



Modulation of magmatic processes by CO₂ flushing

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ABSTRACT

Magmatic systems are the engines driving volcanic eruptions and the source of fluids responsible for the formation of porphyry-type ore deposits. Sudden variations of pressure, temperature and volume in magmatic systems can produce unrest, which may culminate in a volcanic eruption and/or the abrupt release of ore-forming fluids. Such variations of the conditions within magmatic systems are commonly ascribed to the injection of new magma from depth. However, as magmas fractionating at depth or rising to the upper crust release CO₂-rich fluids, the interaction between carbonic fluids and H₂O-rich magmas stored in the upper crust (CO₂ flushing), must also be a common process affecting the evolution of subvolcanic magma reservoirs. Here, we investigate the effect of gas injection on the stability and chemical evolution of magmatic systems.

We calculate the chemical and physical evolution of magmas subjected to CO₂-flushing using rhyolite-MELTS. We compare the calculations with a set of melt inclusion data for Mt. St. Helens, Merapi, Etna, and Stromboli volcanoes. We provide an approach that can be used to distinguish between melt inclusions trapped during CO₂ flushing, magma ascent and decompression, or those affected by post-entrapment H₂O-loss. Our results show that CO₂ flushing is a widespread process in both felsic and mafic magmatic systems. Depending upon initial magma crystallinity and duration of CO₂ input, flushing can either lead to volcanic eruption or fluid release. We suggest that CO₂ flushing is a fundamental process modulating the behaviour and chemical evolution of crustal magmatic systems.

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1. Introduction

Magmatic fluids are mainly composed of H₂O and CO₂, the latter being significantly less soluble in silicate melts (Ghiorso and Gualda, 2015; Newman and Lowenstern, 2002). Crystallisation of silicate magma at depth and/or its ascent through the crust leads to preferential release of CO₂-rich fluids (Blundy et al., 2010; Newman and Lowenstern, 2002; Papale et al., 2006), such that magmas stored in the upper crust contain 40–60 times more H₂O than CO₂ (GEOROC database; Fig. 1a; Barsanti et al., 2009). Thus, magmas stored at shallow depths are, in effect, high temperature chemical reactors exposed to flushing of hot CO₂-rich fluids released from deeper in the magmatic system (Barsanti et al., 2009; Blundy et al., 2010; Evans et al., 2016; Metrich et al., 2004; Moretti et al., 2013; Yoshimura and Nakamura, 2011, 2010). Similar interactions between CO₂-rich fluids and magmas can also occur in carbonate-hosted magmatic systems (Blythe et al., 2015;

Cross et al., 2013; Di Rocco et al., 2012; Iacono Marziano et al., 2007; Jolis et al., 2013; Mason et al., 2017; Preece et al., 2014).

An increase in the partial pressure of CO₂ in the fluid phase in equilibrium with a magma, produced either by CO₂ flushing or by interaction with carbonate, leads to the dissolution of modest amounts of CO₂ in the melt and exsolution of several wt.% of H₂O (Ghiorso and Gualda, 2015; Newman and Lowenstern, 2002; Yoshimura and Nakamura, 2011; Fig. 1a, b). The effects are a net increase of magma volume (i.e. excess fluid volume fraction), progressive magma crystallisation due to reduced weight fraction of dissolved H₂O (Fig. 1a, b; Blundy and Cashman, 2008; Blundy et al., 2010; Riker et al., 2015), and changes in crystallising assemblage and mineral chemistry (Riker et al., 2015).

Previous studies have applied Rhyolite-MELTS (Gualda et al., 2012) to quantify the effect of crystallisation and excess volatile exsolution on the evolution of the physical properties of magma and fluid overpressure (Tramontano et al., 2017; Fowler and Spera, 2008). Here, we use Rhyolite-MELTS to simulate interaction between CO₂-rich fluids and magmas stored in the upper crust and quantify the impact of this process on the chemical and physical evolution of the system. We also simulate simple, adia-

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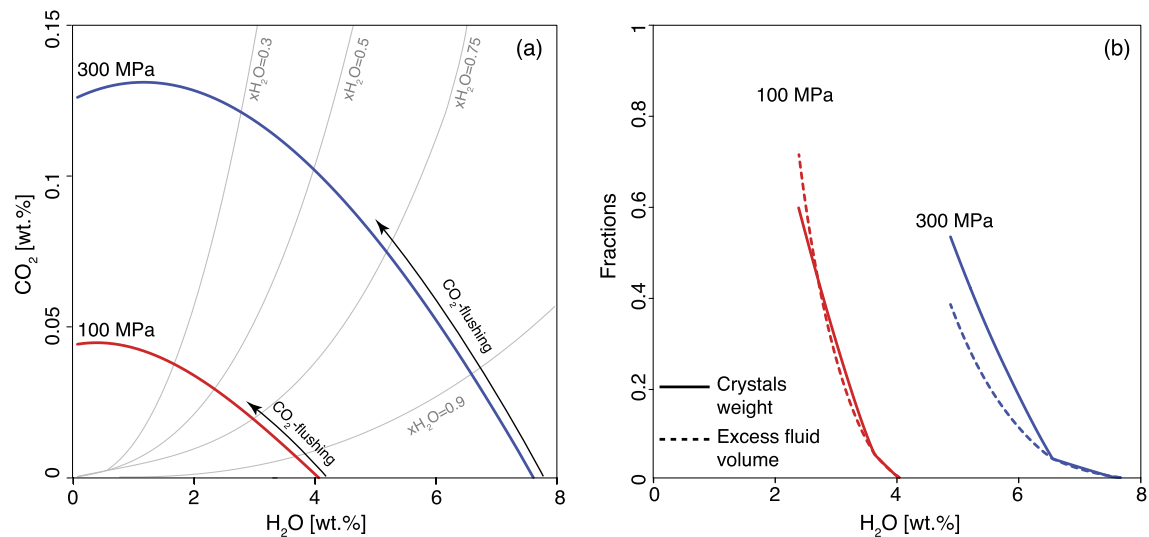


Fig. 1. Variation of dissolved H₂O and CO₂, crystal and fluid fraction as functions of H₂O dissolved in magma. Blue lines refer to calculations performed at 300 MPa, red at 100 MPa. (a) Coloured lines are H₂O and CO₂ solubility isobars for magma saturated in H₂O–CO₂ fluids with different molar fraction of H₂O ($x_{\text{H}_2\text{O}}$); grey lines are isopleths, indicating the H₂O and CO₂ dissolved in magma in equilibrium with fluids of fixed $x_{\text{H}_2\text{O}}$. (b) The continuous and dashed lines show, respectively, the evolution of the crystal (weight) and fluid (volume) fraction during CO₂ flushing as functions of dissolved H₂O. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

Table 1

Initial compositions used for the rhyolite-MELTS simulations.

	CO ₂ -flushing		Ascent (from 500 MPa)		Fluid excess ascent (from 500 MPa)
	Etna (1)	Bishop Tuff (2)	Etna (3)	Bishop Tuff (4)	Etna (5)
SiO ₂	44.19	77.93	44.01	73.23	43.76
TiO ₂	1.74	0.08	1.73	0.08	1.71
Al ₂ O ₃	15.85	12.15	15.79	11.82	16.59
Fe ₂ O ₃	2.49	0.21	2.21	0.15	2.22
FeO	8.96	0.49	9.16	0.48	9.30
MnO	0.21	0.00	0.21	0.00	0.20
MgO	6.90	0.03	6.88	0.03	5.99
CaO	10.96	0.40	10.92	0.41	10.13
Na ₂ O	3.15	3.77	3.14	3.76	3.36
K ₂ O	1.98	4.93	1.98	4.61	2.11
P ₂ O ₅	0.58	0.00	0.57	0.00	0.59
H ₂ O	3.00	H ₂ O-saturated	2.92	5.23	3.04 ^a
CO ₂	0.00	0.00	0.48	0.20	1 ^a
Total	100.00	100.00	100.00	100.00	95.96

The numbers next to 'Etna' and 'Bishop Tuff' are used to refer to these compositions in supplementary Table 2. The H₂O and CO₂ values reported in the table refer to the dissolved amount at the beginning of the simulation.

^a Indicates that an excess volatile phase was present at the beginning of the simulation and the reported H₂O and CO₂ values refer to the total amount of volatile phases present at the beginning of the simulations.

batic decompression of volatile-bearing magmas to compare the effects of these two contrasted processes on the chemical evolution of the residual melt (i.e. melt in equilibrium with fluid phase and crystals). The results of our calculations allow us to explore melt inclusion data collected in systems for which extensive datasets exist (Mt. St. Helens, Merapi, Etna and Stromboli; GEOROC and Blundy et al., 2010; Metrich et al., 2010; Preece et al., 2014). We propose a new approach that can be applied to melt inclusion datasets to distinguish between magma-ascent, interaction with CO₂-rich fluids or post-entrapment H₂O loss. The application of this method to felsic and mafic magmatic systems (GEOROC and Blundy et al., 2010; Metrich et al., 2010; Preece et al., 2014) show that melt inclusion data invariably record interaction between magma and CO₂-rich fluids. Consequently, we focus on the impact of CO₂ flushing on the evolution of the chemical and physical properties of upper crustal magma reservoirs, and discuss the influence of CO₂ flushing on the ability of a magma reservoir to erupt magma and/or release magmatic volatiles.

2. Methods

2.1. Rhyolite-MELTS

We performed calculations using the thermodynamic software Rhyolite-MELTS (version 1.1.0; Ghiorso and Gualda, 2015; Gualda et al., 2012) to simulate the effects of CO₂ flushing and adiabatic ascent on the chemical and physical evolution of volatile-bearing magma. The chemical interaction between pure, hot CO₂ and magma is performed considering no subsequent heat loss from the system. CO₂ is injected at the liquidus temperature of the magma. In the calculations we consider either an initially H₂O-saturated (CO₂-free) rhyolitic magma (composition equivalent to the average melt inclusion composition of the early phase of the Bishop Tuff eruption: Gualda et al., 2012; Ghiorso and Gualda, 2015) or a H₂O-bearing basalt (Etna; melt inclusion composition MI 33 of Metrich et al., 2004; 3 wt.% H₂O; Tables 1, 2) at their respective liquidus temperatures. Rhyolite-MELTS was chosen as it performs all thermodynamic calculations with the latest available solubility data for magmas of a wide variety of compositions

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