What makes a volcano tick—A first explanation of deep multiple seismic sources in ascending magma

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ABSTRACT

At many volcanoes, low-frequency earthquakes have often been associated with the state of a volcanic system and have been employed for eruption prediction. Several models attempt to explain the generation of such earthquakes, but fail to describe their clustering in tight spatial swarms and their highly repetitive nature. We present a new model that not only explains the generation of a single event, but also accounts for the swarm behavior and cyclic activity. By considering magma rupture as a source mechanism of seismic events, we demonstrate that a change in conduit geometry is the most plausible cause for their generation. Our model matches the observed spatial and temporal behavior of low-frequency seismicity and contributes to the understanding necessary to provide estimates of magma ascent rates.

INTRODUCTION

In contrast to normal tectonic earthquakes, low-frequency (LF) volcanic seismic events, observed at volcanoes such as Soufriére Hills, Montserrat (Ottemoller, 2008; Neuberg, 2000), or Mount St. Helens, Washington State, USA (Neri and Malone, 1989), offer key indications about the state of a volcanic system and have been used in attempts to forecast volcanic eruptions (Chouet, 1996). While several models explain the dominant LF characteristic of such events by resonance of a fluid-filled conduit (Neuberg et al., 2006), dike or crack (Chouet, 1996), or more recently by magma "wagging" (i.e., oscillating; Jellinek and Bercovici, 2011), the actual source mechanism that starts the resonance is still controversial. Recent field investigations (Tuffen and Dingwell, 2005), laboratory studies (Tuffen et al., 2008), and numerical models (Goto, 1999; Collier and Neuberg, 2006; Neuberg et al., 2006; De Angelis and Henton, 2011) have suggested rupture of magma as such a source mechanism; however, the existence of simultaneously active sources (Neuberg et al., 2006) has not been explained. Two questions remain unanswered. Where in the volcanic plumbing system are the conditions met to rupture magma? Why can this happen at multiple locations simultaneously? Using improved numerical conduit flow models we demonstrate that locations where magma can rupture are generally shallow, and in order to explain observed deeper source locations (Neuberg et al., 2006), an abrupt change in conduit geometry is necessary. Furthermore, we explain multiple sources via the formation of migrating fracture zones. Our models can explain all of the observed features of simultaneously occurring LF events, which has not been achieved by any previous model. This enables us to provide an improved estimation of magma flow rates at depth that can now be linked directly to observed seismograms, and may lead to the development of seismic forecasting tools.

LF volcanic seismic events often occur in swarms of repeating, similar waveforms (Fig. 1). Since events with similar waveforms must have the same time history and originate from the same location, this suggests that the sources must be stationary. The sources must also be both nondestructive and repetitive, as the event families are persistent through time. Considered in isolation, brittle failure of the magma in glass transition (Tuffen and Dingwell, 2005; Neuberg et al., 2006; Tuffen et al., 2008) is able to meet all of the required criteria for one such source, with the conduit itself acting as a resonator producing the LF component (Collier and Neuberg, 2006); however, this does not explain the patterns seen in Figure 1.

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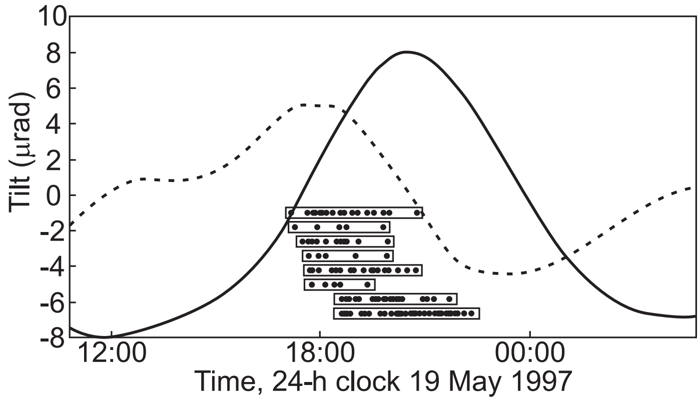

Figure 1. Families of events shown through time from Soufriére Hills Volcano, Montserrat, on 19 May 1997. Each dot represents an individual event; horizontal boxes define families in which each event has similar waveform. Families are compared to tilt and its time derivative (dashed line) record over same period (adapted from Neuberg et al., 2006).

MODELING CONDUIT FLOW

Rather than treating brittle failure of magma in isolation (e.g., De Angelis and Henton, 2011), we determine the conditions that lead to it through an integrated conduit flow model using the Navier-Stokes equation for fully compressible flow in conjunction with the continuity equation and solved through a finite element approach. The conduit model is represented by a 5000-m-long conduit of 30 m diameter, modeled in an axisymmetric domain space. The model parameters are representative of Soufriére Hills volcano, Montserrat, a well-documented dome-building silicic volcano (Barclay et al., 1998; Burgisser at al., 2010; Devine et al., 2003; Giachetti at al., 2010). Water is considered to be the only volatile species and homogeneous bubble nucleation is assumed using the pressure-dependent solubility of water within the melt (Liu et al., 2005). The conduit is treated as a closed system, and degassing processes are not included. The melt viscosity is dependent on the dissolved volatile concentration and temperature (Hess and Dingwell, 1996), and the overall magma viscosity is modeled accounting for the presence of crystals and bubbles (Collier and Neuberg, 2006). A comprehensive description of the model is provided in the GSA Data Repository[1].

Brittle failure of magma in a shear sense is now well documented (Gonnermann and Manga, 2003; Collier and Neuberg, 2006; Neuberg et al., 2006; Tuffen and Dingwell, 2005; Tuffen et al., 2008), and can be represented by the brittle failure criterion (Neuberg et al., 2006):

$$\frac{\eta_s \dot{\varepsilon}}{\tau_s} > 1, \tag{1}$$

where η_s is magma viscosity, $\dot{\varepsilon}$ the shear strain rate, and τ_s the magma shear strength. Brittle failure occurs if the shear stress, $\eta_s\dot{\varepsilon}$, exceeds the

[1]GSA Data Repository item 2012097, detailed description of the model, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

shear strength of magma, τ_s, and throughout this study brittle failure of magma in a shear sense is considered as the only source mechanism for the LF events. Magma may also fail in a tensile failure mode; however, tensile failure is not considered here as the primary source of the LF events, as the energy released from a tensile rupture is much smaller than from a shear rupture at the same strain value (McGarr, 1976), potentially requiring unrealistically large tensile fractures to explain the recorded seismic data. Key to understanding the brittle failure mechanism is the role of the shear strain rate within the magma, which is equal to the lateral velocity gradient, dV/dx, within a cylindrical conduit (Neuberg et al., 2006) or dike:

$$\dot{\varepsilon} = \frac{dV}{dx}. \tag{2}$$

Assuming the magma viscosity and shear strength remain constant, or vary only slightly, any significant increase in $\dot{\varepsilon}$ may lead to brittle failure.

RESULTS

Figure 2 shows the brittle failure ratio versus depth for the upper part of the modeled conduit. A no-slip boundary condition is applied at the conduit wall, leading to high strain rates ($\dot{\varepsilon}$) close to the wall where the lateral velocity gradient is largest. In general, failure is achieved where the magma accent velocity, accelerated by the exsolution and expansion of gas at low pressures, and the magma viscosity, increased by the loss of volatiles from the melt, reach critical levels. Assuming a magma shear strength of 10^7 Pa (Okumura et al., 2010), with the calculated magma viscosity of 3.01^9 Pa·s, failure of the magma only occurs at a shallow level (Fig. 2). Once the magma has fractured, it may ascend in a manner

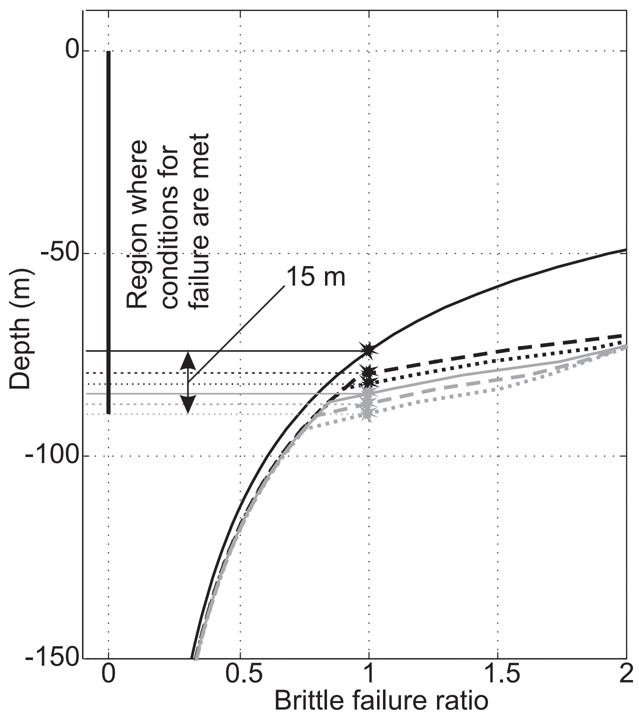

Figure 2. Brittle failure ratio plotted against depth for vertical profile through conduit taken at distance from conduit wall where strain rate, $\dot{\varepsilon}$, is greatest (0.5 m). This distance is not constant along length of conduit, and is dependent on modeled flow. Solid black curve represents initial case of no-slip boundary conditions where brittle failure is first theoretically possible at a depth of 75 m (stars indicate failure depth). Each curve below this defines a new potential failure depth after applying a slip velocity boundary condition based on depth of failure from previous models' results. After six iterative model runs, initial failure depth migrated 15 m deeper.

akin to friction-controlled slip along the generated fractures (Collier and Neuberg, 2006). To simulate the developing fracture zones at the conduit margin in our model, the flow boundary conditions at the conduit wall are altered to a viscous slip velocity condition. When the model is rerun with these new boundary conditions applied above the location of first failure, the subsequent failure depth moves deeper into the conduit. This is a result of a change in the pressure profile within the conduit. A drop in the flow-induced overpressure above the failure depth occurs as a result of the magma being able to move more easily, serving to accelerate the entire magma column as the chamber pressure is kept constant. The shear strain rate below the previous depth of failure is therefore increased, promoting failure now at deeper levels, where non-slip flow boundary conditions are still in place. Figure 2 also shows the brittle failure ratio verses depth for the upper part of the modeled conduit for six iterative model runs. For each subsequent run the failure depth moves to a deeper level, providing a mechanism for the creation of a new LF event source. Since there is an entire region of the conduit that satisfies the failure criterion rather than a single point, this also allows the possibility that several sources can be active at the same time. Conversely, the downward propagation of sources also offers an explanation as to why a particular family of LF events is no longer observed (Fig. 1). The generation of a fracture zone along the conduit wall leads to viscosity-controlled flow conditions and failure being localized on these fractures, without enough stored energy in the system to register a detectable LF event; thus the magma ascends aseismically, in agreement with seismic observations (Neuberg et al., 2006; De Angelis and Henton, 2011). Furthermore, as fractures become more pervasive throughout the magma column they will facilitate escape of the exsolved gas, resulting in an increase in bulk magma viscosity and density, slowing ascent rate, decreasing $\dot{\varepsilon}$, and resulting in conditions dropping below the brittle failure criterion. For our model parameters we find that the depth of failure is always very shallow (<100 m). However, at Montserrat, the observed LF events are located at ~1500 m below the dome (Neuberg et al., 2006; De Angelis and Henton, 2011).

Our modeling shows that failure deeper in the magma column is inhibited as viscosity (η_s) and strain rate ($\dot{\varepsilon}$) are intrinsically linked: if the magma viscosity increases, the ascent velocity decreases, having the overall effect of actually lowering the shear strain for all but the most viscous (shallow) material. This is a result similar to the sensitivity analysis of Collier and Neuberg (2006), where model parameters were varied within a realistic range in an attempt to facilitate failure. To resolve this discrepancy between model and observations, we introduce a constriction within the conduit as a plausible explanation for brittle failure at greater depths (Fig. 3). We test its effect by including a bottleneck region within the conduit at a depth of 1500 m, reducing the conduit diameter from 15 m to 10 m. The bottleneck is 100 m in length, which equates to only 2% of the total conduit length. Figure 3B shows ascent velocity and shear strain rate profiles from the bottleneck region compared to values from the same location of the conduit in an identical model without the constriction. By altering this relatively small region of the conduit, the shear strain rate increases by a factor of four. Crucially, with the exception of small changes in the magma rheology caused by the induced pressure gradients within the bottleneck, the magma viscosity has not been altered. Due to the increased value of shear strain rate the brittle failure ratio will increase by the same factor. By introducing such asperities into the conduit and increasing the strain rate it is possible to drive failure to deeper levels in the conduit that match the location of recorded LF events at Montserrat. The results demonstrate (Fig. 3A) that the entire length of the bottleneck has elevated values of $\dot{\varepsilon}$, indicating that there is an extended region over which failure may occur. However, the highest concentration of strain rate is located toward the top of the bottleneck, a likely position for a primary LF source. Any increase in velocity of the ascending magma, such as those engendered by assuming viscosity-controlled magma ascent

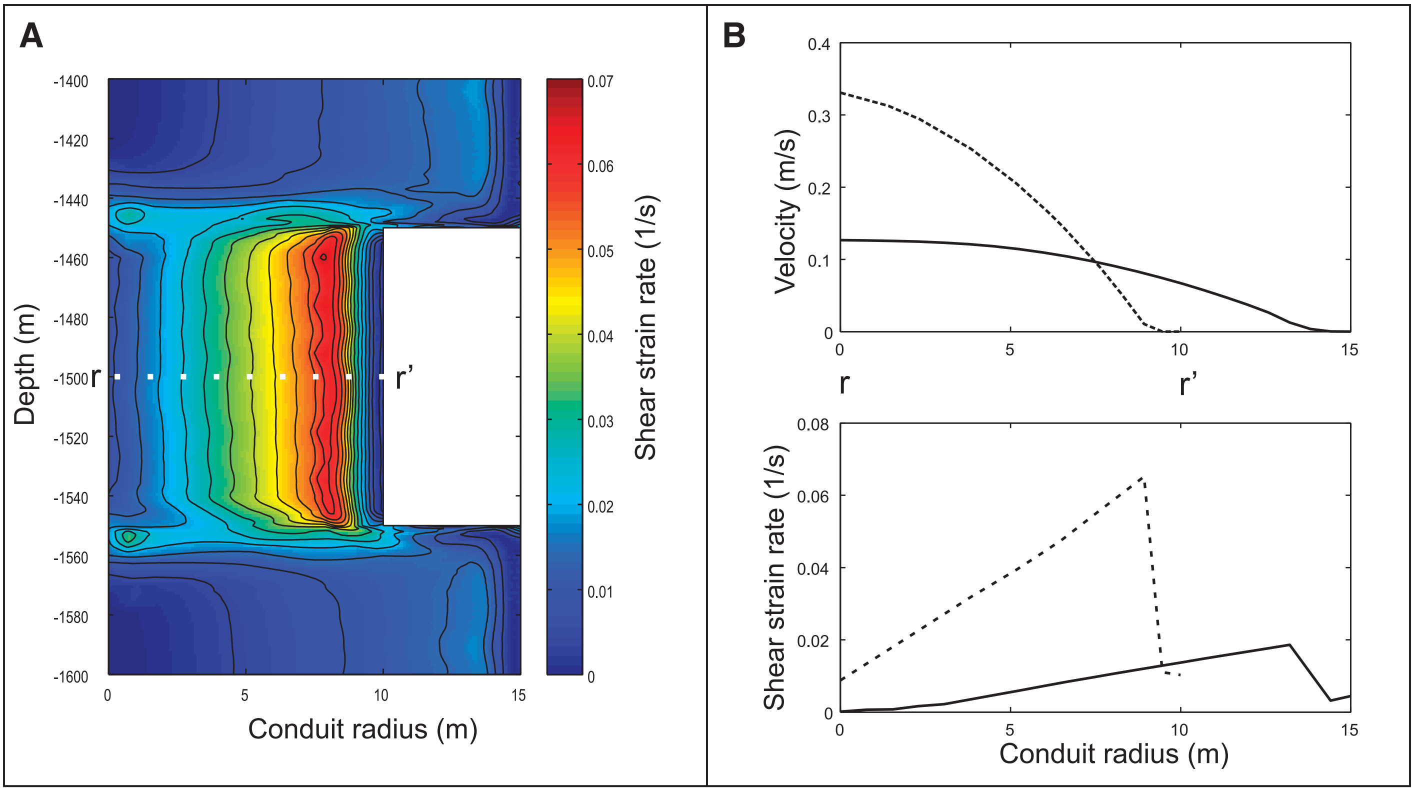

Figure 3. A: Plot of shear strain rate within simple bottleneck of 100 m length that decreases width of conduit from 15 m to 10 m over its length. Plot is overlain by contours of shear strain rate at intervals of 0.005. Values of shear strain rate are seen to be increasing over entire length of bottleneck. B: Cross-conduit profiles taken at same depth for velocity and shear strain rate for case of straight conduit (solid line) and conduit containing bottleneck (dashed line). Both ascent velocity and shear strain rate are significantly increased in the case of conduit with bottleneck present.

along the conduit walls above the first point of failure, may also push a deeper location past the brittle failure criterion, resulting in the generation of further active sources. Although we use a bottleneck in this example, it is representative of a generalized geometry change, and any change in conduit geometry that enhances $\dot{\varepsilon}$ will have a similar effect. The existence of such a deep localized asperity is supported at Montserrat by the location of seismic LF sources, and a similar asperity representing the transition of an elliptical dike into a cylindrical conduit at a similar depth has been independently proposed to explain the deformation pattern observed (Hautmann et al., 2009) or the cyclic activity (Costa et al., 2007).

DISCUSSION

We have shown that for silicic systems only a change in conduit geometry can produce conditions that allow the generation of LF events by brittle failure at the depth range observed at Montserrat, and that brittle failure can account for the creation and halting of LF sources (Fig. 4). In addition, our new conduit flow models also link the temporal behavior of seismic observations to accelerated magma ascent. As the magma moves

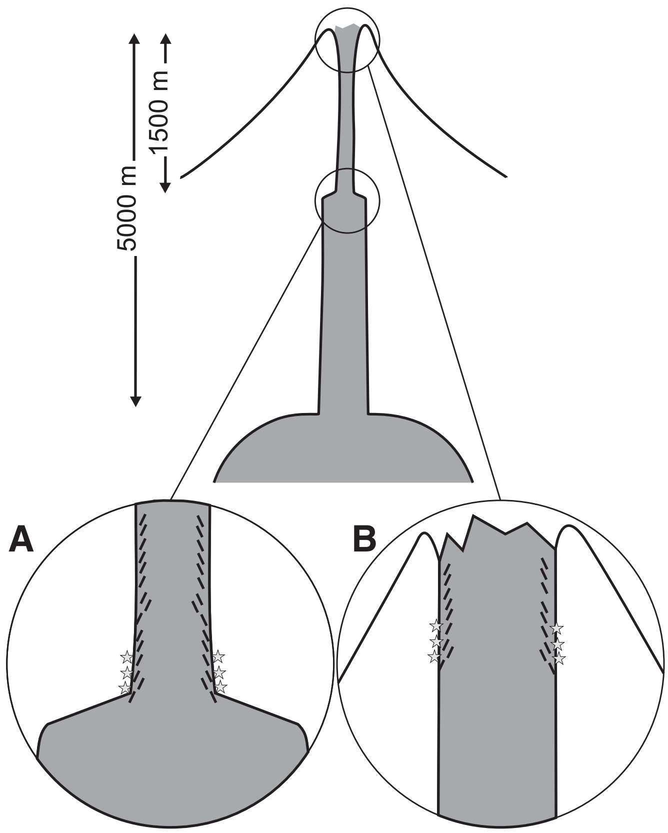

Figure 4. Schematic cross section through edifice displaying key points from model. A: Magma rises from deep chamber within elliptical dike and reaches conditions where it is able to rupture as conduit geometry changes into cylindrical dike ~1500 m below dome. Fractures form (short black lines), leading to generation of low-frequency events (stars). Eventually, failure is localized within existing fracture zones and magma ascends aseismically. B: Without change in conduit geometry, the model suggests fracturing at much shallower level, not supported by seismic observations.

along the conduit wall there is an initial location, strongly controlled by conduit geometry, where the brittle failure criterion is satisfied. Fractures generated at this initial failure location move upward in the conduit, forming fracture zones along the conduit walls which facilitate easier movement of the magma column. This causes the ascent velocity below the fracture zone to increase, tipping the next potential source location over the critical value for failure. This effect propagates down the conduit as magma ascent continues. However, as more sources become active, the fracture zone grows and the magma column starts to move aseismically along existing fractures where previous sources were located. This model provides an explanation for the temporal behavior of seismic sources depicted in Figure 1, and is in agreement with the dynamical behavior of LF swarms on Montserrat (Hammer and Neuberg, 2009), where an overall acceleration of seismic event rates between consecutive swarms is detected.

Furthermore, the model results match the tilt cycle in Figure 1, which can be used as an independent proxy for magma movement at depth. Green et al. (2006) demonstrated that accelerated magma movement will not only increase the pressure in the shallow conduit system (e.g., Hautmann et al., 2009), but contribute to the resulting deformation (here seen as tilt) through traction caused by viscous shear across the conduit wall. Seismicity commences and ceases when the tilt goes through an inflection point, demonstrating that seismicity is only generated if there is significant magma movement. It is this link to magma movement that will allow the model to be utilized in the development of a seismic forecasting tool. By calibrating the amount of seismic slip occurring within the magma during an LF swarm, an estimate of critical magma ascent rates that may lead to dome collapse (Hammer and Neuberg, 2009) can be gained. Also, the same families of LF events can be reactivated each time magma begins to move, explaining why similar families are seen across different periods of activity. Finally, the model places further constraints on the source mechanism of the LF events. While brittle failure of magma in glass transition has been shown here to provide a plausible explanation for the excitation mechanism of LF events as well as the temporal pattern of seismicity observed (Fig. 1), it would prove more difficult to explain such features through alternatives such as the fluid-driven crack model (Chouet, 1996) or magma "wagging" (Jellinek and Bercovici, 2011).

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