Journal of Volcanology and Geothermal Research 285 (2014) 100–117

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

# Influence of extrusion rate and magma rheology on the growth of lava domes: Insights from particle-dynamics modeling

Taha Husain [a,b,*], Derek Elsworth [a,b], Barry Voight [c], Glen Mattioli [d], Pamela Jansma [d]

[a] Energy and Mineral Engineering, G3 Center, The Pennsylvania State University, University Park, PA 16802, United States
[b] EMS Energy Institute, The Pennsylvania State University, University Park, PA 16802, United States
[c] Geosciences, The Pennsylvania State University, University Park, PA 16802, United States
[d] Department of Earth and Environmental Sciences, University of Texas at Arlington, Arlington, TX 76019, United States

ARTICLE INFO

*Article history:*
Received 11 April 2014
Accepted 12 August 2014
Available online 20 August 2014

*Keywords:*
Magma rheology
Lava dome
Emplacement dynamics
Discrete element modeling

ABSTRACT

Lava domes are structures that grow by the extrusion of viscous silicic or intermediate composition magma from a central volcanic conduit. Repeated cycles of growth are punctuated by collapse, as the structure becomes oversized for the strength of the composite magma that rheologically stiffens and strengthens at its surface. Here we explore lava dome growth and failure mechanics using a two-dimensional particle-dynamics model. The model follows the evolution of fractured lava, with solidification driven by degassing induced crystallization of magma. The particle-dynamics model emulates the natural development of dome growth and rearrangement of the lava dome which is difficult in mesh-based analyses due to mesh entanglement effects. The deformable talus evolves naturally as a frictional carapace that caps a ductile magma core. Extrusion rate and magma rheology together with crystallization temperature and volatile content govern the distribution of strength in the composite structure. This new model is calibrated against existing observational models of lava dome growth. Results show that the shape and extent of the ductile core and the overall structure of the lava dome are strongly controlled by the infusion rate. The effects of extrusion rate on magma rheology are sensitive to material stiffness, which in turn is a function of volatile content and crystallinity. Material stiffness and material strength are key model parameters which govern magma rheology and subsequently the morphological character of the lava dome and in turn stability. Degassing induced crystallization causes material stiffening and enhances material strength reflected in non-Newtonian magma behavior. The increase in stiffness and strength of the injected magma causes a transition in the style of dome growth, from endogenous expansion of a ductile core, to stiffer and stronger intruding material capable of punching through the overlying material and resulting in the development of a spine or possibly inducing dome collapse. Simulation results mimic development of a megaspine upon the influx of fresh magma which leads to the re-direction of magma flow, creating a new shear zone and the switching of dome growth from one side to the other. Our model shows similar dome growth dynamics as observed at Soufriere Hills Volcano, Montserrat, indicating a strong correlation between extrusion rate and its subsequent effect on mechanical properties and variations in magma rheology.



## 1. Introduction

Silicic and intermediate composition volcanoes commonly generate lava domes, which are structures that grow by the extrusion of viscous magma from a central volcanic conduit. The solidification and rheological stiffening of magma are controlled by varying degrees of cooling and degassing-induced crystallization. Degassing-induced crystallization is a dominant process for andesitic magma systems such as at Soufrière Hills Volcano (SHV), Montserrat (Sparks, 1997; Melnik and Sparks, 1999) and Merapi Volcano, Indonesia (Hammer et al., 2000; Innocenti et al., 2013a,b). Degassing results in rheological stiffening of magma, which in turn is a consequence of gas exsolution that triggers crystallization of microlites from undercooled melt (Hort, 1998; Melnik and Sparks, 1999; Cashman and Blundy, 2000; Hammer and Rutherford, 2002; Melnik and Sparks, 2002; Woods and Huppert, 2003). The volume fraction of melt and crystal content in the magma control its bulk viscosity (Hess and Dingwell, 1996; Costa, 2005; Melnik and Sparks, 2005). This volume fraction changes with pressure and magma flow rate, and the resulting morphology of a lava dome can be affected (Watts et al., 2002; Melnik et al., 2005).

Of fundamental importance to understanding many volcanic processes as well as mitigating volcanic hazard is detailed knowledge of the conditions required for dome collapse (Voight and Elsworth, 1997, 2000). Causal mechanisms and triggers contributing to individual collapse events include oversteepening of slopes, rainfall-driven gravitational collapse (Elsworth and Voight, 1992; Barclay et al., 1998; Carn

* Corresponding author at: 230 A Hosler, University Park, PA - 16802, United States.

http://dx.doi.org/10.1016/j.jvolgeores.2014.08.013

**Table 1**
Notation.

| Symbol | Description | Unit |
|---|---|---|
| $Q_{3D}$ | Flow rate in 3D geometry | $L^3\ T^{-1}$ |
| $v_{3D}$ | Flow velocity of fluid for 3D geometry | $L\ T^{-1}$ |
| $a_{3D}$ | Area of conduit for a 3D geometry | $L^2$ |
| $v_{3D}^{avg}$ | Average fluid velocity given by Hagen–Poiseuille's flow equation | $L\ T^{-1}$ |
| r | Radius of conduit | L |
| $f_n$ | Normal force applied on the particle in contact with another in PFC2D | $M\ L\ T^{-2}$ |
| $k_n$ | Normal contact bond stiffness | $M\ T^{-2}$ |
| $\delta_n$ | Overlap in the normal direction between 2 contacting particle in PFC2D | L |
| $f_s$ | Shear force applied on the contacting particle in PFC2D | $M\ L\ T^{-2}$ |
| $k_s$ | Shear contact bond stiffness | $M\ T^{-2}$ |
| $\delta_s$ | Particle overlap in the shear direction in PFC2D | L |
| $C$ | Material cohesion | $M\ L^{-1}\ T^{-2}$ |
| $\mu$ | Coefficient of friction of the material | – |
| $\sigma_{max}$ | Tensile strength of the material | $M\ L^{-1}\ T^{-2}$ |
| $\Delta L$ | Change in length on application of normal force on the sample/particle | L |
| $L_o$ | Original length of the sample/particle | L |
| $D$ | Original diameter of the sample/particle | L |
| $E$ | Young's modulus | – |
| $E_c$ | Microscopic modulus for particle–particle contact bond | – |
| $E_p$ | Microscopic modulus for parallel bond | – |
| $\zeta_c$ | Ratio of microscopic modulus to macroscopic modulus for particle–particle contact bond | – |
| $\zeta_p$ | Ratio of microscopic modulus to macroscopic modulus for parallel bond | – |
| $G$ | Shear modulus | – |
| $\Delta x$ | Change in length of the sample/particle in the shear direction | L |
| $\eta$ | Fluid viscosity | $M\ L^{-1}\ T^{-1}$ |
| $k^n$, $k^s$ | Parallel bond normal and shear stiffness respectively | $M\ L^{-2}\ T^{-2}$ |
| $\Delta U^s$ | Shear displacement for a given time step $\Delta t$ | L |
| $V_i$ | Shear velocity for the given time step $\Delta t$ | $L\ T^{-1}$ |
| $y$ | Length of sample/particle in the direction perpendicular to shear displacement | L |
| $w_C$ | Characteristic width of the conduit to represent the 3D flow rate to its representative value for the 2D geometry | L |
| $\phi$ | Friction angle of the material | – |
| $A$ | Area on which force is applied | $L^2$ |
| $A_o$ | Area of sample/particle before deformation | $L^2$ |
| $\tau_{max}$ | Shear strength of the material | $M\ L^{-1}\ T^{-2}$ |
| $\lvert V \rvert$ | Numerical value of pure shear force applied | $M\ L\ T^{-2}$ |
| $T_{liq,sol}$ | Temperature of the magma in the solution state | – |
| $T_{solidus}$ | Temperature of the magma below which the magma solidifies for a given pressure | – |
| $p$ | External pressure acting on the magma during the eruption cycle | $M\ L^{-1}\ T^{-2}$ |
| $a_T$ | Constant for the empirical expression to obtain the phase behavior of the magma at Soufrière Hills Volcano, Montserrat | – |
| $b_T$ | Constant for the empirical expression to obtain the phase behavior of the magma at Soufrière Hills Volcano, Montserrat | – |
| $c_T$ | Constant for the empirical expression to obtain the phase behavior of the magma at Soufrière Hills Volcano, Montserrat | – |
| $d_T$ | Constant for the empirical expression to obtain the phase behavior of the magma at Soufrière Hills Volcano, Montserrat | – |

et al., 2004; Elsworth et al., 2004; Simmons et al., 2004) and internal forcing and gas pressurization (Elsworth and Voight, 1995; Voight and Elsworth, 2000; Elsworth and Voight, 2001; Simmons et al., 2005). For a more comprehensive listing of mechanisms see Voight and Elsworth (1997) (Table 1).

One of the most basic influences on dome stability, the interior structure of a dome, is in general poorly understood (e.g. Hale and Wadge, 2003). The exact mechanical response of the volcanic edifice to magma intrusion is not clear (Annen et al., 2001) despite numerous studies to predict growth and eruption state (Anderson and Fink, 1990; Blake, 1990; Fink and Griffiths, 1990; Fink et al., 1990; Iverson, 1990; Swanson and Holcomb, 1990; Griffiths and Fink, 1993; Elsworth and Voight, 1995; Griffiths and Fink, 1997; Buisson and Merle, 2004; Elsworth et al., 2004). Quantifying the extent to which parameters such as extrusion and cooling rates and material properties including coefficient of friction, cohesional strength and dynamically evolving magma viscosity that control the morphology is important (Blake, 1990; Griffiths and Fink, 1997; Shen, 1998). Because the collapse of lava domes can produce devastating and deadly pyroclastic flows, a quantitative model of the internal structure of the lava dome is desired.

The focus of many previous studies was to predict the flow pattern and most importantly the eruption state of the evolving lava dome (e.g. Anderson and Fink, 1990; Griffiths and Fink, 1997; Shen, 1998). Available data aid the development of more sophisticated models that incorporate an improved understanding of the physics and rheology of the repeated growth and destruction of lava domes (Huppert et al., 1982; Fink and Griffiths, 1990; Iverson, 1990; Griffiths and Fink, 1993; Griffiths, 2000; Buisson and Merle, 2002; Buisson and Merle, 2004; Melnik et al., 2005; Morgan and McGovern, 2005a; Simmons et al., 2005; Hale and Mühlhaus, 2007; Hale et al., 2007; Hale and Wadge, 2008). Some of the previous models illuminate mechanisms that cause a transition from endogenous to exogenous lava dome growth. This transition of lava dome growth from endogenous to exogenous may be critical as it often coincides with significant changes in the extrusion rate and is a prelude to hazardous lava dome collapse events (Watts et al., 2002).

Here we use a two-dimensional numerical model to investigate dome growth on a horizontal surface where growth occurs about the axis of the conduit. The 2D model only considers two force components (neglecting the out-of-plane component for the calculations using the equation of motion and the force–displacement laws) and a moment component, unlike the case of a 3D model (3 components each of force and moment). This model uses the discrete element method (DEM) (Cundall and Strack, 1979) to represent the injection of magma into a central fluid core that evolves on its margins into a brittle

**Table 2**
Dimensions of the model.

| Conduit length (2D) | Equivalent conduit radius (3D) | Conduit width (2D) | Depth of conduit (2D) | Expanse of the base |
|---|---|---|---|---|
| 30 m | 15 m | 23.5725 m | 600 m | 600 m |