



Transfer of volatiles and metals from mafic to felsic magmas in composite magma chambers: An experimental study

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Received 2 March 2016; accepted in revised form 16 November 2016; available online 20 November 2016

Abstract

In order to determine the behavior of metals and volatiles during intrusion of mafic magma into the base of silicic, upper crustal magma chambers, fluid–rock partition coefficients ($D_{\text{fluid/rock}}$) of Li, B, Na, S, Cl, K, Mn, Fe, Rb, Sr, Ba, Ce, Cu, Zn, Ag, Cd, Mo, As, Se, Sb, Te, W, Tl, Pb and Bi were determined experimentally at 2 kbar and 850 °C close to the solidus of mafic magma. In a first step, volatile-bearing mafic glasses were prepared by melting a natural basaltic trachyandesite in the presence of volatile-bearing fluids at 1200 °C/10 kbar in piston cylinder presses. The hydrous glasses were then equilibrated in subsequent experiments at 850 °C/2 kbar in cold-seal pressure vessels, which caused 80–90% of the melt to crystallize. After 0.5–2.0 days of equilibration, the exsolved fluid was trapped by means of in-situ fracturing in the form of synthetic fluid inclusions in quartz. Both the mafic rock residue and the fluid inclusions were subsequently analyzed by laser-ablation ICP-MS for major and trace elements. Reverse experiments were conducted by equilibrating metal-bearing aqueous solutions with rock powder and then trapping the fluid. In two additional experiments, information on relative element mobilities were obtained by reacting fluids that exsolved from crystallizing mafic magma with overlying silicic melts. The combined results suggest that under the studied conditions S, Cl, Cu, Se, Br, Cd and Te are most volatile ($D_{\text{fluid/rock}} > 10$), followed by Li, B, Zn, As, Ag, Sb, Cs, W, Tl, Pb and Bi ($D_{\text{fluid/rock}} = 1–10$). Less volatile are Na, Mg, K, Ca, Mn, Fe, Rb, Sr, Mo and Rb ($D_{\text{fluid/rock}} 0.1–1$), and the least fluid-mobile elements are Al, Si, Ti, Zr, Ba and Ce ($D_{\text{fluid/rock}} < 0.1$). This trend is broadly consistent with relative element volatilities determined on natural high-temperature fumarole gases, although some differences exist. Based on the volatility data and measured mineral–melt and sulfide–melt partition coefficients, volatile fluxing in felsic natural samples may be identified by Cu, Se, Te and Cd-enrichment in magmatic sulfides, and by As, Se, Cd and Bi-enrichment in magmatic apatite.

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Keywords: Volatile fluxing; Magma degassing; Metal volatility; Fluid inclusions; LA-ICP-MS

1. INTRODUCTION

Upper crustal magma chambers commonly show evidence for compositional stratification, with intermediate to felsic magma being present in the upper parts of the magma chamber, and mafic magmas intruding into its base (Fig. 1; e.g., Koyaguchi, 1986; Riehle et al., 1992; Matthews et al., 1999; Saito et al., 2003; Halama et al., 2006; Wiebe,

2016). Upon decompression and crystallization the mafic magmas release CO₂, SO₂ and other volatiles to the overlying intermediate to felsic magmas, which process is thought to be responsible for high fluxes of CO₂ and SO₂ from modern volcanoes (e.g., Andres et al., 1991; de Hoog et al., 2004; Roberge et al., 2009; Christopher et al., 2010; Wallace and Edmonds, 2011), the formation of magmatic anhydrite (e.g., Hattori, 1993; Luhr, 2008; Parat et al., 2011), and the triggering of volcanic eruptions (e.g., Pallister et al., 1992, 1996; Richer et al., 2004; Kaneko et al., 2007). Mafic magmas are also thought to deliver most of the sulfur and metals present in giant porphyry Cu

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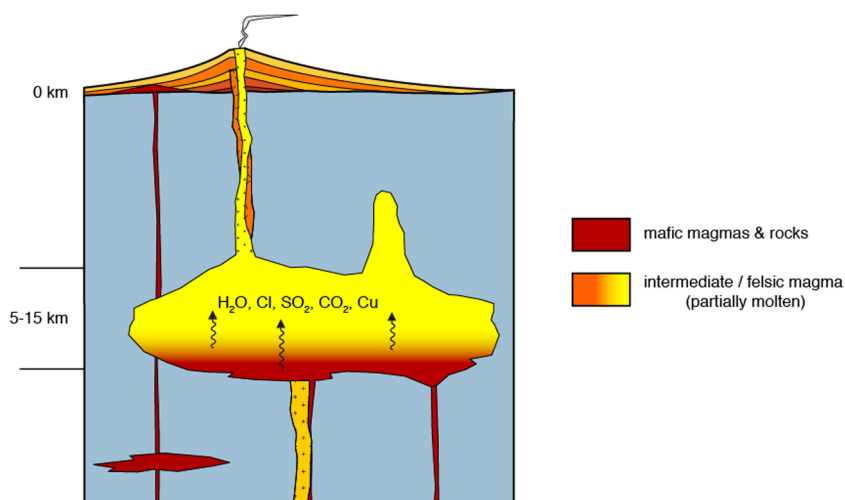


Fig. 1. Schematic view of a compositionally stratified magma chamber underneath a stratovolcano. Volatiles and metals such as Cu are transported by a fluid phase from mafic magmas to overlying intermediate and felsic magmas (modified from Audétat and Simon, 2013).

(\pm Mo, Au) deposits associated with dominantly intermediate to felsic magmas (Keith et al., 1997; Hattori and Keith, 2001; Halter et al., 2005; Audétat and Pettke, 2006; Stern et al., 2007).

The aim of this project is to evaluate the major and trace element composition of the fluids that exsolve from mafic alkaline magmas as they quench against – but do not extensively mix with – a larger body of felsic magma. A typical scenario would be the intrusion of 0.2 km^3 mafic magma with a temperature of $1000\text{--}1100 \text{ }^\circ\text{C}$ into the base of a 1.0 km^3 crystal-rich dacite magma with a temperature of $750\text{--}800 \text{ }^\circ\text{C}$. After thermal equilibration the temperature of both magmas is around $850 \text{ }^\circ\text{C}$, which means that the mafic magma becomes almost fully crystallized, whereas the dacitic magma mush is partially remelted. Most of the volatiles that are originally dissolved in the mafic magma thus exsolve into a free fluid phase that tends to rise and interact with overlying, more felsic magmas. A perfect analogue of this situation has been documented by Eichelberger (1980) for a mafic enclave within a rhyodacitic lava flow of the Medicine Lake Highland Volcano, California: whereas the mafic enclave is highly crystalline and full of vesicles, the surrounding rhyodacitic lava is entirely glassy and bubble-free, suggesting a snapshot at around $850 \text{ }^\circ\text{C}$.

2. EXPERIMENTAL METHODS

2.1. Experimental strategy

Two different kinds of experiments were conducted in this study (Table 1): (1) runs in which fluids in equilibrium with an almost fully crystallized mafic magma were trapped as synthetic fluid inclusions in quartz and subsequently analyzed by LA-ICP-MS, and (2) runs in which the same fluids were allowed to react with an overlying reservoir of hydrous felsic melt, resulting in enrichment of trace elements in the felsic melt. The first approach has the advantage that the fluid can be trapped and its composition be

directly quantified, whereas the second approach has the advantage that it provides higher sensitivity and thus allows data also for relatively fluid-immobile elements such as Al, Ti and Zr to be collected (see below). An important requirement for both types of experiments is that equilibrium is reached between fluid and mafic residue before the fluid is trapped in the form of synthetic fluid inclusions or reacts with felsic melt. To test whether this requirement was met we performed the first type of experiments in both forward or reverse manner (Fig. 2): In the forward experiments volatile-bearing mafic glasses were synthesized at high pressure and temperature in piston cylinder presses, and subsequently crystallized in a separate experiment at lower pressure and temperature in cold-seal pressure vessels. In the reverse experiments aqueous fluid was equilibrated directly with the crystalline starting material at lower pressure and temperature without an intermittent step of melting. In both cases the formation of fluid inclusions was initiated after 0.5–2.0 days run time by in-situ fracturing of the quartz piece. Experiments in which fluids were allowed to react with an overlying reservoir of felsic melt were performed in forward manner, i.e., using hydrous mafic glass as starting material.

2.2. Starting materials

A natural basaltic trachyandesite from Two Buttes, southeastern Colorado (Davis and Smith, 1993; Davis et al., 1996) was used as mafic starting material in all experiments. This rock consists of phenocrysts of clinopyroxene ($\sim 40 \text{ vol}\%$), phlogopite ($\sim 10 \text{ vol}\%$), olivine ($\sim 2 \text{ vol}\%$) and magnetite ($\sim 1 \text{ vol}\%$) set in a finely crystalline groundmass consisting of $\sim 30 \text{ vol}\%$ glass, $\sim 25 \text{ vol}\%$ plagioclase, $\sim 20 \text{ vol}\%$ phlogopite, $\sim 15 \text{ vol}\%$ magnetite and $\sim 10\%$ pyroxene. For reverse runs we directly used finely crushed powder of this rock ($\leq 10 \mu\text{m}$ grain size), whereas for forward runs we prepared volatile-bearing mafic glasses by melting the rock powder in the presence of S-Cl-bearing aqueous fluid spiked with various trace elements (see below)

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