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Timescales of bubble coalescence, outgassing, and foam collapse in decompressed rhyolitic melts

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ABSTRACT

The timescale of degassing and outgassing in hydrous rhyolitic melts is investigated in a wide range of conditions by means of decompression experiments. The evolution of vesicularity, bubble diameter, and number density is characterized as a function of time either of decompression or spent at final pressure, in order to determine the effect of final pressure, temperature, syn- versus post-decompression degassing, melt composition, and microlites, on the timescale of bubble growth, coalescence, and outgassing.

The result suggests that different bubble evolution and degassing–outgassing timescale corresponding to explosive and effusive eruption regimes can be cast in bulk viscosity (melt + bubbles; η_{bulk}) versus decompression time (rather than path) space. The η_{bulk}–time relationship defines three domains of (i) bubble nucleation and growth, restricted to short durations and high η_{bulk} ($<\sim$0.03 h for η_{bulk} $\sim 10^{5-6}$ Pa s), (ii) equilibrium degassing with coalescence increasing from negligible (permeability $> 10^{-13}$ m^2) to extensive (permeability $\sim 10^{-11-12}$ m^2), and (iii) outgassing, restricted to long durations and low η_{bulk} ($>\sim$10 h for $\eta_{bulk} < 10^6$ Pa s; permeability $>10^{-10}$ m^2) that eventually leads to foam collapse.

These findings are applied to the case studies of Mt Pelée and Mt Pinatubo to infer the transition from pumice to dense pyroclasts in volcanic eruptions and the possibility of evolving from an explosive Plinian eruption to an effusive dome-growth event by giving the vesicular magma enough time to outgas and collapse (i.e. hundreds to tens of hours for η_{bulk} $\sim 10^5$ to 10^4 Pa s, respectively). We also show the drastic effect of microlites on re-arranging preexistent bubbles and potentially triggering a late nucleation event.

1. Introduction

Explosive volcanic eruptions have aroused great interest in understanding the mechanisms of degassing and the transitions between explosive and effusive eruptions of silicic magmas. When silicic magmas rise from depth to the Earth surface, gas solubility decreases and the oversaturated melt exsolves gases as bubbles that grow by gas diffusion and vapor expansion. Either bubbles remain isolated and trapped in the melt or they coalesce to form connected gas channels that promote gas escape and eventually foam collapse (Eichelberger et al., 1986). In the case of isolated bubbles, the magma may be overpressurized with gas and trigger a highly explosive eruption, whereas in the case of bubble interconnection, the magma may outgas and erupt effusively. Thus, investigating the whole degassing process (i.e. the dynamics of bubble nucleation, growth, coalescence, and evacuation) is crucial to our understanding of the transitions in eruptive styles. Since the pioneering study of Sparks (1978), degassing and bubble dynamics in silicic melts have been extensively investigated through experiments (e.g. Navon et al., 1998; Gardner et al., 1999; Larsen and Gardner, 2000; Martel and Bureau, 2001; Gondé et al., 2011) and numerical models (e.g. Toramaru, 1989, 1995; Barclay et al., 1995; Proussevitch and Sahagian, 1996, 1998).

Many parameters control the degassing of ascending magmas, such as melt composition, volatile content, temperature, and decompression rate. As a result, it is not always clear which of those parameters dominates bubble evolution and degassing. Many studies have focused on the effect of decompression rate on bubble nucleation in silicic melts (e.g. Mangan and Sisson, 2000; Mourtada-Bonnefoi and Laporte, 2004; Toramaru, 2006; Hamada et al., 2010), whereas others aimed at defining the parameters controlling bubble growth (e.g. Sparks, 1978; Barclay et al., 1995; Lyakhovsky et al., 1996; Proussevitch and Sahagian, 1998; Gardner et al., 1999; Liu and Zhang, 2000). Investigations have also been conducted on the factors promoting bubble interconnectivity, such as coalescence, permeability development, and foam collapse in

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rhyolitic magmas (e.g. Eichelberger et al., 1986; Westrich and Eichelberger, 1994; Klug and Cashman, 1994, 1996; Blower et al., 2002; Larsen et al., 2004; Burgisser and Gardner, 2005; Gardner, 2007; Degruyter et al., 2010; Castro et al., 2012a; Takeuchi et al., 2009). Up to now, bubble nucleation and growth are the most understood processes, thanks to combined natural, experimental, and numerical studies. The conditions of bubble coalescence and foam collapse are so far more poorly understood, although directly linked to the ability of the magma to erupt explosively or effusively.

In order to assess the respective roles of parameters such as melt composition, pressure, and temperature, on the mechanisms and timescales of bubble coalescence and outgassing, we conducted experiments of decompression-induced degassing in hydrated rhyolitic or rhyolite-analogue melts. The choice of the composition is dictated by the fact that rhyolitic melts commonly represent the chemical composition of the matrix that embeds phenocrysts in andesites, dacites or rhyolites. Decompression simulates magma ascent in a volcanic conduit. These new experiments complete a set of previously published decompression experiments that were mainly designed for crystallization studies (Martel and Schmidt, 2003; Martel, 2012; Mollard et al., 2012). The new data are acquired using the same (or very close) hydrated rhyolitic melts as starting material, were decompressed in similar devices, were processed similarly, so that both the new and previous data cover a large range of conditions important for examining the degassing–outgassing processes. We determined the time-evolution of vesicularity, bubble diameter and number density, critical to the characterization of bubble growth, coalescence, and foam collapse as a function of time and bulk viscosity (which depends on melt composition, temperature, H_2O content, and bubble content). By focusing on long-timescale processes in decompressing rhyolite melts, we offer new insights into bubble coalescence and outgassing, which are probably the most elusive stages of the vesiculation process.

2. Experimental and analytical methods

2.1. Composition of the starting materials

Three glass compositions have been used as starting material: two rhyolites (RHY and SHILL) and a haplotonalite (HTN). RHY is the composition of the rhyolitic matrix glass of the andesite of Mt Pelée, Martinique (RHY in wt%: 75.7 SiO_2, 13.1 Al_2O_3, 2.4 CaO, 3.6 Na_2O, 1.9 K_2O, 2.5 FeO, 0.4 MgO, 0.1 MnO, and 0.3 TiO_2). RHY glass preparation is described in Martel (2012). SHILL is the composition of the rhyolitic matrix glass of the andesite of Soufriere Hills, Montserrat (SHILL in wt%: 75.0 SiO_2, 13.6 Al_2O_3, 2.5 CaO, 4.3 Na_2O, 1.7 K_2O, 2.0 FeO, 0.4 MgO, 0.2 MnO, and 0.3 TiO_2). SHILL glass preparation is described in Martel and Schmidt (2003). RHY and SHILL are so similar in composition that we considered them directly comparable. HTN is a 4-component simplified composition of a rhyolite (HTN in wt%: 78.7 SiO_2, 14.1 Al_2O_3, 1.8 CaO, 5.4 Na_2O). HTN glass preparation is described in Mollard et al. (2012). With respect to RHY and SHILL, HTN allows testing any compositional differences due to either an enrichment in SiO_2 (∼3 wt%) or the absence of ferromagnesian oxides.

2.2. Experimental methods

The decompression experiments were all performed in externally-heated pressure vessels at temperatures between 850 and 875 °C from an initial pressure (P_i) of 200 or 150 MPa to final pressures (P_f) varying between 10 and 60 MPa. The series were decompressed either (i) quasi-continuously following decompression rates from 0.2 to 50 000 MPa/h or (ii) rapidly (57–1200 MPa/h) to P_f followed by a dwell time ranging from 4 to 672 h at P_f. The samples were quenched at P_f within ∼1–2 s. For ease, the continuous decompressions not followed by a dwell at P_f were referred as to "syn-decompression" degassing and the rapid decompressions followed by a dwell at P_f were referred as to "post-decompression" degassing although a part of the degassing may have started during decompression. A detailed guide to the experimental procedures is given in the *Supplementary Information_A*, the different decompression series are presented in Table 1, and the experimental conditions are given in Table 2.

Table 1
Summary of the decompression series and their experimental conditions.

Series name	Starting material[a]	T (°C)	P_i (MPa)	P_f (MPa)	Degassing style[b]
850SYN50	RHY	850	200	50	SYN
850SYN30	RHY	850	200	30	SYN
850SYN10	RHY	850	200	10	SYN
850POST50	RHY	850	200	50	POST
850POST30	RHY	850	200	30	POST
850POST10	RHY	850	200	10	POST
875POST50	RHY	875	200	50	POST
875POST50HTN	HTN	875	200	50	POST
860SYN50	SHILL	860	150	50	SYN

[a] RHY for Mt Pelée rhyolite, SHILL for Soufriere Hills rhyolite, and HTN for haplotonalite (compositions given in text).
[b] SYN for syn-decompression degassing and POST for post-decompression degassing, as defined in text.

2.3. Textural analysis of the bubbles

Either half the sample-bearing capsule or the biggest pieces of the sample were mounted in epoxy resin for analysis. Bubbles were investigated using images from optical or scanning electron microscopes (SEM). The images were processed using GIMP open-source software (GNU Image Manipulation Program) and converted into binary images for the determination of the porosity (Φ) and bubble size distribution using the SPO software [fabric analysis using the intercept method developed by Launeau and Robin (1996) and Launeau and Cruden (1998)]. SEM or optical images, together with their corresponding binary images, are shown as time-series in *Supplementary Information_B*. An example of one decompression series is shown in Fig. 1. Our wish was to keep the samples as pristine as possible to avoid introducing bias in the degassing interpretation, but we sometimes had to manually separate touching bubbles where polishing plucking was suspected (e.g. sample D7 in *Supplementary Information_Be*). We checked that this procedure of manual bubble separation did not significantly impact bubble number density (no shift greater than one log unit) or bubble size distribution. For the H_2O-saturated samples, some bubbles were trapped in the melt during the hydration procedure. In the samples decompressed in less than ∼0.1 h, these pre-decompression bubbles were several times larger than the decompression-induced ones and we easily ruled them out from the analyses (e.g. sample SH11 from the 860SYN50 series in *Supplementary Information_Bh*). However, they were no more distinguishable from the decompression-induced bubbles for longer times and were thus counted together. Nevertheless, these initial bubbles likely have a negligible effect on the whole degassing process because they were always in proportion below 1 vol% and in number density several orders of magnitude lower than the decompression-induced bubbles (from measurements carried out on the samples held at P_i and not subjected to decompression).

From the binary images of the samples, we determined the following parameters:

- Φ, the porosity defined as the area ratio of bubbles to bubbles + glass (+ crystals, if any);