Earth and Planetary Science Letters 423 (2015) 210–218

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Viscous plugging can enhance and modulate explosivity of strombolian eruptions

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ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 27 April 2015
Accepted 28 April 2015
Available online 18 May 2015
Editor: T.A. Mather

Keywords:
plugged conduit
eruption dynamics
volcano infrasonic
slug bursting
Taylor bubble
analogue experiments

ABSTRACT

Strombolian activity is common in low-viscosity volcanism. It is characterised by quasi-periodic, short-lived explosions, which, whilst typically weak, may vary greatly in magnitude. The current paradigm for a strombolian volcanic eruption postulates a large gas bubble (slug) bursting explosively after ascending a conduit filled with low-viscosity magma. However, recent studies of pyroclast textures suggest the formation of a region of cooler, degassed, more-viscous magma at the top of the conduit is a common feature of strombolian eruptions. Following the hypothesis that such a rheological impedance could act as a 'viscous plug', which modifies and complicates gas escape processes, we conduct the first experimental investigation of this scenario. We find that: 1) the presence of a viscous plug enhances slug burst vigour; 2) experiments that include a viscous plug reproduce, and offer an explanation for, key phenomena observed in natural strombolian eruptions; 3) the presence and extent of the plug must be considered for the interpretation of infrasonic measurements of strombolian eruptions. Our scaled analogue experiments show that, as the gas slug expands on ascent, it forces the underlying low-viscosity liquid into the plug, creating a low-viscosity channel within a high-viscosity annulus. The slug's diameter and ascent rate change as it enters the channel, generating instabilities and increasing slug overpressure. When the slug reaches the surface, a more energetic burst process is observed than would be the case for a slug rising through the low-viscosity liquid alone. Fluid-dynamic instabilities cause low and high viscosity magma analogues to intermingle, and cause the burst to become pulsatory. The observed phenomena are reproduced by numerical fluid dynamic simulations at the volcanic scale, and provide a plausible explanation for pulsations, and the ejection of mingled pyroclasts, observed at Stromboli and elsewhere.

1. Introduction

Strombolian activity may be very long-lived, with episodes lasting years, decades, or even centuries. This longevity, coupled with the photogenic nature of the explosions, has made some persistently active strombolian volcanoes popular tourist destinations – for instance, more than ten thousand tourists visit the summit of Stromboli itself each year. Although usually benign, strombolian activity spans a range of magnitudes, and includes events that are much more violently explosive and may pose a significant hazard to tourists and nearby communities. It is important, therefore, to determine the factors that cause a usually mildly explosive system to generate more violent explosions.

The discrete explosions that characterise the strombolian eruptive style are interpreted as the impulsive bursting of overpressured gas pockets – or slugs – at the top of a magma column (Chouet, 1974; Blackburn et al., 1976; Burton et al., 2007). Overpressure is a fundamental consequence of large gas bubbles rising from depth and expanding against viscous and inertial retardation as pressure decreases (James et al., 2008; 2009; Del Bello et al., 2012). This behaviour is generally restricted to basaltic or andesitic magmas, because these systems have sufficiently low viscosities to allow bubble coalescence and decoupling of gas slugs from magma over short time scales (order of seconds to hours). Experimental and numerical models within the volcanological literature consider the slug rising through a medium with uniform viscosity and density. These models provide first order explanations of the dynamics of gas expansion, overpressure, and generation of seismic and acoustic signals (e.g., Vergniolle and Brandeis, 1996; Vergniolle et al., 1996; Seyfried and Freundt, 2000; Parfitt, 2004;

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http://dx.doi.org/10.1016/j.epsl.2015.04.034

Table 1
Summary of experimental parameters and scaling to the volcanic case.

Materials	Experimental parameters		Volcanic conditions		CFD simulations	
	Water	Castor	Underlying magma	Plug	Underlying magma	Plug
Density ρ (kg/m^3)	1000	970	1000		1000	1000
Viscosity μ (Pa s)	0.001	0.986	50	50 000	20	20 000
Surface tension σ[c] (N/m)	0.07	0.03	0.4	0.4	0.4	0.4
Gravity g (m/s^2)	9.81		9.81		9.81	
Conduit diameter D (m)	0.025		5		3	
Inverse viscosity N_f	12381.68	12.18	700.36	0.70	814.74	0.81
Dimensionless film[a] λ'	0.09	0.31	0.14	0.33	0.13	0.33
Film cross section A'[b]	0.16	0.53	0.25	0.55	0.24	0.55
Slug radius r_s (m)	0.01	0.01	2.16	1.68	1.30	1.01
Viscosity contrast μ^*	986		1000		1000	
Slug cross section ratio	0.56		0.61		0.60	

[a] Calculated from equation 4.2 in Llewellin et al. (2012).
[b] Calculated from equation 28 in Del Bello et al. (2012).
[c] Data for the volcanic case are from Murase and McBirney (1973).

O'Brien and Bean, 2008; D'Auria and Martini, 2011; James et al., 2009; Kobayashi et al., 2010; Del Bello et al., 2012; Gerst et al., 2013; Kremers et al., 2013; Nguyen et al., 2013; Lane et al., 2013; Sánchez et al., 2014). However, none of these approaches encompasses the presence of a region of degassed, crystalline magma with increased viscosity and strength in the shallow conduit. Such a rheological impedance – which can be termed a 'plug' – is commonly inferred, and physically plausible, at active strombolian-type vents (e.g., Gurioli et al., 2014).

Textural data from many strombolian-type volcanoes support the coexistence of magmas that have contrasting rheology as a result of cooling- and degassing-driven crystallisation (e.g., Taddeucci et al., 2004; Cimarelli et al., 2010; Kremers et al., 2012; Ruth and Calder, 2013). Considering Stromboli as a canonical case during its 'normal' activity, it is very common to find both bubble-rich, crystal-poor textures and bubble-poor, crystal-rich textures intermingled within a single pyroclast (e.g., Lautze and Houghton, 2005; 2007; Polacci et al., 2006, 2009; Colò et al., 2010; D'Oriano et al., 2010; Gurioli et al., 2014). It has been proposed that these textures represent mingling of relatively fresh, gas-rich magma with older, completely or partially degassed magma, in the shallow conduit (e.g., Lautze and Houghton, 2005). Cooling, degassing and associated crystallisation of the magma in the upper conduit cause it to have a much higher viscosity than its deeper, fresh counterpart. This rheological distinction is not to be confused with the so-called 'high porphiricity' (HP or '*black*') and 'low porphiricity' (LP or '*golden*') magma types (e.g., Métrich et al., 2005); these are distinguished on the basis of geochemical and isotopic analyses, with LP magma thought to occupy the system at depths greater than ~3.5 km. At the volcanic scale, rapid expansion of the gas slug associated with the burst process occurs only within the last few tens of meters of the magma column (James et al., 2008). Hence, the region of plug–slug interaction is limited to the shallowest portion of the conduit, entirely within the HP magma domain.

The presence of a plug, and its thickness, must have an important impact on eruption dynamics. For instance, we would expect the viscous plug to retard slug expansion, thereby promoting the development of overpressure within the slug as it rises. We would also expect the plug material and thickness to affect the dynamics of the bursting process. Lautze and Houghton (2007) were the first to suggest, based on field observations, that changing proportions of magma with differing viscosities influenced eruption frequency and vigour, supporting the notion that plug thickness could change over time. These factors introduce additional complexity compared with the unplugged scenario (e.g., Andronico et al., 2008). This complexity might be manifest in the seismo-acoustic signatures of the explosions (e.g., Johnson and Lees, 2000; Lyons et al., 2012), and in the visual character of the explosions. We note, for instance, that recent high-speed videography studies have identified that gas escape during strombolian explosions is typically pulsatory (Taddeucci et al., 2012; Gaudin et al., 2014), suggesting greater complexity than simple bursting of an overpressured slug. Understanding the role that a viscous plug plays in modulating the dynamics of slug ascent and burst is, therefore, of considerable importance in the interpretation of the waveform and amplitude of generated pressure changes (Lane et al., 2013). In order to gain insight into the complex volcanic system (e.g., Gurioli et al., 2014), we use first-order laboratory experiments to evaluate the influence of a Newtonian, high-viscosity plug on gas slug ascent and burst in a vertical tube. Our experiments build on previous work carried out in single-viscosity systems (James et al., 2004, 2006, 2008, 2009; Lane et al., 2013), and we adopt a similar analogue methodology. We also use a computational fluid dynamic model (James et al., 2008; Chouet et al., 2010) to conduct numerical simulations of the same scenario at the volcano scale, in order to explore the applicability of our laboratory results to the natural system.

2. Experimental method

2.1. Scaling considerations

We model an idealised volcanic scenario in which a layer of high-viscosity magma of variable thickness overlies a column of low-viscosity magma. The behaviour of a slug ascending a vertical pipe filled with a viscous liquid may be described via a number of dimensionless groups, namely the Morton number *Mo*; the Eötvös number *Eo*; the inverse viscosity N_f; the Froude number *Fr*; and the Reynolds number *Re* (e.g., Viana et al., 2003; Llewellin et al., 2012). These groups are defined and calculated for the volcanic and experimental scenarios in the Supplementary Content. We show that, in both systems, surface tension plays a negligible role in slug ascent (e.g., Seyfried and Freundt, 2000) hence behaviour is controlled by the inverse viscosity N_f,

$$N_f = \frac{\rho}{\mu}\sqrt{gD^3}, \quad (1)$$

where ρ and μ are the density and dynamic viscosity of the liquid, g is the gravitational acceleration, and D is the tube diameter.

For a canonical representation of parameters at volcano-scale, we choose a viscosity of 5×10^4 Pa s for the plug based on recent estimations for magma in the shallowest part of Stromboli's conduit (e.g., Gurioli et al., 2014) and 50 Pa s for the underlying magma based on minimum accepted values for basaltic melts (Table 1). Although density differences are observed among pyroclasts