Chemical Geology 418 (2015) 158–170

Contents lists available at ScienceDirect

Chemical Geology

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

Experimental mixing of hydrous magmas

Mickael Laumonier *, Bruno Scaillet, Laurent Arbaret, Joan Andújar, Rémi Champallier

Univ d'Orléans, ISTO, UMR 7327, 45071 Orléans, France
CNRS/INSU, ISTO, UMR 7327, 45071 Orléans, France
BRGM, ISTO, UMR 7327, BP 36009, 45060 Orléans, France

ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form 24 August 2015
Accepted 20 October 2015
Available online 24 October 2015

Keywords:
Magma mixing
Mingling
Hydrous
Shearing
Deformation
Texture
Enclave

ABSTRACT

Deformation experiments involving hydrous magmas of different compositions (basalt and haplotonalite) have been performed in a Paterson press at 300 MPa, in the temperature range 600 °C–1020 °C, with water-saturated melts, during 2–4 h. Prior to deformation, the two end-member magmas were annealed at either 950 °C or 1000 °C, yielding magmas with crystal contents in the range 31–53 wt.% and 2 sets of viscosity contrasts. Under the experimental conditions investigated (i.e. moderate shear rates $<10^{-3}$ s^{-1}), mixing/mingling textures appear at temperatures >950 °C. In the temperature range 950–985 °C, a few mixing and mingling textures occur, though both end-members essentially retain their physical integrity. It is only at, or above, 1000 °C that a dramatic jump in mingling efficiency happens, corresponding to a crystal fraction of 45 vol.%. Textures include entrainment of mafic crystals into the felsic magma, mafic–felsic banding, enclave formation, and diffusion-induced interface, the latter only over limited distances (<300 μm) due to the short run durations. In the most strained parcels of interacting magmas, complex mixing/mingling textures were produced, similar to those observed in volcanic and plutonic rocks in arc settings. The experiments show that mixing between hydrous felsic and mafic magmas takes place at around 1000 °C, a temperature which is almost 200 °C lower than mixing under dry conditions. Magma mixing is commonly invoked as a trigger for volcanic eruptions; our experiments suggest that such eruptions can be driven by small (~15 °C) temperature fluctuation in the reservoir. Our results also suggest that slow replenishment of a felsic reservoir by mafic inputs will likely result in stratification between end-members rather than in a homogeneous mixture.

1. Introduction

Magma mixing is commonly observed in nature, in particular in arc magmas, which are characterized by an abundance in volatiles, notably water (Anderson, 1976; Armienti et al., 1983; Blake, 1984; Castro et al., 1990; Coombs et al., 2002; De Rosa et al., 1996; Druitt et al., 1999; Martin et al., 2006a,b; Pons et al., 2006; Pal et al., 2007; Woods and Cowan, 2009; Davi et al., 2010; Eichelberger, 2010; Perugini and Poli, 2012). The effects of mixing are particularly evident when evolved magma chambers stored at upper crustal pressures (P < 400 MPa) are replenished by batches of hot (up to 1250 °C) and mafic magmas (e.g. Sparks et al., 1977; Sakuyama, 1979, 1981; Bacon, 1986; Civetta et al., 1991; Nakamura, 1995; Pallister et al., 1996; Mandeville et al., 1996; Wiebe, 1996; Venezky and Rutherford, 1997; Clynne, 1999; Miller et al., 1999; Browne et al., 2006; Pal et al., 2007; Eichelberger, 2010; Ruprecht and Bachmann, 2010). Magma mixing has an important role in the dynamics of the processes occurring in magmatic reservoirs and it has been proposed as a triggering mechanism of volcanic eruptions (e.g., Sparks et al., 1977; Pallister et al., 1996; Eichelberger, 2010; Kent et al., 2010; Ruprecht and Bachmann, 2010; La Felice and Landi, 2011; Druitt et al., 2012). Mixing depends on the rheological properties of magmas that are in turn strongly affected by volatiles. In particular, dissolved water strongly decreases melt viscosity (Dingwell et al., 1996), affects the fraction of crystals present at a given temperature, which, in turn, affects magma viscosity (Champallier et al., 2008; Caricchi et al., 2007; Picard et al., 2011). Consequently water and volatiles, in general, strongly influence magma behavior and eruptive style, depending on whether the magma holds or loses its volatiles during its transfer to surface (e.g., Jaupart and Allègre, 1991; Martel et al., 1998; Laumonier et al., 2011). However, dynamic experiments designed to explore magma mixing processes at the water-rich conditions found in arc settings in particular are absent (Kouchi and Sunagawa, 1982, 1985; Watson and Jurewicz, 1984; Wyllie et al., 1989; Carroll and Wyllie, 1989; Van der Laan and Wyllie, 1993; De Campos et al., 2008, 2011). So far, most works have been conducted at atmospheric pressure (i.e. using dry magmas), high temperature (1200 to 1400 °C), under static conditions or at high strain rates (~10^2 s^{-1} by Kouchi and Sunagawa, 1982, 1985; ~10^{-1} s^{-1} by De Campos et al., 2008, 2011; and ~10^{-2} s^{-1} by Morgavi et al., 2013a,b). Such conditions, in particular strain rate, are consistent with volcanic eruption processes, but exceed those characteristic of magma reservoirs prior to eruption (10^{-4} s^{-1},

* Corresponding author at: Univ d'Orléans, ISTO, UMR 7327, 45071, Orléans, France.
E-mail address: mickael.laumonier@gmail.com (M. Laumonier).

http://dx.doi.org/10.1016/j.chemgeo.2015.10.031
0009-2541/

Chadwick et al., 1988; Albertz et al., 2005; Hodge et al., 2012). Recently, Laumonier et al. (2014a) deformed two chemically distinct and dry magmas at conditions close to expected magmatic ones, i.e. 900 < T < 1200 °C, 300 MPa and strain rate of 10^{-5} to 10^{-3} s^{-1}. The geometry used imposes simple shear at the interface between the two end-members, to simulate replenishment of a reservoir by a mafic dyke intrusion (Fig. 1A). These dry experiments reproduce most of the textures of magma mixing and mingling observed in rocks (e.g., enclaves, stretched filament, isolated crystal in disequilibrium with their host), clarifying the details of the mechanisms occurring during the incipient stages of mixing. The fraction and the arrangement of crystals appears to be a critical factor for magma mixing, in particular via the existence of crystal network, which controls the magma rheology (e.g., Philpotts et al., 1998; Martin et al., 2006a; Laumonier et al., 2014a; Caricchi et al., 2012). However, the dry conditions explored by Laumonier et al. (2014a) were aimed at limiting quench effects, to better document mixing textures and related mechanisms. Here, we extend our efforts toward hydrous conditions using a methodology similar to that in Laumonier et al. (2014a). To the best of our knowledge this is the first time that the effect of water on the mixing capacity of magmas is experimentally investigated under conditions of temperature, pressure, and strain rate relevant to subduction zone settings.

2. Experimental procedure

2.1. Starting material

A natural basalt and a synthetic haplotonalite were selected as the mafic and felsic end-members for torsion experiments, allowing a direct comparison with previous dry experiments (Laumonier et al., 2014a). The basalt (composition in Table 1) was sampled from the massive part of the Cape Balos flow on Santorini volcano, Greece (Nicholls, 1971; Druitt et al., 1999). It contains phenocrysts of olivine (Fo75) that are set in a matrix of plagioclase, clinopyroxene, magnetite with rare ilmenite and orthopyroxene. Xenocrysts of olivine (Fo78) and plagioclase (An90) are also present, the latter sometimes displaying core sieved textures and inverse compositional zoning (cores: An55–60, rims An80) (Nicholls, 1971; Andújar et al., 2015). The phase equilibria of the mafic material have been investigated by Andújar et al. (2015) and are used as a guideline for our work. The haplotonalitic glass (Table 1) was produced by Schott A.G. (Germany). In the P–T–H_2O range explored it crystallizes plagioclase only and the relationships between crystal fraction, water content, and temperature have been previously determined (Picard, 2009; Picard et al., 2011; Laumonier et al., 2011). The chemical and rheological behaviors of such a plagioclase suspension in a felsic glass are similar to natural felsic magmas (trachyte to rhyolite, e.g. Calanchi et al., 1993; Ferla and Meli, 2006; Davi et al., 2010).

These two starting materials were first hydrated and annealed in an Internally Heat Pressure Vessel (IHPV) at 300 MPa and 950 or 1000 °C, depending on the target crystal fraction. The felsic magmas synthesized at 950 °C and 1000 °C have crystal contents (Φs) of 38 and 31 vol.% respectively, with ~10 μm long plagioclase (An29 to An35) having an aspect ratio of 2–3, along with a few percent of bubbles (<2% in volume) and glass (Fig. 2A; Table 1). The mafic syntheses contain 53 vol.% (at 950 °C) and 45 vol.% (at 1000 °C) of amphibole + plagioclase + pyroxene + magnetite and glass (Fig. 2C & D, Table 1). More details about the preparation and syntheses can be found in the supplementary information.

2.2. Deformation experiments

2.2.1. Experimental set up for deformation experiments

Cylinders of 13.78 to 14.96 mm diameter from first step synthesis products were drilled out and cut into thin disks of 1.16 to 3.34 mm thick to build the experimental torsion assembly while some pieces from different locations in the syntheses were selected to check the suspension homogeneity. Our deformation set up consists of 4 interleaved wafers of felsic/mafic magma synthesized at the same temperature and alternating in composition, always with a felsic disk located atop of the "stack" (Fig. 1B). Layers are named according to their position and composition, e.g. numbering from the top, and ρ and β symbols for felsic and mafic compositions, respectively (Fig. 1B). In all experiments except the run conducted at the lowest temperature (3 layers: ρ1, β2 and ρ3), the upper layer was ρ1 and the lower one is β4 providing 3 interfaces between end-members. The faces of each disk were ground to have parallel sides (thickness variation lower than 0.02 mm) and polished to reduce interface irregularities. The stack of disks (5.33 to 10.93 mm thick) was wrapped in a platinum foil, which did not significantly interact chemically with the sample during the experiments. This assemblage was inserted in turn in a copper or iron jacket and sandwiched between pistons to be located in the isothermal zone of the furnace (±2 °C on 35 mm length determined during furnace calibration). Although in nature strong thermal gradients likely exist between mixing magmas, in this study we tried to avoid any temperature gradient to better constrain the role of melt fraction on mixing. Our experiments hence model the conditions of mixing once thermal equilibrium has been reached between the end-members. The column so prepared was inserted in a Paterson press (Paterson instrument, Australian Scientific Instruments) at ISTO to perform torsion experiments at constant

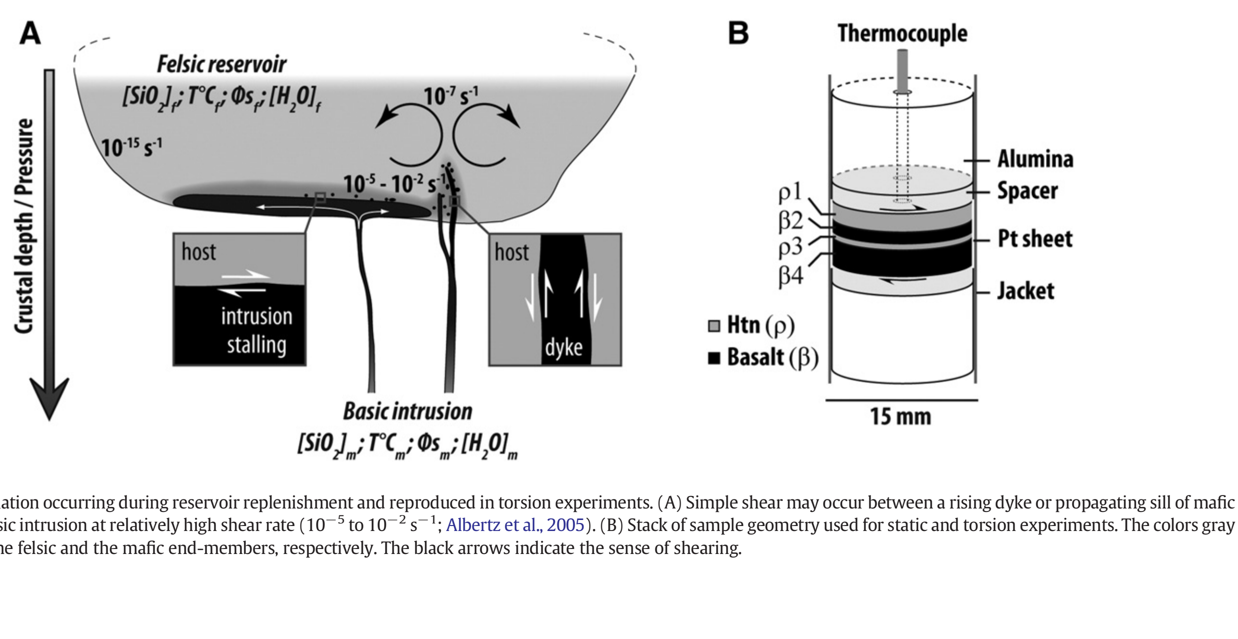

Fig. 1. Shear deformation occurring during reservoir replenishment and reproduced in torsion experiments. (A) Simple shear may occur between a rising dyke or propagating sill of mafic magma within a felsic intrusion at relatively high shear rate (10^{-5} to 10^{-2} s^{-1}; Albertz et al., 2005). (B) Stack of sample geometry used for static and torsion experiments. The colors gray and black refer to the felsic and the mafic end-members, respectively. The black arrows indicate the sense of shearing.