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Megacrystals track magma convection between reservoir and surface

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ABSTRACT

Active volcanoes are typically fed by magmatic reservoirs situated within the upper crust. The development of thermal and/or compositional gradients in such magma chambers may lead to vigorous convection as inferred from theoretical models and evidence for magma mixing recorded in volcanic rocks. Bi-directional flow is also inferred to prevail in the conduits of numerous persistently-active volcanoes based on observed gas and thermal emissions at the surface, as well as experiments with analogue models. However, more direct evidence for such exchange flows has hitherto been lacking. Here, we analyse the remarkable oscillatory zoning of anorthoclase feldspar megacrystals erupted from the lava lake of Erebus volcano, Antarctica. A comprehensive approach, combining phase equilibria, solubility experiments and melt inclusion and textural analyses shows that the chemical profiles are best explained as a result of multiple episodes of magma transport between a deeper reservoir and the lava lake at the surface. Individual crystals have repeatedly travelled up-and-down the plumbing system, over distances of up to several kilometers, presumably as a consequence of entrainment in the bulk magma flow. Our findings thus corroborate the model of bi-directional flow in magmatic conduits. They also imply contrasting flow regimes in reservoir and conduit, with vigorous convection in the former (regular convective cycles of ~150 days at a speed of ~0.5 mm s^{-1}) and more complex cycles of exchange flow and re-entrainment in the latter. We estimate that typical, 1-cm-wide crystals should be at least 14 years old, and can record several (from 1 to 3) complete cycles between the reservoir and the lava lake via the conduit. This persistent recycling of phonolitic magma is likely sustained by CO_2 fluxing, suggesting that accumulation of mafic magma in the lower crust is volumetrically more significant than that of evolved magma within the edifice.

1. Introduction

Many volcanoes, such as Etna and Stromboli in Italy, persistently emit prodigious quantities of gas and heat at the surface without significant accompanying lava flows or tephra production (Francis et al., 1993). The decoupling of gas and thermal energy from the magma efflux has been investigated in several theoretical and experimental treatments that consider exchange flow between two fluids of contrasting density and viscosity (Kazahaya et al., 1994; Stevenson and Blake, 1998; Huppert and Hallworth, 2007; Beckett et al., 2011). These studies suggest that a stable bi-directional flow can develop in volcanic conduits, and reinforce interpretations of the magma dynamics of a number of persistently degassing volcanoes (e.g., Oppenheimer et al., 2009; Shinohara and Tanaka, 2012). Conduit convection suggests substantial endogenous growth of volcanoes (Francis et al., 1993; Allard, 1997) and may explain melt inclusion trends associated with degassing volcanoes (Witham, 2011). While the conclusion that magma convects in conduits feeding many open vent volcanoes seems inescapable, direct evidence has been lacking.

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The potential of zoned crystals to record chemical and physical changes experienced by their host magma has long been recognised (see review by Ginibre et al., 2007). Oscillatory zoning in feldspar is a common phenomenon with several inferred origins. Two main schools of thought have prevailed, originating from studies in the 1920s, and broadly evoke either extrinsic (Bowen, 1928) or intrinsic (Harloff, 1927) mechanisms. The extrinsic school argues that zonation reflects changing pressure, temperature, composition and volatile content of the melt surrounding the crystal via processes such as convection (e.g., Singer et al., 1995) and episodic fluctuations in magma supply. The intrinsic school points to the widely-observed lack of correlation of oscillatory layers between crystals (e.g., Wiebe, 1968; Shore and Fowler, 1996) and argues instead that kinetic processes at the crystal-melt interface are responsible for zonation (e.g., Allegre et al., 1981; L'Heureux and Fowler, 1996). The kinetic models imply high degrees of undercooling at the boundary layer and reproduce the typical sawtooth patterns revealed in electron microprobe (EMP) traverses of oscillatory-zoned feldspar crystals. However, these intrinsic models cannot reproduce low amplitude variations. Nor do they explain multiple resorption episodes, evident in many oscillatory-zoned crystals. Recent studies have highlighted how both mechanisms for generating oscillatory zoning can be manifested in single crystals (e.g. Viccaro et al., 2010), and have used mineral compositional zoning to identify a variety of magmatic processes such as magma recharge, mixing and degassing (e.g., Humphreys et al., 2006; Charlier et al., 2008; Kahl et al., 2013).

Erebus volcano (Antarctica) is renowned for its long-lived phonolitic lava lake, whose behaviour has been explained in terms of the conduit exchange-flow model (Oppenheimer et al., 2009). It is also remarkable for the impressive size to which its most abundant mineral phase, anorthoclase feldspar, grows (Kyle, 1977; Dunbar et al., 1994). These anorthoclase megacrystals (up to 10-cm-long) display exceptional oscillatory zoning and large (up to 600-μm-diameter) melt inclusions (Fig. 1). In this study, we analyse the major element composition of natural anorthoclase crystals and major element and volatile compositions of enclosed melt inclusions, and compare them to anorthoclase crystals and associated melts derived by phase equilibrium and solubility experiments. The experimental data provide a tightly-constrained framework with which to interpret the natural zoning and to retrace the growth history of individual anorthoclase megacrystals.

We start with a brief overview of the Erebus phonolite phase assemblage, including a description of the natural anorthoclase megacrystals, and then describe the different experimental and analytical methods used in this study. We present the results of phase equilibrium experiments, and compare the chemistry of synthetic and natural anorthoclase. We then describe solubility experiments and their relation to analyses of melt inclusions and their host zone within natural crystals. Lastly, we link the chemical zoning in natural anorthoclase to the timescales of magma ascent and descent.

2. Background information

2.1. Mineral assemblage

Erebus volcano (3794 m, 77.58°S, 161.17°E), hosts the world's only phonolitic lava lake. This lava lake appears to have been persistently degassing since the volcano was first observed by James Ross in 1841. This current passive activity is sporadically interrupted by Strombolian explosions that eject fresh bombs on to the crater rim. All bombs analysed since 1972 are virtually identical in terms of mineral assemblage (with one exception) and whole rock and matrix glass major, minor and trace elements (Kelly et al., 2008). This chemical stability extends to older lava flows, such that all lavas erupted from Erebus in the last 20 ka have the same composition (Kelly et al., 2008) making the volcano an ideal system to investigate using experimental petrology tools at equilibrium conditions.

Phonolite bombs are composed chiefly of vesicular matrix glass (∼67 vol%; fragile, easily disintegrated and microlite-free) and anorthoclase feldspar (∼30 vol%) with minor amounts of titanomagnetite (∼1.1 vol%), olivine (∼0.8 vol%), clinopyroxene (∼0.6 vol%) and fluorapatite (∼0.5 vol%), and lesser quantities of pyrrhotite blebs (Kyle et al., 1992; Kelly et al., 2008). Of all mineral phases (described in detailed by Kelly et al., 2008) anorthoclase is the only mineral with compositional zoning.

2.2. Anorthoclase megacrystals

Euhedral anorthoclase feldspar in phonolite bombs are zoned with respect to major (Fig. 1) and trace (Sumner, 2007) elements. The compositional zoning occurs at a variety of scales: the lowest frequency variations shown by some crystals (Fig. 2) have wavelengths of ∼5 mm and amplitude of ∼7 mol% (Or) while higher-frequency variations have a typical wavelength of $\lesssim$800 μm and amplitude of $\lesssim$4 $mol\%_{Or}$. Inter-zone variations are in the range of $Ab_{61–66}$, $An_{21–10}$, and $Or_{14–28}$ (with Ab, An and Or referring to the albite, anorthite and orthoclase end members respectively; Fig. 2). Small-scale elemental maps (Fig. 1) reveal embayment at some zone boundaries, indicating resorption episodes. Hosted in the anorthoclase crystals are large (usually <600 μm across) phonolitic melt inclusions, typically trapped in single growth layers of the anorthoclase (Fig. 1). Natural anorthoclase megacrystals presented in this study were manually separated from phonolitic bombs erupted in 1984 and 2005 (Fig. S1; Table S1).

3. Methods

3.1. Phase equilibria and solubility experiments

The starting material (ERE 97018) used in all experiments is a phonolitic bomb erupted in 1997 and collected at the crater rim (described in Moussallam et al., 2013). All phase equilibria experiments are described in Moussallam et al. (2013) and the present study uses a subset of those experiments whose conditions closely reproduced the natural mineral assemblage.

Water- and CO_2-solubility experiments were conducted across a range of pressures (50, 100, 200, and 300 MPa), temperatures (950 and 1000 °C), and X_{H_2O} (mole fraction of water in the fluid phase, from near 0 to 1) under reduced conditions ($fO_2 \approx$ QFM or below; with QFM being the quartz–fayalite–magnetite redox buffer). We used internally-heated pressure vessels at the ISTO laboratory in Orléans, which can reach pressures of up to 400 MPa under controlled temperatures (up to 1200 °C) and oxygen fugacity conditions. The vessel was pressurised using an argon–hydrogen gas mixture as the pressure medium to control redox state (Scaillet et al., 1992). Heating was applied by a double-wound molybdenum furnace creating a stable "hot-spot" zone. Two S-type thermocouples located on either side of this 5-cm-long "hot-spot" permitted precise control of the heating resistances thus preventing the establishment of thermal gradients.

Experimental charges consisted of natural anhydrous sample powder (30 mg) with $X_{H_2O,loaded}$ [= mole fraction of H_2O added to the capsule, $H_2O/(H_2O+CO_2)$] varying from 0 to 1 (i.e. pure CO_2 to pure H_2O) and loaded in gold capsules (2 cm in length, with 2.5 mm inner diameter and 2.9 mm outer diameter). The capsules were wrapped in liquid nitrogen-soaked tissue to prevent water loss and welded shut. For each experiment, six capsules were placed in a sample holder hung by a thin Pt wire. The temperature gradient along the "hot-spot" zone where the capsules were located was always <2 °C. Rapid quenching was assured by