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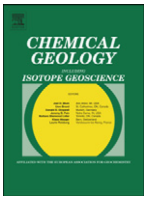

Trace elements in anatectic products at the roof of mid-ocean ridge magma chambers: An experimental study

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A B S T R A C T

At fast-spreading mid-ocean ridges (MORs), the horizon between the axial melt lens (AML) and the overlying sheeted dikes is characterized by extensive anatectic processes. The heat flux of the AML in combination with hydrothermal fluids from above causes high-grade contact metamorphism, which may result in anatexis of the roof rocks above the AML. The products of this process are silica-rich anatectic melts that have the potential to contaminate MOR basalts and residual hornfels. Here, we simulate the complex igneous and metamorphic processes occurring at the AML roof by hydrous partial melting experiments and provide corresponding trace element partition coefficients between melt and residues, which are useful to quantify those processes. We present trace element patterns from experimental anatectic felsic melts and the related residue produced by hydrous partial melting of various types of AML roof rocks. The starting materials used are sheeted dikes and hornfelses from Hole 1256D drilled by the Integrated Ocean Drilling Program. Results are compared with directly-related natural lithologies (i.e., felsic veins and granoblastic hornfels) from the same site. The trace element contents generally overlap with natural examples and experimental melts produced at low water activity ($aH_2O < 0.5$) can be highly enriched in trace elements despite relatively low SiO_2 contents (58.9 to 65.7 wt%). A low aH_2O is required to reproduce the low Al_2O_3 contents observed in natural silica-rich rocks. However, low aH_2O implies that the presence of residual amphibole is not required for anatectic processes Even though residual amphibole is often used as an important phase for explaining trace element characteristics in relevant felsic rocks formed at MORs when modeling anatexis. Because amphibole is lacking in any experimental residue, which is in agreement with natural hornfelses from the dike/gabbro transition at Site 1256, we assume that partial melting within the AML roof rocks proceeds without the participation of amphibole as residual phase. We present a comprehensive set of trace element compositions as well as bulk and mineral/melt trace element partition coefficients obtained from our amphibole-free experimental results for different potential protoliths over a large range of temperature and at different aH_2Os.

1. Introduction

The lower parts of magma chambers at fast-spreading MOR[1]s are composed of a large zone of crystal mush with <20% of melt, topped by a relatively small AML[2] at the transition between crystal mush and sheeted dikes, assumed to be filled locally with nearly pure basaltic melt, the source for MORB[3] (e.g., Dunn et al., 2000; Vera et al., 1990). Seismic, structural, and geochemical studies from fast-spreading ridges imply that the AML is a transient phenomenon that moves up and down and is likely related to the magmatic activity beneath the spreading segments (Coogan et al., 2003; France et al., 2009, 2010, 2013, 2014; Gillis, 2008; Koepke et al., 2008; Pedersen, 1986; Wilson et al., 2006; Zhang et al., 2014). Due to the heat flux of an upward-moving AML in combination with hydrothermal fluids released by dehydration of previously-altered sheeted dikes in the AML roof, complex processes, such as metamorphic overprint (producing hornfels) and hydrous anatexis (producing felsic rocks), occur at this horizon. Hornfels is concentrated at the sheeted dike root zone, forming a conducting boundary layer separating the AML, which is filled with a basaltic magma at ~1200 °C, from

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Abbreviations: aH_2O, water activity; AML, axial melt lens; AS1, analytical session 1; AS2, analytical session 2; BSE, backscattered electron; EPMA, electron probe microanalyzer; fO_2, oxygen fugacity; HFSE, high-field-strength elements; HPM, hydrous partial melting; HREE, heavy rare earth elements; ICP, inductively-coupled plasma; IHPV, internally-heated pressure vessel; IODP, International Ocean Discovery Program; LILE, large ion lithophile elements; mbsf, meters below sea floor; MOR, mid-ocean ridge; MORB, mid-ocean ridge basalt; MREE, medium rare earth elements; N-MORB, normal mid-ocean ridge basalt; REE, rare earth elements; SIMS, secondary ion mass spectrometer.

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[1] Mid-ocean ridge

[2] Axial melt lens

[3] Mid-ocean ridge basalt

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the seawater hydrothermal cells operating at temperatures of max. 400–500 °C (e.g., Gillis, 2008; Lister, 1974); felsic anatectic rocks crosscut the different lithologies of the dike/gabbro transition (e.g., France et al., 2009; Teagle et al., 2012; Wilson et al., 2006). Moreover, these anatectic melts have the potential to contaminate MOR melt (Coogan et al., 2003; Fischer et al., 2016; France et al., 2010, 2013, 2014), which is temporarily stored in the AML and then transported to the seafloor.

At Site 1256 of the IODP[4], located in the eastern Pacific Ocean in ~15-Ma-old crust, the complete upper crust down to the top of the gabbro sequence, interpreted as a frozen AML, was penetrated for the first time (Fig. 1; Wilson et al., 2006). The core drilled at this site, therefore, provides a perfect sample suite to study the interactions between hydrothermal and magmatic processes at AML margins. In the lower ~60 m of the sheeted dike root zone, above the uppermost gabbros, granoblastic hornfels dominate, representing former hydrothermally-altered sheeted dike basalts with a contact metamorphic overprint (France et al., 2009, 2010; Koepke et al., 2008; Wilson et al., 2006). The gabbros of the former AML are separated by two additional sequences of hornfels. Hornfels xenoliths within the gabbros indicate that assimilation in the melt lens of the overlying roof rocks is an important process (France et al., 2009; Koepke et al., 2011; Teagle et al., 2006). Gabbros and granoblastic hornfels of the core drilled at Site 1256 are intruded by cm-thick felsic rocks in the form of irregular patches, veins, and dikelets consisting of quartz-bearing gabbro, diorite, and tonalite with a fine- to medium-grained granular texture. These rocks bear granular plagioclase, quartz, magmatic amphibole (altered to secondary amphibole), Fe-Ti oxides, and clinopyroxenes (see Erdmann et al., 2015 for a detailed petrographic description). They are interpreted as frozen melts generated by hydrous partial melting of altered basalt from the sheeted dike root zone (Erdmann et al., 2015; Fischer et al., 2016; France et al., 2009, 2010, 2014; Koepke et al., 2008; Teagle et al., 2012; Wilson et al., 2006). Despite a very low recovery rate of felsic rocks during IODP expeditions 312 and 335, trace element characteristics of these leucocratic veins are characteristic and show pronounced negative anomalies of Ba, Rb, and Sr and positive anomalies of Zr and Hf relative to normal (N-)MORB (Fischer et al., 2016).

Numerous experimental studies have been published dealing with dehydration melting of amphibolites and greenstones (see summary in Johannes and Holtz, 1996). However, results of these studies are not directly applicable to anatectic processes occurring at the sheeted dike root zone because they mainly focus on processes in the deep continental crust with elevated pressures, often with garnet stable in the residuum. Other studies have included experiments at lower pressure (i.e., 100–200 MPa), but used fresh materials, either rather primitive cumulate gabbro as starting material (Koepke et al., 2004, 2014) or greenstones and amphibolites (Beard and Lofgren, 1991), different from the hydrated, altered basalts and dry hornfels of an AML roof. France et al. (2010, 2014) used, for the first time, a strongly hydrothermally-altered basalt from the lower sheeted dikes as starting material. However, the protolith was sampled in the Oman ophiolite whose geodynamic setting and, hence, significance for MOR processes is controversial because ophiolite composition is generally untypical for MORB (e.g., MacLeod et al., 2013).

In this experimental study we pursue two goals. The main objective of the present study is to experimentally simulate the complex igneous and metamorphic processes occurring at the roof of AMLs, and to provide trace element contents for geochemical modeling of those magmatic processes. MORB contamination at crustal levels has indeed been considered in several studies (e.g., Coogan et al., 2003; Fischer et al., 2016; France et al., 2010, 2013, 2014; Haase et al., 2005; le Roux et al., 2006; Van der Zwan et al., 2015). With new, appropriate trace elements as presented in this paper, models and interpretations of such studies could be significantly improved. In order to provide a comprehensive set of trace element data, we aim to reproduce the typical trace element patterns of natural leucocratic veins by testing different sheeted dike rocks drilled at IODP Site 1256 as possible protoliths for felsic melt generation. Thus, instead of using only one starting material, as has often been done in comparable experimental studies, we aim here to present the whole compositional band width of trace elements in felsic melts produced in such an environment. The lithologies used for partial melting experiments vary from poorly- to strongly-altered basalt, to partially- or fully-recrystallized hornfels (Fig. 1). With the results generated herein we are able to identify which dike material best fit with natural examples and, thus, which material should be considered as the protolith of the anatectic felsic rocks that are observed at AML margins. We used the same experiments performed by Erdmann et al. (2015), who investigated the major element characteristics of melts and residual minerals, but in this study we focus exclusively on trace elements analyzed by SIMS[5]. The second objective is to provide trace element bulk partition coefficients between experimental residue and the corresponding melt, as well as partition coefficients for clinopyroxene/melt and plagioclase/melt. These new data are well-suited for modeling the contamination of MORB by assimilation of anatectic melts, with special focus on the metamorphic and alteration state of the sheeted dike protolith.

Results of the present study complement two previously-published experimental studies dealing with the same natural protoliths: (1) The comprehensive study of Erdmann et al. (2015) aimed to determine the origin of felsic and granoblastic rocks from IODP Hole 1256D by comparing their modal and major element compositions to experimentally-produced anatectic melts and associated residues. The main approach of this study was to explore the effect of varying protolith modal composition, alteration grade, and recrystallization degree on the experimental products. As one of the main outcome, Erdmann et al. (2015) showed that experiments at low aH_2O are the only way to reproduce the low Al_2O_3 values observed in natural anatectic veins from the dike/gabbro transition at IODP Site 1256. However, relatively low SiO_2 values in the experimental melts cast doubt on the question of whether those anatectic melts can be highly enriched in REE and other trace elements as it is observed in natural samples. This study aims to show that an REE and trace element enrichment is possible at these conditions. (2) The study of Fischer et al. (2016) used major and trace element compositions of run products from experiments with one protolith from Erdmann et al. (2015; # D11) to quantify fresh MORB contamination induced by anatectic processes at the roof of AMLs.

2. Material and methods

2.1. Experimental setup

The natural protoliths were crushed and sieved to a grain size of 125–200 μm. For the experiments at 910 °C close to the solidus, we used, in addition to the powder, mm-sized fragments of the starting material ("microrocks") in order to obtain larger melt pools, even though equilibrium conditions are thus hampered for these experiments. All experiments were performed in Au capsules and most were water saturated (by adding deionized water). One experimental series was performed under reduced aH_2O[6] by adding CO_2 to the fluid phase. It is assumed that CO_2 does not play an important role as chemical component (e.g., Feig et al., 2006). All experiments were performed in an H_2-controlled IHPV[7] at the Institut für Mineralogie in Hannover at temperatures from 910 to 1030 °C and a pressure of 100 MPa. The fO_2[8] was set with a defined P_{H2} (depending on the experimental temperature,

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[4] International Ocean Discovery Program

[5] secondary ion mass spectrometer

[6] water activity

[7] internally-heated pressure vessel

[8] oxygen fugacity