Lithos 252–253 (2016) 216–233

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited review article

Extensive, water-rich magma reservoir beneath southern Montserrat

M. Edmonds [a,*], S.C. Kohn [b], E.H. Hauri [c], M.C.S. Humphreys [d], M. Cassidy [e]

[a] *Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK*
[b] *Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol, BS8 1RJ, UK*
[c] *Carnegie Institute of Washington, 5241 Broad Branch Rd, NW, Washington, DC 20015, USA*
[d] *Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK*
[e] *Institute for Geosciences, Johannes Gutenberg University of Mainz, Mainz 55128, Germany*

ARTICLE INFO

Article history:
Received 24 November 2015
Accepted 27 February 2016
Available online 7 March 2016

Keywords:
Pyroxenes
Water
Mush
Andesite
Melt inclusions
SIMS

ABSTRACT

South Soufrière Hills and Soufrière Hills volcanoes are 2 km apart at the southern end of the island of Montserrat, West Indies. Their magmas are distinct geochemically, despite these volcanoes having been active contemporaneously at 131–129 ka. We use the water content of pyroxenes and melt inclusion data to reconstruct the bulk water contents of magmas and their depth of storage prior to eruption. Pyroxenes contain up to 281 ppm H_2O, with significant variability between crystals and from core to rim in individual crystals. The Al content of the enstatites from Soufrière Hills Volcano (SHV) is used to constrain melt-pyroxene partitioning for H_2O. The SHV enstatite cores record melt water contents of 6–9 wt%. Pyroxene and melt inclusion water concentration pairs from South Soufriere Hills basalts independently constrain pyroxene-melt partitioning of water and produces a comparable range in melt water concentrations. Melt inclusions recorded in plagioclase and in pyroxene contain up to 6.3 wt% H_2O. When combined with realistic melt CO_2 contents, the depth of magma storage for both volcanoes ranges from 5 to 16 km. The data are consistent with a vertically protracted crystal mush in the upper crust beneath the southern part of Montserrat which contains heterogeneous bodies of eruptible magma. The high water contents of the magmas suggest that they contain a high proportion of exsolved fluids, which has implications for the rheology of the mush and timescales for mush reorganisation prior to eruption. A depletion in water in the outer 50–100 μm of a subset of pyroxenes from pumices from a Vulcanian explosion at Soufrière Hills in 2003 is consistent with diffusive loss of hydrogen during magma ascent over 5–13 h. These timescales are similar to the mean time periods between explosions in 1997 and in 2003, raising the possibility that the driving force for this repetitive explosive behaviour lies not in the shallow system, but in the deeper parts of a vertically protracted crustal magma storage system.

1. Introduction

Quantifying the water budget of arc magmas is critical for the investigation of a large range of research problems associated with subduction zones, including understanding the subduction cycling of volatiles (Rüpke et al., 2004), arc magma petrogenesis (Baker et al., 1994; Gaetani et al., 1993; Grove and Kinzler, 1986), assimilation of crustal melts (Annen et al., 2006; Petford and Gallagher, 2001), magma oxidation state (Evans et al., 2012; Stamper et al., 2014), melt buoyancy (Spera, 1984), melt rheological properties (Cashman and Blundy, 2000), the role of aqueous fluids in transporting metals (Williams-Jones and Heinrich, 2005) and ultimately, the style of magma eruption at the surface (Castro and Dingwell, 2009; Roggensack et al., 1997). In arcs, ascending, water-rich primitive magmas may stall where their buoyancy prohibits further ascent (Plank et al., 2013) or where they underplate larger volumes of evolved crystal-rich magmas (Bachmann and Bergantz, 2006; Couch et al., 2001), part of large trans-crustal mush zones (Bergantz et al., 2015; Cashman and Blundy, 2013; Christopher et al., 2015; Ruprecht et al., 2012) that may be held at sub-solidus temperatures for long timescales (10^4–10^5 years) (Cooper and Kent, 2014) before being remobilised by magma recharge (Bachmann and Bergantz, 2006; Bergantz et al., 2015; Burgisser and Bergantz, 2011).

The emerging view is that these crystal-rich, intermediate magma reservoirs are vertically protracted (extending down to the mid-crust), consisting of melt-rich lenses, crystal-rich mush (Cashman and Blundy, 2013; Cashman and Sparks, 2013; Cooper and Kent, 2014; Humphreys et al., 2006) and perhaps, in the shallow crust, fluid-rich regions (Christopher et al., 2015). Mingled, intermediate magmas may be assembled by processes that might involve destabilisation, overturn and mixing of such "layers" on short timescales (years) prior to eruptions (Bergantz et al., 2015; Burgisser and Bergantz, 2011), perhaps aided by partial melting at vapour-saturated conditions (Huber et al., 2011). However, the physical location of such regions of magma storage, from which magmas are extracted prior to eruption and the timescales

---

* Corresponding author.
E-mail address: me201@cam.ac.uk (M. Edmonds).

http://dx.doi.org/10.1016/j.lithos.2016.02.026
0024-4937/

on which this occurs, are not fully understood. Where vapour saturation occurs in these protracted magma reservoirs is critical for understanding mush reactivation and magma mixing, as the presence or generation of an exsolved fluid phase increases overpressure and generates mechanical energy. The presence or generation of an exsolved gas phase also allows physical processes such as gas-driven filter pressing to take place (Pistone et al., 2015; Sisson and Bacon, 1999), which might be important for the generation of crystal-poor regions of the melt in the mush. It is therefore imperative that we understand where vapour saturation occurs in these vertically protracted reservoirs. There are also geochemical implications of an exsolved water-rich fluid: once an exsolved gas phase is present, partitioning of other volatile elements may take place, such as sulphur and chlorine (Scaillet et al., 1998; Wallace and Edmonds, 2011) as well as metals that have an affinity for a hydrous vapour phase (Zajacz and Halter, 2009).

Unravelling the petrological record in erupted volcanic rocks to understand melt volatile contents and the architecture of pre-eruptive magma reservoirs is challenging. Traditionally melt inclusions have been the mainstay of such studies (Blundy and Cashman, 2008; Cervantes and Wallace, 2003; Walker et al., 2003), in combination with geobarometers such as those based on clinopyroxene-melt equilibria (Putirka et al., 1996), aluminium in hornblende (Ridolfi et al., 2010) and plagioclase-liquid hygrometers (Lange et al., 2009). Melt inclusions record "snapshots" of melt trapped at intervals through melt differentiation (Kent and Elliott, 2002; Lowenstern, 1995; Métrich and Wallace, 2008). Very often however, the pressures obtained from CO_2–H_2O in melt inclusions are considerably lower than those obtained using crystal-melt equilibria (Neave et al., 2013) and this is ascribed to trapping during magma ascent (Blundy and Cashman, 2005) melt inclusion leakage or CO_2 loss into a shrinkage bubble (Esposito et al., 2014; Hartley et al., 2014; Moore et al., 2015; Sides et al., 2014; Steele-Macinnis et al., 2011; Wallace et al., 2015). The melt inclusion record may even be inherently biased as melts are preferentially trapped along rough crystal surfaces, which form during rapid crystal growth (Faure and Schiano, 2005) or, in the case of plagioclase, during periods of heating, dissolution and reprecipitation (Nakamura and Shimakita, 1998). The inclusions may also be sealed off progressively during periods of magma ascent and degassing at low crustal pressures, resulting in a record indicating variable entrapment pressures (Blundy and Cashman, 2005; Humphreys et al., 2008). Finally, melt inclusions are sometimes not faithful recorders of original trapped compositions: it has been shown that hydrogen diffuses out of olivine-hosted melt inclusions extremely rapidly at low pressures (where a concentration gradient is established due to the degassing of the carrier liquid) and high temperatures (Gaetani et al., 2012) and similar high rates of diffusion are likely through the other crystal phases (e.g. Johnson and Rossman, 2013).

Nominally anhydrous minerals such as pyroxene may hold trace amounts of water in their structure, up to a few hundred ppm (Bell and Rossman, 1992; Grant et al., 2007a; Hauri et al., 2006; Kohn and Grant, 2006) and this may be a promising complementary tool to use alongside melt inclusion analysis of water. Erupted crustal magmatic pyroxenes ought to preserve a record of pre-eruptive melt water contents if such a record is not erased or homogenised by diffusive processes. This record may be deciphered if the partitioning behaviour of water between melt and pyroxene is understood. Previous work has used the hydrogen content of clinopyroxenes and the water content of coexisting melt inclusions in basalts to show that pyroxenes have potential to record both isobaric crystallisation and decompression degassing in their zoning profiles, which are not modified by diffusive processes on typical timescales of eruption (O'Leary et al., 2010; Wade et al., 2008; Weis et al., 2015). In this study we extract a record of hydrogen and major element concentrations in volcanic orthopyroxenes in andesite erupted during a Vulcanian explosion from Soufrière Hills Volcano, Montserrat; and in clinopyroxenes erupted in hybrid basalts from the neighbouring volcano, South Soufrière Hills (Cassidy et al., 2015a). This crystal record is used to infer melt water contents using our established understanding of hydrogen partitioning between melt and orthopyroxene (Aubaud et al., 2004; Dobson et al., 1995; Grant et al., 2006, 2007b; Hauri et al., 2006; Koga et al., 2003; Rosenthal et al., 2015; Tenner et al., 2009), as well as observations of water partitioning between clinopyroxene and melt inclusions (O'Leary et al., 2010; Wade et al., 2008). The estimated melt water contents derived from the pyroxene records are used to infer magma storage pressures, assuming that the melts are vapour-saturated and taking into account the lowered activity of water in the melts due to the presence of dissolved CO_2. The saturation pressures derived from the pyroxenes are compared to those derived from the melt inclusion records and clinopyroxene-liquid barometry for lavas from South Soufrière Hills volcanoes. We evaluate how the water profiles in the orthopyroxenes from Soufrière Hills may have been modified by diffusive loss of water during magma ascent and degassing of the carrier liquid. The potential of large pyroxenes in relatively cool magmas for preserving detailed records of deep magma storage in the arc crust is assessed, along with the implications for understanding the architecture of magma storage beneath the southern part of the island of Montserrat.

2. Geological setting

This contribution focusses on the magmatic system connected to the Soufrière Hills and South Soufrière Volcanoes (SHV and SSH), Montserrat, West Indies, where a substantial body of previous work has laid the groundwork for understanding magma storage and transport. The island of Montserrat is located in the northern part of the Lesser Antilles; a 750 km long chain of volcanic islands formed as a result of the slow (2 cm yr^{-1}) subduction of the North American plate beneath the Caribbean plate (Fig. 1). Montserrat lies on crust that is ~30 km thick (Sevilla et al., 2010). The island comprises four volcanic centres: Silver Hills (2600–1200 ka), Centre Hills (950–550 ka), Soufrière Hills (282 ka to present) and South Soufrière Hills (131 to 128 ka) (Harford et al., 2002).

The Soufrière Hills Volcano erupted crystal-rich andesite magma between November 1995 and February 2010 (Wadge et al., 2014). The andesite is comprised of ~40 vol% macrocrysts (plagioclase, hornblende, orthopyroxene, magnetite, ilmenite and minor rounded quartz) in a groundmass of rhyolitic glass (with 72–75 wt% SiO_2) and a microcryst assemblage similar to the macrocrysts, with the addition of minor clinopyroxene, and without quartz (Humphreys et al., 2009b; Murphy et al., 2000). The andesite contains mafic enclaves with basaltic to basaltic andesite composition and partially reacted macrocrysts inherited from the andesite (Plail et al., 2014). The enclaves exhibit compositions and features suggestive of partial hybridisation between basalt and andesite before enclave formation, typical of enclaves observed elsewhere (Bacon, 1986; Plail et al., 2014; Ruprecht et al., 2012). Dome lavas are highly crystalline; pumices erupted during Vulcanian explosive activity have a range of vesicularities reflecting their position in the eruptive conduit (Giachetti et al., 2010). Sequences of Vulcanian explosions (with durations of a few minutes) in 1997 and 2003 took place quasi-periodically with inter-explosion repose periods of hours to days (Druitt et al., 2002; Edmonds et al., 2006). Based on microcryst textures in the pumice, it has been suggested that the Vulcanian explosions evacuated the upper 1–2 km of conduit and occurred concurrent with the breaching of a dense, degassed plug at the top of the conduit (Clarke et al., 2007). Numerical models, however, suggest that high and cyclic magma discharge rates, which generate Vulcanian explosions, may be generated when magma reservoir pressures increase to some critical level, owing to the non-linear rheological properties of the magma (Melnik and Sparks, 2002), implying that the explosions are driven by some process at depth and not by overpressures generated beneath a conduit-top plug.

It has been proposed, on the basis of ground deformation measured by GPS over fifteen years of eruption, that a dual magma reservoir