1 Mapping Real Time Growth of Experimental Laccoliths: 2 The Effect of Solidification on the Mechanics of Magmatic 3 Intrusion

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9

10 Abstract

11 The dynamics of solidification front growth along the margins of magmas
12 have been widely found to be fundamental in controlling magma transport and
13 emplacement. In this vein, the role of solidification fronts in determining the basic
14 growth mechanics of laccoliths are investigated here in a series of scaled
15 experiments using two contrasting magma analogs, water and molten wax that are
16 injected into a visco-elastic gelatin based crustal analog. In non-solidifying, water-
17 style experiments, intrusion is a relatively simple process. In contrast, wax *magma*
18 emplacement displays a vast palette of compelling behaviors: propagation can slow,
19 stop, and reactivate, and the directionality of lateral growth becomes much more
20 variable. Small flow deviations in water-based intrusions are likely the product of
21 flow instabilities, the result of injecting a viscous fluid along an interface (similar to

Hele-Shaw cell experiments). However, the much more complex emplacement style of the wax experiments is attributed to solidification at the leading edge of the crack. The overall effects of solidification during emplacement can be described by a non-dimensional parameter measuring the relative competition between the rates of crack propagation and solidification at the crack leading edge. In this context, laccolith growth mechanics can be separated into three distinctive characteristic stages. Namely, **I**: A thin pancake style sill initially emanating radially from a central feeder zone, **II**: As solidification stalls magma propagation at the leading edges, enhanced thickening begins, forming a true, low aspect ratio laccolith, and **III**: As stresses accumulate, tears and disruptions readily occur in the solidified margin causing fresh breakouts, thus reactivating lateral growth into new lobes. The competitive combination of these latter stages often leads to a characteristic pulsatile growth. The unexpected richness of these results promises to add fundamentally to the basic understanding of laccolith growth mechanisms, and also adds key observations to growth processes to be sought in field studies that have been hitherto suspected but rarely observed. Despite seemingly simple shapes, the growth history of laccolithic intrusions is likely quite complex.

Keywords: Laccoliths; Laccolith Growth; Magma Dynamics; Gelatin Experiments

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1. Introduction

45 During solidification, magma viscosity increases by a factor of about 10^{16} ,
46 making it one of the most important properties governing magma transport and
47 emplacement (e.g., Marsh, 1981; 1996; 2013). Moreover, it is also perhaps the single
48 magmatic physical property most difficult to accurately emulate in analog
49 experiments due to its dependence on both crystallinity and interstitial melt
50 composition, which are intimately related to temperature. Primarily for this reason
51 and awkwardness in handling, temperature dependent viscosity has often been
52 ignored in experiments involving magma emplacement mechanics, where a magma
53 analog fluid has been commonly chosen as air or water (e.g.: *Air Injection*: Dahm,
54 2000; Bons et al., 2001; Muller et al. 2001; Rivalta and Dahm, 2006. *Water Injection*:
55 Fiske and Jackson, 1970; Takada, 1994; McLeod and Tait, 1999; Menand and Tait,
56 2001; Kavanagh et al., 2006). Notable recent exceptions to this tendency are given
57 by Currier et al. (2010), Currier (2011) Taisne and Tait (2011) and Chanceaux and
58 Menand (2014). Despite the possible fundamental effects of viscosity on
59 emplacement, generally accepted models of laccolith formation have, instead, relied
60 primarily on the visco-elastic nature of the country rock, which governs
61 deformation and fracturing. In a very real sense this is understandable given the
62 long-standing common assumption, inadvertent or not, that low crystallinity magma
63 is more or less ‘instantly’ injected to form many smaller igneous bodies, thereby
64 minimizing the possible importance of viscosity variations. This perspective,
65 however, has progressively changed with the growing recognition that many bodies
66 have been emplaced in a piecemeal fashion (e.g., Menand, 2006; Morgan et al., 2008;
67 Horsman et al., 2010; Patwardhan and Marsh, 2011; Zieg and Marsh, 2012). The

present work thus aims at augmenting previous studies by exploring the influence of viscosity and solidification on laccolith emplacement, and at the same time attempting to be consistent with known magma dynamics and, perhaps, even the broader aspects of lava dynamics.

Laccoliths are magmatic intrusions concordant with local strata. They are characteristically of low aspect ratios ($\sim 1:10$, thickness to diameter), which distinguishes them from high aspect ratio sills ($1:100$ - 1000). Classically portrayed, laccoliths have flat floors and a bell-shaped roof; but there are many concordant, low-aspect ratio intrusions deemed laccoliths that have flat-topped roofs.

Laccoliths were first described by G. K. Gilbert (1877) in his study of the Henry Mountains, where he provided a simple and direct model for their formation. First, a thin intrusion radially emanates from some feeder site; and second, radial growth ceases and thickening ensues in a piston-like motion. The critical transition from radial growth to growth by thickening, however, was not considered. .

Early on, several authors argued that variable magma viscosity may play a role in laccolith formation (Weed and Pirsson, 1898; Paige, 1913; Darton and Paige, 1925). They reasoned that cooling would fully crystallize the thin edges of the intrusion, and subsequent injections, unable to advance radially, would instead be forced to fill the active central portion, thus warping the roof, and forming a bell-shaped intrusion.

From the perspective of plate bending theory, the crust is taken to approximate one or more elastically deformable plates. The shapes of laccoliths can be approximated, therefore, using rock strength, thickness of the overburden, and

magma overpressure; the overall process being broadly similar to the physics of fluid driving the piston of an hydraulic jack buried in elastic overburden. Pollard and Johnson's (1973) novel analysis, which accurately matched many of the basic laccolith spatial features, seemingly struck down the possibility that variable magma viscosity might influence laccolith formation. Based on the conceptual illustrations of Paige's (1913) model of cessation of lateral growth by solidification, they showed that an unrealistically large increase in driving pressure ($\sim 80\times$) is necessary to match the depicted deflections.

More recent studies, however, have raised several issues with regards to the overall applicability of plate bending theory. The equations require that the edges of the plate are clamped in place, that is, the edges are taken as a fixed boundary when moving boundary conditions are perhaps much more applicable. And the equations fail to mimic flat-roofed laccoliths, of which there are many in Nature (Morgan et al., 2008).

Flat-roofed laccoliths, in some systems (e.g. Trachyte Mesa), are, as mentioned above, most certainly the result of multiple, discrete pulses of magma, stacked atop one another (e.g. Menand, 2006; Morgan et al., 2008; Horsman et al., 2010). These have been interpreted as multiple, small intrusions occurring over a range of time, such that each pulse is distinctly separate from the others. In this model, pulses are dynamically isolated, and no single pulse is responsible for the formation of the resulting laccolith. The staggered nature of emplacement therefore clearly suggests the importance of time and cooling and thus also the possible

113 importance of progressive solidification and spatial variations in viscosity,
114 especially around the contacts.

115 Other flat-roofed laccoliths exist, however, that lack obvious signs of pulsed
116 assembly. This is not to say that they are necessarily a single pulse of magma, but
117 rather that evidence otherwise is subtle or cryptic. It could be that these laccoliths
118 are built by multiple pulses, but injections were large enough, or spaced close
119 enough together, that they were able to mingle as fluids, allowing the laccolith to
120 grow as a large magma chamber. Bunger and Cruden (2011) were able to produce
121 flat-roofed laccoliths in simulations using a combination of elastic plate theory and
122 fluid flow equations with moving boundary conditions. Their solution does not
123 require multiple pulses, but rather finds the shape of a magmatic intrusion to evolve
124 through time. Moreover, for instantaneous emplacement, their model replicates
125 Pollard and Johnson's (1973) bell-shaped laccolith, but with time, the intrusion
126 morphs into a flat-roofed laccolith, and eventually into a large, thin sill. However, as
127 Bunger and Cruden point out, the model does not consider the process of
128 solidification, nor does it consider the evolution of the intrusion from its infancy; as
129 the initial condition is an intrusion that is already wider than the overburden is
130 deep.

131 Each of the models presented above has distinctions bearing on laccolith
132 formation, but also each lack certain key physical processes or features. Pollard and
133 Jackson's (1973) model lacks the ability to evolve over time. The model of Bunger
134 and Cruden (2011) lacks processes that occur before an intrusion can be deemed a
135 laccolith. Whereas Pollard and Jackson (1973) require a clamped, fixed boundary,

and Bungler and Cruden (2011) avoid a clamp altogether, we adopt a middle ground alternative. That is, we show here that the process of solidification at the thin distal edges of an intrusion can play a disproportionately large role on the overall emplacement mechanisms of the intrusion. Thus, a solidified margin of a thin sill can potentially act as a clamp. However, this clamp is not necessarily permanent; it can be broken. With growth of the intrusion, the strength of this clamp can be overcome, and the intrusion can once more propagate freely.

We hasten to add, nevertheless, that solidification has been increasingly recognized as a prominent factor in controlling many magmatic flows, especially those in the upper crust where heat transfer is relatively rapid (e.g. Bolchover and Lister, 1999; Whitehead and Helfrich, 1991; Wylie et al., 1999; Taisne and Tait, 2011). It thus seems prudent to revisit the effect of variable magma viscosity on laccolith emplacement mechanics.

There are many methods for investigating the growth histories of laccoliths and intrusions in general. Anisotropy of Magnetic Susceptibility (AMS) has proven useful through the measurement of flow-aligned minerals as an indicator of flow direction, including feeder dike morphology, location, and pulse histories. (e.g. Ferré et al., 2002; Morgan et al., 2008; Horsman et al., 2010). Crystal Size Distributions (CSDs) have been used extensively to analyze cooling and emplacement history in many magmatic bodies including the Sudbury impact sheet (Zieg and Marsh, 2002; 2005) and much smaller sills and dikes (Marsh, 2007; Zieg and Marsh, 2012; Marsh, 2013). 3-D seismic studies have shown intricate complexity of intrusions, some with multiple lobes like flower petals (Hansen and Cartwright, 2006). All of these

methods, however, are observation limited either because intrusions are emplaced at depth and can only be observed remotely, or because uplift and erosion are either incomplete or too thorough, which limits direct sampling. Additionally, the effects of solidification upon intrusion leave behind through annealing and overprinting subtle clues (e.g. cooling rinds), which are easy to overlook or lost altogether from prolonged heating or subsolidus alteration. The satellite based system of Interferometric Synthetic Aperture Radar (InSAR) is useful in locating areas of deformation due to magma movement (e.g. Yun et al., 2006; Ruch et al., 2008; Chang et al., 2010). InSAR may be of great utility in assessing magmatic emplacement models, but because it operates in real time it requires time to build a catalog of intrusive events. Scaled experiments, therefore, provide an alternative to observation-limited approaches, and in a very real sense furnish an intimate history of the connections between dynamics and intrusion initiation and growth.

The experiments presented herein are designed to collect a wide variety of direct observations of a solidifying magma during essentially uninhibited emplacement. The experiments recreate scaled down mafic magmatic intrusions emplaced in the shallow subsurface. This thermo-mechanical analog model of magmatic intrusions permits an extensive exploration of active growth behaviors of laccoliths. In each experiment, magma analog is injected into the base of a gelatin mold made to represent a simplified crustal host rock. The magma analog is allowed to form its own fracture and propagates upward, delicately finding its own level of emplacement in a stratigraphically continuous, but mechanically separate sequence of visco-elastic gelatin. Allowing almost completely uninhibited observation, these

experiments are useful proxies for how magmatic intrusions can grow in Nature. Moreover, replicate experiments were performed using both solidifying and non-solidifying magma analogs so the resulting contrast in behaviors can be clearly attributed to the effects of solidification.

2. Magma Propagation versus Solidification: Theory

Magma solidification dramatically affects flow behavior, which is an effect most readily seen in lava flows where the leading edge repeatedly grows a brittle crust that bursts open allowing a lateral breakout (e.g. Blake and Bruno, 2000; Griffiths and Fink, 1992). On a smaller, but no less dramatic, scale it is this same feature that forms pillow lavas undersea. In fissure type eruptions, progressive solidification relentlessly focuses the flow into localized fountains (e.g., Wylie et al., 1999), and the cyclicity in output at volcanic vents may be similarly attributed to solidification (e.g., Whitehead and Helfrich, 1991). In the end it is solidification that ultimately leads to complete cessation of flow as when solidification fronts meet in the center of a dike (Bolchover and Lister ,1999).

In a propagating magma-filled fracture, propagation causes the country rock to fracture and compress as the crack dilates. As magma enters and makes contact with the fresh crack walls, inward propagating solidification fronts (SFs) essentially cauterize the opening, forming rigid new rock at rates proportional to the local rates of cooling (e.g., Marsh, 1996). The overall physics of this process is exceedingly well known and coupled cooling and solidification models have been directly tested during drilling of Hawaiian lava lakes (e.g. Shaw et al., 1977; Peck et al., 1977;

Marsh, 1989a, b). So, within a propagating dike, or a growing sill or laccolith, two processes act in opposition to one another; solidification acts to stop propagation altogether, while propagation acts to open the crack further (Figure 1A). The size of the solidification front with respect to its location in a propagating magma body is dependent on how fast the magma filled fracture is propagating (Delaney and Pollard, 1982).

The competition between these two processes can be conveniently expressed as a dimensionless ratio between the rate of crack opening, V_{Dil} , and the rate at which solidification acts to seal the crack shut, V_{SF} .

$$Y = \frac{V_{Dil}}{V_{SF}} \quad (1)$$

Where Y can be thought of as a measure of the strength of magma propagation. When $Y > 1$, magma propagation causes the crack to open at a rate faster than solidification can close it, which allows propagation to go on indefinitely. When $Y < 1$, solidification closes the crack faster than it can dilate, stifling further propagation (Figure 1B).

The shape of a fluid-filled crack can be well approximated using Eq. (2.1) of Bolchover and Lister (1999). Although this equation was intended to represent a dike, because of similar morphologies it is perfectly adequate here to represent the thin sill that forms before inflation into a laccolith. The sill thickness, $w(x)$ is given by:

$$w(x) \sim \sqrt{x} \frac{\sqrt{2}K_c(1 - \nu)}{G} \quad (2)$$

224 Here K_C is fracture toughness, ν is Poisson's ratio, G is elastic shear modulus, and x is
 225 location along the long axis of the crack with $x=0$ at the fracture front. The thickness
 226 of the crack can also be written as a function of time by inserting the propagation
 227 velocity, U .

$$x(t) = x + Ut \quad (3)$$

$$w(x, t) \sim \sqrt{x + Ut} \frac{\sqrt{2} K_C (1 - \nu)}{G} \quad (4)$$

228 The progress of solidification can be approximated using the well-known
 229 Fourier Modulus (e.g., Marsh, 2002).

$$L_{SF} \sim \sqrt{\kappa t} \quad (5)$$

230 Where L_{SF} is the characteristic length scale for cooling fronts and κ is thermal
 231 diffusivity; latent heat effects can be included in a constant of proportionality (e.g.,
 232 Jaeger, 1957; Marsh, 2002).

233 A characteristic rate of crack dilation, V_{Dil} , is given by the derivative of (4)
 234 with respect to time; divided by two to isolate dilation in the half-space. Similarly,
 235 V_{SF} is found from (5); such that overall:

$$V_{Dil} \sim \frac{U}{4\sqrt{x + Ut}} \frac{\sqrt{2} K_C (1 - \nu)}{G} \quad (6)$$

$$V_{SF} \sim \frac{\kappa}{2\sqrt{\kappa t}} \quad (7)$$

236 Now forming the dimensionless ratio defined above, and simplifying by monitoring
 237 the leading edge of the crack, where $x=0$,

$$r \sim \frac{\sqrt{2} K_C (1 - \nu)}{2 G} \sqrt{\frac{U}{\kappa}} \quad (8)$$

Y is thus a function of the host rock properties, which control the shape of the crack, the crack propagation velocity, and the magma thermal diffusivity. This result does not consider that the magma front never exists at the crack front (Rubin, 1995). To develop a more exact solution, the magma front must be taken at $x > 0$, which would delay the onset of solidification by $t = x/U$; imparting a minor effect. This result clearly shows continued propagation requires a critical speed for crack dilation to outpace solidification. That is, for any given country rock, it is the ratio U/κ that determines the propagation regime. For large κ , solidification prevails, whereas for large U , propagation prevails. And although cooling is mainly governed by the thermal diffusivity, assuming the wall rock is always cooler than the magma, the velocity U is determined by a host of other parameters.

To anticipate later discussion, it is helpful to consider the factors affecting the propagation velocity for a fully three-dimensional growing sill-like body. As magma migrates away from the feeder dike, it can encounter crustal heterogeneities, like faults, or new lithologies, stress field heterogeneities due to variable pore pressure, variable topography, or even nearby magma chambers; and the leading edge of the flow itself may begin to experience flow instabilities such as viscous fingering (e.g. Pollard et al., 1975; Saffman, 1986). The net result is that propagation velocity cannot be constant everywhere around the growing body. And the style of growth of the intrusion must therefore vary from place to place in response to the local propagation velocity. Thus for any magmatic body, there is no single governing value of Y ; instead, Y varies with space and time.

Furthermore, for a thin mafic sill to transition into a thickening laccolith, it may be a necessary condition that $Y < 1$ over much of the body. If so, solidification is an underappreciated component for laccolith formation.

3. Model Overview: Materials, and Scaling

3.1 Modeled System

The system modeled is intended to represent a shallow magmatic intrusion forming along an interface by elastic deformation of the host rock. The pressure field is lithostatic. The interface is flat and horizontal. The magma analog is injected at constant source pressure as a single pulse of magma, although variations unavoidably occur, as in Nature herself, in flux rate during this pulse, and certainly exist from one experiment to the next. With constant injection pressure, the driving pressure varies in response to changes in flow resistance, or backpressure. Backpressure is a function of the shape and size of the feeder conduit, the shape and size of the sill/laccolith, and the state of solidification. Injection at constant pressure can be interpreted as a very large magma body at depth feeding a significantly smaller high level magma chamber such that the source pressure reduction from deflation during injection is negligible.

3.2 Analogs

Country Rock: Gelatin was chosen as the host rock analog. Gelatin is visco-elastic, fails in tension, and its strength can be altered by the simple addition or subtraction of gelatin powder in the recipe. The appropriateness of gelatin as a

suitable crustal analog has been addressed in some detail by previous experimenters (e.g., Di Giuseppe et al. (2009) and Kavanagh et al. (2013)). Gelatin, as opposed to particle based crustal analogs (e.g. so-called “Sandbox Models”), has the added benefit of transparency, which is key to making observations throughout the emplacement process (Figure 2A). Gelatin used in these experiments is porcine, and was purchased from Great Lakes Gelatin. Following the methods of Kavanagh et al. (2006), the gelatin is poured in two distinct layers, with the top layer being slightly more rigid, which acts to capture the vertically ascending dike. The concentration of gelatin used is 4.1 wt.% for the top layer, and 2 wt.% for the bottom. These recipes result in Young’s moduli for the layers of, respectively, $E_{\text{top}} = 18 \text{ kPa}$ and $E_{\text{bottom}} = 7 \text{ kPa}$. Equation (2) from Kavanagh et al. (2013) was used to calculate the Young’s modulus for each recipe, by producing a single layer batch of each recipe, and measuring the deflection produced by a cylindrical mass. Actual Young’s moduli of gelatin in experiments will deviate from these measured values, because gelatin strength is sensitive to water concentration, which is affected by refrigeration times and in the case of the bottom layer, that it is capped by another layer of gelatin.

Magma: Of the many previous experimental studies involving the dynamics and morphologies of magma transport, surprisingly few have specifically emphasized the effects of solidification and the associated viscosity changes. Most magma analogs previously employed are water (e.g. Fiske and Jackson, 1972; Takada, 1994; Kavanagh et al., 2006), honey (Mathieu et al., 2008), silicone (Roman-Berdiel et al., 1995), or air (Dahm, 2000; Bons et al., 2001; Muller et al., 2001;

Rivalta and Dahm, 2006), none of which have rheologies particularly sensitive to temperature changes.

Several recent studies have used solidifying magma analogs, and all have observed effects different from those of non-solidifying analogs. Currier et al. (2010) and Currier (2011), utilized a slurry of wax and scaled particles to recreate particle tongues in modeled laccolith intrusions in layered gelatin. Taisne and Tait (2011) observed the stepwise ascent of solidifying wax dikes in gelatin, whereas non-solidifying dikes ascended smoothly. Chanceaux and Menand (2014) catalogued various intrusive results from the process of injecting solidifying vegetable oil into layered gelatin. This last study found that the conclusion of Kavanagh et al. (2006)—that sills are produced when a dike encounters a more rigid layer—is an insufficient explanation when considering a solidifying magma.

Both molten paraffin wax and water are used here as magma analogs to contrast emplacement styles with and without the effects of solidification. Both liquid paraffin and water are Newtonian fluids, however, solidified wax is non-Newtonian. The paraffin used has a melting temperature of 62° C, a density of 800 kg m⁻³, a latent heat of 150 kJ kg⁻¹, and a specific heat of 1.5 kJ kg⁻¹ K⁻¹ (Humphries and Griggs, 1977). For coloring, a few grams of colored crayon are added to the much larger mass of paraffin (~600 g). This tiny addition of crayon wax, which has slightly different properties than paraffin wax, has no overall mechanical effect. A last advantage is that, once cooled, the wax can be cleanly removed from the gelatin as a handheld, completely exposed intrusion (Figure 2B).

3.3 Scaling

The appropriateness of the chosen materials is assessed by considering several dimensionless quantities that are reflective of flow behavior, solidification behavior, material deformation, and the resulting intrusive morphologies.

Magma and magma analog should express similar flow behaviors during emplacement, which is gauged by the Reynolds Number (Re), a ratio of inertial forces acting to destabilize laminar flows relative to the stabilizing resistance of viscosity.

$$Re \stackrel{\text{def}}{=} \frac{\rho U 2L}{\mu} \quad (9)$$

Where ρ is density, U is velocity, L is the half-thickness of the channel, and μ is the dynamic or shear viscosity. Small values of Re (i.e., $< \sim 500$) are taken to be laminar flows. The transition to full turbulence varies with channel geometry and smoothness of the channel walls, but is generally on the order of 10^3 . In the experiments there is a wide range of values for channel thickness, viscosity, and velocity. The thickest experimental laccoliths are ~ 3 cm thick, with a liquidus viscosity of $\mu \approx 10^{-2}$ Pa s, and a characteristic velocity on order 1 to 10 cm/s, which gives Re on order 10^2 ; still within the laminar flow regime, similar to most magmatic intrusions where $Re < \sim 1.0$. During experiments, the channel width will decrease with solidification, and viscosity will increase—both of these variations will result in smaller Reynolds numbers, and therefore experiments are laminar during all stages of emplacement.

A second key parameter group to match is the dimensionless Stefan number (Ste), which measures the importance of latent heat relative to enthalpy or sensible heat. That is,

$$Ste \stackrel{\text{def}}{=} \frac{C_p \Delta T}{\Delta H} \quad (10)$$

where C_p is specific heat, ΔT is the temperature range of solidification, and ΔH is the heat liberated by solidification, or latent heat of fusion. Magmas typically solidify over a 200° C range, with $Ste \sim 1$ (see Table 1). For water experiments, Ste is effectively infinite, which emphasizes the complete lack of latent heat relative to enthalpy. The paraffin wax used here has a thin solidification front of ~ 0.5 -1° C, resulting in $Ste \approx 10^{-2}$. Although smaller than for magma, both are low, reflecting the strong role of latent heat, suggesting that paraffin wax solidifies in a fashion approximately similar to magma (see also Brandeis and Marsh, 1989; 1990). Geometrical similarity occurs when corresponding aspect ratios are proportional. Laccoliths typically have aspect ratios near 1:10, which match the wax laccoliths at 1:20-1:8. Water intrusions are typically much thinner and cannot be described as laccoliths, but are more like sills. The aspect ratio of dikes in Nature is approximately 1:100-1:1000. Typical aspect ratios for the feeder dikes in these experiments are ~ 1 :30-1:60. The morphologies of active dikes are likely different from most solidified dikes in that a portion of the melt volume is left behind during transit as solidified margins and upon cessation of flow the driving pressure also subsides. The final resulting solid dike is thus most likely much thinner than the active dike, and possesses a much higher aspect ratio. With this in mind, the

experimental dike aspect ratios, being of a similar order magnitude, are taken to be sufficiently close to those of Nature.

Given these similar behaviors and resulting morphologies between experiments and Nature, we are confident that these experiments are properly scaled and thus closely representative of the natural phenomena they are intended to emulate.

4. Experimentation

4.1 Experimental Setup

The apparatus designed and used here consists of three parts: a pressure source, a wax reservoir, and a gelatin mold (Figure 3). The wax reservoir, acting here as the parental magma chamber, is a modified Arbe Machine Mini Wax Injector. The intended purpose of this injector is to fill plaster molds with wax in a jewelry making technique known as the “Lost Wax” method. Because the injector can be pressurized and contains a built in heating element and thermostat, it makes an attractive magma chamber. Compressed air passes through a regulator at the top (0-5 psi, 1% error) pushing out liquid wax at the base when a ball valve is opened. The wax passes through a disposable plastic tube into the bottom of the layered gelatin mold. A pre-heated tube connects the injector to the gelatin mold, with a separate injector tip lashed to the exit. The injector tip is cut at a 45° taper so that it initiates a penny-shaped crack within the gelatin.

The ‘host rock’ is built by pouring gelatin in stages. Distinct layers are produced by allowing the bottom layer 24 hours to completely cool to ambient

395 refrigerator temperature (2° C) before the top layer is poured, which is also allowed
396 24 hours to set.

397 A HD camera is fixed above the gelatin to capture footage during each run.

398

399 **4.2 Experimental Method**

400 Prior to each experiment, the injector is heated to just above the wax liquidus
401 temperature and the disposable injector line and injector tip are heated in a hot
402 water bath. Both of these actions limit the well-known thermal entry effect where
403 cool thermal boundary layers, initiating solidification, grow progressively along the
404 walls during transport. Water based experiments follow similar protocol, but
405 excluded this heating process.

406 After the injector is brought to pressure, air is bled from the injector line,
407 leaving only air within the injector tip. This air is critically necessary to form the tip
408 cavity at the leading edge of the wax filled crack. Without this tiny dose of air, no
409 dike is formed.

410 The volume of each wax experiment is 650 cm³. There is no control over how
411 much of this volume goes into producing feeder dikes, and so each experimentally
412 formed laccolith is of a slightly different volume.

413 Each experiment is injected at 1.5 psi (10.35 kPa), which may seem large,
414 being of order of the gelatin rigidity, when magma overpressures in Nature are
415 typically perhaps a tenth to a hundredth the rigidity of the host rock. But because
416 the cracks are actively propagating, the actual pressure inside the experimental
417 intrusions is only a fraction of this source pressure. The pressure within the crack

will only be the same as the pressure at the source when the crack is entirely static. Using Eq. (1) of Becerril et al. (2013), which estimates crack thickness based on host rock material properties, driving pressure, and the length of the crack, the thickness of our feeder dikes should be ~8 cm given the driving pressure in the source region. Actual crack thicknesses are typically ~0.5 cm, suggesting magma pressures within the feeder dike are ~300 Pa, which is a value much more in line with observations in Nature.

The experiment comes to completion at the first signs of entry of air into the tube. At this point, all magma analog has drained from the injector.

5. Results

5.1 Water and Wax Morphologies

The results that follow are for wax experiments taken to completion, and water experiments taken to the point of visible edge effects (always less than 650 cm³).

Wax intrusions show much more complex morphologies than water intrusions, both in plan and in cross-section (Figure 2B, Figure 4). In plan view, wax intrusions can have broad embayments or lobate margins. Water intrusions are mostly smooth and semi-circular. In cross-section, wax intrusions are typically neither bell-shaped nor flat-roofed, but instead are typically somewhat between these styles. Yet, they also possess undulations in topography as well as slight ridges

marking the edges of distinct growth events. No water intrusion was extracted, but we safely assume that water intrusions possess fairly flat roofs.

A typical wax laccolith is 2 to 3 cm at its thickest, with a long axis of ~ 20 cm, resulting in an aspect ratio consistent with natural counterparts. Water, on the other hand, produces intrusions that are about a third as thick as wax intrusions. Because water intrusions do not thicken as much as wax intrusions, most of their growth is accomplished via lateral growth. This is the reason why water intrusions experience visible edge effects whereas wax intrusions do not.

Based on aspect ratios, no water intrusions could justifiably be deemed a *laccolith*. Wax intrusions, however, begin as thin sills that later thicken into laccoliths.

5.2 Growth Contours

Using video snapshots, contours of the extent of the intrusions are mapped at one-second intervals as a first step towards quantifying the growth of the intrusions (Figure 4). The entire emplacement histories for experiments are recorded in these maps. The resulting patterns illustrate distinct differences in growth patterns between water and wax intrusions.

Water intrusions grow primarily by lateral growth, with propagation velocities much faster than for wax intrusions. This is indicated by the greater spread between growth contours for water. The fluxes for water intrusions was, however, much lower than for that of the wax intrusions. This is known, because although growth outlines are only shown up to the point of edge effects, water

intrusions were allowed to run to completion, and their durations were significantly longer than for wax intrusions.

Water intrusions also exhibit a simple shape throughout emplacement, growing as semi-circular bodies, with propagation occurring along most, if not all, of the periphery. This style of growth is *radial growth*. The few irregularities that do occur can be attributed to flow instabilities arising from the intrusion process of a viscous fluid between two rigid plates, very similar to experiments performed in Hele-Shaw cells (e.g., Batchelor, 1967).

Wax intrusions begin with radial growth. Once the top gelatin layer captures the dike, wax propagates in a radial fashion away from the feeder, growing as a semi-circular body. This radial growth, however, soon decays into more heterogeneous growth. Propagation along certain portions of the periphery can cease, be redirected, and even arrested, and then suddenly reactivated along once stagnant boundaries. After the decay of radial growth, the shape of the body can become irregular. Experiment 1813, for example, is semi-circular in the early few seconds of growth, but by 7 seconds it is kidney shaped. Many irregularities are eventually reduced with continued growth, with the shape of intrusions trending back towards a semi-circular shape.

5.3 Intrusion Size over Time

Intrusion size in area can also be measured from the growth contours for each time step using the software program Image-J (Figure 5). Also shown on the

same growth plots is the maximum propagation velocity of intrusions throughout emplacement. The direction of maximum propagation velocity is variable, and is not shown in this figure, but is presented in the following section.

Just after dike capture, growth is rapid for both wax and water intrusions. There is a steep gain in area near the origin that flattens out with time. Growth rate then decreases with growth of the intrusion. Water experiments appear to converge on a steady-state growth rate.

Although wax intrusion growth rate decays with time, this growth is invariably punctuated by brief bursts of rapid growth that quickly decrease again. These pulses are seen in figure 5 with a spike in velocity that coincides with a sharp increase in areal growth. Pulses are also clearly evident in figure 4 as greater spacing between growth contours, which often marks a change in the overall shape of the intrusion. Pulsing of any nature is not a feature of water experiments.

Wax intrusions may also undergo periods of time where there is no areal growth. In experiment 2713, for example, for time steps 12-14 seconds, there is no lateral growth. But because wax is still being injected into the intrusion, growth must be accomplished purely through thickening. In the case of experiment 2713, lateral growth resumed with the pulse at time step 15 seconds, but does not occur in all cases. Water intrusions, in striking contrast, never cease propagation anywhere along the entirety of their periphery.

Growth measurements of intrusions through time highlight a pivotal distinction between magma analog growth behaviors: water intrusions emplace

smoothly, whereas wax intrusions grow in an inherently herky-jerky, strongly pulsatile fashion.

5.4 Propagation Direction over Time

The evolution of an intrusion's shape is a direct reflection of the style of emplacement propagation. For a semi-circular body to remain semi-circular, propagation must occur over most of the margin, and propagation rates also need to be nearly constant in all directions. If portions of the periphery slow or stall, the propagation front changes in size and direction. Ultimately, changes in propagation effects a change in the intrusion shape.

Figure 6 maps out propagation fronts throughout the experiments. If the entire margin of an intrusion is actively propagating, propagation is occurring in 360 degrees. For these time steps, the bar in Figure 6 occupies the entire length of the y-axis. As active propagation begins to cease locally, but continues elsewhere, propagation is no longer occurring in 360 degrees. Smaller bars are thus representative of more directed flows. Rapidly varying lengths and locations of bars indicate more variable growth histories.

Also provided in Figure 6 is a small horizontal dash within each bar. This dash indicates the direction of maximum propagation velocity in Figure 5.

The growth fronts for water intrusions remain essentially constant throughout experiments. Major redirections do not occur. Water intrusions continue to propagate, broadly, in the same direction throughout the experiment.

Wax intrusions begin with propagation occurring over a wide periphery. This is their radial growth phase. After a few seconds of growth, however, the propagation front typically becomes more directional, and begins to experience numerous redirections. In some cases, propagation bifurcates, such as in experiment 5313 for time steps 6-7 seconds, indicated by two separate bars.

Figure 7 shows statistics for variations in the maximum propagation direction between time steps for each experiment. Water and wax experiments fall into two distinct groups. Water experiments plot near the origin because propagation fronts remain near constant throughout experiments; any changes in directionality are small. Wax intrusions frequently experience changes in propagation direction; sometimes these are minor redirections, sometimes drastic.

6. Discussion

6.1 Limitations and Errors

All measurements are derived from video footage. No attempt was made to orthorectify the images, and the upward deflection of the top layer of gelatin, caused by the injection of wax below, produces a slight lensing effect by the intrusion. These artifacts are relatively small compared to the overall growth of the intrusions themselves.

No side view footage was possible, which, if available, would help to isolate where inflation is taking place within the intrusions. The container, although translucent, is unfortunately only slightly transparent, which obscured side views.

Wax experiments, because of the temperature at which the wax is injected, also cause some melting of the gelatin host. Although also sometimes occurring in Nature (e.g., Marsh 1989b), generally intrusions are not thought to melt their host rock (e.g. Currier and Marsh, 2009). During melting of the host, there is potential for a change in the deformation style—from elastic/fracture to viscous flow.

The total amount of gelatin melting is relatively minor, especially considering the duration of the experiments. A typical intrusion lasts on the order of ~10 seconds, and using equation (5), the maximum characteristic length over which an isotherm might migrate into the gelatin host rock near the feeder site, and thus in contact with the intrusion for the longest amount of time, is ~3 mm. The size of the melt zone is smaller than this value because of the much higher specific heat of water (in gelatin) over wax, and because melting of the gelatin occurs at an isotherm higher than ambient temperature. Deformation may be slightly more viscous than in Nature within the central portions of wax intrusions, but ~1 mm of melting above the feeder dike is not sufficient to explain ten times that value in thickening. From this analysis, we can assume that most deformation is due to elastic deformation.

Of primary concern within the context of this study, is the amount of melting that takes place at the front of the intrusion, where we argue the most critical phenomenon for laccolith formation occurs; namely the solidification of the magma analog. Here, the time for thermal communication between wax and gelatin is minimal. In fact, at the contact of an actively propagating intrusion, the time for isotherm advance is nil. At the tip of an actively propagating intrusion, any melt zone will be infinitesimally small. No macroscopic evidence for viscous deformation

is observed at actively propagating fronts, such as short-wavelength viscous fingering. We therefore assume that host deformation at the front of actively propagating intrusions is non-viscous in style.

After an intrusion has stalled, however, some viscous effects can take place. In section 6.4.2 below we describe a failure mechanism that would be aided if the host rock behaved viscously. Whether or not this failure mechanism occurs in Nature is unknown, but we do describe some other possible ways in which viscous deformation can occur between the intrusion and host rock in Nature without invoking wall rock melting.

6.2 Water versus Wax Intrusions

There are major striking stylistic differences between how water and wax intrudes, and these differences all stem from the effect of solidification. Solidification acts as a propagation deterrent, altering the fundamental mechanics of intrusion. Wax intrusions are thicker than water intrusions. Wax intrusions possess complex morphologies that evolve over time. Wax intrusions produce laccoliths whereas water intrusions do not. From this last point alone, the solidification of wax makes for more realistic analog intrusions.

Without solidification to impede propagation, liquid everywhere within the intrusion retains the potential for mobility. Propagation proceeds over a large front, with growth only limited by the supply of fluid. The smooth, ellipsoidal shape of water intrusions is thus maintained by an active magma front over most of the periphery of the intrusion (Figure 5 and 7).

The critical difference between water and wax intrusions is that Υ , the ratio of crack opening velocity to solidification front velocity, is a finite number for wax intrusions, but is infinite for water intrusions. Water intrusions are immortal, always remaining mobile. Wax intrusions, however, inevitably undergo a complicated pattern of propagation arrest. Often this effect is local, where a portion of the propagation front lags behind and drops below $\Upsilon = 1$. As solidification locally stalls the flow, magma can be redirected and channeled to still active regions of the magma front, taking the path of least resistance (Figure 4 and 6). The shapes of wax intrusions thus show much more evolution in character over the course of the experiment, transitioning from roughly circular shaped intrusions at the very beginning, to kidney shaped intrusions as large regions of the flow front begin to stall (Figures 4-6).

Sometimes, propagation is slow enough in wax intrusions that $\Upsilon < 1$ along the entire periphery. In this case, all lateral propagation ceases, and the intrusion grows only through thickening. Because solidification leads to enhanced thickening, solidification and variable viscosity play a key role in the development of mafic laccoliths.

6.3 Stages of Laccolith Formation

Corry (1988) summarized three different potential mechanisms of laccolith emplacement and growth: 1) growth at a constant height, much as a solid wedge inserted between strata; 2) as a propagating and thickening self-similar intrusion; and 3) as a thin sill that first intrudes and then inflates as some critical radius is

reached. Corry preferred the latter mechanism, basing this choice on a lack of structural evidence, in the form of multiple hinges, to support the first two mechanisms.

Our experiments provide a convenient test of these possible mechanisms. The two-stage growth model originally envisioned by Gilbert (1877) comes closest to describing the evolution of these experimental laccoliths, but it is an oversimplification. Although a two-stage model may be sufficient to describe the growth of some laccoliths, the entire set of possible growth behaviors is instead encapsulated in a three-stage growth model (Figure 8).

Stage I: Self-similar radial growth ($Y \geq 1$ along periphery)

Stage II: Limited or no lateral propagation, primarily thickening

Stage III: Rapid lateral, breakout propagation, often highly directional, with no thickening or even some deflation

6.3.1 Stage I Growth

Every intrusion, wax or water, begins with Stage I. Fluid from the feeder dike propagates outwards in a near radial pattern, and the crack thickens only slightly in a self-similar fashion. Flow lineations in Nature, interpreted from AMS measurements, show a similar pattern of radial growth from feeders (e.g. Morgan et al., 2008; Horsman et al., 2009). Lateral growth of all intrusions is at first rapid, but growth rate inevitably decays with time as the supply of fluid eventually wanes (Figure 5). This slowing of propagation occurs with both water and wax analogs and

is essentially a geometrical effect. With radial growth, the circumference of the magma front is ever increasing, so that the limited flux of magma from the feeder dike must fill an ever increasing volume growing, in effect, in proportion to the cube of the radius; as in the familiar sensation of inflating a balloon. The net result is an overall decrease in propagation rates.

As propagation rates decrease in solidifying fluids, some regions of the periphery begin to fall below $Y = 1$, which marks the transition from Stage I to Stage II.

6.3.2 Stage II Growth

Stage II growth is characterized by slowed or stalled flow at the magma front. As magma continues to arrive from the feeder dike, growth is accomplished by thickening, and this is when the first true laccoliths form.

Only wax intrusions transition out of Stage I growth. As the propagation rate inevitably diminishes during Stage I, Y decreases, and the inward propagating SFs begin to dominate. These stalled regions inhibit the overall lateral growth of the intrusion, and the continued influx of fresh fluid causes thickening. The act of solidification provides the necessary resistance for inflation. For water experiments, $Y = \infty$ for all non-zero propagation velocities. Water experiments thus remain thin and never mature into laccoliths because they lack the ability to provide sufficient resistance to flow at the periphery, which brings on the necessary thickening.

To form a laccolith, significant deformation must occur within the overburden. One possibility is through widespread deflection in the overburden

over the breadth of the intrusion. Deflections in the overburden are easier to accommodate when the radius of the intrusion is large relative to the thickness of the overburden. Pollard and Johnson (1973) placed limits on the size an intrusion needs to be to form a laccolith, suggesting a critical radius of the intrusion of ~ 3.3 times the thickness of the overburden. Our wax experiments support this finding, but because the water experiments never formed laccoliths, there must be another requirement—a large resistance at the intrusion margin. In our experiments this resistance is accomplished through solidification. Without this increased resistance at the margin, the intruding fluid progresses as a thin-sill *ad infinitum*.

Considering deflections in the context of solidification, if flux rate at the feeder is too low, Y will diminish, and solidification will kill the intrusion before the critical radius for deflection is met. The system remains a thin mafic sill, never transitioning to Stage II growth. If flux rate at the feeder zone is high, Y will remain large longer, and the Stage II transition may occur at an intrusion radius greater than 3.3 times the overburden thickness.

But is solidification alone necessary to provide resistance to propagation? Pollard and Johnson (1973) produced an experimental laccolith in much the same way as our experiments, using a two layered gelatin model, except that they used grease as the magma analog. Grease does not solidify, but it is much more viscous than liquid wax and, perhaps even more important, it possesses a yield strength, which functions much like solidification. Assuming a grease viscosity of order 100 Pa s, their fluid is $\sim$ five orders of magnitude more viscous than both our water or liquid wax. In reality, their grease might well be representative of a rhyolitic magma.

The resistance required in the fluid to deform the crustal analog, then, may have come from simply the high fluid viscosity.

High magma viscosity, be it due to composition or cooling, is necessary to provide the critical flow resistance to induce inflation. For basaltic magmas with much lower viscosity, solidification is critical for laccolith formation.

6.3.3 Stage III Growth

The onset of Stage III marks a return to lateral propagation. Whereas propagation in Stage I is largely radial, propagation during Stage III is often highly directed via breakouts. The transition between Stage II and Stage III coincides with a redistribution of stresses accumulated during Stage II growth. There are several ways in which the solidified margin can rent or tear, which are next discussed.

The initiation of a breakout reinvigorates lateral growth. If the flux of magma through this burst section is faster than that at the conduit, deflation of the intrusion occurs. The laccolith depressurizes by magma flow through the compromised rind, leading to rapid and fairly directional lateral growth of the intrusion. The pulses seen in Figure 4 and 5 are representative of Stage III growth. Pulses begin with fast propagation, but slow as the laccolith depressurizes. Again, Υ will drop below 1 when propagation rates are slow enough, and lateral growth again begins to stall. This leads to a renewed round of thickening of the intrusions, or a return to Stage II growth.

Thus the overall evolution of laccoliths is: growth begins with Stage I, transitions to Stage II, and then cycles between Stages III and II throughout the

remaining growth of the intrusion. This finding may go a long ways in explaining why the aspect ratios of intrusions do not appear to follow a clear relationship with depth (e.g. Fig. 3 from Petford et al., 2000). The final aspect ratios of experimental laccoliths depend primarily on where they terminate in their cycling between Stage II and III. This termination may well be dependent on the overall solidification time of the full intrusion itself, which is a direct reflection of the magma volume.

6.4 Failure Mechanisms

The transition from Stage II to Stage III growth depends intimately on the failure of the new rock rind at the periphery. Although Bolchover and Lister (1999) concluded that dikes are dead once a rind forms at the magma front, their analysis did not apply to laccoliths, and did not take into account all possible failure mechanisms. Recently, Taisne and Tait (2011), found that ascending dike experiments utilizing a solidifying fluid, once arrested, could re-pressurize and thicken and return to active propagation. We have observed a similar feature as Taisne and Tait (2011), but in experimental laccoliths. After many repeated observations we have isolated three ways in which solidified margins fail during the growth of intrusions (Figure 9).

6.4.1 Active Magma Advance

Once solidification dams the margin and growth proceeds by inflation, the overburden begins to warp upwards. Stresses in the overburden are greatest where curvature is greatest. At the edges where curvature is concave up, stresses are

tensile. Away from the edges there is an inflection point followed by downward concavity where the rock is under compressive stress. As inflation progresses, these stresses increase and are transmitted into the solidified margins of the intrusion itself. Because rock is strong in compression and relatively weak in tension, especially when hot and partially molten, a natural weak spot is the margin of the intrusion.

In our experiments, the tensile strength of the margin is overcome by the overall inflation of the intrusion, tearing the solidified marginal rind open and allowing fresh magma to breakout and spill forth. Lateral propagation proceeds anew.

Crystal textures will likely be near identical across such a rupture. Although field evidence for such a phenomenon may be extremely subtle in laccoliths, a similar type of behavior is common in pahoehoe lava flows and pillow basalts. One possible feature that could identify the location of an active magma advance is a subtle ridge along the top and bottom of the intrusion that traces out the location of the pre-rupture intrusion. The ridge itself is the product of a vapor cavity that forms in an identical fashion as the tip cavity at the front of the intrusion. As fresh magma advances, it attempts to fill the void between solidified intrusion and host rock. Because magma is a viscous fluid it cannot fill this void completely, and so a cavity remains.

6.4.2 Cold Wedge Advance

The pressure distribution within a magmatic intrusion differs whether it is propagating or stagnant. During propagation, the pressure of a fluid filled crack is at its minimum at the leading edge of the intrusion. This value further decreases as the intrusion grows in size. Once an intrusion stalls, however, the entire magma body begins to pressurize everywhere towards an equilibrium value. If the solidified margin forms a strong dam that resists tearing, failure can still occur, albeit in a different style.

As solidification fronts meet, the rate of solidification speeds up exponentially, because the volume of magma at the center is now shedding heat from two surfaces. A potential weak area is therefore away from the margin, where solidification fronts have yet to meet.

In this scenario, failure occurs along the top and bottom solidification fronts, and the solidified margin is pushed forward as a cold wedge. Fresh magma rushes in along this rifted margin. The barriers that must be overcome in cold wedge advance are the tensile strength of the solidified margins and the frictional resistance along the contact. Byerlee (1978) found that at 1000 bars pressure the friction factor for a wide variety of rocks, regardless of composition or texture, is ~ 0.85 . This is the coefficient for maximum friction, which is the resistance required to initiate motion. The value of 0.85 is fairly high; most common materials have coefficients < 0.7 . The friction factor at the contact between laccolith and host rock could be augmented by the presence of a lubricant such as a vapor barrier, or if the host material is weak and readily deformed, such as soft sediments, poorly consolidated sedimentary

rocks, or highly fractured crystalline rocks. And exterior vapor barriers may also be produced through dehydration of hydrous minerals by magmatic heating.

There may already exist ample evidence of this mechanism of intrusion advance. The action of cold wedge advance will leave evidence such as slickensides (e.g. Tweto, 1951; Airoidi et al., 2012), small shear zones (e.g. Morgan et al., 2008), or a cataclastic region within the host material. Additionally, the history of magma cooling within the rift zones will be markedly different from the surrounding regions. Within the rifts, fresh magma encounters preheated host rock. This allows for slower cooling of the magma, producing larger and fewer crystals, and possibly melting of the host rock in contact with these margins. The massive feeder zone of the Basement Sill in Bull Pass of the McMurdo Dry Valleys of Antarctica shows this style of behavior with extensive melting of the wall rock (Currier and Marsh, 2009), and this behavior may well also play a role in other systems where there is a clear signature of crustal contamination.

6.4.3 Lamination

Lamination is the process where fresh magma intrudes above an actively cooling solidification front. This typically occurs well away from the margin, near the central region of the intrusion. Although lamination does not reactivate intrusion propagation (Stage III growth), it is a type of margin failure. With lamination, the upper solidified margin begins to founder (e.g. Marsh, 1996; 2002) and fresh magma is emplaced above. It is unclear whether this is the result of the

solidified margin settling due to density differences, or active magma forcibly intruding above, or a combination of both.

Similar to the rift zones of Cold Wedge Advance, the thermal history within a lamination zone will be distinct from its surroundings. The region will have larger and fewer crystals, and the host rock above will potentially undergo partial melting. The primary difference between the Cold Wedge Advance rift zone and a zone of lamination will be in the morphologies of thermal anomalies; with rift zones forming narrow, long regions, aligned sub-parallel to the intrusion margin, and lamination zones likely forming extensive, sub-circular regions.

6.5 Context

6.5.1 Natural vs. Experimental Wax Laccoliths

Magmatic intrusions in Nature are irregularly shaped in map view, with lobes of varying shapes and sizes (e.g., Hansen and Cartwright, 2006; Morgan et al., 2008). Between the two magma analogs tested in this study, wax produced morphologies that are much closer to the overall observed shapes than water-based intrusions. The shape of Trachyte Mesa has been interpreted as outward growth occurring in multiple stages (Morgan et al., 2008), which is more akin to wax intrusions than water, which grows in one long event.

Most laccoliths in Nature are flat-roofed, as opposed to Pollard and Johnson's (1973) plate deflection model. The wax experimental intrusions presented in this study are not flat-roofed, but not exactly bell-shaped either. It is possible that some viscous deformation has allowed for this camber. Another possible interpretation is

that plate deflections are transient. The model of Bunger and Cruden (2011) is consistent with this interpretation, as well as the potential for solidified margin failure as presented in this study.

6.5.2 Laccolith Model

Our model of laccolith inflation ties together neatly the models of Gilbert (1877), Pollard and Johnson (1973), and Bunger and Cruden (2011). Observations of wax experiments show that after dike capture, a thin sill grows first, and as propagation slows inflation of the body occurs. This effect did not occur in water experiments, suggesting that solidification provides a possible boundary clamping mechanism. Our model differs markedly from Paige's (1913) original hypothesis of laccolith formation due to solidification along the edges of the intrusion. Whereas Paige envisioned large regions of the intrusion solidifying, we propose that only a thin dam, on the order of a few meters, is required. Thus, overburden deformation can still occur without the large pressure increases required due to significant loss of radius.

It should also be stated that our model of laccolith formation pertains to intrusions that are fluid in most of its entirety. It is currently unclear whether this is the case for most laccoliths found in Nature. Several thorough investigations of laccoliths in the Henry Mountains have indeed observed the opposite—that the laccoliths in question show clear evidence of a pulsatile growth history, and that each pulse was effectively solidified by the arrival time of the next pulse, such that deformation in the host rock only responded to a small additional aliquot.

Our model does not represent these pulsed laccoliths, but does provide a limited framework for interpreting the growth of pulsed laccoliths. For laccoliths built by stacking thin intrusions one on top of the other, it is clear that each of these pulses never transitioned out of Stage I growth. There are several possible reasons for this.

1. Propagation rates may have been too slow, and solidification could have stifled the intrusion before it became large enough to deflect the overburden.
2. Propagation may have been more directed, decreasing the drop in propagation velocity with growth.
3. The volume injected for any one pulse was too small for widespread deflection.

Ultimately, there is no reason why a laccolith could not form in multiple ways—as an accumulation of thin sheets, as a mostly fluid body, or in other styles still. But whatever the way a laccolith grows, solidification will still play a fundamentally important role.

6.5.3 What is a magma pulse?

Magma pulses occur over a wide temporal spectrum. Batholiths can assemble through pulses spaced out over millions of years (Glazner, 2005). Smaller intrusions, like Trachyte Mesa, grow by pulses spaced out over years to decades. Other major intrusions are only just beginning to reveal their pulsatile growth histories (Zieg and Marsh, 2012). Usu San in Japan, recorded diligently in the

870 sketchbook of a local postman, grew over several months with variations in growth
871 rates.

872 But what of the behavior observed in our wax experiments? Intrusions grow
873 rapidly, then slowly, then rapidly again. This is a pulse-like growth, although a single
874 injected pulse feeds the entire experiment. Can a single pulse of magma produce
875 multiple pulses? What is a magma pulse?

876 There is obviously some ambiguity to the term pulse. To be more precise, we
877 propose two types of pulses; *distinct pulses* and *flow pulses*. Distinct pulses occur in
878 the flux entering the system, where a conduit is opened, feeds an intrusion, and is
879 ultimately shut off. There is some period of time between distinct pulses that feed a
880 system. Flow pulses occur during growth of an intrusion and are the result of the
881 interplay of propagation and solidification.

882

883 **7. Conclusions**

884 Our experiments using water and wax reveal that solidification profoundly
885 affects the intrusive dynamics of any growing magmatic system. Compared to non-
886 solidifying fluids, the increased resistance to flow due to solidification at the
887 intrusive margins makes for thicker intrusions, more irregularly shaped intrusions,
888 more complex growth histories, and leads to the formation of laccoliths.

889 The effects of solidification are unavoidable. Any concordant intrusion in the
890 shallow crust will experience a drop in propagation velocity due to the initial radial
891 growth. Provided that the flux rate is high enough to avoid an early death due to

solidification, the intrusion will eventually transition from Stage I to Stage II growth styles.

Experimental observations suggest that there are potential emplacement behaviors that have not yet been described in the field; such as the tearing of solidified margins in Stage III growth. Whether or not the failure mechanisms observed in experiments exist in Nature can be addressed by seeking the distinct features found in these experiments and very possibly recorded in the final petrographic textures.

The growth of magmatic intrusions is likely much more complex than what has been earlier modeled. It is important to point out that despite all attempts to standardize experiments, every experiment is unique. The experimental approach of wax in gelatin injections opens the possibility of a wide range of investigations.

Lastly, these experiments reemphasize the importance of considering the time-dependent phenomena associated with magmatic intrusions. Incremental accumulation and pulsed growth of magma bodies occurs over multiple timescales (e.g. Glazner, 2005; Menand, 2008; Horsman et al., 2010; Annen, 2011; Zieg and Marsh, 2012). These experiments show that even a single emplacement pulse of magma is not a simple process.

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Figure 1: A) Cross-section schematic of actively propagating and cooling fluid filled fracture. The thickness of the solidification front is shown as a dashed line and is directly tied to the propagation velocity, with slower propagation resulting in thicker solidification fronts. B) Visualizations of different values of Υ . Not considered is the positive feedback that small decreases in propagation velocity will impart on decreases in Υ .

Figure 2: A) Gelatin's transparency allows for observations during injection. Shown are snapshots of experimental wax intrusion taken at four time intervals. The field of view is ~ 30 cm. B) A wax intrusion after cooling and removal from gelatin. Fine features are preserved (notice en echelon dikelets on the edge of the main feeder dike). The overall shape of the intrusion is that of a laccolith. Despite a smooth interface, the intrusion is asymmetric and complex.

Figure 3: Experimental Apparatus. The tube transferring the wax from injector to gelatin is a 30.5 cm length of clear polyvinyl tubing (0.635 cm internal diameter) with a separate injector tip lashed to the exit. This injector tip fits snugly into the polyvinyl tubing and is used to penetrate into the gelatin by 3.75 cm—necessary to form the initial fracture and induce vertical ascent.

Figure 4: Growth Contours for 9 experiments. Contours are drawn at one-second intervals, odd numbers are white, even numbers are grey for ease of viewing. Notice how much more irregular the wax intrusions are than the water intrusions. Wax intrusions show variable rates of growth (more on this in Figure 5), and many redirection in propagation (more on this in Figures 6 and 7).

Figure 5: Area and maximum propagation velocity during emplacement of wax (red) and water (blue) intrusions. Area measurements are the dotted lines, whereas maximum propagation velocity is the solid line. Propagation velocity is high for all experiments in the beginning of intrusion formation, and, overall, decreases with time. Notice how wax intrusions grow as a series of pulses—with spikes in maximum propagation velocity corresponding to large gains in area. This behavior is not seen in water experiments.

Figure 6: Directionality of propagation during emplacement of wax (red) and water (blue) intrusions. The size of the colored bars indicate the regional extent of growth, measured to the closest 15° from the center of the feeder dike. 0° is taken as the

eastern direction, with increasing values in the counter-clockwise direction. The thin black line in each bar indicates the direction of maximum propagation direction for that time step. Grey boxes correspond to no propagation between those time steps. Notice how both the directionality of growth, and direction of maximum propagation are incredibly variable in the wax experiments. Water experiments are much more consistent in their growth direction throughout the experiment.

Figure 7: Comparison of Propagation Direction Statistics. *Change in Direction* refers to the difference between maximum propagation direction (black dash in Figure 6) between time steps. Experiments fall into two groups, with water intrusions propagating mostly in the same direction throughout the experiment, and wax intrusions varying markedly.

Figure 8: Stages of Intrusion Development, with dashed regions showing an earlier state, and solid pink region showing the new state depending on the stage of growth. Stage II and Stage III are the result of the effects of solidification. All intrusions begin as Stage I.

Figure 9: Failure Mechanisms. Stalled fronts can reactivate, and there are several ways in which this can occur. **Active Magma Advance** is when the solidification front at the stalled front is torn open and fresh magma proceeds to propagate the crack forward. **Cold Wedge Advance** is when failure of the solidified margin occurs away from the stalled front, and cold rock is pushed forward wedging apart the host

rock. **Lamination** is when failure only occurs on the top solidified margin, away from the stalled front. Lamination is similar to a solidification front instability.

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Figure 1: A) Cross-section schematic of actively propagating and cooling fluid filled fracture. The thickness of the solidification front is shown as a dashed line and is directly tied to the propagation velocity, with slower propagation resulting in thicker solidification fronts. B) Visualizations of different values of Υ . Not considered is the positive feedback that small decreases in propagation velocity will impart on decreases in Υ .

Figure 2: A) Gelatin's transparency allows for observations during injection. Shown are snapshots of experimental wax intrusion 6313 taken at four time intervals. The field of view is ~ 30 cm. B) A wax intrusion after cooling and removal from gelatin. Fine features are preserved (notice en echelon dikelets on the edge of the main feeder dike). The overall shape of the intrusion is that of a laccolith. Despite a smooth interface, the intrusion is asymmetric and complex.

Figure 3: Experimental Apparatus. The tube transferring the wax from injector to gelatin is a 30.5 cm length of clear polyvinyl tubing (0.635 cm internal diameter) with a separate injector tip lashed to the exit. This injector tip fits snugly into the polyvinyl tubing and is used to penetrate into the gelatin by 3.75 cm—necessary to form the initial fracture and induce vertical ascent. The container holding the gelatin measures 51 cm by 38 cm with 14 cm depth, and has slightly flexible walls. The bottom layer is 7.5 cm thick, and the top, 3.75 cm.

992

993 **Figure 4:** Growth Contours for 9 experiments. Contours are drawn at one second
 994 intervals, odd numbers are white, even numbers are grey for ease of viewing. Notice
 995 how much more irregular the wax intrusions are than the water intrusions. Wax
 996 intrusions show variable rates of growth (more on this in Figure 5), and many
 997 redirection in propagation (more on this in Figures 6 and 7).

998

999 **Figure 5:** Area and maximum propagation velocity during emplacement of wax
 1000 (red) and water (blue) intrusions. Area measurements are the dotted lines, whereas
 1001 maximum propagation velocity is the solid line. Propagation velocity is high for all
 1002 experiments in the beginning of intrusion formation, and, overall, decreases with
 1003 time. Notice how wax intrusions grow as a series of pulses—with spikes in
 1004 maximum propagation velocity corresponding to large gains in area. This behavior
 1005 is not seen in water experiments.

1006

1007 **Figure 6:** Directionality of propagation during emplacement of wax (red) and water
 1008 (blue) intrusions. The size of the colored bars indicate the regional extent of growth,
 1009 measured to the closest 15° from the center of the feeder dike. 0° is taken as the
 1010 eastern direction, with increasing values in the counter-clockwise direction. The
 1011 thin black line in each bar indicates the direction of maximum propagation direction
 1012 for that time step. Grey boxes correspond to no propagation between those time
 1013 steps. Notice how both the directionality of growth, and direction of maximum

propagation are incredibly variable in the wax experiments. Water experiments are much more consistent in their growth direction throughout the experiment.

Figure 7: Comparison of Propagation Direction Statistics. *Change in Direction* refers to the difference between maximum propagation direction (black dash in Figure 6) between time steps. Experiments fall into two groups, with water intrusions propagating mostly in the same direction throughout the experiment, and wax intrusions varying markedly.

Figure 8: Stages of Intrusion Development, with dashed regions showing an earlier state, and solid pink region showing the new state depending on the stage of growth. Stage II and Stage III are the result of the effects of solidification. All intrusions begin as Stage I.

Figure 9: Failure Mechanisms. Stalled fronts can reactivate, and there are several ways in which this can occur. **Active Magma Advance** is when the solidification front at the stalled front is torn open and fresh magma proceeds to propagate the crack forward. **Cold Wedge Advance** is when failure of the solidified margin occurs away from the stalled front, and cold rock is pushed forward wedging apart the host rock. **Lamination** is when failure only occurs on the top solidified margin, away from the stalled front. Lamination is similar to a solidification front instability.

<i>Physical Properties, Host</i>	<u>Gelatin</u>	<u>Rock</u>
Young's Modulus, E	~10 ³ Pa Top Layer: 18 kPa Bottom Layer: 7 kPa	~10 ⁹ Pa
Temperature, T	~2° C	Variable
Host Density, ρ	~1000 kg m ⁻³	~2600-2800 kg m ⁻³
Poisson's Ratio, ν	0.5	0.25
<i>Physical Properties, Fluid</i>	<u>Wax and Water</u>	<u>Basaltic Magma</u>
Viscosity, μ	$\mu_{\text{wax}} \sim 10^{-2}$ Pa S $\mu_{\text{water}} \sim 10^{-3}$ Pa S	~10 ³ Pa S (liquidus)
Fluid Density, ρ	$\rho_{\text{wax}}: \sim 800$ kg m ⁻³ $\rho_{\text{water}}: 1000$ kg m ⁻³	$\rho_{\text{magma}}: \sim 2700$ kg m ⁻³
Fracture Toughness, K_c	~10 ⁶ Pa m ^{1/2} (Solidified Wax: Akanoa et al., 2012)	~10 ⁶ –10 ⁸ Pa m ^{1/2} (Solidified Basalt: Delaney and Pollard, 1981; Balme et al., 2004)
<i>Thermal Properties, Fluid</i>	<u>Wax and Water</u>	<u>Basaltic Magma</u>
Temperature, T	54° C (wax liquidus) ~20° C (water)	~1200° C (liquidus)
Solidification Range, ΔT	~0.5-1° K (Wax)	~200° K (Basalt)
Latent Heat, ΔH	150 kJ kg ⁻¹ (Wax, Humphries and Griggs, 1977)	~40 kJ kg ⁻¹
Specific Heat, C_p	1.5 kJ kg ⁻¹ K ⁻¹ (Wax, Humphries and Griggs, 1977)	~1.0 kJ kg ⁻¹ K ⁻¹
Thermal Diffusivity, κ	~10 ⁻⁶ m ² s ⁻¹	~10 ⁻⁶ m ² s ⁻¹
<i>Intrusion Characteristics</i>	<u>Experiments</u>	<u>Nature</u>
Characteristic Magma Velocity, U	~10 ⁻² -10 ⁻¹ m s ⁻¹	~10 ⁰ m s ⁻¹
Characteristic Emplacement Time	~10 ¹ -10 ² s	~10 ⁶ to 10 ⁸ s (months to decades)
Maximum Thickness, H	~10 ⁻² m	Variable
Diameter, L	~10 ⁻¹ m	Variable
Final Aspect Ratio (H/L), Intrusion	1:20-1:8	~1:10 (laccoliths)
Dike Length	~10 ⁻¹ m	Variable
Dike Thickness	~10 ⁻² -10 ⁻³ m	Variable
Aspect Ratio, Dike	1:30-1:60	~1:100-1:1000

Table 1: Properties of experimental materials and their counterparts in Nature

Figure 1

Figure 2

A.

t=1 sec.

t=4 sec.

t=8 sec.

t=9 sec.

B.

Figure 3

Figure 4

WAX

WATER

10 cm

Figure 5 **Exp. 1813**

Figure 6

Figure 7

Figure 8

Stage I:
Self-Similar
Growth

Stage II:
Inflation
Dominant

Stage III:
Deflation and
Propagation

Figure 9

Active Magma Advance

Cold Wedge Advance

Lamination