PS Shallow Conduit Behavior of Silicic Magma Chambers: A Detailed Thermal Model*

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Abstract

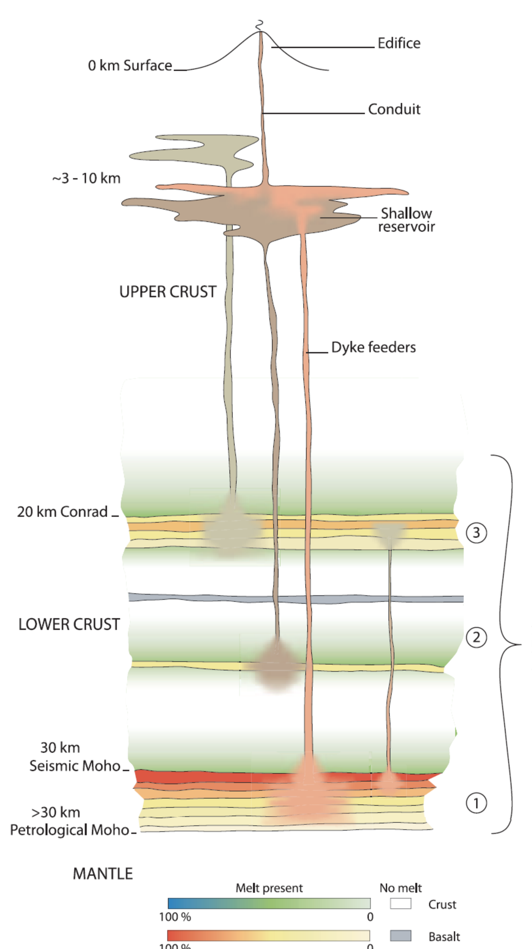
New theories of MOHO-depth silicic magma genesis (Annen et al, “The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones” (doi:10.1093/petrology/egi084) demand a reconfigured shallow storage and ascent model that adequately describes observation, experience and genetic properties. My work is in pursuit of construction such a model. Firstly, we will empirically and theoretically evaluate petrologic behaviors of the mantle/crust material (under a modified geotherm at the Moho) as a “hot zone” area of accumulating basalt melt injections, as an accommodation zone for dykes through which low viscosity melts travel, and (more shallowly) as a residence for partially evolved magma in chambers that feed directly to the surface. These observations will maintain close ties to thermodynamic responses, feedbacks and adjustments, which will be used to inform the thermodynamic state of the system at each step. Secondly, geodetic measurements taken over many years at active volcanoes (most notably, the Soufriere Hills volcano in Montserrat) will be used to develop models of surficial modification due to injection and ejection of new materials and to inversely evaluate that behavior in light of the modified system parameters suggested by our research. Finally, we will examine the seismic signatures of volcanic events as a key inverse modeling constraint. One of the most interesting aspects of this shallow thermal model will be its applicability to geothermal energy technology in the future. A new understanding of thermal behavior in the shallow crust may enable the pursuit of creative and revolutionary new clean, safe and ubiquitous energy reserves for global consumption.

SHALLOW CONDUIT BEHAVIOR OF SILICIC MAGMA CHAMBERS: A DETAILED THERMAL MODEL

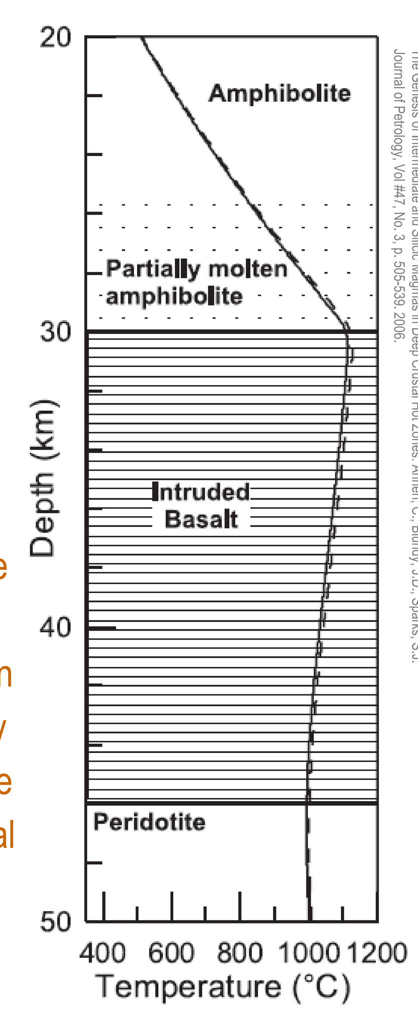
THERMAL, FLUID DYNAMICAL & PETROLOGICAL MODELING PREDICATED ON NEW THEORIES OF DEEPER SILICIC MAGMA GENESIS FOR MORE ACCURATE PHYSICAL & GEOLOGICAL INVERSE PREDICTIVE POTENTIAL RE: THE SHALLOW CHAMBER & PLUMBING SYSTEM

Cathina L. Gunn de Rosas; advising professor Glen Mattioli: University of Texas at Arlington, Department of Earth and Environmental Science ; May 2012

SILICIC MAGMA GENESIS: NEW THEORIES



The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones: Annen, C., Blundy, J.D., Sparks, S.J. Journal of Petrology, Vol #47, No. 3, p. 505-539. 2006.



The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones: Annen, C., Blundy, J.D., Sparks, S.J. Journal of Petrology, Vol #47, No. 3, p. 505-539. 2006.

New models proposed by Annen et al (2005) suggest that mantle wedge decompression in subduction zones emplaces the resultant hydrous basalt melts at Moho depths, rather than into the shallow crust where previous models have imagined them. This theory implicates an entirely new picture of deep-Earth processes, thermal gradient modification and morphological make-up (including a strong argument for the development of mafic crystallized residue that may ***constitute the seismic Moho*** above the petrologic Moho).

Annen et al propose that shallow crust injection of a basalt cannot generate the kind of heat necessary to melt the surrounding crust sufficiently to produce the volume of water required for low-viscosity and eventual ascent. It is likely that if the chemical evolution of intermediate magmas were restricted to the shallow crust, mafic melts would merely inject, crystallize while approaching equilibrium with the cold surrounding material, melt some insufficient portion of the crust and suffer a viscous death *in situ*. The model predicts a longer-lived magma-chamber situation in which the thermal gradient of the Earth keeps the bulk melt heated while magma evolution takes place.

One of the key points of this model is that, over time, the Moho-depth magma chamber will actually ***devolve*** as added injections ramp up the average temperature in the chamber and less crystallization occurs. It also describes how and why evolved melts will often possess very low viscosity (high pH_2O, temperature and pressure) and may actually ascend through fractures and/or dykes far more quickly than usually imagined, with an ***adiabatic superheating*** that re-melts phenocrysts and xenocrysts and precludes crystallizing anything new until reaching the water saturation point for its evolutionary stage.

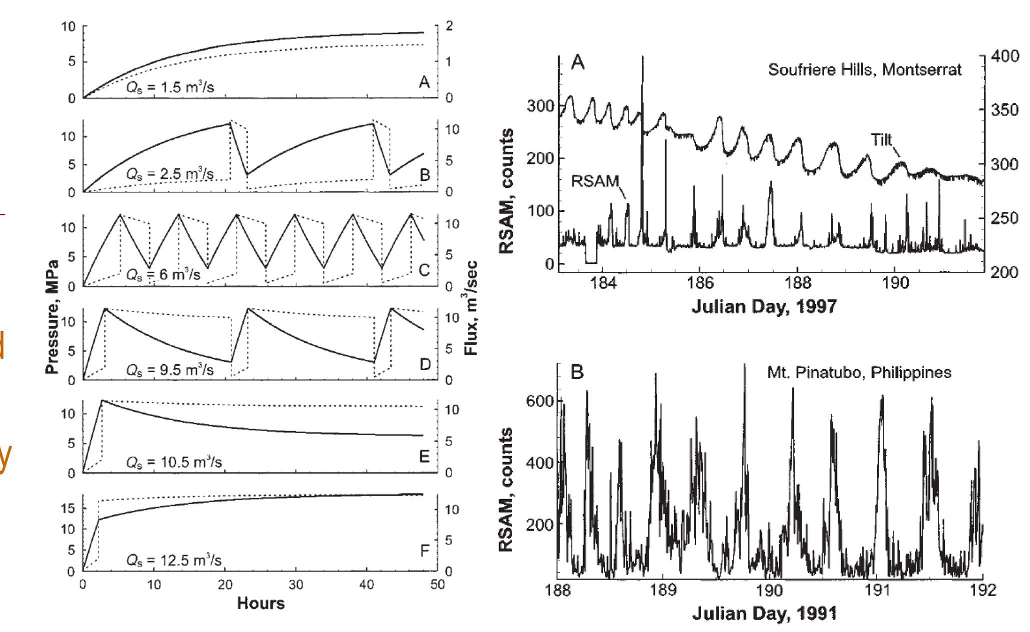
SEISMICITY AS A MODEL CONSTRAINT

Degassing and decompression have long been accepted as the most important factors in shaping shallow magma behavioral characteristics (e.g. the oscillatory behavior of silicic melts, the changing viscosity with decompression, microlite crystallization).

If these are processes that cannot, or often do not, take place over protracted lengths of time *in-situ* in a shallow magma chamber at low pressures and while rapidly (relative to greater depths in the geotherm at least) cooling, then a complete re-evaluation of silicic magmatic systems and the interpretation of their attendant symptoms may be in order. This is the main focus of my research.

This holistic model with new predicates taken from related models like those of Annen, et al, Voight & Sparks, et al and Hoblitt & Denlinger may reveal clues that have thus far eluded us; including possible subtle and recognizably unique seismic signatures that may be observable results of hydraulic fracturing in the brittle zone or the undulating viscous evolution of an ascending melt and it's resulting velocity shifts.

Our new expectations of ascent rates, viscosity and conduit geometry will be shaped by this new vision of silicic melt genesis and its mode of ascent. Some very rigorous and revealing work in the cyclic seismic rumblings and geodetic surface tilt related to volcanic events has already been done. The seismic oscillations at Soufriere Hills volcano in Montserrat have been observed and described in detail as their amplitude and patterns relate to the movement of magma through the shallow conduit plumbing system.



ABOVE: Cyclic eruptive behavior of silicic volcanoes: Roger P. Denlinger, Richard P. Hoblitt. Cascades Volcano Observatory, 5400 MacArthur Blvd, Vancouver, WA 98661. Geology; May 1999; v. 27; no. 5; p. 459–462

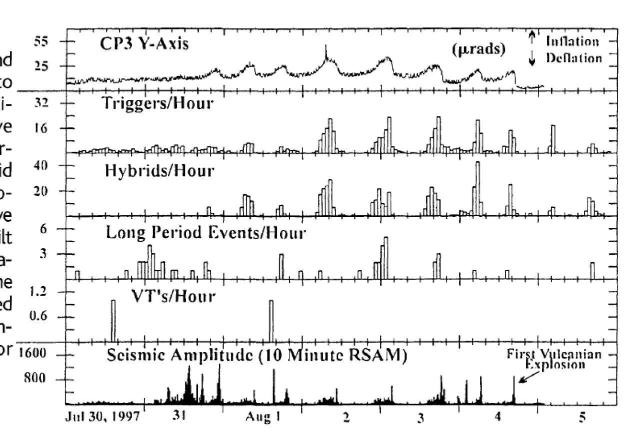


Fig. 4. Tilt at CP3 and seismicity for 30 July to 6 August. Strong amplitude tilt rises above background level, in correspondence with hybrid earthquake swarms. Sporadic LP activity is above background. *Y*-axis tilt data are used because radial tilt goes off-scale; the tiltmeter was destroyed on 5 August, after the onset of a series of major vulcanian explosions.

LEFT: Magma Flow Instability and Cyclic Activity at Soufriere Hills Volcano, Montserrat, British West Indies: *B. Voight, R.S.J. Sparks, A.D. Miller, R.C. Stewart, R.P. Hoblitt, A. Clarke, J. Ewart, W.P. Aspinall, B. Baptie, E.S. Calder, P. Cole, T.H. Druitt, C. Hartford, R.A. Herd, P., Jackson, A.M. Lejeune, A.B. Lockhart, S.C. Loughlin, R. Luckett, L. Lynch, G.E. Norton, R. Robertson, I.M. Watson, R. Watts, S.R. Young*
Science, Vol. 283, No. 5405 (Feb. 19, 1999), pp. 1138-1142: Stable URL: http://www.jstor.org/stable/2896747

Denlinger and Hoblitt (1999) use this seismic data to suggest that the melt can be modeled successfully as a Newtonian fluid with a **constant viscosity** so that flow rate as a function of time (Q(t)) increases inversely to the pressure drop of ascent. This behavior is modeled by equation 1, where P(t) is the variable pressure, viscosity (η) is a constant, R is the conduit radius and v_w is the slip rate. The change in rate ($^{dQ(t)}/_{dt}$) and the constant β is also defined (*eq 1 & 2*). "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-contacts (Durand et al., 1996). When $v_w = 0$, slip is not occurring and the equation describes non-oscillatory 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 … The constant β in equation 2 is given by" equation 3 (Denlinger & Hoblitt, 1999). "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" (Denlinger & Hoblitt, 1999).

Equations from Denlinger & Hoblitt, 1999

$$Q(t) = \pi R^2 v_w + \frac{P(t)\pi R^4}{8\eta L} \quad (1)$$

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

$$\beta = \frac{a_1 J_1(a_1)\rho L}{R^2} \quad (3)$$

This model suggests that flow increases with time until frictional coupling (which also increases up to a point) with the conduit wall is lost at some threshold velocity and slip occurs. It is this pressure/coupling conduit build-up and release during slip that ostensibly drives the seismic oscillation recorded in the figures for 1991 and 1997 above.

A conflicting view that observes the same seismic signatures but describes them as the result of a flow that decreases with time and is halted by the viscous creation of a conduit plug is presented by Voight & Sparks et al. This model suggests that changes in viscosity are not negligible and that pressure build-up occurs (*P(z) in equation 4*) as a function conduit shape (U), flow rate (Q), outlet viscosity at z = 0, (V_0) and the integral function where b and n are constants (Voight et al, 1999).

$$P(z) = UQV_0 \int \exp(-bz^n)dz \quad (4)$$

These two very intriguing perspectives on the seismic data (and ground tilt/surficial deformation data) observed at the Soufriere Hills Volcano, Montserrat are a key point in both the evaluation and testability of our developing model. A goal of the model will be to flesh out which view is more indicative of reality and why. A clearer understanding of the signature oscillatory behavior at silicic magma centers will be a momentous step toward our total understanding of volcanic events as well as the development and implementation of a pragmatic system of hazard management.

METHODOLOGY

- Theoretical evaluation of the mantle and crust as a "hot zone" area of accumulating basalt melt injections, as an accommodation zone for dykes through which low viscosity melts travel, and (more shallowly) as a residence for partially evolved magma in chambers that feed directly to the surface.
  - These models will incorporate thermodynamic responses, feedbacks and adjustments, which will be used to inform the thermodynamic state of the system at each step. The thermal conditions will be interconnected to properties of the chamber's surrounding material.
  - Petrologic structural, chemical and deformational character will play a major role in the model.
  - Non-Newtonian fluid dynamical modeling will be implemented to track the magma fluid evolution in terms of volatiles (content and volume) viscosity and chemistry to evaluate whether viscous evolution is significant in driving shallow oscillatory behavioral patterns.
- Surficial deformation evaluation utilizing precise geodetic measurements gathered over many years (most notably, the Soufriere Hills volcano in Montserrat) will be evaluated and continue to be gathered from the existing network of geodetic equipment in place.
  - These measurements will serve as a useful constraint and provide datum for inverse modeling of the physical deformation to describe and refine conduit geometry.
- Seismic reverberations in tandem with volcanic events (before, during and after) will be evaluated as a constraint and contributor to the models and may be a key piece of the data set as it will most usefully lend itself to prediction and prevention regarding dangerous volcanic events. This effort will begin with the work of Denlinger and Hoblitt as well as Voight et al.
- Empirical quantification of petrologic behavior of the mantle and crust material under a modified geotherm placed at the Moho by sample observation of rocks at the Soufriere Hills Volcano, Montserrat will be conducted to constrain and test evolutionary melt models.
- The final product of this research will be a dynamical multi-parameter model that can be adjusted to fit various circumstantial and stage-related variables to model and predict for a multi-faceted range of volcanic edifices.

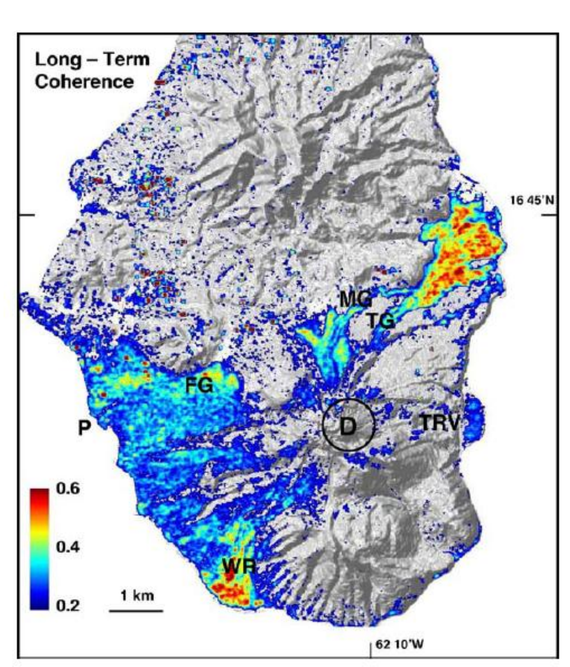


Fig. 1. Map of the long-term (1998–2000) coherence measured from ERS SAR phase returns from the surface of Montserrat. Note the low coherence on the lava dome of Soufrière Hills Volcano (D) and in the Tar River Valley (TRV). P marks the waterfront of the destroyed town of Plymouth, WR=White River, FG=Fort Ghaut, MG=Mosquito Ghaut and TG=Tuitt's Ghaut. Grey tone shows topography in areas of low coherence.

LEFT
Ground deformation at Soufrie`re Hills Volcano, Montserrat during 1998–2000 measured by radar interferometry and GPS
G. Wadge a, G.S. Mattioli, R.A. Herd
Environmental Systems Science Centre, University of Reading, UK
Department of Geosciences, University of Arkansas, USA
Montserrat Volcano Observatory, Montserrat, West Indies
Journal of Volcanology and Geothermal Research 152 (2006) 157-173

BELOW
Implications of Magma Transfer Between Multiple Reservoirs on Eruption Cycling
Derek Elsworth, et al.
Science 322, 246 (2008); DOI: 10.1126/science.1161297

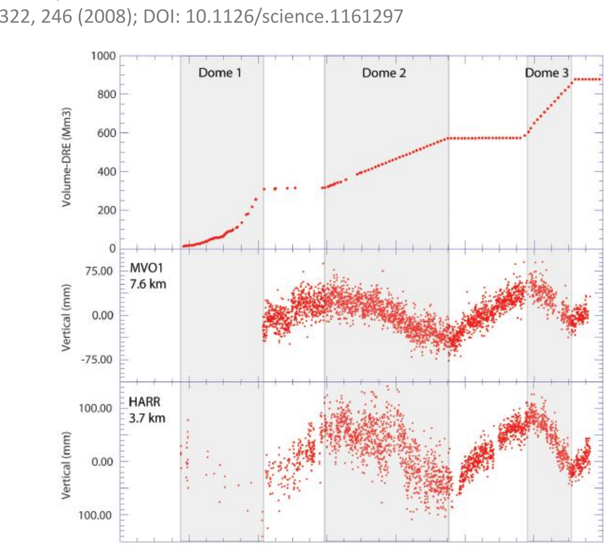


Fig. 2. Efflux of dense rock equivalent (DRE) from the SHV over time. Eruptive activity indicates three distinct active/repose cycles. Also shown is the evolution of station velocities within these prescribed cycles of activity. Resulting mean velocities are reported in table S1. Flux data from 1995 through early 1998 are from Sparks et al. (15) and data from 1998 are from electronically published MVO reports (6).

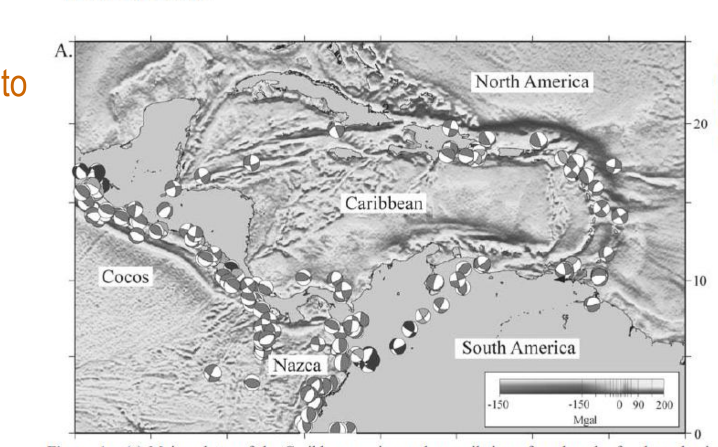


Figure 1. (a) Major plates of the Caribbean region and compilation of earthquake focal mechanisms showing present-day plate kinematics. Base map is a satellite-derived gravity map of the Caribbean compiled by *Sandwell and Smith* [1997]. Focal mechanisms shown in red are from earthquakes from 0 to 75 km in depth; blue mechanisms are from earthquakes 75 to 150 km in depth; and green mechanisms are >150 km in depth.

LEFT
Oblique collision in the northeastern Caribbean from GPS measurements and geological observations
Paul Mann, Eric Calais, Jean-Claude Ruegg, Charles DeMets, Pamela E. Jansma, and Glen S. Mattioli
Tectonics, Vol. 21, NO. 6, 1057, doi:10.1029/2001TC001304, 2002

GOALS & APPLICATIONS OF THE WORK

- Construct & model detailed thermal conductive & convective behavioral characteristics through various shallow crustal mediums, taking into account both the thermal properties of the surrounding rock as well as the evolving thermal properties of non-Newtonian magma.
- Effectively describe the viscous, volatile & thermal evolution of magma during ascent in a holistic, non-Newtonian way (strong emphasis in fluid dynamics)
- Describe the resultant silicic evolution of magma chemistry based on a presumptive chemical "devolution" in mature chambers at depth.
- Create a working computer model to predict & inversely describe both magma (chemistry, proclivity to stall, etc.) & conduit characteristics (size, geometry, petrology, etc.)
- This model can be coupled with surficial deformation models to heavily aid in the understanding & preventative "damage control" aspects of volcanology.
- There are also direct correlations with the kind of shallow crust thermal understanding that is critical to geothermal/hydrothermal energy technological advances.