



# Temperature evolution during magma ascent in basaltic effusive eruptions: A numerical application to Stromboli volcano



G. La Spina<sup>a,b,\*</sup>, M. Burton<sup>a,b</sup>, M. de' Michieli Vitturi<sup>b</sup>

<sup>a</sup> School of Earth, Atmospheric and Environmental Sciences, University of Manchester, United Kingdom

<sup>b</sup> Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy

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## ABSTRACT

The dynamics of magma ascent are controlled by the complex, interdependent processes of crystallisation, rheological evolution, gas exsolution, outgassing, non-ideal gas expansion and temperature evolution. Temperature changes within the conduit, in particular, play a key role on ascent dynamics, since temperature strongly controls the crystallisation process, which in turn has an impact on viscosity and thus on magma ascent rate. The cooling produced by gas expansion is opposed by the heat produced by crystallisation, and therefore the temperature profile within the conduit is quite complex. This complexity means that unravelling the dynamics controlling magma ascent requires a numerical model. Unfortunately, comprehensive, integrated models with full thermodynamic treatment of multiple phases and rheological evolution are challenging to produce, due to the numerical challenges involved. Until now, models have tended to focus on aspects of the problem, without a holistic approach in which petrological, thermodynamic, rheological and degassing processes, and their interactions, were all explicitly addressed and quantified.

Here, we present a new, multiphase steady-state model for magma ascent in which the main physical and chemical processes, such as crystallisation, degassing, outgassing, rheological evolution and temperature variations, are quantitatively calculated. Basaltic magma's crystallisation and flow are sensitive to initial temperature and volatile content, and therefore we investigate temperature variations during magma ascent in a basaltic system with a range of volatile contents. As a test case, we use one of the most well-studied recent basaltic effusive eruptions: the 2007 eruption of Stromboli, Italy.

Assuming equilibrium crystallisation and exsolution, we compare the solutions obtained both with and without an isothermal constraint, finding that temperature variations within the conduit have a significant influence on the ascent dynamics and therefore cannot be ignored when modelling basaltic volcanism. Furthermore, we find good agreement between model results and volcanological observations when the non-isothermal condition is assumed. We investigate, through a sensitivity analysis, the role of magma chamber temperature on mass flow rate and crystal content. We find that a temperature variation of 30 K at the base of the conduit has a bigger effect on mass discharge rate than an increase of 1 wt% in water content. Finally, we find that whilst variations in initial CO<sub>2</sub> concentration can affect the temperature, pressure and viscosity profiles along the conduit, they do not alter the macroscopic behaviour of the system.

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## 1. Introduction

Volcanoes exhibit a wide range of eruption styles, from relatively slow effusive eruptions, generating lava flows and lava domes, to explosive eruptions, in which very large volumes of fragmented magma and volcanic gas are ejected high into the at-

mosphere. Magma ascent dynamics in a volcanic conduit play a key role in determining the eruptive style of a volcano. However, due to the lack of direct observations in the conduit itself, numerical models, constrained with observational data, provide invaluable tools for quantitative insights into the complex magma ascent processes.

Numerical modelling of magma ascent is challenging, due to the complex, interdependent processes of crystallisation, rheological evolution, gas exsolution, outgassing, non-ideal gas expansion and temperature evolution. Therefore, models of magma as-

\* Corresponding author at: School of Earth, Atmospheric and Environmental Sciences, University of Manchester, United Kingdom.

E-mail address: giuseppe.laspina@manchester.ac.uk (G. La Spina).

cent require simplifications to the governing equations and the numerical computation of the solution. Initial models assumed a single gas phase, isothermal conditions, no gas–magma separation and crystal–free magma (e.g. Wilson, 1980; Wilson and Head, 1981). Later models reduced these simplifications, introducing gas–magma separation (e.g. Vergnolle and Jaupart, 1986; Dobran, 1992), crystals (e.g. Papale and Dobran, 1994; Melnik and Sparks, 2002a) and different volatile species (e.g. Papale, 1999; Papale, 2001). However, the temperature evolution of the magmatic mixture within the conduit remained a challenge. Melnik and Sparks (2002a) calculated a temperature profile within the conduit, but as a function of the dissolved water content, rather than an energy conservation equation. Starostin et al. (2005), proposed a transient model where they solved also for the energy conservation equation, but considering no crystals in the magmatic mixture, and a single gas phase. In recent years, further models were proposed in the literature (e.g. Costa et al., 2007; Kozono and Koyaguchi, 2009; Degruyter et al., 2012), but none of them have solved for the energy conservation equation, for different volatile species and for different crystal components all at the same time. Such a solution is a requirement in order to examine the temperature evolution of magma during ascent, as well as the impact that changing volatile concentrations have on the magma ascent process.

Investigation of the role of volatiles is particularly important due to the recent, dramatic improvement in our ability to measure volcanic gas compositions (Allard et al., 2005; Aiuppa et al., 2007; Burton et al., 2007a) and emission rates (Galle et al., 2003; Burton et al., 2009), using in-situ, ground- and space-based remote sensing techniques. Measurements of gas flux allow constraints to be placed on magma mass flow rates both during an eruption and in quiescent periods (e.g. Francis et al., 1993), if the original volatile contents and degree of degassing of the magma are known. Variations in both gas flux and gas compositions can give clues to magma dynamics that may herald a change in activity (Duffell et al., 2003; Aiuppa et al., 2007).

Ideally, therefore, a numerical model of magma ascent would explicitly calculate different gas species exsolution behaviour and multiphase, separated gas and magma flow. In order to adequately describe flow dynamics a quantitative model of crystallisation would also be required, capable of describing the behaviour of each significant mineral phase. The degree of crystallisation and dissolved water concentration would be an input to a model of viscosity, which would, in turn, control the flow dynamics. Finally, such a model should take account of the thermodynamics of all of the processes described above. Here, we present a new, integrated, numerical model of magma ascent which fulfils these requirements, and allows new insights into the evolution of temperature and role of volatiles during magma ascent.

## 2. Steady-state conduit model

Our model is a steady-state development from the transient model presented by La Spina (2014). In that work, the governing multiphase equations for two-phase compressible flow (with two velocities and two pressures) was produced using the theory of thermodynamically compatible systems (Romenski et al., 2010). This approach, in an evolution from the classical one adopted in Melnik and Sparks (2002b), Costa et al. (2009b), Kozono and Koyaguchi (2012) and de' Michieli Vitturi et al. (2013), allows the formulation of a conservative hyperbolic system of partial differential equations, coupled with non-differential source terms. Here, in order to better describe the multi-component nature of the system, we extend the La Spina (2014) model including:

- $n_g$  different exsolved and dissolved gas species,

- $n_c$  different crystals,
- non-ideality for exsolved gas components through the Van der Waals equation of state.

The flow of the magmatic multiphase multi-component mixture along the  $z$ -axis is treated as a continuum and the state of the two phases, denoted by the index  $k = l, g$ , is characterized by its volume fraction ( $\alpha_k$ ), mass density ( $\rho_k$ ), velocity ( $u_k$ ), and specific entropy ( $s_k$ ). The first phase represents a “liquid” phase, a mixture of melt, crystals and dissolved gas, while the second phase represents a “gas” phase, i.e. the bubbles of exsolved gases. Thus, for the volume fractions, the saturation constraint  $\alpha_l + \alpha_g = 1$  holds. Since the second phase is always referred to as the exsolved gas phase, we will use the term  $g_i$  to refer to the  $i$ -th gas component. The term  $d_i$  is used to refer to the  $i$ -th dissolved gas component, the subscript  $m$  is used for the melt, while  $c_j$  is used to refer to the  $j$ -th crystal component.

Since the focus of our study is multiphase dynamics, separation of the gas phase from the liquid phase is permitted (i.e.  $u_l \neq u_g$ ); melt, crystals and dissolved gases have the same velocity ( $u_l = u_m = u_{d_i} = u_{c_j}$ ), whilst exsolved gas components cannot separate from one another ( $u_g = u_{g_i}$ ). Different pressures between the gas and liquid phases are permitted ( $P_l \neq P_g$  where  $P_l = P_m = P_{d_i} = P_{c_j}$  and  $P_g = P_{g_i}$ ), but in this work we forced an instant equilibration of pressure, resulting in  $P_l = P_g$ . Different phases are assumed to be in thermal equilibrium ( $T = T_m = T_{d_i} = T_{c_j} = T_{g_i}$ ).

The steady-state one-dimensional system of conservation equations is derived from the theory of thermodynamically compatible systems (Romenski et al., 2010), where the conservation equations of mass, momentum and energy are expressed not for separate phases, but for the whole mixture:

$$\frac{\partial \rho u}{\partial z} = 0, \quad (1)$$

$$\frac{\partial}{\partial z} \left[ \sum_{k=l,g} \alpha_k \rho_k u_k^2 + \alpha_k P_k \right] = -\rho g - \frac{8\mu_l u_l}{r^2}, \quad (2)$$

$$\frac{\partial}{\partial z} \left[ \sum_{k=l,g} \alpha_k \rho_k u_k \left( e_k + \frac{P_k}{\rho_k} + \frac{u_k^2}{2} \right) - \rho x_l x_g (u_l - u_g) (s_l - s_g) T \right] = -\rho g u - \frac{8\mu_l u_l^2}{r^2}, \quad (3)$$

where we have defined the mixture density as  $\rho = \alpha_l \rho_l + \alpha_g \rho_g$  and the mixture velocity as  $u = x_l u_l + x_g u_g$ , where  $x_l$  and  $x_g$  are respectively the mass fractions of the liquid and gas phase. Furthermore  $g$  is the gravitational acceleration,  $\mu_l$  is the viscosity of the liquid phase, and  $r$  is the conduit radius, which is assumed to be constant,  $e_l$  and  $e_g$  are the specific internal energies, and  $s_l$  and  $s_g$  are the specific entropies.

Eq. (1) is the conservation equation for the mixture density. Eq. (2) is the balance law for the mixture momentum, such that the flow rate is driven by the pressure gradient and limited by gravity and the fluid viscosity. Eq. (3) is the mixture energy balance law, in which variations in total energy (the sum of kinetic and internal energy) are controlled by the energy lost due to the resistance to flow by gravity and friction. As in Melnik and Sparks (2002b), Costa et al. (2009b) and Degruyter et al. (2012), the viscous terms included in the momentum and mixture energy equations are derived from the Poiseuille approximation for 1D laminar flow. The model has been designed to describe only effusive activity, therefore no terms concerning fragmentation have been included in the model.

Furthermore, we include the balance law for the liquid volume fraction:

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