GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 16, PAGES 3075-3078, AUGUST 15, 2001

Non-stationary entrainment and tunneling eruptions: A dynamic link between eruption processes and magma mixing

George W. Bergantz

Department Earth and Space Sciences, University of Washington, Seattle WA

Robert E. Breidenthal

Department of Aeronautics and Astronautics, University of Washington, Seattle WA

Abstract. The products of many intermediate arc volcanoes and batholiths manifest compositional complexity with mafic and mixed material occurring early and through-out a period of eruption and pluton assembly. We present a vesiculation model suggesting that the progressive and repeated vesiculation of volatile-rich magmas yields a super-linear buoyancy acceleration. This style of non-stationary entrainment provides a mechanism for compositional reversal, the intimate co-occurrence of mixed and un-mixed magmas, and rapid, chaotic crystal and melt dispersal. Under some circumstances, entrainment can cease entirely, producing eruptions with compositional tunneling where nearly unmixed mafic, or newly intruded silicic magma, exits first.

Introduction

The volcanic and plutonic products of arc volcanoes and continental caldera systems are usually interpreted to display a top-down eruption and assembly sequence with more felsic material being erupted initially. This concept has been generalized with the idea of evacuation isochrons [*Blake,* 1981; *Spera,* 1984]. However, this view has recently been challenged with a model that proposes that compositional diversity is dominated by processes of reintrusion [*Eichelberger et al.,* 2000] and variable entrainment. In addition, the volcanic products of some arc volcanoes display a reversal in the compositional sequence with mafic and mixed magmas erupting near the start and intermittently throughout a period of unrest. These reversed eruptions typically have a complex and non-monotonic progression of compositions and styles of mixing between basaltic to basaltic andesite, and dacitic endmembers [*Coombs et al.,* 2000; *Nakamura,* 1995; *Pallister et al.,* 1992]. The magma mixing processes can have a rise-time as short as days to weeks, consistent with intermittent episodes of mixing throughout the period of volcanic activity. We argue below that a new, but simple entrainment model can accommodate both these sets of observations. We propose that these features are expressions of eruption "tunneling." In our model, the co-occurrence of tunneling eruptions and magma mixing represents endmembers of a common process: Abrupt transitions in the mode of entrainment during progressive buoyant instability by vesiculation.

A number of models for magmatic systems emphasize the consequences of mafic or silicic magma intruding into the roots of a felsic magma chamber [*Bindeman,* 1995; *Eichelberger,* 1980; *Huppert et al.,* 1982; *Sission and Bacon,* 1999; *Sparks et al.,* 1977]. A common feature of these models is the role of vesiculation as a source of mechanical potential energy for magma mixing. The recent recognition that mafic arc magmas may contain from 3 to 6 wt. % water [*Sission and Bacon,* 1999; *Sisson and Grove,* 1993] provides additional support for the vesiculation models.

However, the importance of vesiculation has been discounted [*Snyder and Tait,* 1996], as the predicted degree of mixing and entrainment (see Figure 2 of [*Huppert et al.,* 1982] and Figure 4 of [*Youngs,* 1991]) is not consistent with the observations from the geological systems considered above. The essence of the criticism is the common assumption that the instability that accompanies the vesiculation of mafic magma produces stationary entrainment. In stationary enrainment, the mixing is rate-limited by the rotational period of the largest-scale vortex which must be proportional to its Lagrangian age [*Breidenthal et al.,* 1990]. The mixed fluid resides in the vortex cores which yields thorough, progressive mixing at ever-larger length scales as the multiphase instability grows [*Bergantz and Ni,* 1999; *Linden et al.,* 1994; *Youngs,* 1991]. This precludes the preservation of complex mingled features at many scales and does not provide for more primitive, or newly arrived material, to emerge unmixed early in the eruption. However if the entrainment is rendered non-stationary by the introduction of an externally imposed time scale, the vortex rotation period can lock onto the forcing time scale. This can reduce or termi-

Paper number 2001GL013304.
0094-8276/01/2001GL013304$05.00

nate entrainment (mixing) entirely by reducing the size of the vorticies [*Johari and Paduano,* 1997; *Kato et al.,* 1987].

We suggest below that stationary entrainment is not inevitable, and propose that non-stationary entrainment is consistent with the geological observations and the models of reintrusion and vesiculation. Our model is based on calculations that demonstrate that the potential energy, or buoyancy acceleration $g'(z)$, for tunneling eruptions can increase as the instability grows. This can arrest and/or delay entrainment and mixing, and in the absence of extreme viscosity or density ratio is the only known way to provide for both tunneling eruptions and a complex schedule of styles of mixing.

A model for tunneling eruptions

We begin with the proposition that vesiculation of newly-intruded silicic or resident mafic magma at the floor of a silicic chamber can lead to a density reversal, which will yield a Rayleigh-Taylor type instability. As the instability grows, tilted segments of the mafic-felsic interface generate vorticity. In stationary entrainment, these vortex sheets will roll-up and provide the mechanism for entrainment and subsequent mixing. However if the buoyancy acceleration, $g'(z)$, is increasing in the direction of transport, the incipient vortex is saturated by its own fluid, and entrainment (and thus mixing) ceases even though interpenetration of the mafic and felsic magmas continues. If this tunneling process continues to eruption, the gas phase can become interconnected, producing phase-relative-motion and separation [*Yoshida and Koyaguchi,* 1999].

We define the buoyancy acceleration as

$$g'(z) = \frac{2(\rho_{silicic} - \rho_{mafic})}{(\rho_{silicic} + \rho_{mafic})}, \tag{1}$$

where ρ is the bulk density of the respective magma and the vertical coordinate z is normalized by the distance between the depth at which the mafic and felsic magmas have the same density at the value $z = 0$, and by the fragmentation depth defined by the presence of 50% volatiles at $z = 1$. Equation (1) differs from the usual Boussinesq approximation in that the local values of the density contrast are used, which explicitly provides for in situ stratification and the mechanism of non-stationary entrainment.

There are two obvious models for entrainment. In the first case, the buoyancy acceleration $g'(z)$ increases linearly with height z above the plane $z = z_0$ at which the density of the two magmas is just equal. Then the gradient

$$\frac{dg'(z)}{dz} = \frac{1}{\tau_0^2}, \tag{2}$$

defines a time scale τ_0.

Assuming that the entrainment rate is negligible, the flow accelerates at approximately $g'(z)$, so that

$$g'(z) = \frac{d^2z}{dt^2} = \frac{z}{\tau_0^2}, \tag{3}$$

The solution is

$$\frac{z}{z_0} = \frac{g'(z)}{g_0'(z)} = e^{\frac{t}{\tau_0}}, \tag{4}$$

where z_0, the amplitude of the initial perturbation, and τ_0, the imposed time scale of the acceleration, are related by

$$g_0'(z) = \frac{z_0}{\tau_0^2}. \tag{5}$$

In the second case, the characteristic vortex rotation period $\tau = \delta/w$ is taken to be $(\tau_0 - \beta t)$, where δ is the width of the vortex and $w = dz/dt$ is its vertical speed. This corresponds to a "super-exponential" flow proposed to exhibit negligible entrainment. It is self-similar, in that the vortex rotation period declines by a constant fraction at each rotation for $\beta > 0$. This is in contrast to ordinary turbulence, $\beta = -1$, in which the rotation period increases by a constant fraction at each rotation, and mixing is enhanced.

If the vortex does not entrain, $\delta = \delta_0 = constant.$ Consequently

$$g'(z) = \frac{dw}{dz} = \frac{d^2z}{dt^2} = \frac{\beta\delta_0}{(\tau_0 - \beta t)^2}, \tag{6}$$

The solution is

$$\frac{z}{\delta_0} = -\left(\frac{1}{\beta}\right) ln\left(1 - \frac{\beta t}{\tau_0}\right), \tag{7}$$

and

$$g'(z) = \left(\frac{\beta\delta_0}{\tau_0^2}\right) e^{\frac{2\beta z}{\delta_0}}. \tag{8}$$

The buoyancy acceleration is now an exponential function of space and a super-exponential function of time. This contrasts with the first case, where $g'(z)$ is a linear function of space and an exponential function of time.

In analogy with earlier work on accelerating flows [*Breidenthal,* 1986; *Eroglu and Breidenthal,* 1998], the entrainment rate in the first case would be modestly reduced from non-accelerating turbulence such as ordinary Rayleigh-Taylor flow. The buoyancy imposes one time scale on the flow, the constant vortex rotation period τ_0. However, in the second case, there are two time scales imposed on the flow at any instant, the present rotation period and the next one. For large values of β, the entrainment rate is predicted to essentially vanish. The mafic intrusion would entrain some small amount of silicic magma in the initial linear domain of the first case, and little thereafter if $g'(z)$ became exponential. This would allow for vesiculating mafic material to penetrate without mixing and erupt by tunneling through resident silicic magma.

As a simple physical model, suppose $g'(z)$ in a magma chamber is proportional to z for small z, as in the first case, and then increases exponentially with z for large

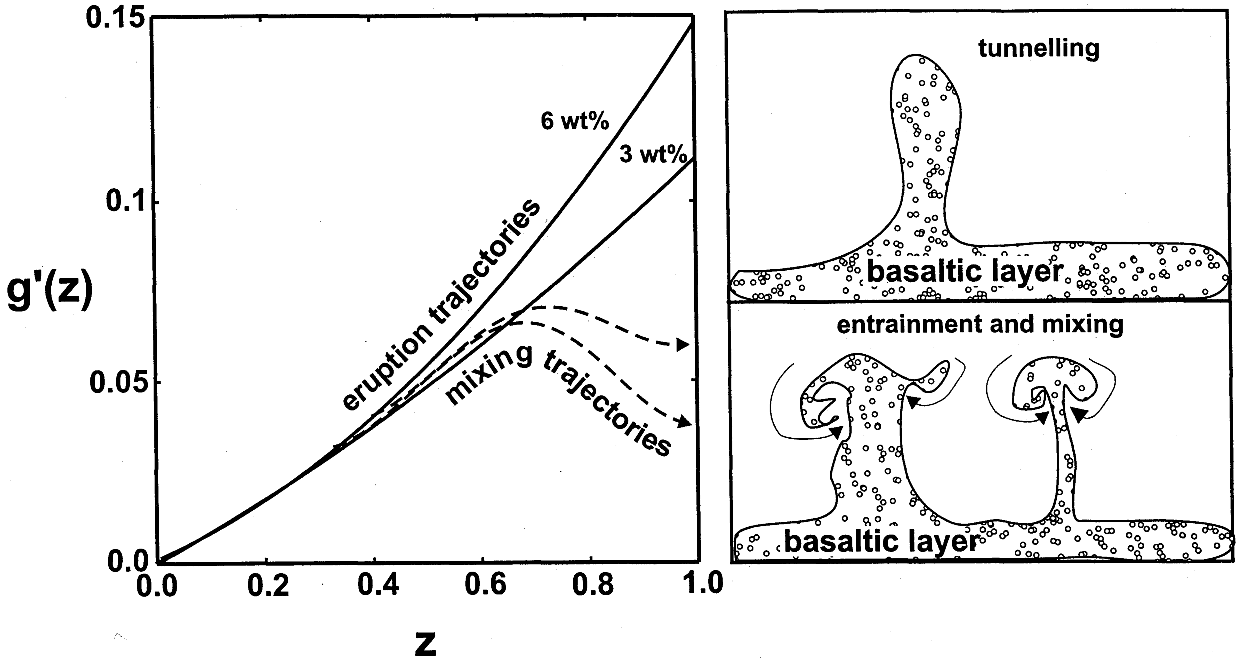

Figure 1. The buoyancy acceleration (equation 1) for arc basalt under dacite for two initial water contents of basalt. Increasing z is moving toward the surface. The state of each system was calculated using the MELTS code [*Ghiorso and Sack* 1995]. The calculation represents equilibration at the depth of incipient vesiculation of mafic magma on ascent. Because of the initial density contrast and co-precipitation of solids and volatiles, the density reversal does not occur until after some bubbles have formed. This also provides ample sites for bubble nucleation and it is assumed that there is negligible delay in vesiculation. The viscosity contrast between basalt and dacite varies by less than an order of magnitude during instability.

z, as in the second case. An initial perturbation displacing some mafic fluid above $z = 0$ would lead to a finger of it accelerating upward as vesiculation progressively increased its buoyancy. The requirement is that the buoyancy acceleration, $g'(z)$, is increasing at a linear spatial rate. Figure 1 shows the buoyancy acceleration, $g'(z)$, as a function of the dimensionless penetration distance from the originally unstable interface. The reduced gravity reflects the progressive density contrast between the vesiculating basalt and the over-lying silicic magma.

Examples of magma mixing from both volcanic and plutonic rocks suggests that most tunneling instabilities may fail. Recall that the entrainment rate is a sensitive function of $g'(z)$. Thus if the magma reservoir was stratified by density, a rising finger of mafic or newly-intruded silicic magma could find itself suddenly in a different environment, where $g'(z)$ was no longer exponential. Indeed, if $g'(z)$ became constant or decreased with z, the entrainment rate would dramatically increase, as shown in the dashed lines in Figure 1. This deceleration enhances entrainment, and this could lead to abrupt and rapid local mixing, yielding locally heterogeneous mixtures, and stalling the instability. It is the failed instabilities that provides the opportunities for mixing as expressed by efficient crystal and melt gathering and dispersal as documented by [*Davidson and Tepley III,* 1997]. As long as the retarding effects of viscous forces resist the strain of the bulk flow, the evidence of failed instabilities survives as enclaves.

Alternatively, the enclaves can burst or become dismembered by strain, distributing their contents locally and allowing for local and repeated re-entrainment of mixed debris in subsequent convective flow. The point is that vesiculation leading to initially non-stationary entrainment, that then fails, can repeatedly distribute mafic and partially mixed material locally, but widely, through-out the vertical span of the chamber on short time scales. Lastly, if the mafic magma is not sufficiently water-rich, or conditions for density reversal, $g'(z) > 0$, are not present, there will only be heat transfer between resident magma and mafic additions [*Robinson and Miller,* 1999].

Acknowledgments. We are grateful to C. Newhall, D. Yuen, M. Manga, M. Jellinek, V. Kress, J. Eichelberger, P. Wallace and B. Marsh for discussion and comments, although the conclusions are the authors responsibility. NSF grant EAR-9805336 to G.W.B. provided support.

References

Bergantz, G.W., and J. Ni, A numerical study of sedimentation by dripping instabilities in viscous fluids, *Int. J. Multiphase Flow, 25*, 307-320, 1999.

Bindeman, I.N., Retrograde vesiculation of basic magma in shallow chambers: Model of genesis of mafic inclusions in silicic and intermediate rocks, *Petrology, 3*, 576-587, 1995.

Blake, S., Eruptions from zoned magma chambers, *J. Geol. Soc. London, 138*, 281-287, 1981.

Breidenthal, R.E., The turbulent exponential jet, *Phys. Fluids, 29*, 2346-2347, 1986.

Breidenthal, R.E., V.R. Buonadonna, and M.F. Weisbach, Molecular mixing via jets in confined volumes, *J. Fluid Mechanics, 219*, 531-544, 1990.

Coombs, M.L., J.C. Eichelberger, and M.J. Rutherford, Magma storage and mixing conditions for the 1953-68 eruption of Southwest Trident volcano, Katmai National Park, Alaska, *Contri. Mineral. Pet., 140*, 99-118, 2000.

Davidson, J.P., and F.J. Tepley III, Recharge in volcanic systems: Evidence from isotope profiles of phenocrysts, *Science, 275*, 826-829, 1997.

Eichelberger, J.C., Vesiculation of mafic magma during replenishment of silicic magma reservoirs, *Nature, 288*, 446-450, 1980.

Eichelberger, J.C., D.G. Chertkoff, S.T. Dreher, and C.J. Nye, Magmas in collision: Rethinking chemical zonation in silicic magmas, *Geology, 28 (7)*, 603-606, 2000.

Eroglu, A., and R.E. Breidenthal, Exponentially accelerating jet in cross-flow, *AIAA J., 36*, 1002-1009, 1998.

Ghiorso, M.S., and R.O. Sack, Chemical mass transfer in magmatic processes IV, *Contri. Mineral. Pet., 119*, 197-212, 1995.

Huppert, H.E., R.S.J. Sparks, and J.S. Turner, Effects of volatiles on mixing in calc-alkaline magma systems, *Nature, 297*, 554-557, 1982.

Johari, H., and R. Paduano, Dilution and mixing in an unsteady turbulent jet, *Exp. Fluids, 23*, 272-280, 1997.

Kato, S.M., B.C. Groenewegen, and R.E. Breidenthal, On turbulent mixing in nonsteady jets, *AIAA J., 25*, 165-168, 1987.

Linden, P.F., J.M. Redondo, and D.L. Youngs, Molecular mixing in Rayleigh-Taylor instability, *J. Fluid Mechanics, 265*, 97- 124, 1994.

Nakamura, M., Continous mixing of crystal mush and replenished magma in the ongoing Unzen eruption, *Geology, 23 (9)*, 807-810, 1995.

Pallister, J., R.P. Hoblitt, and A.G. Reyes, A basalt trigger for the 1991 eruptions of Pinatubo volcano?, *Nature, 356*, 426- 428, 1992.

Robinson, D.M., and C.F. Miller, Record of magma chamber processes preserved in accessory mineral assemblages, Aztec Wash pluton, Nevada, *Am. Min., 84*, 1346-1353, 1999.

Sisson, T.W., and C.R. Bacon, Gas-driven filter pressing in magmas, *Geology, 27 (7)*, 613-616, 1999.

Sisson, T.W., and T.L. Grove, Temperatures and H_2O contents of low-MgO high-alumina basalts, *Contri. Mineral. Pet., 113*, 167-184, 1993.

Snyder, D., and S. Tait, Magma mixing by convective entrainment, *Nature, 379*, 529-531, 1996.

Sparks, R.J.S., H. Sigurdsson, and L. Wilson, Magma mixing: a mechanism for triggering acid explosive eruptions, *Nature, 267*, 315-318, 1977.

Spera, F.J., Some numerical experiments on the withdrawl of magma from crustal reservoirs, *J. Geophys. Res., 89 (B10)*, 8222-8236, 1984.

Yoshida, S., and T. Koyaguchi, A new regime of volcanic eruption due to the relative motion between liquid and gas, *J. Volc. Geothermal Res., 89*, 303-315, 1999.

Youngs, D.L., Three-dimensional numerical simulation of turbulent mixing by Rayleigh-Taylor instability, *Phys. Fluids A, 3*, 1312-1320, 1991.

G.W. Bergantz, Department of Earth and Space Sciences Box 351310, University of Washington, Seattle, WA 98195 USA. (e-mail: bergantz@u.washington.edu)

R.E. Breidenthal, Department of Aeronautics and Astronautics, Box 352400, University of Washington, Seattle, WA 98195 USA.

(Received April 13, 2001; accepted June 06, 2001.)