Earth and Planetary Science Letters 349-350 (2012) 161–170

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

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

The effects of outgassing on the transition between effusive and explosive silicic eruptions

W. Degruyter [a,*], O. Bachmann [b], A. Burgisser [c], M. Manga [a]

[a] Earth and Planetary Science, University of California, Berkeley, USA
[b] Department of Earth and Space Sciences, University of Washington, Seattle, USA
[c] Institut des Sciences de la Terre d'Orléans, CNRS/INSU, France

ARTICLE INFO

Article history:
Received 20 October 2011
Received in revised form
18 June 2012
Accepted 28 June 2012
Editor: T. Elliot
Available online 9 August 2012

Keywords:
Effusive–explosive transition
Conduit
Textures
Permeability
Outgassing

ABSTRACT

The eruption style of silicic magmas is affected by the loss of gas (outgassing) during ascent. We investigate outgassing using a numerical model for one-dimensional, two-phase, steady flow in a volcanic conduit. By implementing Forchheimer's equation rather than Darcy's equation for outgassing we are able to investigate the relative influence of Darcian and inertial permeability on the transition between effusive and explosive eruptions. These permeabilities are defined by constitutive equations obtained from textural analysis of pyroclasts and determined by bubble number density, throat–bubble size ratio, tortuosity, and roughness. The efficiency of outgassing as a function of these parameters can be quantified by two dimensionless quantities: the Stokes number, the ratio of the response time of the magma and the characteristic time of gas flow, and the Forchheimer number, the ratio of the viscous and inertial forces inside the bubble network. A small Stokes number indicates strong coupling between gas and magma and thus promotes explosive eruption. A large Forchheimer number signifies that gas escape from the bubble network is dominated by inertial effects, which leads to explosive behaviour. To provide context we compare model predictions to the May 18, 1980 Mount St. Helens and the August–September 1997 Soufrière Hills eruptions. We show that inertial effects dominate outgassing during both effusive and explosive eruptions, and that in this case the eruptive regime is determined by a new dimensionless quantity defined by the ratio of Stokes and Forchheimer number. Of the considered textural parameters, the bubble number density has the strongest influence on this quantity. This result has implications for permeability studies and conduit modelling.

1. Introduction

The efficiency of gas escape during the ascent of silicic magma governs the transition between effusive and explosive eruptions (Slezin, 1983, 2003; Eichelberger et al., 1986; Jaupart and Allegre, 1991; Woods and Koyaguchi, 1994; Gonnermann and Manga, 2007). If the gas can escape readily from the magma, an effusive outpouring of lava occurs. On the other hand, when the gas stays trapped within the ascending magma, it provides the potential energy needed to fragment the magma and produce an explosive eruption. Gas can separate from magma through a network of coalesced bubbles or fractures, both horizontally into the conduit walls and vertically to the surface (Stasiuk et al., 1996; Melnik and Sparks, 1999; Tuffen et al., 2003; Gonnermann and Manga, 2003). Here we study vertical gas segregation through a network of bubbles in order to quantify the effects of permeability on the outcome of an eruption.

Juvenile pyroclasts contain information on the pore-scale geometry of the magma at the time they are quenched. Pyroclasts ejected by Vulcanian eruption, for example, preserve some evidence for the effusive dome-forming phase prior to fragmentation. Formenti and Druitt (2003) found that syn-explosion bubble nucleation may occur, resulting in a uniformly distributed porosity change of $<15\%$, which suggests that porosity trends with depth are approximately preserved in the pyroclasts. Giachetti et al. (2010) used such pyroclasts to determine pre-explosive conditions of the 1997 eruptions at Soufrière Hills Volcano, Montserrat. Products of Plinian eruptions on the other hand can record the state of the magma at fragmentation provided post-fragmentation deformation is limited. This is true for highly viscous magmas and relatively small pyroclasts. A snapshot of the outgassing history can thus be found in these pyroclasts, and measuring their permeability can provide insights into outgassing (Fig. 1; Klug and Cashman, 1996; Melnik and Sparks, 2002a; Rust and Cashman, 2004; Bernard et al., 2007; Takeuchi et al., 2008; Wright

* Corresponding author.
E-mail address: wim.degruyter@berkeley.edu (W. Degruyter).

0012-821X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2012.06.056

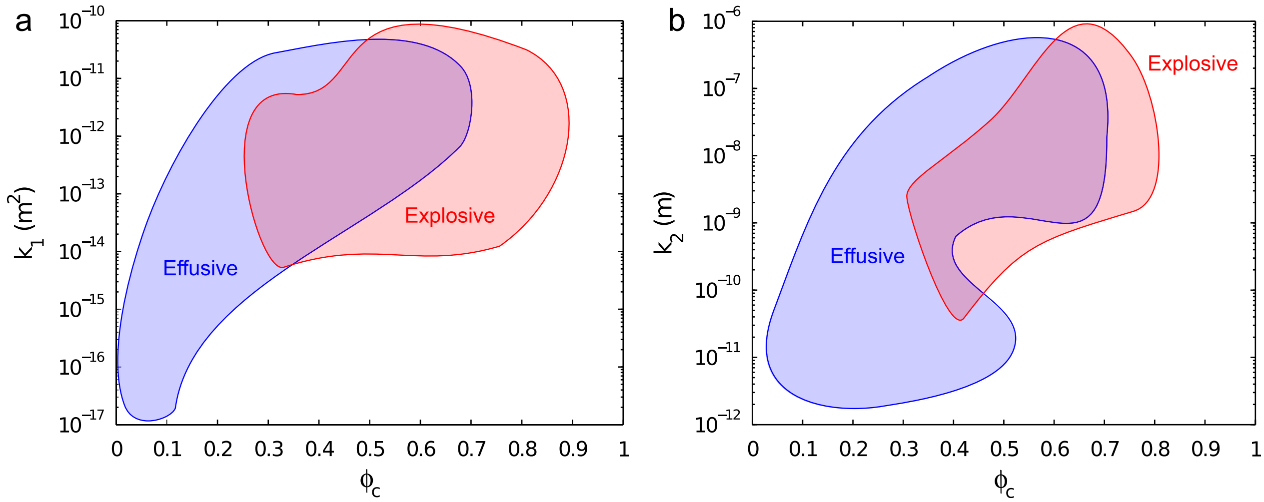

Fig. 1. Summary of the relationship between of connected porosity ϕ_c and permeability. The blue area represents the spread in data collected on pyroclasts from effusive eruptions, the red area represents the data spread on pyroclasts from explosive eruptions for (a) Darcian permeability k_1 (Wright et al., 2009), and (b) inertial permeability k_2 (Rust and Cashman, 2004; Mueller et al., 2005; Takeuchi et al., 2008; Bouvet de Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009). Data from pyroclasts ejected by Vulcanian explosions are treated as effusive. Data are mostly from silica-rich pyroclasts, but also includes mafic products as porosity–permeability data does not appear to depend on composition. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

et al., 2009; Bouvet de Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009).

It has been suggested that outgassing during magma ascent can be described by Forchheimer's law (Forchheimer, 1901; Rust and Cashman, 2004), an extension to Darcy's law, which accounts for the effects of turbulence

$$\left|\frac{dP}{dz}\right| = \underbrace{\frac{\mu_g}{k_1}U}_{\text{viscous term}} + \underbrace{\frac{\rho_g}{k_2}U^2}_{\text{inertial term}}, \quad (1)$$

where z is the direction of flow, P is the pressure, U is the volume flux, μ_g is the viscosity, ρ_g is the density of the gas phase. The Darcian permeability, k_1, and the inertial permeability, k_2, account for the influence of the geometry of the network of bubbles preserved in the juvenile pyroclasts. Fig. 1 compiles permeability measurements as a function of the connected porosity found in pyroclasts. In general, permeability increases with increasing porosity, but there is large variability in the data sets. Effusive products are overall less porous than their explosive counterparts, but have a similar range over 5–6 orders of magnitude in Darcian and inertial permeability.

Textural studies have shown that the spread of permeability found in juvenile pyroclasts is caused by the variation in size, shape, tortuosity, and roughness of connected channels through the network of bubbles (Fig. 1; Blower, 2001; Bernard et al., 2007; Wright et al., 2006, 2009; Degruyter et al., 2010a,b). Several constitutive equations that link these parameters to the Darcian and inertial permeability have been proposed. In the present study we use the Kozeny–Carman or equivalent channel equations as discussed by Degruyter et al. (2010a)

$$k_1 = \frac{r_t^2}{8}\phi_c^m, \quad (2)$$

$$k_2 = \frac{r_t}{f_0}\phi_c^{(1+3m)/2}, \quad (3)$$

with ϕ_c the connected porosity, r_t the throat radius (the minimum cross section between two coalesced bubbles). The parameter m is the tortuosity or cementation factor connected to the tortuosity τ using Archie's law

$$\tau^2 = \phi_c^{1-m}, \quad (4)$$

with the tortuosity defined as the length of the connected channels divided by the length of the porous medium. The parameter f_0 is a fitting constant that only appears in the expression for k_2, which we refer to as the roughness factor. We adapt this formulation for outgassing in a conduit flow model and apply it to two well-studied eruptions: (i) the Plinian phase of the May 18, 1980 eruption of Mount St. Helens, USA (MSH 1980) and (ii) the dome-forming eruptions of August–September 1997 at Soufrière Hills Volcano, Montserrat (SHV 1997). These case studies allow us to understand the implications of using Forchheimer's equation rather than Darcy's equation for outgassing during an eruption. We use scaling to quantify the relative importance of the textural parameters and show where further understanding is needed.

2. Model

Conduit flow models have been successful in the past to demonstrate how gas loss determines eruption style (Woods and Koyaguchi, 1994; Melnik and Sparks, 1999; Yoshida and Koyaguchi, 1999; Slezin, 2003; Melnik et al., 2005; Kozono and Koyaguchi, 2009a,b, 2010). We adapt the model from Yoshida and Koyaguchi (1999) and Kozono and Koyaguchi (2009a,b, 2010), which assumes a one-dimensional, steady, two-phase flow in a pipe with constant radius. Relative motion between the magma (melt+crystals) and gas phase is accounted for through interfacial drag forces. The exsolution of volatiles is in equilibrium and the magma fragments when the gas volume fraction reaches a critical value ϕ_f. We consider fragmentation governed by a critical strain rate (Papale, 1999) and critical overpressure (Zhang, 1999); details are in Appendix B. This changes the flow from a permeable foam to a gas phase with pyroclasts in suspension at which point the magma–gas friction and wall friction forces are adjusted. The model of Kozono and Koyaguchi (2009a) is adapted for our purpose in two ways: (i) the description of the magma rheology and (ii) the description of the interphase drag force.

The governing equations are

$$\frac{d(\rho_m u_m(1-\phi))}{dz} = -\frac{dn}{dz}q, \quad (5)$$