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Title: THE TRANSITION FROM DIAPIRISM TO DIKE INTRUSION: IMPLICATIONS FOR PLANETARY VOLCANISM

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A. Introduction

Magma transport processes influence the rate of magma transport and how far the magma travels before it freezes, the degree to which the magma communicates chemically with the host rock, the morphology of volcanic landforms on planetary surfaces, the interplay between magmatism and regional tectonics, and even the direction the magma moves. The primary question motivating this research is: How does magma rheology influence the mechanisms by which it is transported through planetary lithospheres? It is widely recognized that on Earth basaltic intrusions typically take the form of narrow dikes, while granites are typically found in more equidimensional plutons. Several explanations for this observation have been offered over the last 50 years. While basalts and rhyolites vary somewhat in temperature and density, the major difference is the 2 to 8 orders of magnitude contrast in viscosity. The significant ductile strains associated with many granitic plutons has led to the statement that the occurrence of granites in diapirs rather than dikes results from the fact that there is insufficient viscosity contrast between the magma and wall rock for the granite to intrude narrow cracks. A second explanation states that granites are so viscous that they cannot propagate far before freezing. Despite the length of time these explanations have been around, there has been relatively little effort to investigate them quantitatively. My goal has been to evaluate these explanations through a series of well-posed numerical models. These models can be tested by the decades of field data collected by structural geologists that have yet to be integrated into any coherent theory, and the results should have important implications for volcanism on the terrestrial planets.

B. Summary of work completed to date

Work completed following submission of original proposal but prior to 04/01/93:

(1) To assess the role of magma/host rock viscosity contrast, I examined numerically the problem of a viscous dike emanating from the top of a rising diapir in a viscoelastic medium [Rubin, 1993a]. The conclusion was that for expected ratios of the excess magma pressure at the dike entrance to the elastic stiffness of the host rock, the host rock must be more than 11 to 14 orders of magnitude more viscous than the magma in order to behave as essentially elastic during dike intrusion. While such viscosity contrasts seem surprisingly large, they are easily achieved by basalts and by most granites as well. However, very viscous granites might have a viscosity contrast of only 9 orders of magnitude with hot host rock. For such dikes the viscous dike opening displacement would exceed the elastic displacement by one to two orders of magnitude. At the same time, these dikes would have thickness:length aspect ratios of 1:100 or so, not the 1:10 or 1:1 required to generate a pluton. Thus the occurrence of granites in equidimensional plutons cannot be ascribed to the effect of insufficient viscosity contrast during dike *propagation*. This analysis did not examine the potential importance of magma/host rock viscosity contrast during dike *initiation*.

(2) To assess the influence of magma viscosity on the ability of dikes to transport magma from a source region without freezing, I examined the thermal/mechanical problem of dike propagating down a temperature gradient as it leaves a magma reservoir [Rubin, 1993b]. The magma and host rock temperatures are equal at the contact. Whether the dike is able to survive thermally, and ultimately feed a fissure eruption, depends upon the competition between the rate at which propagation widens the dike, and the rate at which magma freezing constricts the aperture available for magma flow. If the magma is intruded at its freezing temperature, so that freezing is slowed only by the release of latent heat of crystallization, a remarkably simple solution results. In this case, the thermal fate of the dike is determined by a single parameter β (essentially a dimensionless thermal diffusivity). For β greater than a single critical value, propagation is not possible because freezing would constrict the dike faster than propagation could widen it. Estimates of the relevant quantities (for the Earth) suggest that for most basalts β is only one-tenth the critical value, whereas for granites it is 100 times the critical value. Thus freezing apparently discriminates more efficiently between basalt and rhyolite dikes than does magma/host rock viscosity contrast. However, the scaling is such that β is proportional to the excess source pressure to the $-5/2$ power, but to viscosity only to the $1/2$ power. Therefore a 5 order of magnitude increase in viscosity can be offset by a one order of magnitude increase in excess source pressure. This can account for the occasional thick granite dike found far from its source.

Work completed since 04/01/93:

(1) *Continuing examination of the thermal problem:* Most of my time since the award date has been spent extending the thermal analysis in (2) above to magmas intruded at some temperature ΔT above the solidus [Rubin, 1993d (included as Appendix A)]. When $\Delta T=0$, either the dike can propagate or it can't, depending upon β . However, if $\Delta T>0$, then any dike could propagate at least some distance before freezing. Useful heat can enter the dike as latent heat L , or as $c\Delta T$, where c is heat capacity. For most dikes $L>c\Delta T$, but it is important to examine the case $\Delta T>0$ in order to explain field observations of dike thickness and occurrence as a function of distance from the source (such as a granitic pluton). Addressing this problem has necessitated developing new techniques for computing unsteady, as opposed to self-similar, dike growth. The results indicate that the most important changes introduced by the excess temperature can be accounted for simply by introducing a new parameter $\beta_{\Delta T}$, defined by substituting $(L+c\Delta T)$ for L in β . The conclusion is that for $\beta_{\Delta T}$ only 2 to 3 times the critical value of β determined for $\Delta T=0$, the dike will be halted by freezing shortly after the tip encounters rock at temperatures below the magma solidus. This can explain why granite dikes are common near granite plutons but rare elsewhere. It also runs counter to recent claims that dikes only 2 to 7 m thick are capable of transporting granites through the crust [e.g., Petford et al., 1993]; such claims do not address the question of whether dikes can survive to reach these thicknesses in the first place. I expect to submit the manuscript detailing these results by March, 1993 [Rubin, in preparation].

These results have implications for volcanism on Venus and the Moon. The scaling of β is such that a two order-of-magnitude increase in magma viscosity can be offset by a one order-of-magnitude decrease in temperature gradient leaving the source region. If melting on Venus takes place under dry conditions, then the viscosity of granitic melts would be 2 to 3 orders of magnitude greater than on Earth; it is very unlikely that the higher surface temperature would reduce the temperature gradient leaving the source by anything close to this amount. Thus silicic volcanism seems to be significantly more difficult on Venus than on the Earth, a conclusion that has implications for the interpretation of "pancake-like" domal features [Fink et al., 1993]. In addition, the unsteady dike propagation formulation with freezing is a necessary step towards determining the source conditions necessary for lunar basalts to erupt through 60 km of low-density crust.

(2) *Dike growth in a partial melt:* While the expected viscosity contrast between granite melts and their host rock seems to be sufficient for the propagation of narrow granite dikes, given a constant pressure source, it is possible that this viscosity contrast is low enough to suppress crack initiation. I have recently begun to model magma-filled crack growth in a partial melt. A simplified

analysis, that assumes deformation of the host rock to be elastic, suggests that for some range of crack length l ($1 \text{ m} < l < 100 \text{ m}$, for reasonable parameters) the propagation rate is nearly constant and equal to $(\Delta p_o / K_{Ic})^2 (kG/\eta)$, where Δp_o is the amount by which the background melt pressure exceeds the least compressive stress, K_{Ic} is the Mode-I fracture toughness, k is permeability, G is host rock elastic stiffness, and η is magma viscosity. In this regime the melt pressure in the crack is essentially uniform and growth is rate-limited by the influx of magma via porous flow. For larger cracks growth is rate-limited by channel flow as well, and magma buoyancy would become important. An interesting result is that for reasonable parameters, crack growth in a basaltic partial melt is fast enough that the matrix would respond essentially elastically, but that for a granitic partial melt, the propagation rate would be 5 or 6 orders of magnitude less and host-rock deformation would be dominantly viscous. This results in a negative feedback in which even more melt would have to enter the crack to continue to meet the propagation criterion, causing a further velocity reduction and increasing the chance that time-dependent stress relaxation at the crack tip would inhibit crack extension. The next steps will be to include viscoelastic deformation of the host rock, to determine when viscous deformation dominates, and magma buoyancy within the channel. The latter is very interesting because in the absence of buoyancy the porous flow is into the dike, but with buoyancy flow may be directed away from the dike near the dike top. Geochemical evidence for flow directed away from the dike has been found in mantle peridotites [Kelemen *et al.*, 1992].

(3) *Melt transport through the lithosphere:* As of December 21, 1993, I have hired Dominique Gillard, a post-doc from the University of Alaska, Fairbanks, to work with me interpreting earthquakes associated with magma transport beneath Hawaii. While there has been much speculation regarding the mechanics of magma transport through the lithosphere, very few direct observations are available to constrain these ideas. I believe that earthquakes from the surface down to 60 km depth in Hawaii represent a potential wealth of information concerning the nature of magma transport, but that continued theoretical advances and observations are required to fully exploit these data. I have recently shown how inelastic deformation of the host rock during dike intrusion is very sensitive to the ambient stress into which the dike is intruded [Rubin, 1993c]. I am currently adapting these results to predict the types of earthquakes that may be produced by intrusion, and Gillard is relocating and determining focal mechanisms for these events. We will also be modeling the stresses within the bending Pacific plate. Gillard is being funded jointly by this proposal and by NSF grant EAR-9219824. We expect to submit an AGU abstract by March 3.

C. References

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Magma Freezing in Near-Source Dikes

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The inability of viscous rhyolite dikes to propagate far from magma source regions may contribute to the typical occurrence of granites in quasi-equidimensional plutons. Flow of hot fluid through a cooler slot can be divided into a near-source region, or thermal entrance region, where most of the heat entering the slot resides in the fluid, and a downstream region where most of this heat has been lost to the solid. The thermal entrance length is proportional to the fluid velocity and the square of the channel thickness. For a near-source (two-dimensional, constant source pressure) dike, both velocity and thickness are proportional to dike length, so the thermal entrance length scales as the dike length cubed. Thus sufficiently short dikes are always less than the thermal entrance length, and magma reaching the dike tip has lost most of its heat (relative to the local wall rock temperature). If dikes are to survive thermally, then the dike length must exceed the thermal entrance length by the time the magma front reaches wall rock at temperatures below the magma solidus. For reasonable parameters this critical length at which (dike length) = (thermal entrance length) might be only 10 m for a basalt but 1 to 10 km for a rhyolite.

Two-dimensional finite difference solutions are obtained for the temperature distribution within growing dikes propagating down a temperature gradient when the wall-rock and magma temperatures are equal at the dike entrance. The dike thickness is determined by elasticity. Latent heat is included as an increased heat capacity over the crystallization interval, but in the first models magma viscosity is unaffected by cooling. Results from models that include temperature-dependent viscosity but handle dike shape only approximately may also be shown. The current results support inferences from an earlier self-similar model in which magma was intruded at the freezing temperature. The critical dimensionless group is the ratio of the time for heat to diffuse across the dike, to the time for propagation to double the dike thickness. For reasonable parameters, many (most?) rhyolite dikes will have difficulty leaving the source region. While transport of granites via dikes has become a popular concept recently, some mechanism for making this process "difficult" can help explain the occurrence of quasi-equidimensional plutons over a wide range of crustal depths. Preventing dikes from leaving a pluton aids ductile shortening of the host rock by keeping the least compressive stress (parallel to the contact) below the magma pressure (normal to contact).