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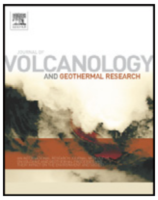

Conduit convection driving persistent degassing at basaltic volcanoes

F.M. Beckett [a,*], M. Burton [b], H.M. Mader [a], J.C. Phillips [a], M. Polacci [b], A.C. Rust [a], F. Witham [a,1]

[a] Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, via della Faggiola 32, 56126 Pisa, Italy

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ABSTRACT

The persistent release of gas at basaltic volcanoes where there is a low magma eruption rate can be driven by an exchange flow of magma in the conduit, in which gas-rich magma ascends, degasses and crystallises and then sinks back down the conduit. The driving force of the flow is provided by the density difference between the buoyant bubble-rich magma at depth and the dense degassed crystallised magma at shallow levels. In this study we attempt to constrain the physical and chemical processes driving an exchange flow of magma at Stromboli, Aeolian Archipelago, Italy. The model uses a simple, cylindrical geometry. We define degassing and crystallisation paths of the ascending and descending magmas, constrained by gas flux and melt inclusion data given in the literature, to produce a three-phase model of ascending and descending magmas driving persistent gas fluxes. We calculate the viscosity of the three-phase magma using end-member rheological models for bubble and crystal suspensions. Combining our modelled magma properties with analogue exchange flow experiments we can relate the regime of magma flow driving persistent degassing to pressure. At pressures $\lesssim$90 MPa ($\lesssim$3 km) the viscosity ratio is $\lesssim$100 and the regime is predicted to be side by side flow with both ascending and descending magmas adjacent to a portion of the conduit wall. At pressures $\gtrsim$90 MPa ($\gtrsim$3 km) the viscosity ratio between the ascending and descending magma is $\gtrsim$100 and the flow is predicted to be core annular flow, with the ascending vesiculating magma in the inner core and the more crystalline degassed magma flowing down along the conduit wall. By analogy, we hypothesise that degassed magma would flow down along the walls in dike-like plumbing geometries that have been proposed for the deeper Strombolian system. Analogue experiments suggest that exchange flows do not overturn under conditions of maximum volume flux; we use an empirical relationship to characterise the volume flux of the exchange flow and show that the radius of a cylindrical conduit required to account for the observed persistent gas flux at Stromboli at 0.1 MPa is ~1 m.

1. Introduction

Persistent gas fluxes at many active basaltic volcanoes such as Etna (Sicily, Italy), Stromboli (Aeolian Archipelago, Italy), Izu Oshima (Japan) and Masaya (Nicaragua) cannot be reconciled with the exclusive degassing of magma erupted during effusive and explosive episodes. At Etna, Allard (1997) estimates that ~80–90% of gas emissions are generated by magma that is never erupted. At Stromboli ~50,000 t d^{-1} of magma must be degassed to account for the persistent gas flux of ~200 t d^{-1} sulphur dioxide (SO_2) (Allard et al., 2008). Normal Strombolian explosive activity and effusive eruptions emit on average only ~530 t d^{-1} of solid matter (Allard et al., 1994) and thus the extruded magma flux represents ~1% of the magma processed during persistent degassing. To account for the continuous supply of gas and heat recorded, where there is no significant extrusion of magma, an exchange flow of magma within the conduit is inferred, driven by the density difference between dense degassed magma at shallow levels and buoyant gas-rich magma deeper within the system (Kazahaya et al., 1994; Harris and Stevenson, 1997; Stevenson and Blake, 1998). To interpret gas emissions and understand changes in activity at persistently active basaltic volcanoes therefore require some knowledge of the flow regime of the exchange flow, and how its volume flux relates to the degassing regimes observed and the physical properties of the magma: its viscosity and density and thus crystallinity, vesicularity and the composition of its melt.

Experimental studies of exchange flow in vertical cylindrical pipes, where the volume flux of the ascending fluid is matched by an equal flux of descending fluid, have shown that the flow regime of an exchange flow is a function of the viscosity ratio $\beta = \mu_2/\mu_1$, the viscosity of the more viscous fluid divided by the viscosity of the less viscous fluid (Stevenson and Blake, 1998; Huppert and Hallworth, 2007; Beckett et al., 2011). In this study we explore how to apply the experimental observations to a persistently degassing basaltic volcano. We use Stromboli as a case study as there are extensive data sets on the chemical composition of its magma and well constrained measurements of the flux and composition of the gas released. However,

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* Corresponding author at: Met Office, Fitzroy Road, Exeter EX1 3PB, UK.
E-mail address: frances.beckett@metoffice.gov.uk (F.M. Beckett).

[1] Now at Combustion and Turbines, Rolls-Royce, Bristol BS34 7QE, UK.

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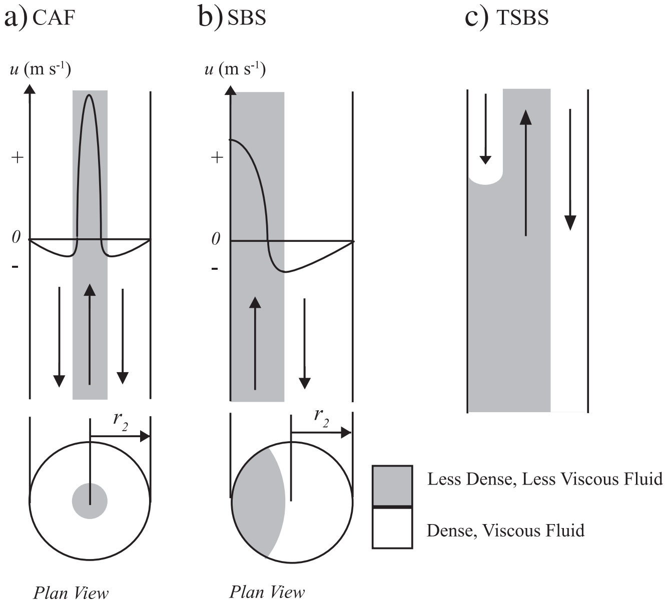

Fig. 1. Cartoon to show the flow types of buoyancy driven, laminar, exchange flow in a vertical pipe, a. Core annular flow (CAF), b. Side by side (SBS) flow and c. Transitional side by side (TSBS) flow. Arrows indicate the dominant flow direction, however at the fluid interface the less viscous fluid flows downwards, in the same direction as the more viscous fluid, as indicated by the velocity profiles for CAF and SBS flow.

application of the experimental observations requires that we know the density and viscosity of the magma as a function of pressure during both ascent and decent. Using melt inclusion (MI) data given by Métrich et al. (2010) and measured gas flux data (Burton et al., 2009), we use VolatileCalc (Newman and Lowenstern, 2002) and MELTS (Ghiorso and Sack, 1995; Asimow and Ghiorso, 1998) to constrain the crystallisation and degassing path of ascending and descending magma as a function of pressure. We then apply new methods to characterise the multiphase rheology of the ascending and descending magma, accounting for its crystallinity, vesicularity and melt composition. To calculate the rheology of the three-phase system we explore two approaches: in the first the viscosity of the bubble suspension is calculated taking the crystals plus melt as the suspending fluid; in the second the viscosity of a crystal suspension is calculated taking the bubbles plus melt as the suspending fluid. It is shown that there is no significant difference in the calculated viscosities from the two methods. Using the calculated viscosity and density of the magma as a function of pressure, we determine the Reynolds number of an exchange flow at Stromboli and show that the flow is laminar, and thus we can apply experimental observations of low Reynolds number exchange flows. We calculate the viscosity ratio between the ascending and descending magma as a function of pressure and define the flow regime of an exchange flow at Stromboli. Although the degassing behaviour at Stromboli and the properties of its magma are well constrained, the geometry of its feeder system remains unclear and likely includes dyke-like structures (Chouet et al., 2003). All experimental studies of exchange flow have been conducted in cylindrical pipes and in order to apply the experimental results we assume a single cylindrical conduit, the most thermally efficient and mechanically robust geometry for a steady-state system. This conduit geometry is an over-simplification and we discuss the limitations of this approach and the implications for defining the flow regime of an exchange flow of magma at persistently degassing basaltic volcanoes.

2. Background

There have been a number of theoretical, numerical and experimental studies that have attempted to better understand how a density driven exchange flow can drive persistent gas fluxes at basaltic volcanoes (Kazahaya et al., 1994; Stevenson and Blake, 1998; Huppert and Hallworth, 2007; M.R. Burton et al., 2007; Beckett et al., 2011; Kerswell, 2011; Palma et al., 2011; Molina et al., 2012). Stevenson and Blake (1998) presented analogue experiments of simple transient exchange flows in which the flow regime in a vertical cylindrical pipe was found to be core annular flow (CAF), with the less viscous fluid ascending up the centre of the pipe and the more viscous fluid descending down the walls in an outer annulus. Imposing a CAF geometry they present a theoretical model to constrain the conduit radius required to drive gas fluxes by assuming that the overturn rate of magma is proportional to the gas flux. Dimensional analysis shows that in a cylindrical conduit magma exchange flux is proportional to the conduit radius to the fourth power, and thus the radius of the conduit is highly insensitive to the volume flux of the exchange flow. The properties of the exchanging fluids are estimated assuming that one represents magma in a chamber at a depth of 2 km and the other a shallow degassed magma. They take typical properties for basaltic magma and assume that properties are independent of pressure for each fluid and so do not account for degassing and crystallisation paths, such that ascending magma has a water content of 0.5 wt.% and a crystallinity of 30 vol.%. They

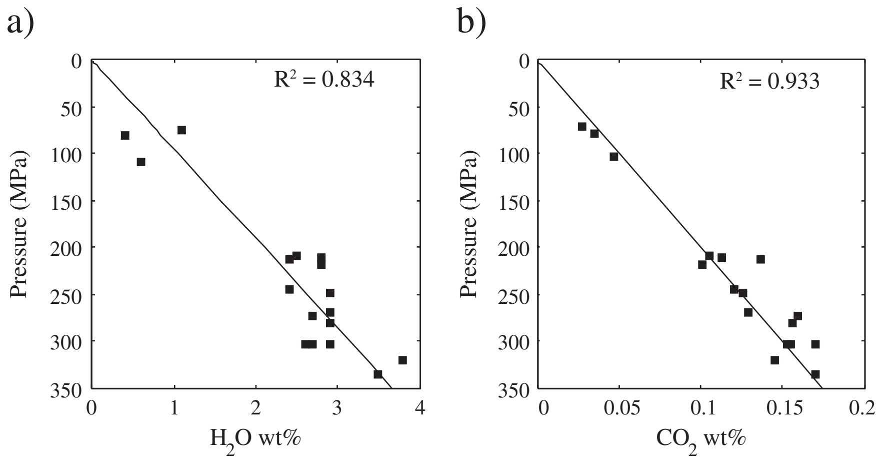

Fig. 2. Saturation pressures of MI found in olivine in the pumice and scoria ejected at Stromboli given by Métrich et al. (2010) calculated using VolatileCalc (Newman and Lowenstern, 2002) assuming closed-system degassing. Simple linear fits allow us to define the degassing path, such that a. $X_{H_2O} = 0.0105 \cdot P$ and b. $X_{CO_2} = 0.0005 \cdot P$.