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Experimental Investigation of Dike Propagation Influenced by Graben Topography and Magma Viscosity Using Analog Modeling

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Abstract

Understanding dike behavior under varying topographical stresses is essential for predicting volcanic vent locations. This study employs an experimental approach to assess how local stress fields and magma viscosities influence dike propagation in a graben. Fluids with different viscosities (analogues for magma) were injected into the base of a layered elastic gelatin medium that was molded with an elongated topographic low. A range of intrusion geometries were created, from vertical dikes to arcuate and inclined sheets, sills and laccoliths. The results show that high-viscosity dikes deflect toward the graben fault scarp at greater depth, whereas low-viscosity dikes favor rotation about their axis in the upper crust. In addition, mechanical layering of shallow crustal layers and their interfaces controls whether dikes arrest in the subsurface or erupt. Furthermore, in two-layer crustal systems, the presence of the graben on the surface, which modifies the stress field in the host material and hence controls intrusion formation, causes a transition from sill to laccolith. Our results help explain how and why a dike will propagate to the surface or arrest within the crust. We show that forecasting vent location in the presence of a graben requires knowledge

25 of the regional and local stress field resulting from topography, and related pressures within the
26 dike. Overall, the study advances our understanding of the mechanisms controlling dike
27 propagation and volcanic eruption in a graben setting and highlights the need for further
28 investigations into their role in regional tectonics and volcanic risk forecasting.

29 **Keywords:** *Eruption, vent, unloading, deflection, rotation, stress, viscosity*

1. Introduction

Dikes are magma-filled fractures that propagate from reservoirs toward the Earth's surface, either creating new pathways or exploiting pre-existing weaknesses in the crust (Kavanagh, 2018; Rivalta et al., 2015). Their trajectories are primarily governed by the regional stress field, propagating perpendicular to the minimum compressive principal stress (σ_3) and parallel to both the maximum (σ_1) and intermediate (σ_2) compressive principal stresses (Roberts, 1970; Roman et al., 2021; Sigmundsson et al., 2015). Local stress perturbations related to faults, topography, and crustal heterogeneity have been shown to modify dike paths. Magma composition and viscosity fundamentally control ascent dynamics. Felsic magmas, with higher silica content, are often more viscous and ascend less efficiently than mafic magmas. High water content lowers viscosity and promotes faster ascent, whereas degassing, cooling, and crystallization increase viscosity and can halt dike propagation (Abdullin et al., 2024; Chevrel et al., 2019; Dingwell et al., 1993; Schmiedel et al., 2021). Abdullin et al. (2024) show that felsic magmas may rise rapidly from ~30 km to ~10 km before viscosity increases cause arrest. Viscosity also governs sheet intrusion behavior, influencing segment geometry and eruption style. Schmiedel et al. (2021) demonstrate how viscous dikes feed explosive eruptions and reveal that high-viscosity magmas form blunt segment tips, unlike the tapered tips of low-viscosity magmas. Understanding these processes is essential for forecasting vent locations during volcanic unrest.

A topographic low, such as a rift or caldera, may deflect the propagation path of a dike depending on the magma buoyancy, edifice size, and crustal properties (Gaete et al., 2019; Maccaferri et al., 2015; Maccaferri et al., 2014). In volcanic regions, topographic unloading refers to zones where the surface load on the crust is relatively reduced, generating a stress region that can modify dike propagation pathway and eruption potential. Such unloading features commonly form through extensional tectonics that create rift valleys, caldera collapse events that remove

significant overlying rock, or flank collapse that reduce vertical loading on parts of the edifice. Maccaferri et al. (2014) used numerical models to investigate dike intrusion in a rift setting where unloading stresses are associated with tectonic extensional regimes in an elastic crust. Their simulations demonstrated that rift geometry critically controls emplacement: narrow and deep rifts inhibit eruptions and instead favor off-axis eruptions, whereas wider and shallower rifts promote eruptions within the rift itself. Maccaferri et al. (2015) examined dike propagation into different rift systems, in which a dike could be affected by fault scarps. Their results suggested that the distribution of vents in the footwall resulted from a stress field induced by crustal unloading applied on the hanging wall. They also noted that the distance of a vent from a fault scarp is influenced by the height of the fault scarp. Maccaferri et al. (2014), and Corbi et al. (2016) addressed how dike propagation is affected by the presence of a caldera and observed that unloading stresses promote circumferential dikes. Similarly, Gaete et al. (2019) documented the formation of cone sheets in caldera analogs when unloading stress was high enough to arrest vertical ascent. Mantiloni et al. (2021) demonstrated that the degree of dike deflection depends on both stress regime and initiation point, with greater deflection occurring under compression than tension. Collectively, these studies underscore the importance of unloading stresses induced by topographic changes in shaping dike trajectories.

The upper crust is composed of many rock layers that vary in their mechanical properties, and interfaces between rock layers may influence dike propagation and trajectory (Gudmundsson, 2011). As a dike propagates to the Earth's surface, this heterogeneity may arrest vertical propagation and change it to lateral propagation, and in the case of a weak interface, potentially inducing a sill to accumulate (or laccolith, lopolith, etc.; Kavanagh et al., 2006, 2017; Valentine and Krogh, 2006). Rivalta et al. (2015) demonstrated that when the upper layer is weaker (rigidity

ratio < 1), dikes readily propagate upward into the overlying crust. By contrast, when the upper layer is stronger, dikes stall at the interface, accumulate laterally, and form sills until overpressure forces renewed upward propagation. These results are consistent with gelatin experiments by Kavanagh et al. (2006), who found that high rigidity ratios favor sill development, whereas balanced driving pressure and rigidity can yield sill–dike hybrids. Further, sills tips may evolve into laccoliths when lateral propagation exceeds roughly three times the overburden thickness (Kavanagh et al., 2006; Pollard & Johnson, 1973). Numerical models by Taisne and Jaupart (2009) similarly showed that density contrasts modify ascent style: lower-density upper layers promoted vertical propagation, while high overpressure at interfaces favored sill formation. Overall, crustal heterogeneity plays a central role in intrusion style, with rigidity and density contrasts dictating whether dikes ascend, stall as sills, or evolve into hybrid geometries (Kavanagh et al., 2017).

When multiple dikes are emplaced in close spatial or temporal proximity, their stress fields interact. Analog experiments show that a propagating dike can deflect toward or away from an adjacent dike depending on the spacing and stress ratio between them, and that coalescence can occur when the shear stress generated by the first dike exceeds approximately 20% of the excess pressure in the second (Watanabe et al., 2002). Dike propagation is also influenced by pre-existing fractures, with dikes decelerating when propagating between fractures separated by less than ~200 m (Le Corvec et al., 2013). These dike–dike and dike–fracture interactions are relevant to volcanic fields where multiple intrusive events occur in a shared stress environment, as in the Hat Creek Graben, USA (Rahimi & Bursik, 2025).

Magma viscosity and magma rheology have important effects on dike ascent rate, geometry and the internal flow dynamics (Kavanagh et al., 2025). Magma viscosity varies depending on composition, temperature, volatile content, and phenocryst content (Leshner & Spera, 2015;

Lockwood & Hazlett, 2013). Bubbles suspended within the melt can cause non-Newtonian shear-thinning behavior to occur if sufficient strain rates are reached (e.g. Mader et al., 2013), but magma can be appropriately modelled as a Newtonian fluid (constant viscosity) for many stages of magma ascent, particularly when crystal and bubble fractions are low (Kavanagh et al., 2025). Modifications to magma viscosity can lead to dike ascent rates varying by many orders of magnitude (Baker, 1998). Scaillet et al. (1998) estimated a critical viscosity value for a dike to propagate at $\sim 10^6$ Pa.s, under the assumption that the maximum excess pressure in magma chambers is 20 MPa, and based on the tensile strength of wall rocks (Takeuchi, 2004). However, Takeuchi (2004) stated that magma with viscosity $> 10^6$ Pa.s can propagate following the precursory eruption of less-viscous magma. In this case, the propagation of rhyolitic dikes, which have viscosities far higher than those of common basalts, occurred after an initial eruption of lower-viscosity magma, supporting this interpretation (e.g., Summer Coon volcano -Harp, 2021; Poland et al., 2004). Additionally, experimental and theoretical work suggests that higher-viscosity magmas form thicker intrusions because greater driving pressures are required to sustain propagation (Lister & Kerr, 1991; Wada, 1994). Wada (1994) estimated that a 1-m wide dike forms when the viscosity of mafic magma is $10^1 - 10^2$ Pa.s, whereas silicic magma with a viscosity of $> 10^8$ Pa.s tend to form thicker dikes with thicknesses of tens of meters (e.g. Schmiedel et al., 2021).

Overall, the coupling of magma viscosity and host-rock stress conditions control whether a dike continues vertically to the surface, deflects laterally to form a sill, or stalls in the crust. Analog experiments therefore provide an important tool to understand coupled flow and deformation processes, providing important datasets to benchmark numerical counterparts. While geodetic and seismic observations provide insights into dike behavior during unrest (Lewi et al., 2025), uncertainty remains about whether an eruption will occur (Isken et al., 2025). Dike

propagation is inherently complex, necessitating diverse research approaches to improve the interpretation of the signals of magma movement which might lead to eruption. Enhancing our knowledge through experimental modeling is therefore crucial to improve predictions of dike trajectories and vent locations.

This paper reports the findings from analog laboratory experiments that simulate the propagation of dikes with varying viscosities near graben structures, using the Hat Creek Graben as a case study. The experiments involve the creation of a gelatine crust analog cast with an elongate topographic low, injecting fluids with different viscosities into both homogeneous and heterogeneous (layered) elastic media and employing sequential and simultaneous injection techniques. The experimental outcomes are analyzed to understand their implications for dike dynamics within natural rift environments around the world. We discuss how these experimental insights are critical for enhancing volcanic hazard assessments and improving predictions of future eruption sites in a graben setting.

2. Methods

2.1. Geological context and case study selection

The Hat Creek Graben (HCG), northeastern California, USA, is an excellent area in which to explore the effects of an unloaded topography (i.e., the presence of a topographic low) on dike propagation and the effects of magma viscosity on dike emplacement and vent locations. The HCG is topographically mature yet little eroded and it has experienced eruptions of two compositionally and rheologically distinct magma types: tholeiitic basaltic and calc-alkaline basaltic andesite (Turrin et al., 2007). The calc-alkaline basaltic andesite in the south of Hat Creek Graben ranges in age from 77 ± 11 ka to 46 ± 7 ka whereas the tholeiitic basalt is represented by the 24 ± 6 ka lava flow that filled the graben and extended to ~ 30 km northward (Figure 1) (Clynne et al., 2012; Muffler et al., 2012; Turrin et al., 2007). These magma types

have produced different arrangements and morphologies of volcanic vents in close spatial and temporal proximity and within an active tectonic zone. The HCG is characterized by a topographic depression of ~ 570 m extending over a length of 47 km, and the graben width range from ~12 km in the north to ~4 km in the south (Figure 1). The fault systems that bound the graben show dip ranges from 60°-85° (Blakeslee & Kattenhorn, 2013; Kattenhorn et al., 2016; Paguican & Bursik, 2016).

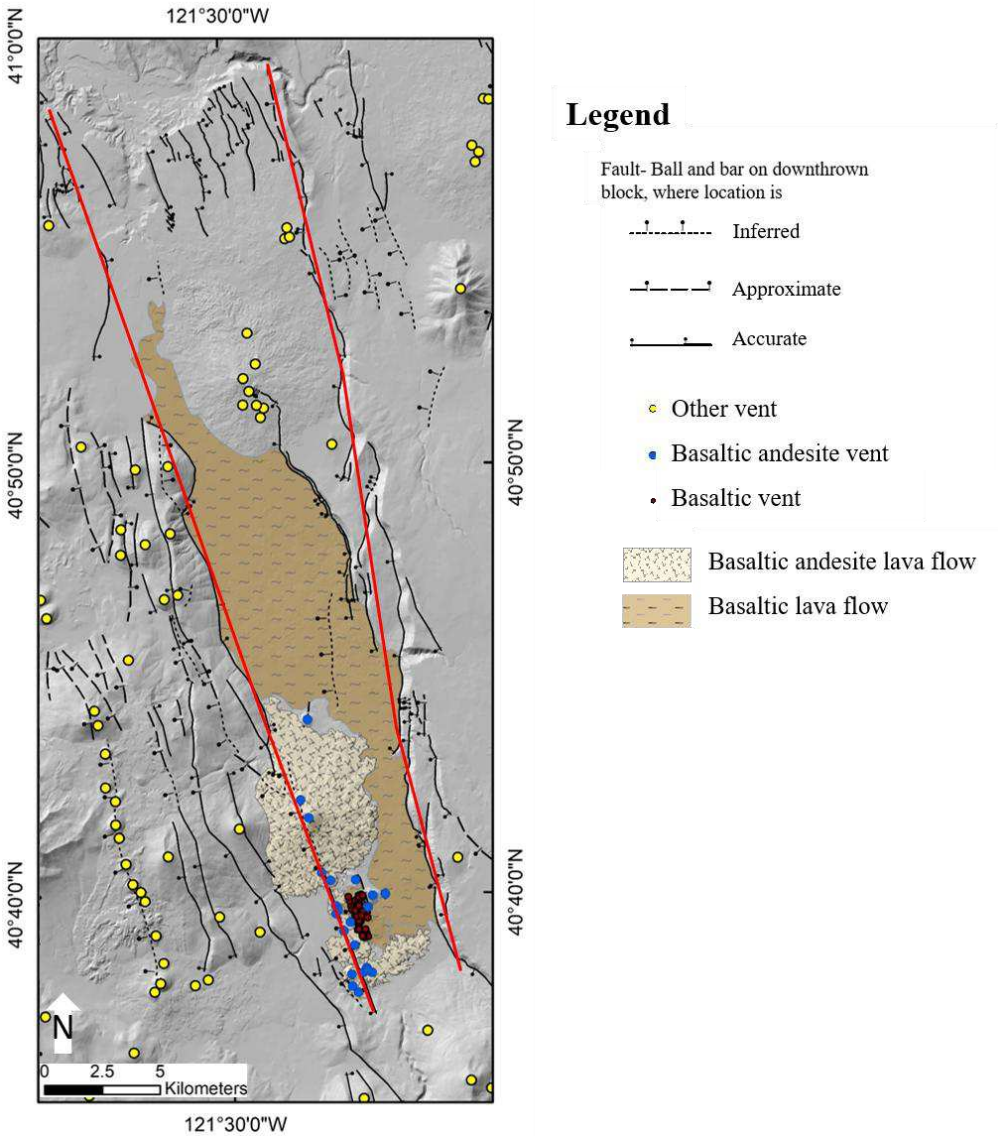
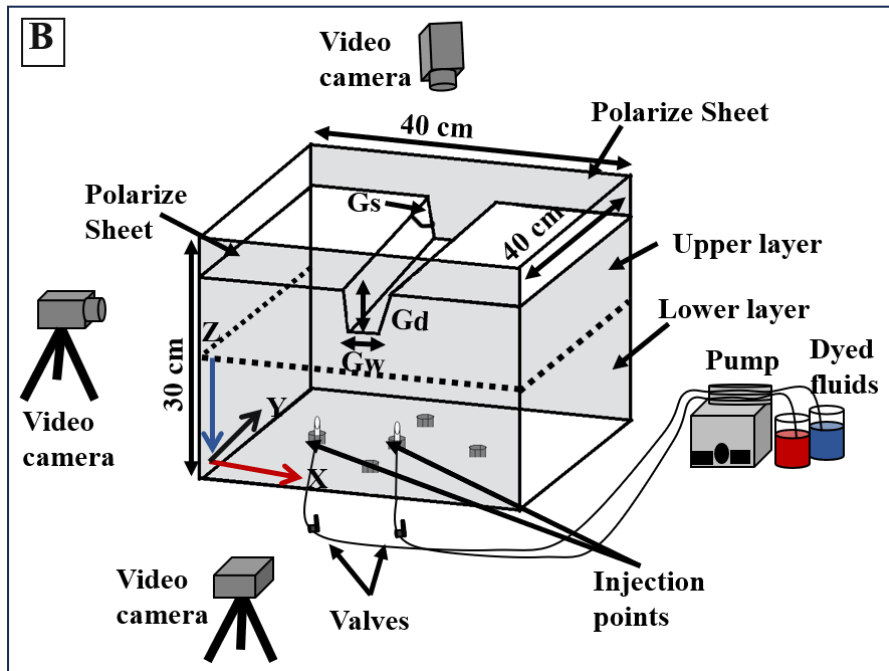
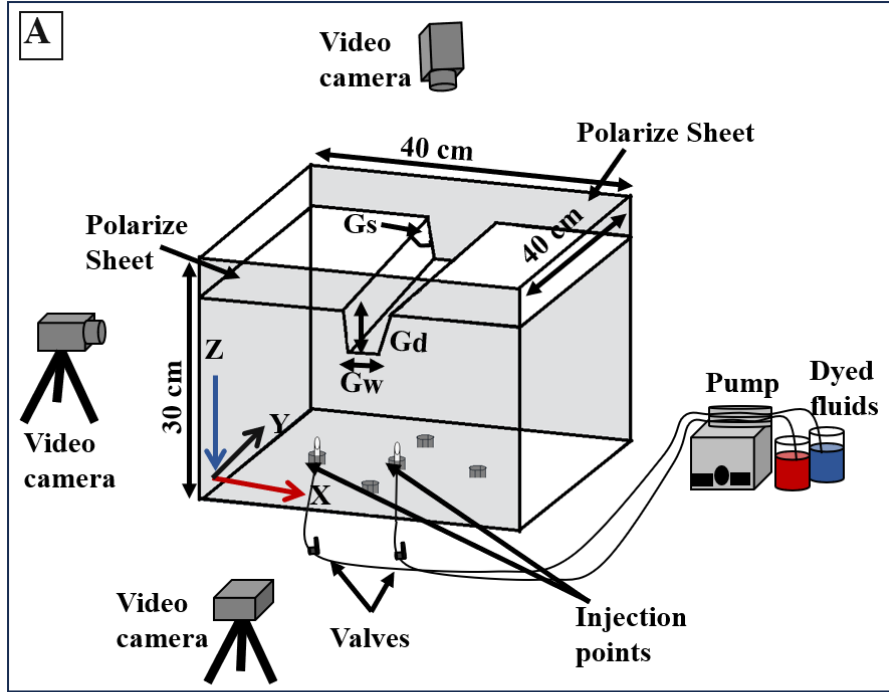


Figure 1 Map of the Hat Creek Graben (HCG) showing major fault systems, with ticks on the downthrown side of normal faults, and different lava flow compositions. Brown- basalt of Hat Creek; Beige- basaltic andesite. Vent

locations are shown in blue for basaltic andesite magma, red for basaltic magma, and yellow for other vents that out of the scope of this study. The red lines denote the inferred graben boundaries.

2.2. Experiment setup

We performed experiments using water and xanthan gum (XG) solutions as magma analogs, and gelatin as an elastic crust analog, to study the influence of magma viscosity, topography, and mechanical layering on dike propagation. Gelatin is widely used in dike modeling due to its elastic and fracture properties that resemble upper crustal rocks when properly scaled (e.g. Kavanagh et al., 2013). Experiments were conducted in a transparent Perspex tank ($40 \times 40 \times 30 \text{ cm}^3$) (Figure 2), filled with gelatin mixed to achieve different concentrations to achieve varying Young's moduli and therefore simulate different rock characteristics. To closely replicate the dimensions of the natural setting under study (Figure 1) and accurately align the graben's centerline with the central injection point, a specialized hollow mold with a width ranging from 4 to 8 cm, bounded by flanks inclined at 75° , was constructed to produce a linear cavity along the tank's y-axis. Two fluids of contrasting viscosity represented the two magma types: water to simulate basalt magma, and xanthan gum (XG) to simulate basaltic andesite magma.



171

172 Figure 2 Schematic diagram of the experimental setups in polarized light, where dyed water and Xanthan gum fluid
 173 (red and blue, respectively) were injected into the base of a gelatin slab using a peristaltic pump. Two polarizing
 174 sheets (pale grey) are attached to the front and back of the tank. Three HD video cameras record images in the X-Z,
 175 Y-Z, and X-Y directions. A) Single-layered system with fixed graben geometry and different fluid viscosities. B) Two-
 176 layered system with fixed graben geometry. In both panels, G_d = graben depth, G_w = graben width, and G_s = graben
 177 slope; these parameters are defined in Table 1.

2.2.1. Gelatin preparation and mechanical properties measurement

Gelatin was prepared using pig-skin gelatin powder (260 Bloom, 10 mesh, supplied by Gelita UK), dissolved in hot distilled water ($\sim 90^{\circ}\text{C}$). The hot mixture was then poured into the tank, which was then filled to 25 cm with the remaining cold distilled water (5°C) to get the necessary concentration. The tank was covered and refrigerated at 5°C ; the curing time for each batch is reported in Table 1. Young's modulus (E) was measured for each batch by placing a known load on the gelatin surface and recording the deflection, following Kavanagh et al. (2013). Measured values of E are reported in Table 1.

2.2.1.1. Single-layered experiments.

Single-layer, homogeneous gelatins models were prepared to understand how fluids with different viscosities (water and xanthan gum) react to an unloaded stress field, and to examine the effect of dike-dike interaction. A graben-like geometry was established by using a plaster mold with an inward dipping flank (75°) separated by a 4-8 cm wide horizontal plane with a length of 40 cm. The mold was covered by plastic film to allow an easy release and avoid any damage at the floor and wall of the graben during its removal. A thin layer of vegetable oil was carefully poured onto the surface of the gelatin to inhibit the development of a toughened “skin” on the surface. The mold was then placed onto the gelatin surface where its position was fixed relative to the center of the injector using plastic tape. Hot water was poured into the mold to increase its weight and facilitate lowering of the graben to a specific depth. The tank was then covered with a plastic film and placed in the refrigerator for cooling at 5°C , while time was recorded. When the gelatin became solid at a particular time, it was removed from the refrigerator, and the plaster mold was removed. The oil layer was then removed off the gelatin surface with a spoon and paper towel, and the final graben depth was measured (Table 1).

2.2.1.2. Two-layered system experiments

Layered experiments were conducted to investigate the effects of crust heterogeneity on dike propagation. These experiments were prepared in two stages: the first (lower) layer was prepared using the single-layer method above. When the first layer reached the gel point, corresponding to a thickness L_1 (Table 1), the second (upper) layer was added. The upper-layer gelatin solution was cooled to $\sim 43^\circ\text{C}$, and then poured into the remaining cold distilled water (10°C) to reach a final mixture temperature of $\sim 22^\circ\text{C}$. This temperature was selected to minimize remelting of the lower layer while maintaining a relatively weak mechanical interface between the layers, which is known to influence intrusion propagation and emplacement behavior (e.g., Kavanagh et al., 2015). The tank was subsequently covered with oil and placed in the refrigerator for final solidification.

The elastic properties of the gelatin were characterized by measuring Young's modulus following established procedures for gelatin analog models (Kavanagh et al., 2013). Young's modulus ranged between 5–10 kPa, depending on gelatin concentration and curing time (Table 1). Full measurement procedures and calibration details are provided in Supplementary Material S1.

2.2.1.3. Fluid preparation

To investigate the effect of magma viscosity, two fluids were used as magma analogs: water behaves as a Newtonian fluid ($\mu \approx 10^{-3} \text{ Pa}\cdot\text{s}$), analogous to a basaltic magma, and a 0.15 wt% XG solution as the basaltic andesite magma analog. The 0.15 wt.% XG solution was prepared by dissolving 1.5 g of XG powder in 998.5 mL of distilled water and mechanically stirring for 24 hours. XG is a shear-thinning fluid; its effective viscosity during dike propagation was estimated at the experimental strain rate (dike velocity/dike half-width) following Williams et al. (2022), giving values of 7.0×10^{-2} to $22 \times 10^{-1} \text{ Pa}\cdot\text{s}$ across the experiments. Dike half-width values of $W_d =$

224 1.4×10^{-3} m for basalt (water) and $W_d = 2.2 \times 10^{-3}$ m for basaltic andesite (XG) were taken from
225 direct laser dike-profile measurements reported by Kavanagh et al. (2025), in which dike
226 maximum thicknesses of 2.8 mm and 4.4 mm respectively were measured under equivalent
227 experimental conditions. Full rheological characterization using a cone-plate rotational rheometer
228 and Carreau-Yasuda model fitting is provided in Supplementary Material S2.

Table 1 Experimental parameters and variables. D_G = graben depth, θ = fault dip, wt.%= gelatin concentration, H= gelatin layer thickness, t= time gelatin has been left to cure in the refrigerator (hours), T=gelatin temperature, Inj. fluid=Injection fluid (central, offset) (W=water, XG= Xanthan gum), Inj. type=type of injection method (Sq=sequential, Sm=simultaneous), E= Young's modulus, and Q = volumetric flux rate. The final result of central injection fluid; G= erupted in-graben, FS= erupted through a fault scarp, C= canoe-like sheet formation and L= laccolith formation.

	D_G (cm)	Wt. (%)	H (cm)	t (h)	T (°C)	Inj. fluid	Inj. type	E (Pa)	Q (m³/s)	Result
Single-layered system with different fluid viscosities										
HCG5A, 5B	5.5	3.5	24.4	62	9.2	W	Sq	7376	W=3.9	G
HCG 6A, 6B	5.5	4	24.8	24	11	XG, W	Sq	5570	XG=3.0	FS
HCG6.1A, 6.1B	5.5	4	25.8	67	5.2	W, XG	Sq	8942	XG=3.0	G
HCG7A, 7B	5.5	4	24.4	40	9	XG	Sq	5599	XG=3.0	FS
HCG 8	4	4	25	42	10	XG, W	Sm	9921	XG=3.1	FS
HCG 9	4.9	4	24.4	27	11	W, XG	Sm	5729	XG=3.1	G
HCG 10	4.6	4	25	22	10	W	Sm	5105	XG=2.9	C
Two-layered system with fixed graben geometry										
HCG 11A, 11B	3.7	$L_{y1}=2.5$ $L_{y2}=2.5$	$L_{y1}=12.2$ $L_{y2}=6.45$	$L_{y1}=90$ $L_{y2}=65$	8.9	W	Sq	5056	W=3.9	L
HCG 12	3.7	$L_{y1}=2.5$ $L_{y2}=2.5$	$L_{y1}=12.4$ $L_{y2}=6.55$	$L_{y1}=88$ $L_{y2}=62$	6.4	W, XG	Sm	5001	XG=3.0	L
HCG 13	5.2	$L_{y1}=2.5$ $L_{y2}=3$	$L_{y1}=16.2$ $L_{y2}=8.7$	$L_{y1}=89$ $L_{y2}=67$	7.9	W	Sm	6851	W=3.9	G

2.2.2. Injection methods

An analog dike was initiated by making a narrow vertical incision into the base of a gelatin slab, which controlled dike orientation. A metal syringe with a tapered tip was sealed with petroleum jelly and connected to a peristaltic pump. The volumetric flow rate (Q) was determined by measuring the discharge volume into a graduated cylinder over a fixed time interval. Water injections used ($Q = 3.9 \times 10^{-7} \text{ m}^3/\text{s}$), and XG injections used ($Q = 2.9 \times 10^{-7}$ to $3.1 \times 10^{-7} \text{ m}^3/\text{s}$). Injections were made at two positions: centrally (beneath the graben centerline) and at a distal off-graben position 10 cm from center. In simultaneous experiments both injections ran concurrently; in sequential experiments the off-graben injection initiated only after the central injection had reached at the surface.

2.2.3. Imaging and data processing

Subsurface stress was visualized photoelastically using two polarizing filters fixed to the front and rear walls of the tank; differential stress concentrations appeared as color fringes, with higher fringe orders indicating greater stress (Gaete et al., 2019). Dike propagation and surface deformation were recorded using three high-definition cameras: one imaging the X–Z plane to capture stress fringes, a second imaging the Y–Z plane to monitor dike geometry, and a third positioned overhead to observe surface deformation in the X–Y plane. Video sequences were analyzed using Tracker software (v5.1.3) to quantify dike length, dip, tip position (X–Z plane), width (Y–Z plane), rupture length, and eruption location relative to the graben centerline.

2.2.4. Scaling

The experiments are scaled to natural dike systems following Kavanagh et al. (2013). The key scale factors are: length $L^* = 1 \times 10^{-5}$ (1 cm in the model $\approx$ 1 km in nature); Young's modulus

$E^* = 10^{-7}$ to 10^{-5} ; dike velocity $V^* = 2 \times 10^{-4}$ (water) and 7×10^{-4} (XG), corresponding to natural velocities of ~ 0.5 m/s and ~ 0.14 m/s respectively; timescale $T^* = 3 \times 10^{-3}$ (1 s in the experiment ≈ 5 minutes in nature). Two dimensionless parameters govern dike behavior: $\Pi_1 = \frac{P_o}{P_v}$, the ratio of dike overpressure to viscous resistance, and $\Pi_2 = \frac{P_{un} \Delta x_l}{\mu V}$, expressing the competition between topographic unloading and viscous resistance. These parameters control dike deflection, rotation, and vent location, and are used to interpret experimental outcomes. Full derivations of forces, scale factors, and the Buckingham Π dimensionless group analysis are provided in Supplementary Material S2.

2.2.5. Numerical model

To characterize the stress field beneath the graben and assess how it influences dike propagation, 2D plane-strain finite element models were constructed in COMSOL Multiphysics. Floor and wall boundaries were fixed (zero displacement); the gelatin surface was a free surface loaded only by gravity, matching the experimental configuration. Model dimensions matched the experiments exactly. Material properties used were: $E = 6,000$ Pa, $\nu = 0.49$, $\rho = 2,700$ kg/m³.

3. Results

3.1. Experiments

Experiments were performed to investigate the influence of graben unloading, injection offset, stratigraphic layering (single- vs. two-layer systems), and fluid viscosity on dike propagation and geometry. The range of experimental conditions is summarized in Table 1.

3.1.1. Single-layered system with different fluid viscosities

A series of experiments were conducted to understand the effect of topography on propagation of dikes having different viscosities, where an experimental water dike represented

basaltic magma, and a XG dike represented basaltic andesite magma. Graben geometry was fixed to be deep, but with width varying from 4 cm at the front of the tank to 8 cm at the back of the tank, to represent the along-strike widening of the graben in the case study area. Sequential and simultaneous injection methods were used. The experimental outcomes were classified according to the resulting dike geometry and vent location.

3.1.1.1. Basaltic andesite dike, fault scarp eruption

Dikes erupted through the fault scarp were associated with the deflection of XG dikes, where fluids were injected beneath the graben center. This outcome occurred in both sequential and simultaneous injection methods. Three stages were developed during dike propagation: 1) sub-vertical dike propagation, 2) dike deflection, and 3) eruption.

Stage 1: Sub-vertical dike propagation

The dike initially propagated sub-vertically, creating its penny-shaped (in Y-Z plane) crack with a dip angle of $\sim 85^\circ$ and a length of ~ 12 cm. However, the dike velocity decreased by 0.05 cm/s from the start of propagation as it started to deflect from the vertical axis.

Stage 2: Dike deflection

The second stage was associated with a continuous dike deflection from the vertical to reach a dip angle of $\sim 45^\circ$ and a length of ~ 16 cm. This deflection allowed the dike to propagate beyond the graben wall with horizontal distances of < 1 cm from the edge of the graben floor. During this stage, the propagation velocities were maintained at $\sim 0.03 \pm 0.01$ cm/s. This stage ended when dikes reached the level of the graben base (Figure 3.A-B).

Stage 3: Eruption

Once the dike encountered the level of the graben base, two behaviors were observed: 1) the dike velocity increased by ~ 0.03 cm/s, and 2) lateral acceleration of the dike tip was observed

as the distance between dike tip and the free surface of the graben wall was less than 4 cm. Hence, the free surface “attracted” the dike to erupt through the graben wall, causing an initial rupture of 1.4 to 1.8 cm breadth (Figure 3.C).

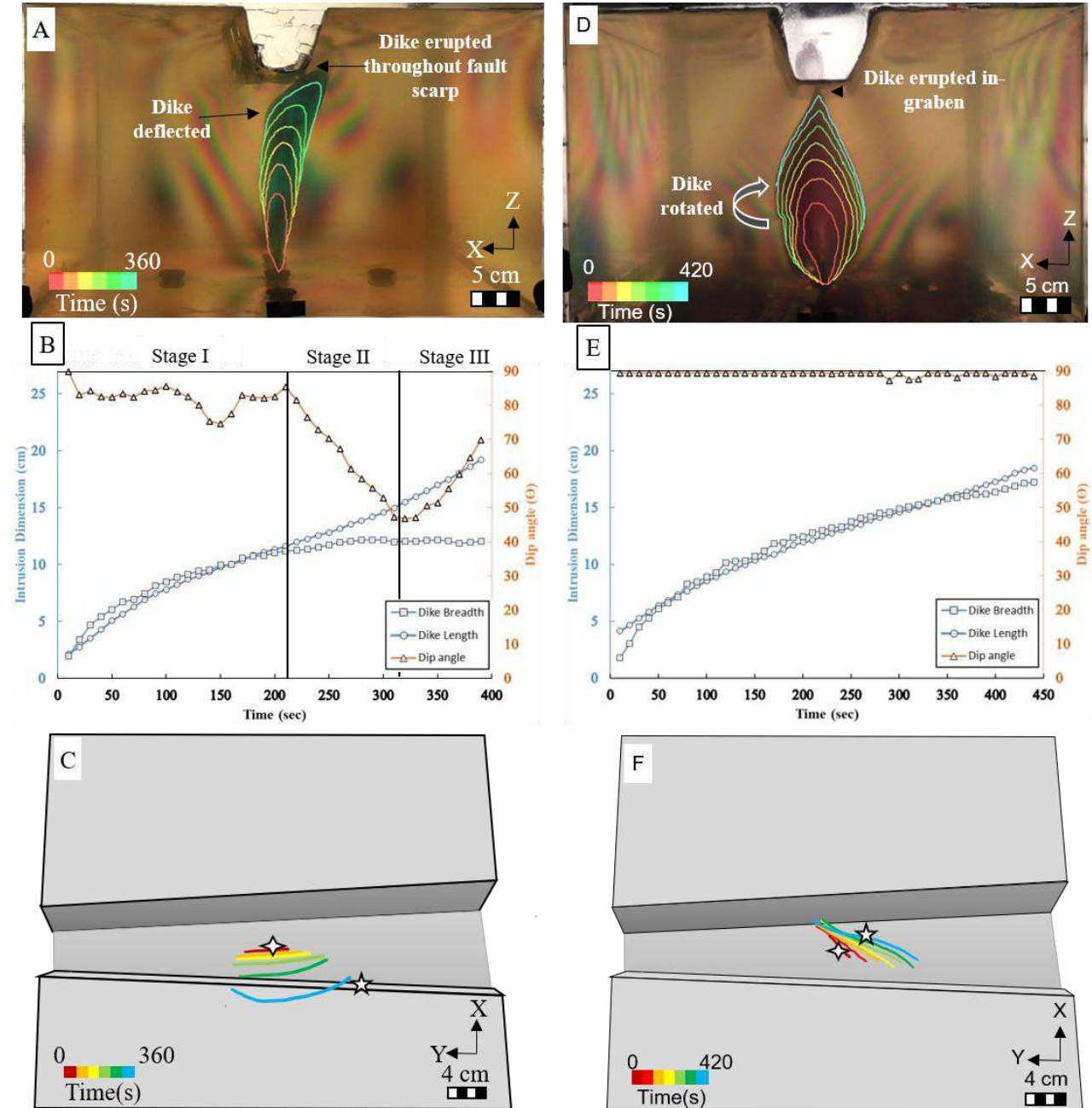


Figure 3 Dike propagation during sequential injection experiments. A-C) XG dike: A) Front view in the in the X-Z plane showing dike deflection toward the graben wall (Experiment HCG7, see table 1), B) Dike length (cm), breadth (cm), and dip angle (θ) over time (s), and C) Top-down X-Y view showing eruption through the fault scarp. D-F) Water dike: D) Front view showing sub-vertical propagation toward the graben base (Experiment HCG6.1, see table 1), E) Dike length (cm), breadth (cm), and dip angle (θ) over

time (s), and F) Top-down X-Y view showing the in-graben vent location. In panels C and F the diamond marks the injection location, star is the eruption location, and colored lines show the dike leading edge during propagation every 60 s.

3.1.1.2. Basalt dike, in-graben eruption

In-graben eruptions were mainly associated with basalt dikes, regardless of the injection method. Basalt showed little deflection; instead, most basalt dikes tended to rotate about their vertical axis. In-graben eruption was formed in two stages: 1) sub-vertical dike and 2) dike rotation and eruption.

Stage 1: Sub-vertical dike

During the first stage, the dike propagated sub-vertically to a length of ~5 cm, after which it began to rotate about its vertical axis.

Stage 2: Rotation

During rotation, vertical propagation velocity decreased by 0.01 cm/s and then remained approximately constant until eruption. The dike intersected the graben base at a non-zero azimuth. Because the dike rotated around its axis, it was hard to measure dike breadth directly from one plane. Thus, the dike breadth was estimated from both X-Z and Y-Z planes.

The dike rotated about its vertical axis without showing signs of segmentation. The shape asymmetry ratio (dike breadth/dike length) changed as the dike propagated (Figure 3.D-E). The asymmetry ratio was 0.85 at the mid-point and reduced to 0.80 right before eruption. The dike exhibited a blunt tip. The dike erupted in-graben causing a rupture of 1 cm breadth, at an azimuth of 45° relative to the graben axis (Figure 3.C).

Overall, the water dike propagated toward the graben base and erupted in-graben without showing any sign of deflection, and the horizontal distance between vent location and graben centerline was < 2 cm.

3.1.2. Two-layered system with different fluid viscosities

The two-layered experiments aimed to understand the effect of layer properties and heterogeneities on dike propagation in the presence of a graben. In two experiments, the mechanical coupling between upper and lower layers was weak (HCG11 and 12), whereas HCG13 had strong interlayer coupling. The results are presented for the weak- and strong-interface cases.

3.1.2.1. Weak interface, sill and laccolith geometry

The dike propagated into the lower layer forming a penny-shaped crack (in Y-Z plane) until it reached the weak interface and then propagated laterally to form a sill. Continued fluid injection thickened the sill into a laccolith. This sequence occurred in both sequential and simultaneous injections and with both fluids.

The growth of intrusion can be classified into four stages. Stage 1 was associated with decreasing the dike velocity by 0.02 cm/s within the first 130 seconds. The dike deflected to a dip angle of $\sim 55^\circ$ in the lower layer due to the presence of the graben.

The second stage was marked as a transition from dike to sill, where the velocity increased to ~ 0.13 cm/s as the dike intercepted the interface, followed by decreasing velocity in the sill to 0.01 cm/s. The sill tip propagated laterally from 1.90 cm at the beginning of stage 2 until it reached a length of ~ 7.50 cm in one direction. The total cross-sectional length of the sill was 15 cm (Figure 4.A-B).

The third stage was marked by a rapid increase in velocity to 0.39 cm/s, associated with laccolith formation in which the sill width rapidly increased by 0.30 cm. The growth of the laccolith was followed by decreasing sill tip velocity (Figure 4.A-C).

The fourth stage was associated with growth of the laccolith, in which it accumulated under and along the graben (Figure 4.C). Laccolith accumulation beneath the graben coincided with uplift of

the graben floor. In these experiments, the dike-to-sill transition occurred at the weak interface, whereas the sill-to-laccolith transition developed beneath the graben.

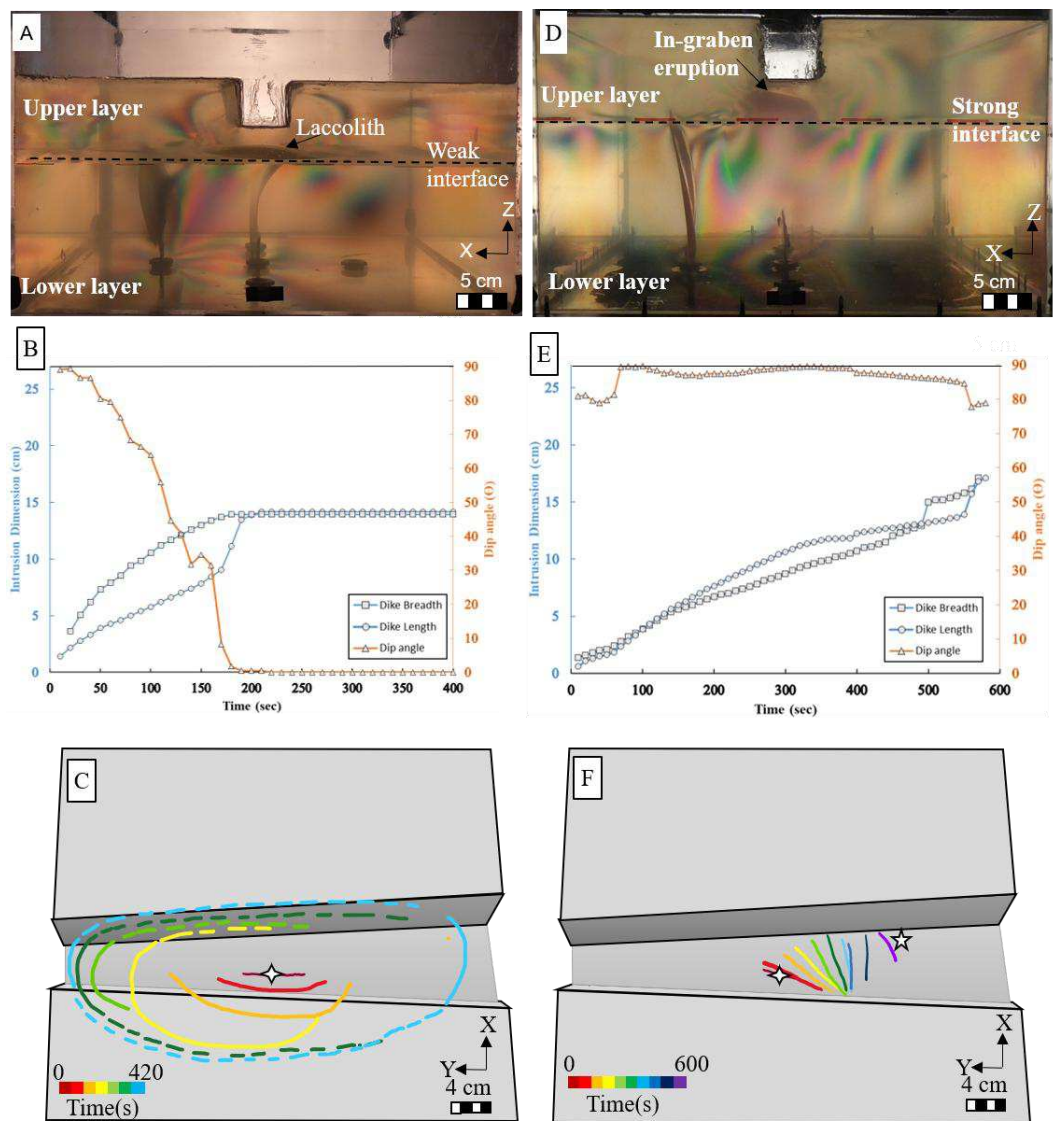


Figure 4 Dike propagation during simultaneous injection experiments, where both dikes are basalt (water) in a two-layer system. The right panel shows a strong interface between layers, and the left panel shows a weak interface (Experiments HCG12 and HCG13, see Table 1). A) Dike penetrates the upper layer and erupts into the graben. B) Dike length (cm), breadth (cm), and dip angle (ϑ) over time (s). C) Top-down X-Y view of in-graben vent location showing dike rotation. D) Dike transitions into a sill and subsequently develops into a laccolith. E) Dike-sill growth is shown by changing length (cm) and breadth (cm), and dip angle (ϑ) over time (s). F) Top-down X-Y view showing the dike deflecting into a sill and laccolith accumulation is controlled by graben geometry. The diamond marks the injection location, star is the eruption location, and colored lines show the dike leading edge during propagation every 60 s Strong interface, propagating dike

3.1.2.2. Strong interface, propagating dike

The central dike growth can be classified into three stages. Stage one was associated with dike propagation into the lower layer up to the interface, showing rotation about its vertical axis (Figure 4.D). The second stage was marked by decreasing dike velocity as it penetrated the interface (Figure 4.E). Finally, the third stage was associated with the dike intruding the interface between layers and propagating into the upper layer to erupt. As the dike rotated and propagated into the upper layer, its dip angle was decreased to 78° when the dike long dimension in map view became perpendicular to the graben axis. This stage was ended by an in-graben eruption as dike velocity increased to 0.21 cm/s. The fissure eruption associated with the central dike had an azimuth of 71° and a rupture length of 5.5 cm. The distance between vent location and graben centerline was 3 cm (Figure 4.F).

In experiments HCG 11 and 12, the rigidity ratio between upper and lower layers was ~ 1 , and the interface between the two layers was weak. Thus, the intrusion propagated in the lower layer as a dike and then propagated laterally to form a sill at the interface between the two layers. The rigidity ratio in experiment HCG13 was >1 and there was a strong interface. Thus, the dike eventually penetrated the interface and propagated into the upper layer. These experiments suggest that the interface controls the propagation of the dike and sill formation. Furthermore, the presence of the graben controls the geometry of intrusion such that transition from sill to laccolith is promoted.

3.1.3. Dike-dike interaction

Sequential and simultaneous two-dike experiments produced contrasting interaction outcomes. In sequential injections, the offset dike was introduced immediately after the central dike reached the gelatin surface. In simultaneous injections, the two dikes propagated concurrently

within overlapping stress fields. Therefore, dikes may influence each other and hence affect their geometry and propagation.

In sequential injections, the offset dike propagated sub-vertically and erupted at the gelatin surface without an observable change in geometry attributable to the central dike. These experiments provide a reference case for the simultaneous-injection results. When two dikes propagate simultaneously, dike overpressure influences the propagation of the second dike by modifying the stress field in the host material as shown on Daniels and Menand (2015); Ito and Martel (2002). In HCG8, where both dikes were XG, the central dike propagated along the maximum compressive principal stress, σ_1 , trajectory modified by the graben and showed no observable deflection attributable to the offset dike. In experiments combining a central water dike with an offset XG dike, the offset dike showed the larger trajectory modification.

The shape of one intrusion can influence the propagation of the other dike. In experiment HCG10, once the central dike deflected off-graben and developed a canoe sheet, the extent of the canoe-sheet below the graben added a local compressional stress to the host material (Figure 5). As a result, the off-set dike bent outward, away from the graben. These simultaneous-injection experiments show that dike-dike interaction becomes more apparent when lateral propagation reduces the distance between the intrusions.

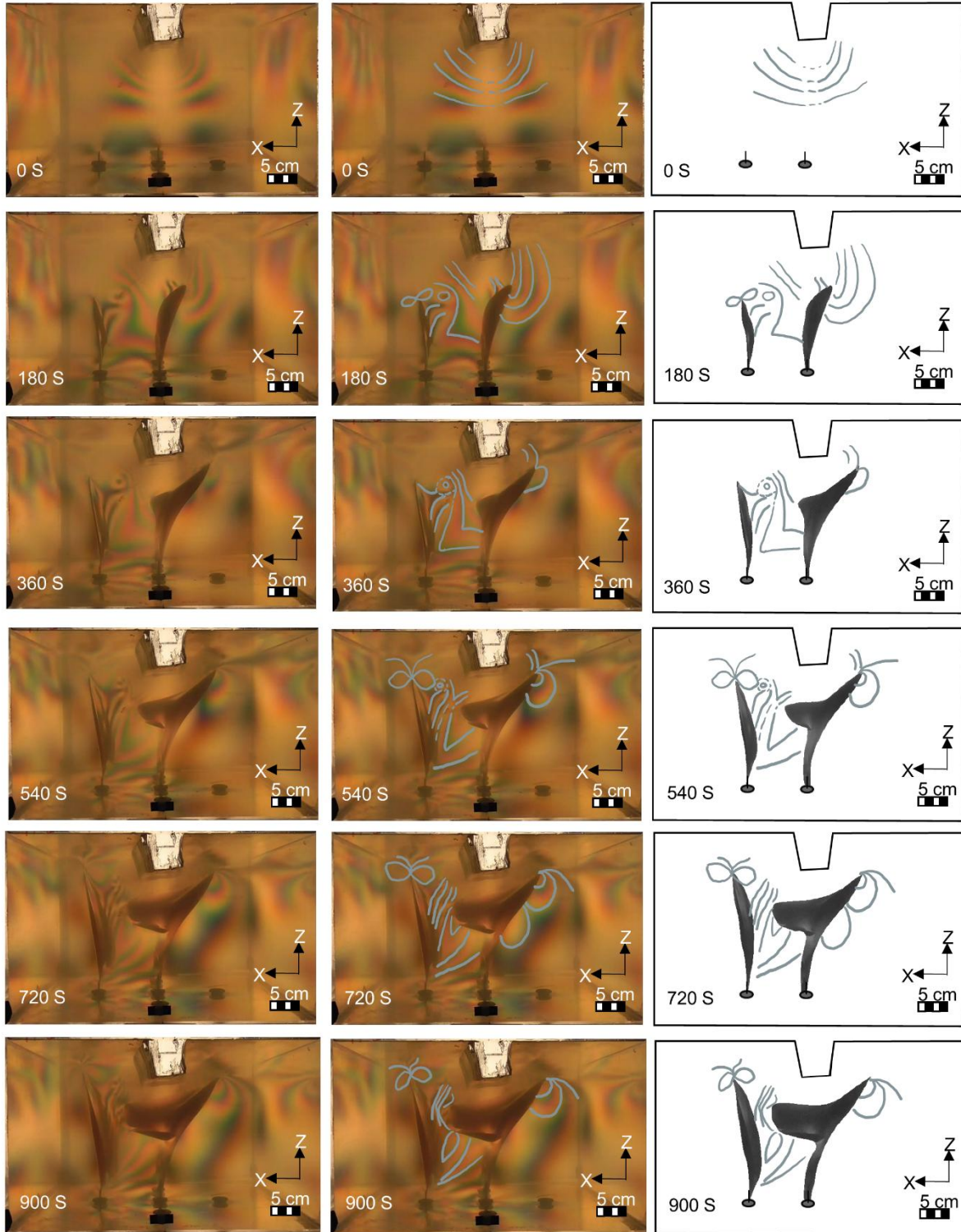


Figure 5 Dike-dike interactions over time in experiment HCG10. Left) photographed in polarized light (X-Z plane), Center) photographed in polarized light with mapping overlaid, and right) mapping interpretation. Differential-stress contours generated by graben and simultaneous injections show complex interaction that is associated with outward deflection of the offset dike.

3.2. Numerical model

COMSOL plane-strain models were performed to gain insight into the orientation of the stress axes for the experimental geometry (Figure 6). The models show that the maximum compressive principal stress, σ_1 , rotates from vertical at depth to horizontal beneath the graben floor, then progressively returning to vertical beyond the graben walls, being no longer affected by the graben. For the narrow, deep graben (Figure 6.A-B), this rotation is steep and spatially concentrated. For the wider graben (Figure 6.C-D), it is more gradual and extends over a greater lateral distance. Because the experimental graben widens from 4 cm at the front of the tank to 8 cm at the back, the σ_1 orientation varies along strike at a given X-Z position.

The experiments are consistent with this modelled stress rotation. Higher-viscosity XG dikes began to deflect from the vertical at a length of ~ 12 cm, corresponding to the depth at which σ_1 begins to rotate beneath the graben floor in Figure 6. In contrast, lower-viscosity water dikes propagated through the same perturbed stress field with substantially less deflection. Thus, the model explains the depth and direction of the stress perturbation, whereas the experiments show that the resulting dike trajectory also depends on the fluid properties of the intrusion.

The results are consistent with the results of previous workers for other cases of unloading topography, such as a caldera depression (Maccaferri et al., 2015). Thus, in general, the numerical model suggests that experimental dikes should become inclined as they propagate, and then realign to vertical. This is, in fact, what is described by Rahimi et al. (2025), such that for a narrow and deep graben (Figure 6.A), the dike favors erupting off-graben. However, if the graben is deep and wide (Figure 6.D), the canoe sheet develops because the dike will deflect to a greater sub-horizontal distance (Rahimi et al., 2025). The effect of stress distribution in experiment in this paper (graben widening toward back of tank) is quite complex, resulting in σ_1 and σ_2 varying

along the y-axis at the same position in the X-Z plane. Specifically, the inclination of σ_1 decreases towards the back of the tank at a given X-Z coordinate. Hence, dike rotation away from the graben centerline toward the north (back of tank) may result in dikes that are little deflected (e.g., Experiment HCG9).

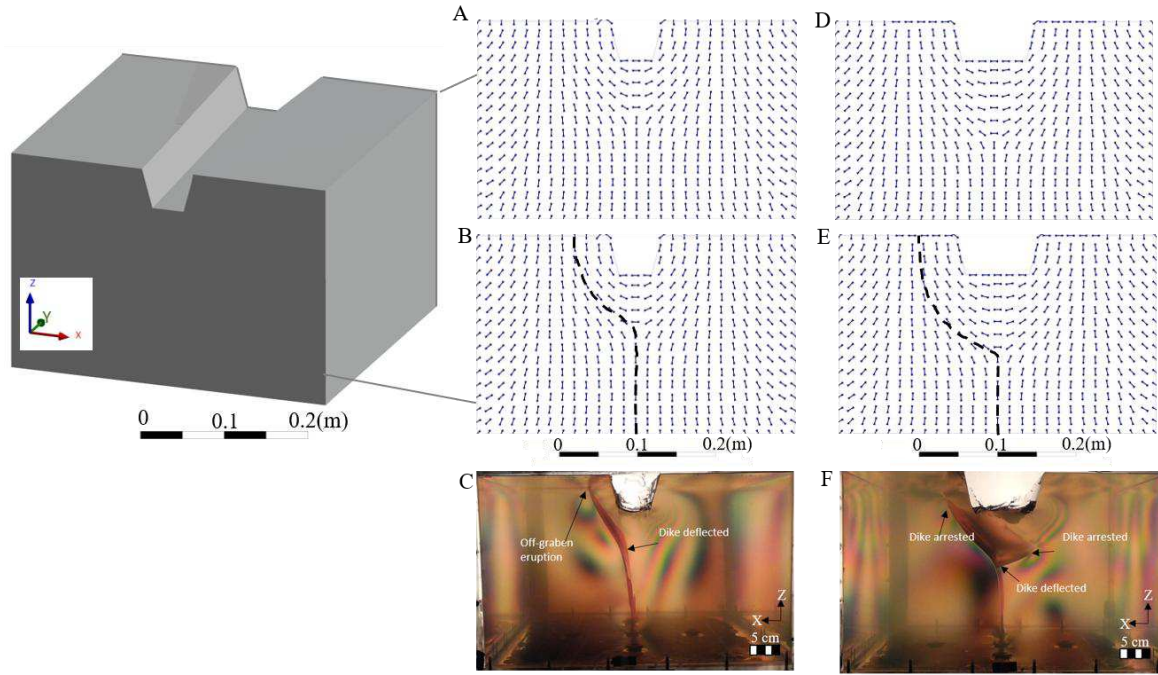


Figure 6 The orientation of the maximum compressive stress (σ_1) is affected by the presence of the graben. A) The direction of σ_1 in the front of the tank, where the graben width is 4 cm, B) The direction of σ_1 in the center of the graben, where the width is 6 cm. C) The direction of σ_1 in the back of the tank, where the graben width is 8 cm.

4. Discussion

4.1. The effect of dike viscosity

The effect of dike viscosity on dike propagation and vent location relative to the graben centerline can be explored by plotting $\Pi_1 = \frac{P_0}{P_V}$, against $\Pi_2 = \frac{P_{un} \Delta x_1}{\mu V}$. The dimensionless plot illustrates how dike viscosity controls dike propagation and the amount of dike deflection (Figure 7, compare red dots and blue dots). For low viscous resistance relative to driving force (relatively inviscid water), $\Pi_1 > 1$, meaning that the pressure drop to drive deflection was not matched by the viscous resistance. On the other hand, for large viscous resisting force relative to driving force

(viscous XG), $\Pi_1 \ll 1$, the viscous pressure drop at maximum deflection far exceeded the pressure that drove deflection, hence deflection was viscosity limited. In other words, as viscosity increases, the resistance to dike propagation increases, the dike velocity decreases and transit time increases. As a result, the viscous forces more easily slow and eventually arrest dike deflection.

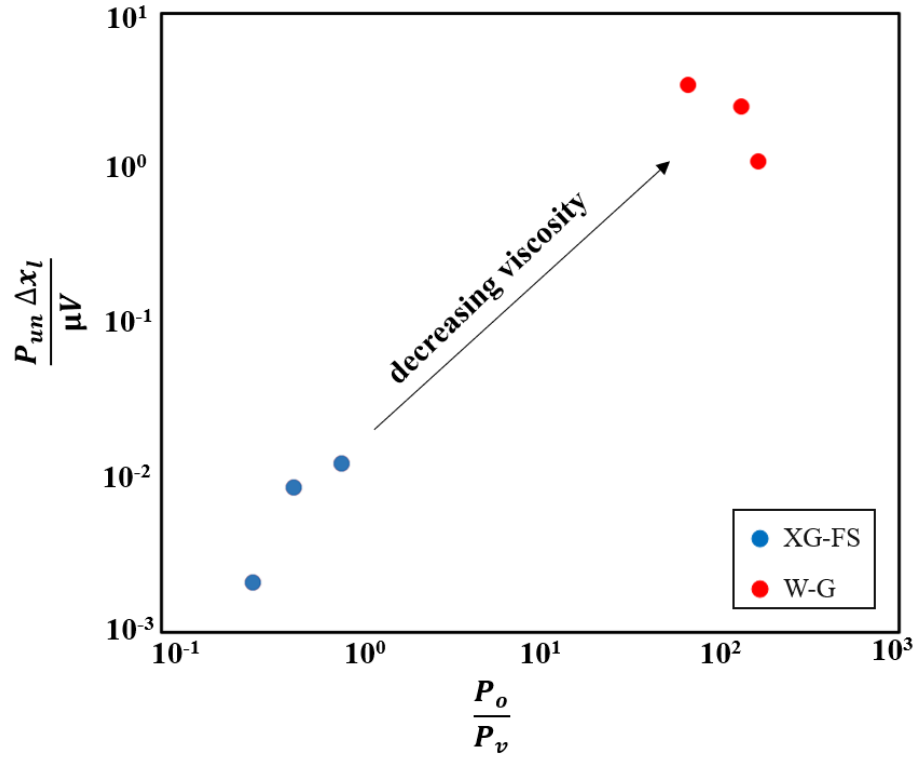


Figure 7 Log-log dimensionless diagram of dynamic parameter controlling vent location and dike velocity. XG-FS — viscous dike analog to basaltic andesite dike that erupted through a fault scarp; W-G — less viscous dike analog to basaltic dike that erupted in-graben. The dimensionless parameters $\Pi_1 = \frac{P_o}{P_v}$, and $\Pi_2 = \frac{P_{un} \Delta x_l}{\mu V}$

In the experiments, the value of Δx_l was found to be less than or equal to 2 cm for in-graben eruptions and approximately 3 cm for fault scarp eruptions. Considering the deep graben and varying viscosity of the water and XG dikes, Π_2 yielded a value of approximately 10^1 for the basalt dike and a value in the range of 10^{-2} for the basaltic andesite dike. Although an increase in the value of Π_2 would seem to indicate more deflection away from the graben centerline, the lower

value for the more deflected dike (basaltic andesite) in Π_1 highlights the influence of viscosity, which was three orders of magnitude greater in the basaltic andesite dike than in the basalt dike. The results highlight the importance of considering the viscosity of the magma when analyzing the behavior of dikes.

The tip of the lower viscosity and higher overpressure dike may modify the local compressive principal stresses to allow eruption in the graben. This is in good agreement with the numerical model on unloading conducted by (Corbi et al., 2016; Pinel et al., 2017), where dikes deflected at different angles depending on the dike overpressure relative to unloading pressure. Figure 6 displays the output of a numerical model, showing the orientation of the maximum compressive principal stress, σ_1 , in the gelatin. The numerical model shows that σ_1 is vertical at depth, where dikes propagate vertically. Moving upward toward the graben, σ_1 rotates sub-horizontally just beneath it. Comparing dike trajectories in the experiments with σ_1 in the numerical experiment suggests that the basaltic andesite dike favors deflection in early propagation due to its slow propagation in the rotated stress field, whereas the basalt dike is relatively inertial, and so less sensitive as σ_1 rotates, and hence has a low potential to be deflected.

Based on the experimental results, the different vent locations or deflections are not only controlled by graben geometry but also by the internal properties or dynamics of the dike, which highlights the effect of dynamic variables on dike deflection and rotation.

4.2. Dike rotation

In the experiments, dike rotation was controlled by two main factors: graben geometry and internal properties, specifically dike overpressure and viscosity. The experimental dikes exhibited different behaviors depending on their viscosity. During propagation, the apparent viscosity of the XG fluids ranged from 0.46 to 1.96 Pa.s. Compared to water, the more viscous fluid propagated

within a wider dike and, as it slowed, its viscosity increased further due to time-dependent effects and decreasing strain rate. As the graben width varies along the axis, σ_2 and σ_3 are oblique to the mean strike direction. Thus, as the dike propagated into the region where the stress was modified, two behaviors occurred depending on the dike's viscous pressure. When the dike has higher viscous pressure, such as basaltic andesite, the dike feels the rotation of σ_1 at greater depth, hence is deflected, following the trajectory of σ_1 (e.g., Figure 3.A-B). For a dike with lower viscous pressure, such as a basalt dike, the dike velocity is high, so the dike propagated faster and less closely followed the trajectory of σ_1 , rising nearly vertical. Therefore, the dike encounters an oblique σ_2 and σ_3 in the near surface under the graben, which causes an outward rotation (e.g., Figure 3.D-E). The experimental results suggest that dike rotation occurred in the shallow crust, where the rotation of compressive principal stresses is controlled by asymmetric unloading.

4.3. Influence of injection type (sequential/simultaneous)

The presence of a graben showed no effect on off-set dikes, as the re-orientation of the compressive principal stresses was limited to a small region below the graben. The results of experiments with dike-dike interaction confirm that in sequential injection, the central dike does not affect the off-set dike, as the off-set dike propagates without any change in its geometry. The sequential injection results agree with what had been seen by Daniels and Menand (2015), where the interaction between the first and second dike decreases as the spacing between two injection points increases.

In simultaneous injections, the effect of dike-dike interaction is dependent on dike overpressure. The results suggest that any dike causes a local compression in the host material, which causes any other dike to rotate or deflect. The extent of these local compressive stresses

depends on dike overpressure. This implies that the stress concentration at a dike tip may especially influence another dike.

4.4. Influence of two-layered system

The development of intrusion shape and geometry is dependent on the host rock properties and stress field distribution. The results agree with (Kavanagh et al., 2017) that the transition from dike to sill occurs due to a weak interface between layers. In addition, the accumulation of sills to form a laccolith occurred because of the graben, which modified the stress field in the host material, hence controlled intrusion development. As a result, a laccolith developed beneath and along the graben axis, which causes the graben floor to uplift. Thus, the stress field due to the graben is the main factor that influenced the formation and geometry of the laccolith, especially as the laccolith tended to be elliptical in map view in the experiment, with a long axis coincident with that of the graben. In addition, the laccolith grew by emplacement of dikes from different injection points, which controlled the growth rate of the laccolith.

In experiment HCG13, the dike propagated through the interface and into the upper layer, where the interface between the two layers was strong. Therefore, the strength of the interface between layers is the main parameter that controlled the intrusion geometry, and the stress field distribution then influenced the developing intrusion geometry as it propagated in the upper layer. Finally, the fluid viscosity did not significantly influence the intrusion geometry as both fluids developed laccoliths.

5. Conclusions

This study presents a series of analog experiments designed to investigate the influence of magma rheology on intrusion pathways and vent localization within a graben-controlled stress environment. Different observations of dike rotation and deflection were observed in the

experimental graben that was an analog of the case study area, the Hat Creek graben. The experimental basalt dikes show a tendency to erupt in-graben with less deflection, with a distance of <2 cm from vent to the graben centerline. The experimental basaltic andesite dike has a greater chance of deflection and eruption through the fault scarp, with a distance of >3 cm from the graben centerline.

Dike–dike interactions in the experiments were strongly influenced by the relative overpressure of each injection. When two dikes propagated simultaneously in close proximity, the evolving stress field from one dike exerted significant influence on the other, leading to geometric modifications beyond simple deflection. In several cases, the breadth (or lateral extent) of one dike increased asymmetrically, suggesting that local stress concentration effects altered the fracture propagation mechanics. These results indicate that stress interference between adjacent dikes can influence not only their trajectories but also their final dimensions, particularly when propagation occurs under comparable overpressures and within overlapping stress fields.

Experimental basalt dikes were erupted with a markedly different strike than that of the graben, similar to what is seen at HCG, suggesting that the unloaded stress field from the graben influenced dike rotation. There are two possible explanations for dike rotation: 1) the dike encountered an oblique intermediate and minimum compressive stresses at shallow depth, or 2) the dike became segmented due to changing shear stress on dike walls during propagation at shallow depth, forming *en echelon* dike segments (Reches & Fink, 1988; Clemente et al., 2007). Given that there was no imposed shear, and that segmentation was not seen in the experiments, alternative (1) is more likely in this laboratory system.

The mode of propagation of a dike in a two-layered system mainly depends on the interface between the two layers. When the interface was weak, the dike deflected into a sill and ultimately

developed into a laccolith. However, dikes propagated into the upper layer when the interface was strong. Once arrested near the interface, the unloading stress caused by the existence of the graben controlled the transition from sill to laccolith. The results suggest that the likelihood of eruption in or off graben, or through the fault scarp, as well as vent orientation relative to graben orientation depend on graben geometry, mechanical layer properties, and magma composition.

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Author Contributions

KR: Conceptualization, Methodology, Formal analysis, Interpretation, Data Curation, Writing - Original Draft, Funding acquisition

MB: Supervision, Analysis, Interpretation, Writing - editing

JLK: Conceptualization, Methodology, Validation, Resources, Writing - Review & Editing

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