Cyclic eruptive behavior of silicic volcanoes

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ABSTRACT

Silicic volcanism seems chaotic: the styles, magnitudes, and/or timing of successive eruptions may be without apparent pattern, or patterns may merge, fade, or abruptly change. However, geophysical monitoring of recent eruptions shows that some silicic volcanoes can exhibit cyclic eruptive behavior wherein periods of explosive activity or rapid extrusion alternate with periods of repose. The cycles are commonly observed in time-averaged amplitudes of eruption-related seismicity and also have been observed in ground-surface tilt data. When tilt and seismicity are both observed during oscillatory behavior, as at Soufriere Hills volcano on Montserrat, British West Indies, they correlate in time. Cycle periods range from hours to days, and cycle amplitudes and waveforms vary widely. Complex oscillatory behavior is also sometimes observed during high-pressure (tens of MPa) extrusion of industrial polymer melts. With this phenomenon as a guide, we construct a simple dynamic model for the oscillatory behavior of erupting volcanoes. We propose that cyclic eruptions result from Newtonian flow of compressible magma through the volcanic conduit combined with a stick-slip condition along the conduit wall, in analogy to the behavior of industrial polymers. If magma is forced into the conduit at a constant rate, pressure and flow rate rise. If the flow rate through the conduit exceeds a threshold value, the flow resistance abruptly drops as the magma slips along a shallow portion of the conduit wall. This reduces resistance to flow and causes the flow rate to jump to a higher value. If this enhanced flow rate exceeds the supply rate, both pressure and flow rate decline as the compressed magma in the conduit expands. Eventually slip ceases as the magma reattaches to the conduit wall at a flow rate less than the supply rate. Consequently pressure begins to increase, and the cycle begins again. This simple model reconciles a variety of disparate phenomena associated with cyclic silicic volcanism and provides a paradigm to interpret cyclic eruptive behavior.

INTRODUCTION

At times, many silicic volcanoes exhibit cycles wherein periods of explosive activity or rapid extrusion alternate with periods of repose (e.g., Hoblitt et al., 1996; Voight et al., 1998). In some cases, the cycles are equally spaced in time; in other examples, the spacing changes in some regular fashion. Much of this cyclicity has only been recognized within the past few decades, as geophysical monitoring methods have been developed that reveal subtle patterns of activity invisible to the unaided observer. Cycles are commonly observed in real-time seismic amplitude measurement (RSAM), the time-averaged amplitude of volcanic seismicity (Endo and Murray, 1991), but have also been observed in tilt, i.e., the slope of the local ground surface (Voight et al., 1998).

The detailed time-variable nature of these phenomena is diverse at the same volcano as well as at different volcanoes, yet this diversity may result from small changes in the dynamic balance between flow resistance and the rate of pressurization produced by magma supply. This concept—that complex dynamic behavior results from the dynamic balance of magma supply and flow resistance—was introduced by Hoblitt et al. (1996) for the 1991 Mount Pinatubo eruptions and was reiterated by Voight et al. (1998) for the 1997 activity at Soufriere Hills volcano, Montserrat. We demonstrate here that simple processes may be coupled together in a quantitative, mechanical model that can be used to interpret complex eruptive behavior at silicic volcanoes. We first present some examples of cyclic eruptive behavior and discuss analogous behavior observed in the extrusion of industrial polymer melts. We then present our model and show how changes in supply rates and flow resistance can control the eruptive behavior.

CYCLIC ERUPTIVE BEHAVIOR

Cyclic patterns of seismicity and/or ground deformation (Fig. 1) were documented at Mount Pinatubo, Philippines, in 1991 (Hoblitt et al., 1996; Mori et al., 1996), and Soufriere Hills volcano, Montserrat, British West Indies, in 1996–1997 (Voight et al., 1998). Some waveforms exhibited by the time series for RSAM and/or ground-surface deformation are typically asymmetric. Eruption-related seismicity waxes and wanes in phase with ground-surface tilt (Fig. 1) because both respond to pressure changes. The volcano inflates as the pressure increases and deflates as pressure decreases. The pressure declines as the lava extrusion rate at the dome increases. These extrusion surges often trigger rock avalanches or pyroclastic flows, which appear as spikes on the declining limb of the RSAM cycles and are associated with deflation in the tilt (Fig. 1).

At Soufriere Hills, the periods in seismicity and tilt ranged from ~4 to 30 h and the oscillations in both records continued for weeks. Cyclic behavior was first observed in the seismicity (RSAM) records beginning in July 1996, when the record of dome growth constrained the average supply rate (Q_s) to between 2 and 3 m^3/s (Sparks et al., 1998). The oscillations in the RSAM records initially had low amplitudes, and no tilt-measurement station was close enough to the vent to detect any pressure oscillations in the conduit. By August 1996, RSAM records showed strongly oscillatory seismicity, and dome-growth records placed Q_s between 3 and 4 m^3/s. Tilt data taken close enough to the vent (i.e., Chances Peak; Voight et al., 1998) to be sensitive to conduit pressure oscillations are only available for December 1996 (Q_s between 2 and 3 m^3/s), and May–August 1997 (Q_s increasing from ~5 m^3/s in May to between 6 and 10 m^3/s in August). Both near-vent tilt and RSAM were

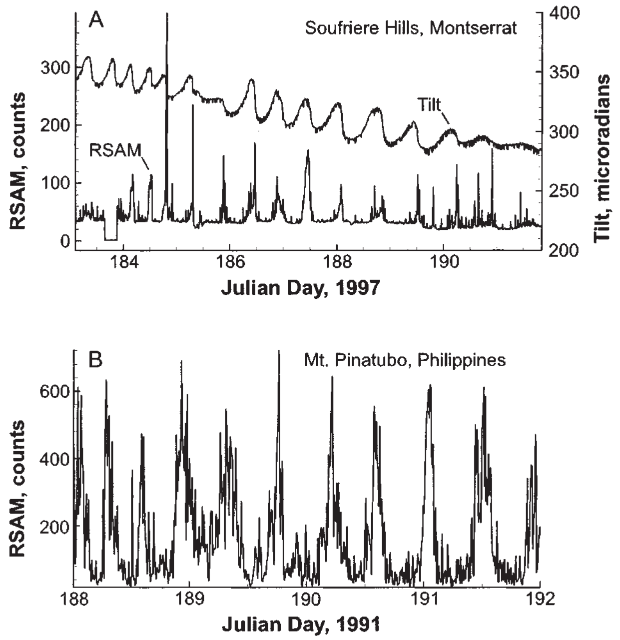

Figure 1. Cyclic ground surface tilt and real-time seismic amplitude measurement (RSAM) at Soufriere Hills volcano, Montserrat, and RSAM records from Mt. Pinatubo following its climactic eruption in June 1991. Cyclic variations in seismicity at both volcanoes are associated with variations in flow of magma in conduit; RSAM peaks correspond to periods of rapid extrusion.

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oscillatory during this period and were strongly correlated in time. Similar RSAM oscillations having periods of 7 to 10 h were observed at Mount Pinatubo following the climactic eruption in 1991; tilt data are not available for comparison. At both volcanoes oscillation periods were observed that do not fit any multiple of Earth or ocean tides. This behavior may, however, be analogous to that observed in industrial melt extrusion experiments.

OSCILLATORY BEHAVIOR OF POLYMER MELTS DURING HIGH-PRESSURE EXTRUSION

Many industrial polymer melts are known to exhibit oscillations in pressure and volume flux when extruded at high pressure (Leonov and Prokunin, 1994). In these experiments, a piston forces melt out of a reservoir and through a small diameter capillary tube or a slit die. Although the piston velocity, and thus the supply rate, is constant, the extrusion rate of melt and the driving pressure in the tube may oscillate in time. The oscillation period ranges from a few seconds to tens of seconds and pressure amplitudes range to 30 MPa. Oscillations only occur when the supply rate is within a particular range; above and below that range the output flux approaches the supply rate without oscillating.

Experimental results have implicated boundary processes as the likely cause of the oscillations. For example, direct observation of the melt oscillation process through stress birefringence and flow visualization shows that either slip or intense shear occurs at the wall when flow-rate jumps occur (Legrand and Piau, 1998). Thus, in addition to rheology, modeling efforts have focused on processes that occur at or near the melt-wall contact.

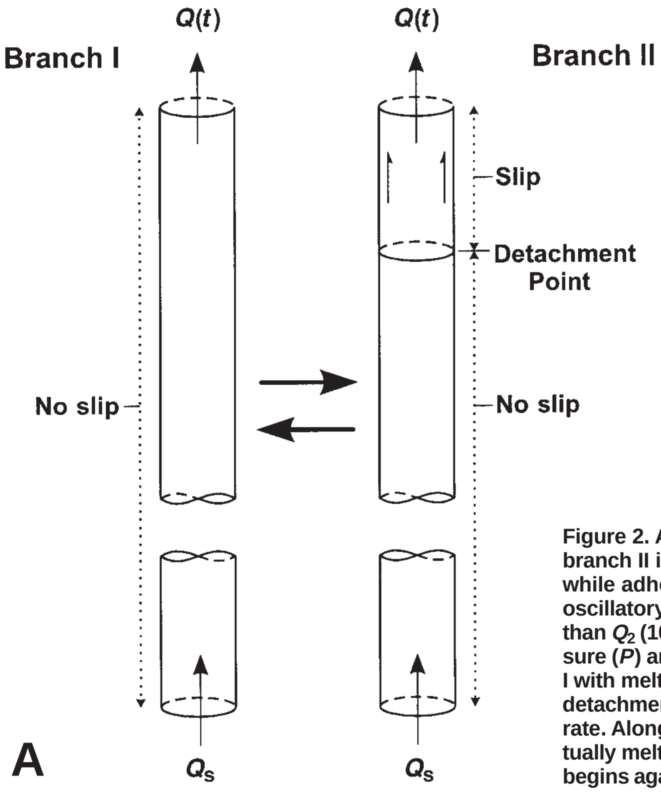
The most successful models require the specification of special boundary conditions near the wall. Building on efforts by Molenaar and Koopmans (1994) and Durand et al. (1996), Den Doelder et al. (1998) compared three models: a Newtonian fluid with a stick-slip boundary condition, a Johnson-Segalman-Oldroyd (JSO) fluid with a no-slip boundary condition, and a Newtonian fluid imbedded concentrically within a very thin second Newtonian fluid of much lower viscosity with a no-slip boundary condition. Only the first and third models are capable of describing the spurt flow observed in experiments, whereas the JSO (or shear thinning) fluid will not oscillate. These results were verified by numerical modeling studies by Jay et al. (1998), who also found that fully developed, plug-like flows are formed a short distance downstream of the transition from stick to slip when a frictional boundary condition is used. This was anticipated by Adewale and Leonov (1997), who concluded that oscillations were due to boundary processes and that rheology was of secondary importance.

DESCRIPTION OF A MODEL FOR CYCLIC ERUPTIONS

To model cyclic eruptions we adopt the simplest successful model used for polymer melts. Compressible magma is forced into a volcanic conduit at a constant rate, and laminar flow of the melt occurs with a stick-slip condition for sliding of the magma along shallow portions of the conduit wall. We assume that the melt has a Newtonian rheology; i.e., its viscosity is constant and does not depend upon shear rate or pressure. Thus both the magma pressure and the shear stress that the flowing magma exerts on the conduit wall increase linearly with magma supply rate.

The geometry of the model volcanic system is shown in Figure 2. By analogy with polymer literature, the magma column below the depth at which slip occurs is our reservoir of compressible melt, and the length of conduit over which slip occurs is our capillary. The depth at which slip begins is the detachment point, which is the maximum depth at which the wall shear stress exceeds the wall shear strength. It is well established (Paterson, 1978) that brittle shear failure within the Earth's crust is pressure dependent: the greater the depth, the greater the threshold for shear failure. Thus if the threshold for shear failure is exceeded at some depth, slip will occur from that depth to the surface. We assume that the depth over which slip occurs is small compared to the length of the conduit.

If the magma flux increases sufficiently the shear stress will exceed the shear strength of the magma-wall contact, and slip will occur. The critical flux that marks the onset of slip is designated Q_1; the corresponding pressure is P_1. The onset of slip only slightly affects the magnitude of the shear stress along the wall, but it greatly increases the shear rate. With wall slip, the magma behaves as a Newtonian fluid but has an abnormally high flow rate for the same pressure drop in the conduit. If this enhanced flow rate exceeds the supply rate, the conduit pressure drops and the compressed magma expands. As the pressure drops, the output flux decreases until slip ceases as the magma reattaches to the conduit wall at second critical flux Q_2 and pressure P_2. The cycle then starts over as wall slip is zero and the flux



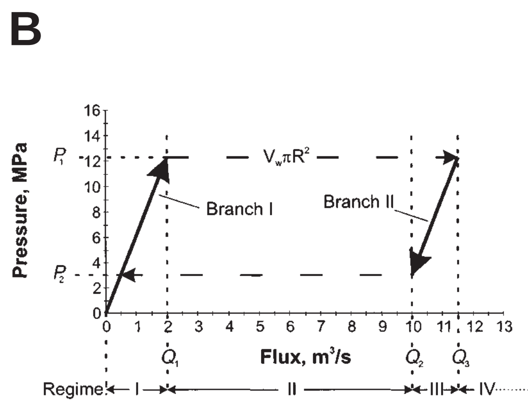


Figure 2. A: Conduit model. Along branch I in B, melt adheres to conduit wall. Along branch II in B, melt slips along near-surface portion of conduit (hundreds of meters) while adhering to remainder of conduit. B: Hysteresis in flow resistance that drives oscillatory flow. Nonoscillatory flow occurs for supply rates $Q_s < Q_1$ (2 m^3/s) or greater than Q_2 (10 m^3/s). For supply rates between Q_1 and Q_2, oscillatory flow occurs as pressure (P) and flow rate follow path shown by arrows. Pressure increases along branch I with melt adhering to wall everywhere. At Q_1, P_1 melt slips along conduit wall above detachment point and flux jumps from branch I to branch II as wall slip enhances flow rate. Along branch II, melt production exceeds supply and pressure decreases. Eventually melt readheres to conduit wall at Q_2 and P_2, flux switches to branch I, and cycle begins again. Such behavior is observed in high-pressure extrusion of polymer melts.

and pressure drop conform to Poiseuille flow. Because flux Q_2 is greater than Q_1 but pressure P_1 is greater than P_2, the pressure-flux changes describe a hysteresis loop, which for our example is illustrated in Figure 3.

As shown by Durand et al. (1996) and Den Doelder et al. (1998), this system may be approximated by coupling two differential equations, as follows. Combining conservation of mass with an equation of state leads to a differential equation for pressure change,

$$\frac{dP(t)}{dt} = \frac{K_f}{V}\left[Q_s - Q(t)\right], \tag{1}$$

where $P(t)$ = pressure at detachment depth, t = time, K_f = bulk modulus, V = magma volume of entire conduit, Q_s = constant magma supply rate, $Q(t)$ = the instantaneous output flux at the surface, and zero surface pressure is assumed. Integrating the stress equilibrium for a Newtonian fluid in the radial and axial directions, with axial flow only, leads to a differential equation for flux change,

$$\frac{dQ(t)}{dt} = \frac{1}{\beta}\left[P(t) - f(t)\right], \tag{2}$$

where $P(t)$ is the instantaneous pressure obtained from equation 1. The drag function $f(t)$ is given by

$$f(t) = \frac{8\eta L}{\pi R^4}\left[Q(t) - v_w \pi R^2\right], \tag{3}$$

where η = viscosity, L = length of conduit undergoing slip, R = conduit radius, and v_w = slip rate. Equations 1 and 2 are coupled by the pressure $P(t)$ and flux $Q(t)$, and drive oscillatory flow in the conduit through the alternating appearance and disappearance of wall slip v_w. For steady flow, Den Doelder et al. (1998) showed that the solution to equations 1 and 2 can be expressed as

$$Q(t) = \pi R^2 v_w + \frac{P(t)\pi R^4}{8\eta L}. \tag{4}$$

This equation is an approximation based on the assumption that the shear stress at the wall drops only slightly when slip begins, and is supported by experimental data for polymer melt-steel contacts (Durand et al., 1996). When $v_w = 0$, slip is not occurring and the equation describes nonoscillatory Poiseuille flow. When $v_w > 0$, the first term represents the flux enhancement produced by wall slip. The flux-enhancement term corresponds to the offset between the two branches of the hysteresis loop in Figure 2b. The constant β in equation 2 is given by

$$\beta = \frac{a_1 J_1(a_1)\rho L}{R^2}, \tag{5}$$

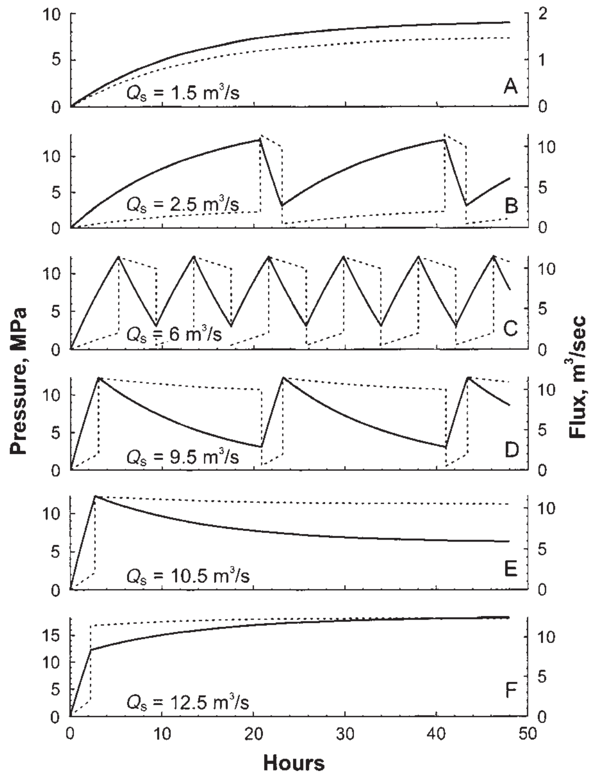
where a_1 is the first root of the Bessel function J_0, and J_1 is the derivative of J_0. The constant β expresses the ability of the magma to adjust the flow rate by changing the pressure drop along a cylindrical conduit. This parameter is estimated by differentiating the startup flow of an incompressible fluid in a conduit with respect to time (Bird et al., 1960, p. 126–130). The compressibility of melt is low enough that the difference in startup flow between incompressible flow and compressible flow is small compared to the period of oscillation, so this is a reasonable approximation.

The hysteresis loop in Figure 2B and the pressure-history curves in Figure 3 help illustrate the four behavior regimes of the model system. Branch I describes nonslip behavior and branch II describes behavior during slip. When the magma supply flux Q_s is less than Q_1, the output flux monotonically increases toward the supply rate (regime I, Fig. 3A). When Q_s is between Q_1 and Q_2, the output flux and pressure cycle through the hysteresis loop (regime II, Fig. 3, B, C, and D). When Q_s is between Q_2 and Q_3, the outflux initially climbs to a peak value, then monotonically decreases toward the supply rate (regime III, Fig. 3E). When Q_s is greater than Q_3, the output flux monotonically increases toward the supply rate (regime IV, Fig. 3F), just like regime I. For polymer melts, flux thresholds Q_1, Q_2, and Q_3 are usually determined experimentally.

DISCUSSION

The key elements of the oscillation model presented here are that (1) the magma is fed into the conduit at a constant rate; (2) the magma is compressible; and (3) the magma is Newtonian, and slips on the shallow parts of the conduit wall when the supply rate exceeds a threshold value. The model rheology is supported by experimental data showing that silicic magma is Newtonian at eruptive temperatures (Hess and Dingwell, 1996), and analysis of active reverse faults around the base of growing domes (Chadwick et al., 1983) supports the assumption that slip often occurs at shallow levels along the conduit walls. Although the model incorporates the assumption of a constant supply rate, this assumption is not rigid; i.e., changing the supply rate will merely change the behavior of the system. However, as long the supply rate is approximately constant, the periods and amplitudes of the pressure and output flux oscillations will be approximately constant.

With a Newtonian fluid, magma compressibility is required for oscillations to occur because then energy can be alternately stored and released as the magma alternately sticks and slips along the conduit wall. Incom-



PARAMETERS

Density (ρ): 2300 kg/m^3

Bulk modulus of melt (K_f): 0.3 Gpa

Conduit radius (R): 12 m

Conduit length for volume (V): 5 km

Viscosity (η): 10^8 Pa·s

Magma supply rate (Q_s): 1.5 to 12.5 m^3/sec

Length of slip (L): 500 m

Figure 3. Change in pressure cycle shape that results from varying supply rate for hysteresis loop shown in Figure 2. A: 1.5 m^3/s; B: 2.5 m^3/s; C: 6 m^3/s; D: 9.5 m^3/s; E: 10.5 m^3/; F: 12.5 m^3/s. Supply rates <2 m^3/s (Q_1 in Fig. 2) and >10 m^3/s (Q_2 in Fig. 2) do not produce oscillations. Supply rates between Q_2 and Q_3 produce initial peak in pressure that then decays to constant value. Waveform asymmetry results from supply rate closer to one end of hysteresis loop than other. This provides paradigm to interpret oscillatory behavior of erupting volcanoes.

pressible fluids can only store energy and exhibit oscillations if their rheology is visco-elastic (Adewale and Leonov, 1997). However, magmas are compressible, even in the absence of a gas phase, and given their typically high initial water contents we can safely assume that silicic magmas usually possess a separate gas phase which will enhance their compressibility. Hence, a visco-elastic rheology is not required for oscillations to occur.

For systems having supply rates, Q_s, within the oscillatory regime (regime II, Fig. 3), the shapes of the pressure and flux versus time waveforms are sensitive to the position of Q_s relative to Q_1, the rate at which detachment occurs, and Q_2, the rate at which reattachment occurs. When the supply rate is within and near the low end of the oscillatory range, the onset of each oscillation is gradual because the force differences driving the pressure increase are small. The falling limb is steep because a large force imbalance drives it. The opposite is true for supply rates approaching the reattachment rate: the rate of pressure increase in each oscillation is high relative to the rate of each pressure decline. Supply rates midway between Q_1 and Q_2 produce nearly symmetric waveforms. The oscillation period increases along with viscosity, volume, or conduit length. Increasing the bulk modulus or conduit radius shortens the cycle period. If we progressively increase the supply rate from Q_1 to Q_2, the period will at first decrease, and then increase.

The chief parameters available to document oscillatory eruptive behavior of volcanoes are the volumetric extrusion rate, the waveform, the period of pressure fluctuations recorded in ground surface tilt, and the period of fluctuations in volcanic seismicity recorded in RSAM. Dome-extrusion rates are typically difficult to measure on the time scale of the oscillations and are usually calculated as mean supply rates from changes in extruded lava volume over time intervals of days to months. In the context of this paper, these mean supply rates are equivalent to Q_s.

For the Soufriere Hills volcano, oscillations first appeared in the RSAM record when Q_s increased to about 2 m^3/s. This provides a good estimate of Q_1. From dome-growth rates (Sparks et al., 1998), we estimate with less confidence that the upper bound for oscillatory behavior (Q_2) occurs near 10 m^3/s. We use these estimates, the parameter values given in Figure 3, and equations 1 and 2 to produce the pressure-flux curves shown in Figure 3. The density in Figure 3 (parameters) is from Montserrat lavas (Sparks et al., 1998). The conduit geometry is estimated from measurements of other stratovolcanoes, chiefly Mount St. Helens (Moore et al., 1981) and Mount Redoubt (Benz et al., 1996). The bulk modulus is 47 GPa for vesicle-free melt at Mount St. Helens (Alidibrov et al., 1997), and studies of foams suggest that gas vesicles reduce this by two orders of magnitude. The length of conduit undergoing slip, L, is estimated from thrust-fault data at Mount St. Helens (Chadwick et al., 1983). The faults extended more than 200 m from the edge of the dome, and laboratory experiments of the process (Denlinger and Holmes, 1994) show that conduit slip at twice this distance is required for faults to extend this far.

In the unembellished form of the model presented here, we have assumed that the viscosity and bulk modulus are constant with depth and time. This is not true in nature; both will change when dissolved gas comes out of solution and escapes as magma rises from depth. However, even in this rudimentary form, the model at least qualitatively reconciles a variety of disparate phenomena associated with cyclic silicic volcanism.

CONCLUSIONS

The complex oscillatory eruptive behavior observed at silicic volcanoes may result from the alternate sticking and slipping of compressible magma along the conduit wall, analogous to the behavior of industrial polymer melts during high-pressure extrusion experiments. The oscillatory behavior can be modeled by introducing compressible magma into a cylindrical conduit at a constant rate, and by assuming that the resultant flow is Newtonian with the added flux enhancement of wall slip when the flow rate exceeds some threshold value. This simple model reconciles a variety of disparate phenomena associated with cyclic silicic volcanism.

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