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MORB differentiation: *In situ* crystallization in replenished-tapped magma chambers

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Abstract

The differentiation of mid-ocean ridge basalt (MORB) is investigated with a focus on intermediate- to fast-spreading ridges and two recently proposed differentiation mechanisms: (i) differentiation in replenished-tapped-crystallizing (RTX) magma chambers, and (ii) chromatographic element separation during melt-rock reaction in the lower crust. There is compelling evidence in the petrology and geochemistry of MORB indicating that magma chambers at mid-ocean ridges behave as open systems, as required on thermal grounds in locations where a steady-state magma chamber exists. It has recently been suggested that the commonly observed over-enrichment of more-to-less incompatible elements during MORB differentiation can be explained by such an RTX model. However, the petrology of samples from the lower oceanic crust suggests an alternative mechanism could produce this over-enrichment. Clinopyroxene crystals in oceanic gabbros are commonly strongly zoned in incompatible elements with crystal rims apparently having grown from melts with very high incompatible element abundances. Elevated Zr/LREE in clinopyroxene rims, which has been interpreted as indicating growth from a melt in which these elements had been fractionated from one another by melt-rock reaction (chromatographic separation), is shown to be more simply explained by post-crystallization diffusive fractionation. However, the high incompatible element abundances in crystal rims demonstrates that the interstitial melt in crystal mush zones becomes highly differentiated. Disaggregation of such mush zones is indicated by the crystal cargo of MORB and must be accompanied by the return of interstitial melt to the eruptible reservoir – a form of *in situ* crystallization. Both a magma chamber undergoing closed system *in situ* crystallization, and a RTX magma chamber in which crystallization occurs *in situ*, are shown to be capable of reproducing the differentiation trends observed in MORB. Simple stochastic models of the latter process suggest that significant variations of incompatible element abundances and ratios, at a constant MgO content, are likely to be generated from a single parental melt compositions. Additionally, parental melt compositions will generally be substantially more depleted than would be suggested if only fractional crystallization is considered. This has important implications for understanding the composition of the upper mantle. For example, the Sm/Nd of MORB are likely to be significantly lower than that of the Moho-crossing melt complicating analysis of the Nd-isotopic evolution of the upper mantle.

1. INTRODUCTION

The compositions of mid-ocean ridge basalts (MORB) provide a window into the composition and temperature of the upper mantle. However, it has long been known that MORB compositions are more evolved (e.g., lower Mg# = Mg/(Mg + Fe) in molar units) than primary mantle

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melts and that they have compositions close to low-pressure cotectics. This demonstrates that erupted melt compositions are strongly influenced by low-pressure crystallization (e.g., O'Hara, 1968). However, low-pressure differentiation has generally been thought to play a minor role in changing the ratios of incompatible elements in MORB; this is largely because incompatible elements are difficult to fractionate from one another during perfect fractional crystallization. The favoured place to produce variations in incompatible element ratios has generally been in the mantle, either due to differences in melting (extent, process, etc) or mantle composition. This is despite several early studies noting that apparently co-genetic suites of MORB show evidence that partial crystallization can fractionate incompatible elements in ways not expected during perfect fractional crystallization (Bryan et al., 1976; White and Bryan, 1977; Perfit et al., 1983; Hekinian and Walker, 1987).

Recently, O'Neill and Jenner (2012) reopened the debate about whether incompatible element abundances and ratios in MORB provide a transparent window into the mantle or are significantly modified by differentiation processes. Using a global dataset of MORB major and trace element compositions (Jenner and O'Neill, 2012) they demonstrated that with decreasing MgO content there is more enrichment in incompatible element abundances than can be achieved by fractional crystallization. The extent of enrichment of incompatible elements correlates with the elements bulk partition coefficient meaning that more-to-less incompatible element ratios increase with differentiation. They propose that a series of steady-state replenished-tapped-crystallizing (RTX) magma chambers along the global ridge system can explain these observations. However, this model requires a specific relationship between the mass fractions of melt crystallized in, and tapped from, the steady-state magma chamber with both of these decreasing with decreasing melt MgO content (their Fig. 4b; see Section 3).

Plutonic rocks from the lower oceanic crust are the crystallization products of MORB differentiation and hence provide important insights into the processes involved in driving compositional variations in erupted basalts (e.g., Coogan, 2014). Relative to the upper crust, lower crustal rocks are strongly depleted in incompatible elements. Moreover, the extent of depletion correlates with both the elements bulk partition coefficient, and with the variability of the element in the overlying upper crust (Coogan et al., 2001). For example, La is roughly twice as enriched in the upper crust relative to the lower crust compare to Lu (Coogan, 2014). However, the concentration of incompatible elements in plutonic rocks is strongly influenced by any "trapped melt" (Barnes, 1986), complicating the use of whole-rock compositions of plutonic rocks in understanding MORB differentiation.

In part because of the problems associated with "trapped melt", the compositions of minerals in plutonic rocks have generally been thought to be more informative about differentiation processes than bulk-rock analyses. The basic premise is that spot analyses of minerals can be used to directly calculate parental melt compositions by dividing by an appropriate partition coefficient. Trace element analyses of clinopyroxene in oceanic gabbros show strong fraction of more-to-less incompatible elements both from core-to-rim within individual crystals and within regional and global datasets (Ross and Elthon, 1997; Coogan et al., 2000a; Gao et al., 2007; Drouin et al., 2009; Lissenberg et al., 2013). Incompatible element abundances can vary by an order of magnitude from core-to-rim within a clinopyroxene crystal despite major and compatible minor elements showing little variation. Most striking is the substantial fractionation of Zr from the LREE's that has been interpreted to indicate that within the crystal mush Zr behaves significantly more incompatibly than the LREE. Based on the assumption that the clinopyroxene compositions record growth from melts with equally variable trace element compositions, the observed fractionation of Zr from LREE's has been suggested to be generated by porous melt migration and melt-rock reaction (Coogan et al., 2000a; Gao et al., 2007; Lissenberg et al., 2013). Return of such differentiated interstitial melt to an eruptible reservoir could lead to substantial fractionation of incompatible element ratios in the mixed magma. This has been proposed as an alternative mechanism to explain the over-enrichment of incompatible elements in MORB (Lissenberg et al., 2013; Coogan, 2014). However, the use of mineral compositions to track melt differentiation relies on the largely untested assumption that elements are immobile after crystal growth (Coogan, 2014).

Here the differentiation of MORB is reconsidered. After recapping some key observational constraints on MORB differentiation (Section 2) the RTF model of O'Neill and Jenner (2012) is re-examined with a focus on intermediate-to fast-spreading ridges where steady-state magma chambers are common (Section 3). The use of the compositions of mineral in oceanic gabbros to determine their parental melt compositions is considered in Section 4 and it is demonstrated that post-crystallization diffusion modifies mineral compositions preventing simple determination of their parental melt compositions. Thus, models of melt-rock reaction in a crystal mush, based on mineral trace element compositions, need reconsidering. That said, there is unambiguous evidence that interstitial melts become highly enriched in incompatible elements and return of this melt to an eruptible reservoir (*in situ* crystallization) is hence examined (Section 5). *In situ* crystallization in a magma chamber undergoing replenishment and tapping is able to explain the global incompatible trace element over-enrichment observed in the MORB dataset of Jenner and O'Neill (2012) and the range of compositions in a broadly cogenetic suite of MORB and plutonic rocks from Hess Deep. We conclude that *in situ* crystallization in a magma chamber undergoing replenishment and tapping is consistent with the geochemistry and petrology of the oceanic crust, as well as thermal constraints. This has important implications for the interpretation of MORB in terms of mantle processes and composition (Section 6).

2. OBSERVATIONAL CONSTRAINTS ON MORB DIFFERENTIATION

Models for the differentiation of MORB, and crystallization of the plutonic section of the oceanic lithosphere,