from mantle to surface.

1. Introduction

Mid-ocean ridge basalts (MORB) offer important insights into upper mantle compositional structure that have helped reveal the ubiquitous nature of chemical and isotopic heterogeneity across multiple length scales in the Earth (e.g. Dupré and Allègre, 1980; Sobolev and Shimizu, 1993; Agranier et al., 2005). That we see this heterogeneity reflected in MORB indicates two important facts: (1) that mantle stirring has been too inefficient to erase all record of the processes that have brought the solid Earth to its current state (Coltice and Schmalzl, 2006) and (2) that melt mixing during transport out of the mantle and storage in the crust is often at least partially incomplete in primitive basalts and their melt inclusions (Sobolev and Shimizu, 1993; Spiegelman and Kelemen, 2003; Maclennan, 2008; Rudge et al., 2013). We can therefore use the chemistry of basalts as an accessible record of planetary evolution, which due to subduction recycling not only constrains the history of the solid Earth, but that of the hydrosphere and atmosphere as well (e.g. Allègre et al., 1987).

However, to be able to interpret the chemistry of basalts in terms of mantle composition we must be able to separate out the multiple processes modifying their chemistry during transit from source to surface. Of these processes, those occurring in crustal and shallow mantle magma chambers are key for determining the major, trace and volatile element content of a magma and the resemblance of these chemical observables to those in the original mantle melts. Clearly a dominant low pressure magmatic process is fractional crystallisation, which for a single parental melt composition generates a predictable suite of differentiated magmas lying along a liquid of descent. Our success in empirically and thermodynamically modelling liquid lines of descent is what has allowed fractionation to be normalised out in parameters such as $Na_{8.0}$ (Na_2O at 8 wt% MgO), to obtain global trends in oceanic basalts reflecting primary thermal and chemical conditions in the mantle (Klein and Langmuir, 1987; Jackson and Dasgupta, 2008; Gale et al., 2014). Yet, given the wide range of basalt major and trace element compositions that are predicted for polybaric near

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fractional melting of the mantle (Kelemen et al., 1997a), it is somewhat surprising that simple fractionation paths are observed at all.

The formation of simple liquid lines of descent by cogenetic suites of basalts hints at the efficiency and importance of magma mixing during basalt differentiation, which drastically narrows the chemical variability found in even relatively primitive magmas. For a magma experiencing fractional crystallisation alone the original mantle derived chemical signals are relatively robust, provided incompatible trace element or isotopic ratios are studied. However, mixing between chemically diverse magmas will operate to bias and limit the mantle source signals preserved, even for these otherwise robust elemental and isotopic tracers. What is more, this bias is likely to occur systematically according to tectonic setting and magma supply (Sinton and Detrick, 1992; Rubin and Sinton, 2007; Rubin et al., 2009). As much of our understanding of mantle chemical structure comes from studying basalt chemistry, it is crucial we consider mixing as well as fractional crystallisation when attempting to reconstruct mantle composition and structure. However, despite the likelihood of magma mixing having an important role in basalt petrogenesis, the timescale, locus, and extent of mixing during magma transport and storage remains uncertain.

1.1. *Magma mixing in whole rock and melt inclusions records*

Magma mixing has been recognised in the local whole rock and glass records from mid-ocean ridge and ocean island settings using major and minor elements (Rhodes et al., 1979; Rhodes, 1983; Perfit and Chadwick, 1998; Rubin et al., 2001), trace elements (Bergmanis et al., 2007), uranium series systematics (Lundstrom et al., 1995) and radiogenic isotopes (Stracke et al., 2003). The pioneering work of Sobolev and Shimizu (1993) and Sobolev (1996) showed how high forsterite olivine-hosted melt inclusions can record greater chemical variability than their carrier liquids, and thus that some mixing must be occurring simultaneous to crystallisation in the crust or shallow mantle. Maclennan et al. (2003a) and Maclennan (2008) formalised this concept with mixing theory and new melt inclusion observations from Iceland that quantified the collapse in geochemical variability occurring during fractional crystallisation. Concurrent mixing and crystallisation (CMC) was the term adopted by Maclennan et al. (2003a), and is that used here, to describe the process whereby mixing occurs as an intrinsic part of the differentiation process, aided by the thermochemical nature of magma chamber convection (Martin et al., 1987).

Magma mixing has also been built into models describing the global systematics of mid-ocean ridge geochemistry, which sought to explain the degree of enrichment of incompatible elements during differentiation (O'Hara, 1977; O'Neill and Jenner, 2012). O'Neill and Jenner (2012) also noted the greater variability of P_2O_5 and K_2O in the highest MgO groups of basalts, and it is this potential for the whole rock and glass record to capture CMC that I will explore in this paper.

1.2. *Approach*

The work here is closest in approach to that of Rubin and Sinton (2007) and Rubin et al. (2009) in considering the global MORB dataset as a whole and seeking to extract evidence for coherent patterns of mixing. Whilst Rubin and co-workers focused on the link between geochemical diversity, spreading rates and melt supply, the complementary emphasis of this paper is demonstrating the systematic role of magma mixing during differentiation within diverse suites of MORB, and the length scale on which these mixing trends can be observed. In particular, I develop a set of statistical tools that enable the global dataset of MORB geochemistry to be interrogated at once, whilst accounting for local and regional differences in basalt composition that otherwise mask systematic patterns of magma mixing. Critically, these tools allow for rigorous testing of the significance of CMC patterns and the length scales over which they are resolvable in suites of MORB.

In this paper the homogenisation of primary mantle derived chemical variability will be tracked using incompatible trace element ratios and isotopes. The key property of these geochemical indices that enables CMC to be identified is that they are effectively conservative during fractional crystallisation: trace elements such as La are incompatible and partition into the liquid rather than the early crystallising phases olivine, plagioclase and clinopyroxene (see Appendix B of Shorttle et al., 2014); heavy mass isotope ratios such as $^{143}Nd/^{144}Nd$ undergo little stable isotope fractionation, which in any case would be normalised out in the mass fractionation corrections of mass spectrometry. Therefore, fractional crystallisation drives a magma through isotope versus MgO space, or incompatible trace element ratio versus MgO space, along nearly horizontal vectors. This means that if fractional crystallisation was the sole process operating during differentiation, the primary (high MgO) diversity of basalts would be preserved across all MgO. In contrast, differentiation trends that converge at low MgO are indicative of mixing.

In investigating CMC I first use data from some of the most densely sampled ridge segments on Earth, Iceland's neovolcanic zones, to demonstrate that CMC is manifest in high sample number whole rock records that span a range of MgO. Using the observations from Iceland to build a conceptual model of crustal-scale magmatic mixing processes I then extend the study to three regional case studies, from the North East Pacific, the Central Mid-Atlantic, and South East Indian Ocean where along-ridge sample coverage is good. In each case CMC is found to be operating to reduce the geochemical variability present in the most evolved basalts. Lastly, I interrogate a global compilation of MORB major and trace element chemistry for similar signs of CMC. In order to overcome local differences in the diversity and composition of primary mantle melts I demonstrate how the geographic normalisation of data can be used to bridge the gap between observations made on a small scale – at single ocean islands and ridge segments – to the entire global dataset of MORB chemistry. By analysing the geochemical variability in MORB over a range of length scales I identify a transition at between 100 and 300 km at which the simple relationships between geochemical variability and indices of differentiation appear. This result demonstrates that on short length scales mantle chemical structure and magmatic processes operate coherently in the creation and destruction of geochemical variability.

2. Methods

2.1. *The dataset*

The global database of MORB compositions I statistically interrogate for evidence of CMC is that compiled by Gale et al. (2013), which has been carefully curated to mitigate the effects of inter-lab biases, duplicate analyses and off-axis samples. Removing duplicate analyses is particularly important when studying the length scales at which local geochemical patterns emerge from global systematics, because the presence of duplicates will artificially create chemical similarity between samples over short distances. The Gale et al. (2013) dataset has also been filtered for data quality based on canonical trace element ratios. Although this filtering, if too severe, could potentially remove some of the signal of mantle derived variability required to track magma mixing, subsequent analysis will show there is still abundant geochemical variability to track CMC. In this sense the results presented could be viewed as a conservative estimate of the significance of CMC in global MORB.