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Conditions and threshold for magma transfer in the layered upper crust: Insights from experimental models

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[1] Magma transfer, i.e., dike propagation, is partly controlled by Young's modulus (elasticity) contrasts (ratio upper layer to lower layer modulus) in the host rock. Here we try to better constrain the elasticity contrasts controlling the propagation velocity of dikes and their arrest. We simulate dike propagation in layered elastic media with different elasticity contrasts. Salted gelatin and water represent host rock and magma, respectively. For common density ratios between magma and host rock (~ 1.1), velocity variations are observed and a critical threshold in the elasticity contrast between layers results in the Young's modulus ratio of 2.1 ± 0.6 . Naturally occurring elasticity contrasts can be much higher than this experimental threshold, suggesting that dike arrest due to heterogeneous elastic host rock properties is more frequent than expected. Examples of recently deflected or stalled dikes inside volcanoes and the common presence of high-velocity bodies below volcanoes suggest that better defining elasticity contrasts below volcanoes helps in forecasting eruptions. **Citation:** Ritter, M. C., V. Acocella, J. Ruch, and S. L. Philipp (2013), Conditions and threshold for magma transfer in the layered upper crust: Insights from experimental models, *Geophys. Res. Lett.*, 40, 6043–6047, doi:10.1002/2013GL058199.

1. Introduction

[2] Understanding magma ascent and extrusion is crucial to forecast eruptions and better assess volcanic hazards. Eruptions are usually fed by dikes: several factors control dike propagation, including magma input, buoyancy, solidification, and mechanical contrasts within the host rock [e.g., Gudmundsson, 2011a, 2011b; Taisne and Tait, 2011]. In particular, heterogeneous mechanical properties within the host rock may (a) accelerate or decelerate dikes approaching discontinuities, depending on the mechanical contrast [Rivalta *et al.*, 2005]; (b) arrest propagating dikes [Gudmundsson, 2006] or lower their dip, making their ascent difficult [Gudmundsson, 2011a; Maccaferri *et al.*, 2011]; (c) cause formation of sills at weak interfaces between layers of different mechanical properties [Gudmundsson, 2011a; Kavanagh *et al.*, 2006] or densities [Taisne and Jaupart, 2009].

[3] As dike propagation means that a fracture propagates through brittle-elastic rock, Young's modulus (elasticity, hereafter E) is the most important mechanical host rock

property to consider [Gudmundsson, 2011b]. E is the ratio of stress to the resulting strain in a solid body (Hooke's law). It is a measure of a material's stiffness. "Stiffness" also depends on the body's shape and the boundary conditions. E , however, is a material constant independent from the size and shape of the body and may directly be related to the fracture toughness of a material, which according to Weertman [1971] governs dike propagation. As E is much more convenient to determine experimentally than fracture toughness, here we characterize mechanical properties in terms of E and E contrast (ratio of upper layer to lower layer modulus). Materials with high E are referred to as "stiff" in rock mechanics.

[4] While the importance of E contrasts within the host rock for controlling dike propagation is widely recognized, few studies attempted to provide a threshold for the minimum contrast to arrest dikes. These studies considered dike arrest with weak interfaces between layers [Kavanagh *et al.*, 2006; Maccaferri *et al.*, 2011] or initially inclined dikes [Maccaferri *et al.*, 2010]. In general, E contrast for vertically propagating dikes through strong interfaces is of one order of magnitude [Rivalta *et al.*, 2005]. In nature, this contrast may occur between rocks with very different E values [Gudmundsson, 2011b], suggesting a limited control on dike arrest. This study aims at better constraining this threshold and its possible occurrence in nature. To this aim, we simulate dike propagation in layered elastic media (gelatin), testing different E contrasts. Our critical value for E contrast is much lower than previously thought. This value may be commonly found in nature, suggesting that dike arrest due to E contrasts is much more frequent than expected.

2. Scaling and Experimental Setup

[5] Gelatin and water were used to simulate host rock and magma, respectively. Pigskin-derived gelatin behaves brittle-elastic between 5–10°C and for loading times < 30 min. Its mechanical properties can be controlled through its concentration [Di Giuseppe *et al.*, 2009]. Salt was added to adjust the density ratio gelatin/water to ~ 1.1 , similar to the one of host rock/magma in nature.

[6] Our scaling procedure is based on Kavanagh *et al.* [2013], most suitable for the rise of buoyant dikes. Gelatin's E (E_g) $\approx 10^3$ Pa, as determined prior to experiments using the procedure of Kavanagh *et al.* [2013] and repeating measurements for different ages of the gelatin within the timespan relevant for the experiments. We use the following dimensionless scaling ratios between model and nature for the propagation velocity V^* and E^* [Kavanagh *et al.*, 2013]:

$$L_b^* = \left(\frac{K_c^*}{\Delta\rho^*} \right)^{\frac{2}{3}}$$

$$V^* = (\Delta\rho^*)^{\frac{1}{6}} K_c^* \frac{1}{\rho_{\text{solid}}^*}^{-\frac{1}{2}}$$

$$E^* = \Delta\rho^* L_b^* \left(\frac{L}{\Psi} \right)^*$$

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Figure 1. Side view sketch of the experimental setup.

with L_b = buoyancy length, K_c = fracture toughness of host material, $\Delta\rho$ = density difference between host material and fluid, ρ_{solid} = density of host material, and L/Ψ = length-to-aperture ratio of the dike.

[7] The in situ fracture toughness of crustal rocks is K_c (nature) $\approx 10^8 \text{ Pa m}^{1/2}$ [Rivalta et al., 2005] and that of gelatin is [Kavanagh et al., 2013]

$$K_c(\text{gel}) = (1.4 \pm 0.1)\sqrt{E}$$

[8] Assuming $E_m = 3.5 \text{ kPa}$, we obtain $K_c^* = 8.3 \times 10^{-7}$. The density difference between magma and host rock is $\sim 200 \text{ kg m}^{-3}$ (assuming $\rho_{\text{solid}} = 2800 \text{ kg m}^{-3}$) and is set to 100 kg m^{-3} in the models; thus, $\Delta\rho^* = 0.5$. L/Ψ in nature is $\sim 10^4$ [Gudmundsson, 2011b] and $\sim 10^2$ in the models.

[9] Therefore, the geometric, kinematic, and dynamic scaling factors are

$$L_b^* = 1.4 \times 10^{-4}$$

$$V^* = 2.0 \times 10^{-4}$$

$$E^* = 7.0 \times 10^{-7}$$

[10] For common values of layer thickness $\sim 1 \text{ km}$, $E = 10 \text{ GPa}$ and dike propagation velocity $\sim 1 \text{ km/day}$ are representative for nature [Gudmundsson, 2011b]. From the above relationships we obtain the following parameters used in our experiments:

$$l_m \approx 1.4 \times 10^{-1} \text{ m}$$

$$V_m \approx 2.4 \times 10^{-4} \text{ m s}^{-1}$$

$$E_m \approx 7.0 \times 10^3 \text{ Pa}$$

[11] The gelatin was prepared according to Di Giuseppe et al. [2009]. Salt water with $c_{\text{NaCl}} = 10 \text{ wt.}\%$ was used instead of distilled water to increase the density. A first layer of warm gelatin solution was placed in a tank ($30 \times 45 \times 30 \text{ cm}$; Figure 1) within a refrigerator at 5°C . When it had cooled to 14°C , $\sim 7 \text{ h}$ later, a second layer of gelatin solution with different concentration was carefully placed on top. After 15 h , both layers were stiff and the contact welded. Dyed water was then

injected, at a constant rate of 1.9 ml s^{-1} , into the gelatin from below using a peristaltic pump and a syringe. The developing dike was recorded with video cameras at a frame rate of 7.5 Hz from the side and above (Figure 1). The videos were decomposed into single images, and the dike dimensions were determined by counting pixels using a MATLAB script.

3. Results

[12] Seven models with different E_u/E_l (indices “u” and “l” denoting properties of the upper and lower layer, respectively) are presented (Table 1). Dike propagation in the lower layer, before reaching the interface, was similar in all the experiments, independent of boundary conditions: Upon injection, a crack with aspect ratio (width/height) > 1.5 formed. It progressively expanded horizontally and even more upward, decreasing its aspect ratio to ~ 1 . Further growth was mostly directed upward. When approaching the interface, the experimental dike resembled an upside-down teardrop with $0.8 > \text{aspect ratio} > 0.4$. Once the dike reached the interface, we observed two distinct behaviors that depended on the imposed boundary conditions.

[13] 1. Behavior A: The upper layer is much stiffer than the lower one ($E_u/E_l > 2.8$). A representative experiment is DA-08. In this experiment, the dike could not penetrate into the upper layer. As it reached the interface, the dike stopped ascending and propagated laterally. Its shape resembled first an anvil and later a truncated ellipse (Figure 2a).

[14] 2. Behavior B: E of the upper layer is similar to that of the lower one ($0.4 < E_u/E_l < 1.4$). A representative experiment with a slightly stiffer upper layer is DA-18. When the dike reached the interface, it first propagated laterally, then soon pierced the interface and finally propagated upward. Its final shape after crossing the interface resembled a bell on top of an anvil (Figure 2b). The anvil became narrower with decreasing E of the upper layer. It disappeared when E of the upper layer was less than that of the lower one (DA-24, DA-31; $0.4 < E_u/E_l < 1$). In this case the dike became wider in the upper layer and acquired a mushroom shape.

[15] The variation of the height of the propagating dike, normalized to the thickness of the lower layer, as a function of time shows that all dikes except DA-08 cross the interface (Figure 3a); at the same time, their velocity increases (DA-24, DA-31), decreases (DA-18), or remains constant (DA-25, DA-26, and DA-29). This variation of velocity depends on E of the host rock: The higher it is in the upper layer, the lower is the ascent velocity of the experimental dikes across the interface. The higher propagation velocity of DA-08 is only apparent, because the dike height is normalized to the lower layer, thinner in this case.

Table 1. Young’s Modulus (E) and Layer Thickness (l) for Each Model^a

Model	E_{lower} (kPa)	E_{upper} (kPa)	l_{lower} (cm)	l_{upper} (cm)
DA-08	2.5	7	9	6
DA-18	2.5	3.5	21	9
DA-24	7	3.5	21	9
DA-25	3.5	3.5	21	9
DA-26	2.5	2.5	21	9
DA-29	2.5	2.5	21	9
DA-31	2.5	1.1	21	9

^aThe indices “lower” and “upper” refer to properties of the lower and upper layer, respectively.

Figure 2. Side view photographs of experimental dikes shortly before the end of the experiment. (a) Case A: DA-08, with E of the upper layer much higher than that of the lower one. (b) Case B: DA-18, with E of the upper layer only slightly higher than that of the lower one.

Figure 3. (a, b) Temporal evolution of dike height normalized to thickness of the lower layer for experiments with different E contrasts (indicated by the numbers next to the lines). Dike heights are measured along the dike, not vertically, and can therefore differ for the same layer thickness due to slight differences in dike inclination. In Figure 3a E of the lower layer is kept constant; in Figure 3b E of the upper layer is kept constant. (c) Velocity ratio versus E ratio (see text for definition) for all experiments (blue diamonds). The inset shows an exponential curve fitted to the data (black line) and a comparison with data published by Rivalta et al. [2005] (red squares).

[16] Figure 3b shows a set of experiments with constant E in the upper layer and variable E in the lower one. It may be higher (DA-24), similar (DA-25), or lower (DA-18) than that of the upper layer. As a result, the observed ascent velocities in the lower layer differ. However, the velocities also differ in the upper layer, although E is constant there. This suggests that the ascent velocity of a dike in one layer may be partly varied by the elastic properties of the layer below.

[17] The variation of the ascent velocity of a dike at the interface, or its piercing capability, can be expressed by the ratio v_u/v_l with v_u and v_l being the ascent velocities shortly after and before the interface, respectively. Ratios > 1 indicate acceleration, ratios < 1 indicate deceleration. Figure 3c shows the variation of the velocity ratio as a function of the E ratio E_u/E_l . The relationship converges to zero for E ratios between ~ 1.5 and ~ 2.8 or 2.1 ± 0.6 . This means that for $E_u/E_l > 2.1 \pm 0.6$ dike propagation into the upper layer becomes hindered. The inset of Figure 3c shows the integration of our data (diamonds) with those of *Rivalta et al.* [2005] (squares), which confirm our result, allowing us to extrapolate an overall exponential behavior.

[18] We anticipate that the nonlinear trends of propagation of the dikes with heights > 1 in Figures 3a and 3b may be explained by the thickness of the upper layer in some experiments being lower than the buoyancy length of the dikes [*Kavanagh et al.*, 2013]. This may result in a dike propagation velocity not completely adjusted to the new environment in the upper layer.

4. Discussion and Conclusions

[19] Our experiments provide two main novel results:

[20] 1. The ascent velocity of a dike that just entered the upper layer may still be dependent on the elastic properties of the lower layer. This results from the fact that when the dike has just crossed the interface, part of its nose region is still in the lower layer. Therefore, E of the lower layer still controls the pressure inside the dike and thus the ascent velocity of the dike tip in the upper layer. This effect is expected to last until the nose region of the dike has completely entered the upper layer. Therefore, the ascent velocity of a dike does not only depend on the elastic properties of the host rock at the dike tip but also on those along its entire nose region.

[21] 2. For common density contrasts between magma and host rock (~ 1.1), the critical threshold in the E contrast between the upper and lower layer is $E_u/E_l > 2.1 \pm 0.6$. Above this threshold the dike will not propagate into the upper layer, consistently with theoretical and observational studies [*Gudmundsson*, 2011a]. This allows us to constrain more precisely an E threshold previously inferred, which varied by nearly one order of magnitude (Figure 3c, inset) [*Rivalta et al.*, 2005]. In nature, E contrasts inside a specific volcano are rarely known. However, reported values of E for rock samples usually span within two orders of magnitude, between 10^9 and 10^{11} Pa [*Gudmundsson*, 2011b, and references therein]. Accordingly, only the juxtaposition of rocks with high E contrast might have met the threshold previously inferred in *Rivalta et al.* [2005]. This suggested that E contrasts may have had a very limited control on dike arrest in nature.

[22] Our experimental results allow us to increase the resolution of this process, suggesting that a much smaller E

contrast in the order of ~ 2 is required to hinder dike propagation. As E contrasts in nature are usually much higher than this, dike arrest due to a variation in the mechanical properties of the host rock may be much more frequent and viable than expected. The critical value may depend on additional parameters not tested here as fluid inflow rate and viscosity. However, the experiments of *Rivalta et al.* [2005] had a constant injected mass of air, rather than constant inflow; their overall similar behavior suggests that both the inflow rate and fluid viscosity should not significantly affect our critical value.

[23] The possibility of dikes getting arrested more easily than previously thought is crucial to understand the rise of magma in the upper crust and to determine the probability of an eruption. Most ascending dikes stall at depth and do not trigger or feed any eruption [*Gudmundsson*, 2006; *Moran et al.*, 2011]. Several factors may be responsible for this, such as decreasing magma input, lower density of the host rock, cooling and solidification of magma, changes in the stress field due to the volcano load, or mechanical layering of the host rock. Our results suggest that the percentage of failed eruptions related to mechanical layering may be significantly higher than previously expected. Such layering may be responsible for the arrest or deflection of dikes inside volcanoes, influencing the probability of an eruption at a certain location.

[24] A noteworthy case of a dike that became deflected during its ascent occurred in 2004 at Asama volcano, Japan [*Aoki et al.*, 2009, Figure 4a]. The dike rose reaching the base of a high-velocity and high-resistivity zone stopped its ascent and propagated laterally towards the lateral end of the high-velocity zone; then it continued its ascent, reached the summit, and erupted. We do not attempt to evaluate any poorly constrained E value below Asama. However, the behavior of the laterally propagating Asama dike is qualitatively consistent with our experiments with $E_u/E_l > 2.1$, whereas the behavior of the vertically propagating dike resembles the experiments with $E_u/E_l < 2.1$.

[25] Another example of a stalled dike is from the Parícutin volcano, Mexico, in 2006 [*Gardine et al.*, 2011]. Here the propagation of seismicity implied the rise of a dike up to 4–5 km and then its lateral propagation. The magma may have reached neutral buoyancy, found a discontinuity, or encountered a mechanic barrier [*Gardine et al.*, 2011]. Available models of the crustal basement below Parícutin suggest that only very moderate density contrasts may occur at 4–5 km depth, whereas the lithological variability of the host rock [*Ortega-Gutiérrez et al.*, 2008] makes E contrasts seem a more likely explanation for dike arrest. Although the behavior of the dikes in these natural examples may be theoretically explained by different processes, as nonuniform stress fields [*Watanabe et al.*, 2002; *Maccaferri et al.*, 2011], it is likely that dike deflection and arrest is related to E contrasts. Our data suggest that these processes may be much more common than previously expected during volcano unrest and “failed eruptions” [*Moran et al.*, 2011]. This hypothesis is also supported by tomographic data that repeatedly highlight shallow high-velocity bodies below volcanoes, usually interpreted as solidified and stiffer magma, as at Etna and Vesuvius. These upper crustal bodies may form mechanical barriers to the rise of deeper magma, altering the propagation path of dikes and also preventing eruptions.

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