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1 **The impact of unloading stresses on post-caldera magma intrusions**

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9 **Abstract**

10 Calderas represent morphological depressions several kilometers in diameter, and the
11 unloaded crustal stresses they produce can form rapidly (e.g. Pinatubo, 1990) or slowly (e.g.
12 Hawaii, 2018). Active calderas are known as sites of persistent magma intrusions, and yet the
13 dynamics of their shallow plumbing system is not well constrained. We use scaled laboratory
14 experiments to study how experimental intrusions are created beneath a caldera by injecting
15 dyed water (magma analogue) into the base of an elastic gelatin solid (crust analogue) with a
16 cylindrical cavity in its surface to mimic a caldera-like topography. The evolving dike geometry
17 and stress field were qualitatively determined using polarized light, and digital image
18 correlation allowed the incremental and total strain to be quantified by tracking passive-tracer
19 particles in the gelatin that fluoresced in a thin 2D vertical laser sheet. Our results show that
20 the unloaded stress field from a caldera can cause a divergence of vertical dikes, and leads to
21 circumferential dikes and cone sheets. When the caldera was large the initially vertical dike
22 became arrested, then grew laterally via circumferentially-propagating en echelon segments;
23 these eventually joined to complete a cone sheet that was parallel to, but extended outside
24 and beneath, the large caldera. When the caldera was small, a circumferential dike erupted,
25 producing a short fissure which was outside, but parallel to, the caldera. We suggest that the
26 distinct curved geometry, velocity, strain and stress characteristics of circumferential dikes
27 and cone sheets can be used to interpret the origin and growth of post-caldera magmatism
28 and the likelihood of eruption in caldera systems.

29 **Keywords:** Caldera, cone sheet, gelatin analogue modeling, circumferential dike, digital
30 image correlation

31 **Highlights**

- 32 • Circumferential dike and cone sheet dynamics are modeled
- 33 • Unloaded stress (caldera) affects intrusion geometry, velocity, strain and stress
- 34 • Early stages of circumferential dike and cone sheet growth are identical
- 35 • Cone sheets grow laterally at depth via en echelon arcuate segments

36 **1. Introduction**

37 Calderas are associated with some of the largest volcanic systems (e.g. Yellowstone, USA)
38 where topographic lows form due to subsidence along caldera ring faults (Cole et al., 2005).
39 Caldera-forming events can be rapid (Mt Pinatubo in Philippines, 1990, e.g. Pallister et al.,
40 1996) or slow (Kilauea volcano in Hawaii, 2018, e.g. USGS, 2018) and may form due to
41 explosive volcanic eruptions (Cole et al., 2005) or gradual drainage of a deep reservoir by
42 lateral intrusion. Despite the largest cataclysmic eruptions being produced during the
43 formation of the caldera itself (Jellinek and DePaolo, 2003), unrest at calderas and relatively
44 small post-caldera eruptions are frequent and pose a significant hazard to the population.
45 Caldera systems are active sites of mineralization, and understanding their development and
46 impact on the volcanic plumbing system is important for georesources, e.g. copper-porphyry
47 deposits (e.g. Blundy et al., 2015), and carbonatite-hosted Rare Earth Elements (e.g. Le Bas,
48 1987). Irregular topographies and crustal loads are common in volcanic terrains, from tectonic
49 rift zones (e.g. Afar and Iceland) to laterally collapsed sectors of a volcanic edifice (e.g. Mt St
50 Helens, USA), unstable volcanic islands (e.g. La Palma, Canary Islands), ice unloading, and
51 excavation of quasi-cylindrical craters associated with volcanic vents, calderas, tuff cones and
52 diatremes.

53 Field observations suggest that post-caldera magmatism typically occurs via inclined sheet
54 intrusions (Burchardt et al., 2011). These may take a variety of forms (e.g. Burchardt et al.,
55 2018). In this paper we use the terms ‘circumferential dike’, which have an arcuate horizontal
56 section, and ‘cone sheet’, which taper downwards towards a central point and have a circular
57 horizontal section, to distinguish and reflect the end member intrusion geometries, without
58 reference to their process of formation. These intrusion types are common igneous magma

59 bodies, are a major constituent of sub-volcanic plumbing systems, and may feed eruptions in
60 caldera settings (e.g. Bagnardi et al., 2013; Chadwick et al., 2011).

61 There are several contrasting conceptual models to explain cone sheet formation, but these
62 often do not invoke the presence of a caldera. For example, Galland et al. (2014) carried out
63 an experimental study of cone sheet development by injecting oil into compacted silica flour
64 with a flat topography. They found that cone sheets formed due to a dynamic dimensionless
65 ratio which included the effects of magma viscosity and host-rock deformation mode. In
66 comparison, Magee et al. (2012) proposed that cone sheets form by lateral propagation of
67 regional dikes from an adjacent source, whereas other authors invoke stress changes from a
68 central magma chamber at depth (Anderson, 1936; Geshi, 2005; Johnson et al., 1999; Schirnick
69 et al., 1999). These fundamentally different models demonstrate there remains uncertainty in
70 the growth dynamics of the magmatic system, and cone sheets in particular. Accurately
71 interpreting the surface signals of magma movement for hazard assessment at active
72 volcanoes ultimately depends on the quality of the models upon which these inferences are
73 made (Di Vito et al., 2016; Guldstrand et al., 2017).

74 The emplacement, propagation and geometry of magma intrusions are influenced by several
75 related factors including density contrasts between magma and host-rock, the ambient stress
76 field (tectonic, regional or local), stress barriers, the physical properties of the intruding
77 magma (e.g. viscosity), and mechanical heterogeneities in the crust such as rock layering and
78 faults (see reviews by Burchardt et al., 2018 and; Rivalta et al., 2015). A commonly explored
79 scenario is that of dike propagation beneath a volcanic edifice where crustal loading influences
80 the tendency for magma to stall at depth or erupt, and whether an eruption occurs in the
81 summit or flank of the volcano (Kervyn et al., 2009; Maccaferri et al., 2011), depending on the
82 magma buoyancy, edifice size and crustal layering (density, rigidity and interface weakness).

83 The load from a volcanic edifice can cause the attraction of dikes located away from the
84 volcano, and in some cases promote their lateral (blade-like) propagation rather than vertical
85 growth (Watanabe et al., 2002). This supports the hypothesis that dikes change their
86 trajectory during propagation in response to perturbations of the maximum compressive
87 stress (σ_1), whose orientation may vary due to local or regional compression or extension of
88 the medium (Anderson, 1936; Maccaferri et al., 2011; Mathieu et al., 2015; Rivalta et al.,
89 2015).

90 Magma propagation under a topographic low, such as a caldera, has been relatively
91 unexplored, despite such unloaded stress fields being common features in volcanic terrains
92 (Corbi et al., 2015; Mathieu et al., 2008). Numerical and analogue modeling suggest that a
93 caldera geometry in a volcanic edifice induces unloading stresses that in a cohesive, crystalline
94 rock may favor the emplacement of laminar intrusions with circumferential and/or radial
95 shapes and sills (Corbi et al., 2016, 2015).

96 Despite the significance of post-caldera magmatism, questions remain regarding the nature
97 of magma intrusion in an unloaded crust. We present results from gelatin laboratory
98 experiments that model the emplacement of a dike in the vicinity of a caldera-like topography.
99 The experiments integrate measurements of sub-surface strain evolution and stress evolution
100 using digital image correlation and polarized light, respectively. Our results test existing
101 models of circumferential dike and cone sheet development and assist in their interpretation
102 by constraining their geometry, propagation pathway, sub-surface deformation and likelihood
103 of eruption.

104 **2. Modeling Framework**

105 **2.1. Scaling and selection of analogue materials**

106 Following the approach described by Merle (2015), we define a laboratory prototype scaled
107 geometrically (ratio of distances is constant in nature and the prototype), kinematically (the
108 geometric scaling is maintained over time), and dynamically (the ratio of the mechanical forces
109 between nature and the model is constant). Our selected analogue material for the crust is
110 gelatin, and for magma we have selected water (see Supplementary Table S1 for detailed
111 scaling). Gelatin has been very well studied in scaled laboratory experiments to simulate
112 elastic process in the crust associated with magmatic intrusions (Di Giuseppe et al., 2009;
113 Kavanagh et al., 2013). Gelatin is a visco-elastic material and its transparency allows the
114 evolving dynamic process of dike propagation to be visually tracked in an experiment (Takada,
115 1990; Watanabe et al., 2002). When used at low concentration (2-5 wt.%) and at low
116 temperature (5-10 °C) it behaves elastically over the timescale of an experiment (Kavanagh et
117 al., 2013), which lasts approximately 10 minutes. Gelatin has been intruded by a range of fluids
118 to simulate dike emplacement (see Janine L Kavanagh et al., 2018 for a review). We have
119 chosen water as the magma analogue as it is a low-viscosity fluid (10^{-3} Pa s) and is slightly less
120 dense than the gelatin ($\Delta\rho = 6 \text{ kgm}^{-3}$). It is a suitable analogue to simulate intrusions of low to
121 intermediate viscosity magma that is mostly driven by the overpressure of liquid from a
122 distant source (Kervyn et al., 2009), and it has been used in several previous experiments that
123 study dike propagation (Kavanagh et al., 2018; McLeod and Tait, 1999).

124 We define the geometric scale between nature n and prototype p in our experiments as the
125 length scale factor:

$$126 \quad L^* = \frac{L_p}{L_n} \quad [1]$$

127 Giving $L^* = 1.0 \times 10^{-5}$ such that 1 cm in the laboratory represents 1 km in nature, considering
128 that in nature the size of calderas range from 1 km to tens of kilometers in diameter (see Table

129 S1). An alternative length scale factor is the buoyancy length L_b when magma buoyancy drives
 130 the rock fracture (Corbi et al., 2016; Kavanagh et al., 2013; Merle, 2015):

$$131 \quad L_b^* = \left(\frac{K_c}{\pi^2 \Delta \rho g} \right)^{\frac{2}{3}} \quad [2]$$

132 where K_c is the fracture toughness of the host medium, $\Delta \rho$ is the density contrast between
 133 host rock and magma, and g is gravity (Taisne and Tait, 2009). Therefore we calculate $L_b^* =$
 134 4.1×10^{-5} (see Table S1). Overall, the two length scales (Equations 1 and 2) agree as they are
 135 within the same order of magnitude.

136 We have used two contrasting approaches to scale the stresses in our experiments: firstly we
 137 scale the elastic deformation of the host material, and secondly we scale the unloading
 138 pressure associated with the caldera. Firstly, we calculate the strain scale factor e^* :

$$139 \quad e^* = \frac{a}{b} \quad [3]$$

140 where a is the dike thickness and b is the dike width. This means $e^* = 10$ when $e_n = 0.002$
 141 and $e_p = 0.02$ in gelatin (Kavanagh et al., 2013). We define a Young's modulus scale factor
 142 $E^* = 3 \times 10^{-7}$, as $E_n = 10^9 - 10^{10}$ (Kavanagh et al., 2013) and $E_p = 300 - 3000$ (see Table
 143 S1). As the elastic deformation of the gelatin can be defined by the relationship between stress
 144 (σ), strain (e) and Young's modulus (E) (Gudmundsson, 2006; Merle, 2015):

$$145 \quad \sigma^* = E^* e^* \quad [4]$$

146 This gives $\sigma^* = 3.0 \times 10^{-6}$ (see Table S1). We also use the unloading pressure scale factor:

$$147 \quad \sigma^* = P_U^* = \rho_r^* g^* D^* \quad [5]$$

148 where D is the caldera depth and ρ_r is the host rock density. As $\rho_r^* = 0.37$ and $D^* = 1 \times$
 149 10^{-5} , this gives $\sigma^* = 3.7 \times 10^{-6}$. The agreement between the stress values calculated from
 150 both of these approaches (Equation 4 and 5) confirms that we have properly scaled our
 151 experiments.

152 **3. Experimental methodology**

153 **3.1. Gelatin Preparation and Young's modulus measurement**

154 We use pigskin gelatin solids (20 Mesh, 260 Bloom; supplied by Gelita UK) prepared at 2.5
155 wt.% by dissolving the appropriate amount of gelatin powder into water at 80°C. The mixture
156 preparation requires three stages: an initial stage where a concentrated mixture is created
157 and left to cool until it reaches ~ 30°C, then the remaining water is added at 5°C to achieve a
158 mixture temperature of ~23°C. Some experiments required the addition of passive-tracer
159 particles, coated in Rhodamine-B which fluoresces in laser light, to the liquid gelatin in order
160 to apply Digital Image Correlation (DIC) analysis (Sutton et al., 1983). For this purpose, 20-50
161 µm diameter fluorescent particles (peak fluorescence wavelength: 590 nm) are added to the
162 gelatin mixture following the method described by Kavanagh et al. (2015). A clear-Perspex
163 tank (40 cm square-base, 30 cm high; Figure 1) is then filled up to 23 cm height and the mixture
164 stirred until it reaches the gel point (21°C) to obtain a homogeneous distribution of particles
165 in the solid gel. A caldera-like geometry is established using a round, plastic container (9 or 12
166 cm diameter) placed onto the gelatin surface and fixed into position relative to the central
167 injection port in the base of the experimental tank using plastic tape. The depth of the caldera
168 is controlled by adding water to the plastic container so that it is submerged by 4 cm depth.
169 Subsequently, the gelatin mixture is covered with vegetable oil which is carefully poured onto
170 its surface to inhibit dehydration, the tank is then covered with plastic wrapping and then left
171 to cool and solidify in a refrigerator set at 5°C for 20 hours. The tank is then taken from the
172 refrigerator, and the plastic container is removed from the center of the gelatin solid by filling
173 it with hot water to allow an easy release and avoid any damage at the floor and/or wall of
174 the caldera that is formed. The oil is then carefully removed using a spoon and paper towel,
175 and the actual depth of the caldera is measured (typically 3-4 cm, see Table 1).

176 Immediately prior to the experiment starting, the Young's Modulus of the gelatin is calculated
177 by measuring the deflection to the gelatin surface caused by two cylindrical brass loads placed
178 sequentially on the gelatin slab (see Supplementary Table S2 for load properties). The load is
179 placed away from the corner of the tank to minimize any wall effects. The Young's Modulus
180 is calculated using the following equation (Kavanagh et al., 2013):

$$181 \quad E = \frac{mg(1-\nu^2)}{\Psi w} \quad [6]$$

182 where m is the load mass, g is the acceleration due to gravity, ν is the Poisson's ratio (0.5 for
183 gelatin (e.g. Kavanagh et al., 2013; Watanabe et al., 2002)), Ψ is the load diameter, and w is
184 the deflection of the surface produced by the load. The average Young's modulus from each
185 load placement is then reported (see Table 1).

186 **3.2. Experiment Setup**

187 Two imaging techniques were used on the experiments to study the subsurface processes
188 associated with dike growth and evolution using two different sets of apparatus:
189 photoelasticity for visualizing stress (Figure 1A), and tracer particle for measuring sub-surface
190 strain and displacement (Figure 1B). To create an experimental dike, a small cut is made in the
191 bottom of the gelatin slab, which controls the orientation of the initial dike. A metal pipe with
192 a tapered end is inserted into this slit and dyed water is injected using a peristaltic pump at a
193 constant volumetric flow rate (Q) of $3.9 \times 10^{-7} \text{ m}^3/\text{s}$. The fluid velocity (V) is approximated by
194 dividing Q by the cross-sectional area of the 1 mm-diameter injection outlet. Injections were
195 made at two different offset positions (0.0 cm and 1.0 cm, relative to the center of the caldera)
196 beneath two different caldera sizes (see Table 1).

197 **3.2.1. Photoelasticity setup**

198 Polarized light is known to be a useful tool to visualize the stress distribution in two
199 dimensional elastic problems (Crisp, 1952; Watanabe et al., 2002). We use the photoelastic
200 property of gelatin with the purpose of understanding the interaction of the local stresses
201 with those of the pressurized experimental dike, making a qualitative description of the
202 changes in the stress field during the intrusion development. The sequence of colored fringes
203 represents the gradient of the differential stress ($\sigma_1 - \sigma_3$) perpendicular to the light
204 propagation direction, and the increasing fringe order represents linearly increasing stress
205 (Crisp, 1952); which in the experiments depend on the caldera diameter and caldera depth.
206 The photoelasticity experimental setup (Figure 1A) consists of two polarized sheets attached
207 to the front and back walls of the tank (x-z plane), and two HD video cameras positioned to
208 record images with polarized light (x-z plane, perpendicular to the dike plane) and artificial
209 light (y-z plane, parallel to the dike plane).

210 **3.2.2. Tracer particle setup**

211 The tracer particle experiment setup requires the use of a high intensity laser that was
212 configured to fire at 1 Hz and produce a vertical, thin sheet (approximately 1 mm thick) in the
213 gelatin slab centered on the injection point (Figure 1B, see also Kavanagh et al., 2015). A New
214 Wave Solo-PIV III Nd-YAG Laser provides 50 mJ pulses of energy between 3 and 5 ns and 532
215 nm wavelength. The laser firing and acquisition is controlled by Dantec Dynamic Studio
216 software and synchronized to a MP CCD camera fitted with a 35 mm Nikon lens (Figure 1B).
217 Longpass (550 nm wavelength) filters fitted to the CCD camera allow only the fluorescent light
218 reflected by the particles to be captured.

219 A 2D calibration image is required for post-experiment image processing. Prior to the
220 experiment tank being filled with gelatin, the tank is filled with water and a white calibration
221 plate with equally-spaced black dots of known size and spacing was aligned with the laser

222 beam in the center of the experimental tank. An image is then captured for later data pre-
223 processing using DIC.

224 **3.3. Data processing**

225 In order to study the evolution of the growing intrusion geometry, we first track the vertical
226 dike tip trajectory in the x-z plane using video images from the polarized light setup (Figure
227 1A). This is conducted at intervals of one frame every 5 seconds using the free Java software
228 Tracker vs 4.10.0 (Brown, 2012). The coordinate origin is set as the top of the needle in the
229 calibrated model, and the position of the vertical dike tip is manually tracked over time. The
230 velocity of the dike tip, and the local dip angle relative to horizontal, is simultaneously
231 computed.

232 DIC is then used to quantify the sub-surface displacement vectors and total strain due to the
233 dike intrusion, at an interval of one image every 5 seconds (0.2 Hz), by using the commercial
234 image analysis tool StrainMaster, implemented in the DaVis software package vs. 8 (LaVision).
235 The calibration image captured prior the experiment is imported into DaVis in a pre-processing
236 stage to scale the results in dimensional units. This process converts the scale from pixels to
237 distance units, and corrects any distortions through the de-warping function. The incremental
238 strain is then calculated by implementing a 'Least Square Matching' algorithm (LSM-
239 algorithm), which operates using an optical flow approach (Fleet and Weiss, 2006). Three
240 seeding points are defined within the reference image, and these are static windows of initial
241 size 121 x 121 pixels that experience no deformation in the experiment. The interrogated area
242 then increases in size with each iteration implementing the 'region grow' algorithm. Outlier
243 and Smoothing filters are then applied, and a mask function is added to exclude the tank walls
244 and caldera cavity from the analysis. The incremental strain is summed to give the total strain.

245 For very small displacement gradients, the strain tensor values are defined by Cauchy's
246 infinitesimal tensor:

$$247 \quad \epsilon_{ij} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad [7]$$

248 where v is the vector component and x the spatial axis. As the experiment observations are
249 carried out in two dimensions (x - z or y - z plane), the lineal deformation in the x or y -direction
250 and in the z -direction are determined by the normal strain components:

$$251 \quad \epsilon_{xx} = \frac{\partial u}{\partial x} \quad \text{or} \quad \epsilon_{yy} = \frac{\partial v}{\partial y} \quad [8]$$

252 and,

$$253 \quad \epsilon_{zz} = \frac{\partial w}{\partial z} \quad [9]$$

254 Thus, the shear strain is given by:

$$255 \quad \epsilon_{xz} = \epsilon_{zx} = \frac{1}{2} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \quad \text{or} \quad \epsilon_{yz} = \epsilon_{zy} = \frac{1}{2} \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \quad [10]$$

256 **4. Results**

257 In total 19 experiments were conducted to explore the influence of caldera unloading and
258 injection offset on dike propagation, geometry and growth. The experimental results are
259 grouped into two end-member geometries: circumferential dikes and cone sheets, however
260 transition geometries are also observed (see Table 1). We detail our experimental
261 observations and results below using representative experiments as examples grouped by
262 their end-member geometries.

263 **4.1. Circumferential dikes**

264 Circumferential dikes are formed in our experimental series only in the presence of a small
265 caldera (Table 1) and in three stages: 1) sub-vertical dike, 2) inclined sheet, and 3) ascent to
266 eruption (see Supplementary Video Figure S1). When the injection position is offset, these
267 three stages occur earlier and their transitions happen at greater depth than when the

268 injection is central. The details of each stage of circumferential dike formation and eruption
269 are now described.

270 **4.1.1. Stage I: Sub-vertical dike**

271 Polarized light shows the unloading stress field induced by the caldera in the pre-injection
272 state (Figure 2Ai). When the injection starts, a vertical dike is produced (Figure 2Aii and 2Bii)
273 creating its own stress field that is focused in a small region around the dike tip and
274 intensifying in magnitude and extent as the dike grows upwards until it reaches a vertical
275 length of 9.2 cm by the end of this stage (Figure 2Aii). At this time, the dike grows near vertical
276 with a dip angle of approximately 80° (Figure 3A). During this stage there is an initial rapid
277 acceleration followed by velocity deceleration (Figure 3B). The DIC analysis (Figure 4) shows
278 the displacement vectors are small and radiate out from the entire dike length, and the total
279 normal strain component e_{xx} (Figure 4Bi) is large (14×10^{-2}) compared with the vertical
280 ($e_{zz} 4 \times 10^{-2}$, Figure 4Ci) and shear components ($e_{xz} 4.5 \times 10^{-2}$, Figure 4Di).

281 **4.1.2. Stage II: Inclined sheet**

282 In Stage II, the dike moves away from the caldera center with a maximum height of 12.8 cm
283 in the end of this stage (Figure 2Aiii and 2Biii). In terms of stress, this stage is distinguished by
284 the colored fringes from the dike visually interacting with those of the caldera (Figure 2Aiii). It
285 coincides with a rapid decrease in the dip angle (from 80° to 40°, Figure 3A) and a slight
286 acceleration of the vertical tip (Figure 3B). Overall the direction of displacement is upwards
287 and towards the caldera, and its maximum amplitude is less than 5 mm (Figure 4Aii, Bii, Cii).
288 The total strain during Stage II (Figure 4Aii) has slightly decreased in the normal horizontal
289 strain (e_{xx} down to 11×10^{-2}), but has increased in the vertical and shear components
290 (e_{zz} and e_{xz} up to 10×10^{-2} and 9×10^{-2} , respectively); e_{xx} is distributed along the length

291 of the vertical dike and inclined limb (Figure 4Bii), whereas there are local concentrations in
292 e_{zz} (Figure 4Cii) and e_{xz} (Figure 4Dii) at the tip.

293 **4.1.3. Stage III: Ascent to eruption**

294 The final stage of circumferential dike development is acceleration to eruption to form a
295 circumferential fissure (Figure 2Aiv and 2Biv). In our experiments all circumferential dikes
296 erupted. During this final stage, there is no visual interaction between the dike stress field and
297 that from the caldera. The dike dip angle gradually increases to 60° and then broadly maintains
298 this (Figure 3A). The vertical tip decelerates gradually, but then accelerates towards eruption
299 (Figure 3B). The maximum opening of the inclined limb of the dike is 7.8 mm thick (Figure 4
300 Aiii), generating the largest magnitude of the total displacement vectors which are oriented
301 towards the caldera (Figure 4Biii, Ciii, Diii). The total strain just before eruption produces the
302 maximum deformation during injection, producing visible uplift of the caldera floor. The
303 largest component of total strain is vertical at $e_{zz} 22.5 \times 10^{-2}$ (Figure 4Ciii), with similar
304 values in total horizontal and shear strain (e_{xx} and e_{xz} up to 17.5×10^{-2} ; Figure 4Biii and
305 4Diii).

306 **4.2. Cone sheets**

307 Cone sheets were formed in the presence of the large caldera six times (see Table 1), and
308 transitional geometries (partial cone, but with dike eruption) were formed four times. The
309 cone sheets are formed in four stages (see Supplementary Video Figure S2), with the first two
310 stages being identical to the circumferential dike formation. Stage I is a sub-vertical dike, Stage
311 II is an inclined sheet, Stage III is lateral growth, and Stage IV is cone sheet completion.
312 Similarly to the circumferential dike, when the injection position is offset this results in earlier
313 and deeper transitions between the stages.

314 **4.2.1. Stage I: Sub-vertical dike, and Stage II: Inclined sheet**

315 The pre-injection stress pattern induced by the large caldera shows more fringes that extend
316 to greater depths in the gelatin slab (Figure 5Ai) compared to the small caldera (Figure 2Ai).
317 Similarly to the small caldera experiments, the first two stages of cone sheet growth are: 1)
318 sub-vertical dike (Figure 5Aii, Bii), which then changes dip and develops into 2) an inclined
319 sheet (Figure 5Aiii, Biii). During Stage I we observe a moderate decrease in the dip angle from
320 85° to 75° (Figure 3C) and velocity deceleration (Figure 3D), as the dike reaches 9.3 cm height.
321 During Stage II the dike changes dip angle from 75° to 35°, accelerates from 0.6 to 1.4 cm/s,
322 and reaches 12.6 cm height by the end of Stage II.

323 The total displacement and total strain (normal and shear components) of cone sheet growth
324 are measured in the x-z plane (Figure 6) and y-z plane (Figure 7). During Stages I and II, the
325 majority of the propagation is out of the y-z plane and so only minor displacements and total
326 strain are recorded in this view (Figure 7Ai, Bi, Ci, Di, Aii, Bii, Cii, Dii). Stage I of cone sheet
327 formation (Figure 6Ai) has maximum total strain in the horizontal normal component ($e_{xx} =$
328 11×10^{-2} , Figure 6Bi), with this distributed across the whole dike, with lower vertical and
329 shear total strain components (e_{zz} and $e_{xz} = 4 \times 10^{-2}$; Figure 6Ci and 6Di). In contrast, Stage
330 II has maximum total strain in the vertical normal component ($e_{zz} = 12 \times 10^{-2}$; Figure 6Cii),
331 with lower horizontal and shear total strain components (e_{xx} and $e_{xz} = 8 \times 10^{-2}$; Figure 6Bii
332 and 6Dii). There are also similar displacement vectors to those observed in Stages I and II of
333 the circumferential dike formation, with low magnitude displacements (<5 mm in Stage I, and
334 5-10 mm in Stage II) radiating out from the dike.

335 **4.2.2. Stage III: Lateral dike growth by arcuate segments**

336 Following initial vertical dike growth (Stage I) and then divergence to a dipping dike (Stage II),
337 a new direction of intrusions establishes at the turning point h (see Table 1). Stage III of cone
338 sheet growth is marked by the Stage II dike dip angle stabilizing at approximately 60° (Figure

339 3C), and the vertical growth rapidly decelerating indicating an arrested dike (Figure 3D). Two
340 circumferential and laterally-propagating en echelon arcuate segments then form close to the
341 turning point (Figure 3C), specifically from the lower part of the inclined sheet (Figure 5Aiv
342 and 5Biv). In the x-z plane, the total displacement vectors increase in magnitude relative to
343 Stage II to be >10 mm, and the maximum displacement continues being oriented radially
344 towards the caldera (Figure 6Biii, Ciii, Diii). The largest total strain is the vertical normal
345 component ($e_{zz} = 37.5 \times 10^{-2}$; Figure 6Ciii) followed by the shear component ($e_{xz} = 23 \times$
346 10^{-2} ; Figure 6Diii) and horizontal normal component ($e_{xx} = 20 \times 10^{-2}$; Figure 6Biii). In Stage
347 III, the cone sheet emerges in the y-z plane as the inclined, laterally-propagating arcuate
348 segments penetrate the laser sheet (Figure 7Aiii). This produces maximum total displacement
349 of 10 mm (which is slightly less than measured in the x-z plane), and a maximum vertical
350 deformation ($e_{zz} = 12 \times 10^{-2}$; Figure 7Ciii) compared to horizontal ($e_{yy} = 7 \times 10^{-2}$; Figure
351 7Biii) and shear components ($e_{yz} = 9 \times 10^{-2}$; Figure 7Diii); which are all lower than strains
352 measured in the x-z plane.

353 **4.2.3. Stage IV: Cone sheet completion**

354 The fourth and final stage of cone sheet formation is the completion of the cone geometry
355 (Figure 5Av and 5Bv). This occurs when the laterally-propagating arcuate segments of Stage III
356 join to create a circular profile in the horizontal plane without erupting. The final cone sheet
357 geometry has a range of forms spanning 'cocktail-glass', 'bowl' and 'trumpet' forms (Figures
358 5, 6 and 7), in agreement with cone sheet geometries described by Burchardt et al. (2018). In
359 transitional geometries, Stage III still produces the lateral sub-surface arcuate segments but
360 they do not join. Instead, at some moment the vertical ascent of the dike is reinitiated, at the
361 location where it first became arrested, and this results in an eruption. Therefore, transitional

362 geometries do not reach Stage IV and have growth behavior and a final geometry that is
363 intermediate to the circumferential dike and cone sheet.
364 Stage IV has a slight decrease in the dip angle starting immediately after the arcuate segments
365 join (Figure 3C), and the velocity decrease is maintained (Figure 3D). The thickest opening of
366 the inclined sheet was 13.63 mm (Figure 6Aiv), which produced displacements greater than
367 10 mm focused directly beneath and towards the caldera (Figure 6Biv, Civ, Div). The maximum
368 strain occurs in the vertical normal component, reaching $e_{zz} = 55 \times 10^{-2}$ in the x-z plane
369 (Figure 6Civ) and $e_{zz} = 50 \times 10^{-2}$ the y-z plane (Figure 7Civ). The total strain is up to $e_{xx} =$
370 20×10^{-2} and $e_{yy} = 12 \times 10^{-2}$ in the horizontal components (Figures 6Biv and 7Biv,
371 respectively), and $e_{xz} = 35 \times 10^{-2}$ and $e_{yz} = 22.5 \times 10^{-2}$ in the shear component (Figures
372 6Div and 7Div, respectively).

373 **5. Discussion**

374 **5.1. Circumferential dike or cone sheet? Comparison with previous experiments**

375 Our experimental series has produced a spectrum of thin sheet-like intrusions, all of which
376 were parallel to the circular caldera, and with end-member geometries of an erupted
377 circumferential dike (Figure 2) and an intrusive cone sheet (Figure 5). The development of
378 these different end-member geometries was similar. Both circumferential dikes and cone
379 sheets propagated at dip angles which reached almost vertical (Figure 3A, C; Figure 8), but the
380 circumferential dikes dip angle ranged from $\sim 40^\circ$ compared to 30° for the cone sheets (Figure
381 8). These dip values are similar to those in nature, for example the trachytic to phonolitic cone
382 sheets of the Tejeda Complex, Gran Canaria which intruded intra-caldera deposits (Schirnick
383 et al., 1999), and the mafic cone sheets of the Ardnamurchan central igneous complex, NW
384 Scotland which intruded into the base of an ancient basaltic volcano (Richey and Thomas,
385 1930).

386 Circumferential dikes and cone sheet geometries have been studied in previous laboratory
387 experiments. Using a granular material to represent the properties of the brittle crust and a
388 flat topography, Galland et al. (2014) found that cone sheets form when the magma source is
389 shallow with respect to the intrusion's width, or when the injection velocity or viscosity is high.
390 Corbi et al. (2016) created buoyant air-filled dikes in gelatin edifices which had a topographic
391 depression simulating a caldera. Similarly to our experiments, they observed that the
392 unloading stress field leads to the formation of circumferential dikes. They found that magma
393 buoyancy plays a key role in the dike geometry and the eruption location, and our experiments
394 support this work even though we did not include a volcanic edifice. When the unloading
395 stresses were particularly large we found this was able to stop eruption and cause a full-cone
396 sheet to develop, whereas Corbi et al. (2016) did not form cone sheets.

397 The caldera diameter was the key parameter in determining the outcome of our experiments:
398 circumferential dikes always developed in the presence of the 9 cm caldera diameter, and a
399 spectrum of transitional to cone sheet geometries were associated with the 12 cm caldera
400 diameter topography (see Table 1). Following the approach of Galland et al. (2014), we have
401 analyzed our experiments further by considering the outcomes related to dimensionless Pi-
402 numbers (Figure 9). The first Pi-number is geometric:

$$403 \quad \Pi_1 = \frac{h}{d} \quad [11]$$

404 where h is the depth at which bending of the dike first occurs, and d is the horizontal extent
405 of the intrusion (see Table 1). The second Pi-number considers the fluid-flow properties and
406 extent of unloading stress relative to lithostatic loading:

$$407 \quad \Pi_2 = \frac{\mu v}{d(P_L - P_U)} \quad [12]$$

408 where μ is the fluid viscosity, V is the velocity of the fluid, P_L is the lithostatic pressure, and P_U
409 is the unloading pressure due to the presence of the caldera (see Supplementary Table S1).
410 Figure 9 shows our experiments occupy three distinct regions in this non-dimensional space,
411 with cone sheets forming at low Π_1 and Π_2 values, circumferential dikes forming at high Π_1
412 and Π_2 values, and transitional geometries forming at intermediate Π_1 and Π_2 values.
413 Geophysical constraints on parameter values that would populate the Π_1 and Π_2 equations in
414 nature (see Supplementary Table S1 for example) suggest that magnitudes of Π_1 and Π_2 in
415 nature are high compared to our experiments. For example, at Rabaul Volcano in Papua New
416 Guinea (Kennedy et al., 2018) the corresponding Π_1 value is 1.5 and the Π_2 value is 3×10^{-5} .
417 This means, according to our models, the most likely intrusion form geometry at Rabaul
418 Volcano would be circumferential dikes.

419 **5.2. Circumferential dikes and cone sheets in nature**

420 The Ardnamurchan cone sheets are perhaps the most-famous of all cone sheets, but there are
421 contrasting models to explain their origin. Burchardt et al. (2013) used 3D projections to
422 propose that the Ardnamurchan cone sheets originate from a single, elongated and
423 temporally evolving magma chamber. This model is in contrast to Richey and Thomas (1930)
424 who originally proposed three centers, and Magee et al. (2012) who proposed lateral magma
425 flow from an adjacent magmatic source in a compressional stress field. We show
426 experimentally that local unloading stresses can cause an initially vertical dike originating from
427 directly beneath a caldera to stall in the crust and grow laterally to form a cone sheet. This is
428 relevant to the Ardnamurchan central igneous complex, as our model does not require input
429 from neighboring systems to build a cone sheet (in contrast to Magee et al., 2012) and does
430 not make assumptions about the nature of the magma chamber at depth (as is the case in
431 Burchardt et al., 2013). Instead we demonstrate that such geometries could be formed purely

432 due to local unloading stresses. It is unclear whether or not there was a caldera present at the
433 time when the Ardnamurchan cone sheets formed (Brown and Bell, 2006), but calderas are
434 thought to have been present in the region at the time of intrusion (Troll et al., 2000).

435 Articulated magma intrusion geometries, made up of circumferential sub-vertical dikes close
436 to the caldera rim which dip towards sub-horizontal sills below the caldera floor, have often
437 been needed to fit crustal deformation data at calderas. Geodetic studies of magma intrusion
438 associated with the 2005 circumferential fissure eruption of Fernandina volcano in the
439 Galapagos (summit caldera: 5 km x 6.5 km) presented pre-eruptive (Bagnardi et al., 2013) and
440 co-eruptive (Chadwick et al., 2011) surface deformation that was recorded using
441 Interferometric synthetic aperture radar (InSAR). Inverse models of the data suggested the
442 intrusion which fed the eruption had a curved and circumferential laminar geometry and
443 originated from a sill, thus showing similar geometry to our experimental circumferential
444 dikes. The continuous vertical growth and final eruption of our experimental circumferential
445 dike agrees well with the Chadwick et al. (2011) model of intrusion leading to the 2005
446 eruption of Fernandina (Corbi et al., 2015).

447 Overall, we suggest that the common modeling assumption of flat geometries, such as planar
448 sheets opening dislocations or cracks, the availability of suitable analytical solutions, and the
449 need to keep the number of model parameters low, may have limited our ability to recognize
450 curved geometries such as those we propose here. Deep cone sheet intrusions may produce
451 low-amplitude uplift that may be a satisfyingly fit for pressurized sub-horizontal cracks below
452 the caldera floor, which is a feature ubiquitously found by geophysical and geodetic surveys
453 at calderas worldwide.

454 **5.3. Arcuate segment development and lateral dike growth**

455 Lateral propagation of a circumferential dike has been evidenced by geological records, but
456 rarely from geophysical monitoring. Geological evidence of lateral flow during cone sheet
457 development was found by Magee et al. (2012) using magnetic fabrics preserved within
458 crystalline cone sheets. However, they interpreted this as evidence of magma being sourced
459 from an adjacent magma chamber, but our results show that such crystalline fabrics could
460 result from a cone sheet intrusion whose magma source was directly beneath an unloaded
461 topography. Geophysical evidence of lateral propagation of a circumferential dike firstly came
462 from the 1989 seismic swarm at Mammoth Mountain, Long Valley caldera, California (Prejean
463 et al., 2003) where earthquake hypocenter migration into a ring structure was interpreted as
464 fluid which triggered seismicity on a ring fault, but it would be also consistent with lateral
465 propagation (0.4 km/month) of a conical opening crack filled with magma or other magmatic
466 fluid evidenced by the migration of seismicity over time. Therefore, our model observations
467 are support the interpretation of lateral magma migration recorded by the seismic data.
468 Secondly, reconstructing ground displacement at the pre-eruptive phase in Monte Nuovo,
469 Campi Flegrei caldera (1935 AD), Di Vito et al. (2016) recognized a circumferential source
470 extending from the center, eccentrically towards the caldera rim, that transfers felsic magma
471 laterally to feed eruptions at the caldera margin, which has been the eruptive magma path for
472 the last 5 ka. In the laboratory, both circumferential dikes and cone sheets had their lowest
473 ascent velocities when the dikes were growing at intermediate dip angle (40-80°), and their
474 highest velocities coincided with the lowest and highest dip angles (Figure 8).

475 Circumferential lateral propagation was present in the growth of our experimental cone sheet
476 intrusions by the establishment of laterally propagating arcuate segments, and the cone sheet
477 geometry initiated at the bending location of the dike (h). We interpret the development of
478 en echelon arcuate segments in our experiments to be associated with stress rotation, due to

479 the influence of the caldera stress field which causes lateral propagation and crack opening
480 under mixed-mode loading (Mode I and Mode III) thus creating shear at the growing tip
481 (Pollard et al., 1982).

482 **5.4. Limitations of our models**

483 Our experimental approach was not to reproduce the natural complexity of magma intrusion
484 in the presence of calderas, but to focus on the effect of the magnitude and extent of the
485 unloading stress on the type of intrusion formed and how it grew. Inelastic host-rock
486 deformation was not considered in our models, and yet this may be important in the shallow
487 crust and in a caldera setting in particular, where rocks may have been damaged due to the
488 caldera-forming process (see Galland et al., 2018 for a review). On a local scale, an inelastic
489 host-rock rheology may dampen the transference of rock deformation signals, due to local
490 compaction and grain rotation, and may increase the possibility of dike segmentation
491 occurring. We did not consider rock layering, yet volcanic settings are likely to be mechanically
492 variable, and previous work has demonstrated how rigidity layering can promote the
493 formation of sills beneath a rigid layer (Kavanagh et al., 2006). Calderas also have fault systems
494 that are likely to influence magma propagation (Browning and Gudmundsson, 2015). Recent
495 experimental work using particle image velocimetry (Kavanagh et al., 2018; Kavanagh, 2018)
496 to model magma flow in dikes is challenging existing dike propagation models, and
497 demonstrates how consideration of the host rock deformation and the magma flow dynamics
498 are needed to develop the next generation of dike emplacement models. The additional
499 impacts of faults, mechanical layering and magma flow dynamics on magma propagation in
500 caldera settings should be the focus of future multidisciplinary and experimental work.

501 **6. Conclusions**

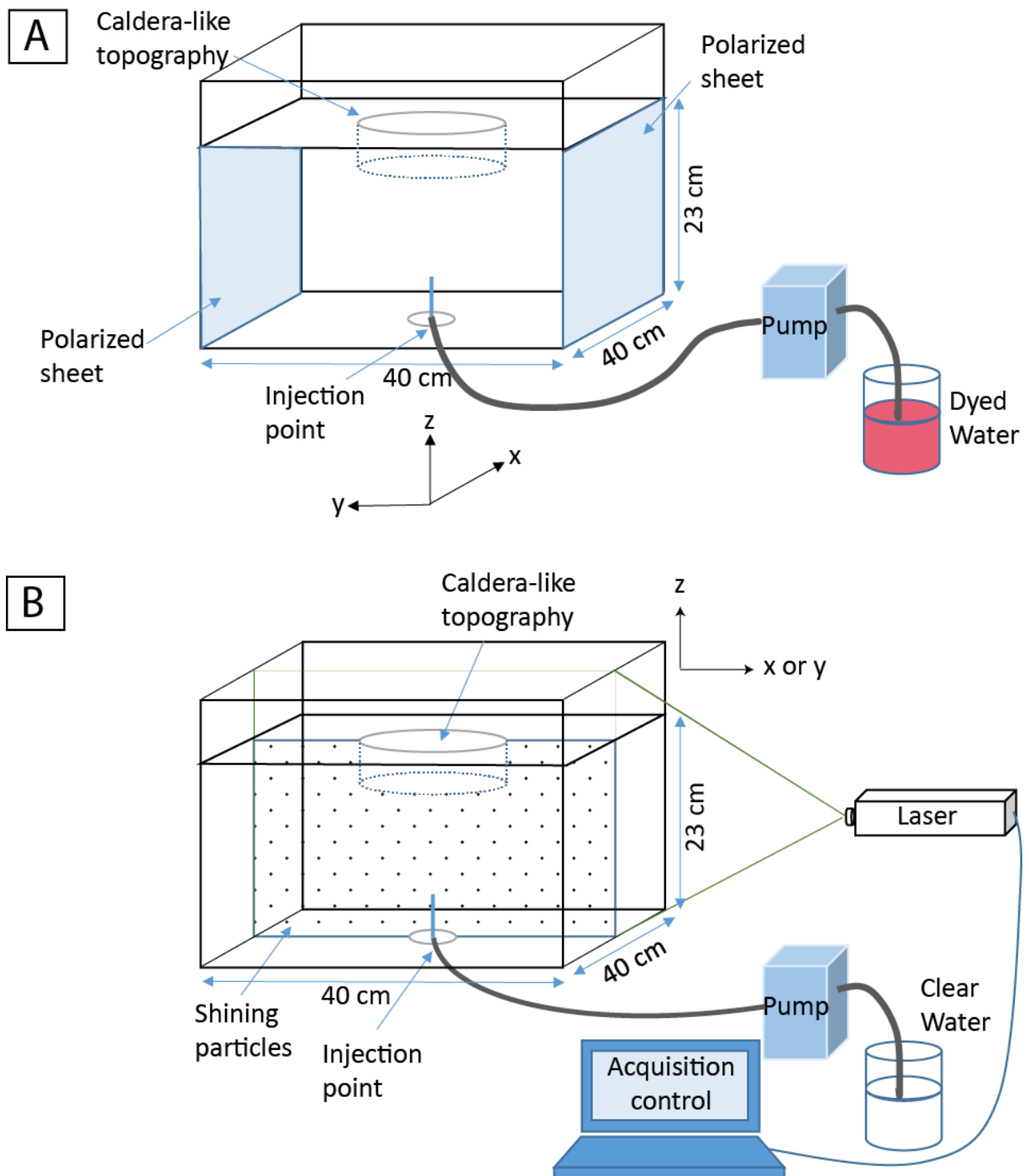
502 We produced experimental circumferential dikes which erupted, and intrusive cone sheets
503 that grew by lateral propagation of en echelon arcuate dike segments. Both originated from a
504 single dike beneath a caldera-like topography in an elastic material. We also formed
505 transitional geometries that were intermediate to these end-member forms. Circumferential
506 dike and cone sheet intrusion dynamics occurred in stages of development which are reflected
507 by their geometric (dip angle), kinematic (velocity) and dynamic (stress and strain) evolution.
508 We identified 3 stages of circumferential dike development (I. Sub-vertical dike; II. Inclined
509 sheet; III. Ascent to erupt) and 4 stages of cone sheets (I. Sub-vertical dike; II. Inclined sheet;
510 III. Lateral growth by arcuate en echelon dike segments, and IV. Completion of the cone sheet).
511 Our results show there are many similarities between the dynamics of cone sheets and
512 circumferential dikes. Our summative dimensionless phase diagram suggests that their
513 occurrence can be related to geometric, fluid flow, and lithospheric unloading conditions.
514 We have proposed a new origin and emplacement for cone sheets that originate from purely
515 vertical dike growth. However, our analysis suggests that conditions in nature seem to be
516 unfavorable for cone sheets to form due to crustal unloading in a caldera setting, and that
517 circumferential dikes and transitional-cone sheet geometries are more likely to form. Our
518 models can help the interpretation of InSAR, GPS and seismic data from active systems, and
519 contribute to the production of more accurate models of magma sources beneath calderas.
520 An important new implication of our models for volcano monitoring is that the conditions for
521 circumferential dike formation appear to be more prevalent in nature. Significantly, it may not
522 be possible to distinguish whether an intrusion will be likely to erupt or not until it has
523 propagated into the shallow crust, which is when it is also likely to be propagating at its fastest
524 rate. This new understanding of magma intrusion dynamics will help to reconstruct the history
525 of ancient calderas, and to forecast unrest and eruptions in active ones.

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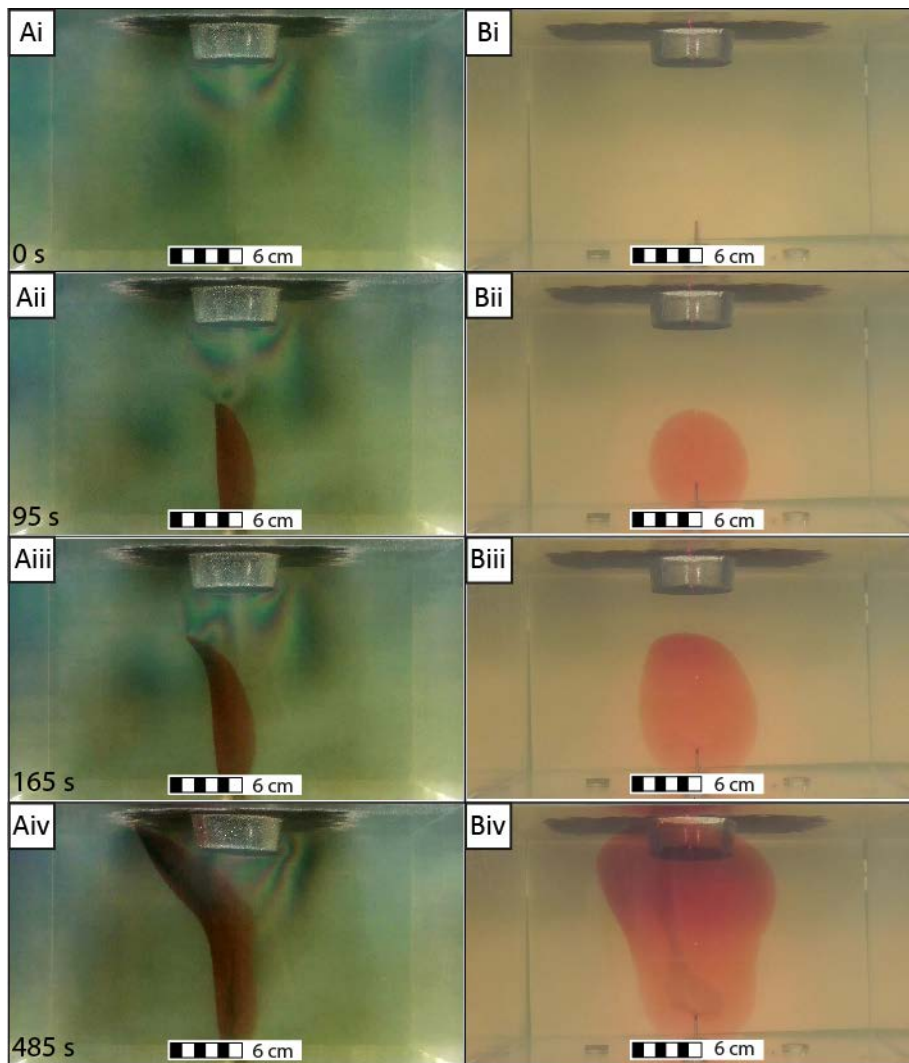
Experiment code	C [cm]	X [cm]	D [cm]	Wt.%	H [cm]	t [hr]	T [°C]	E [Pa]	Q [m ³ /s]	Result	h [cm]	d [cm]	Analysis Method
AG-07	9.0	0.0	3.31	2.5	22.6	20.5	5	2675	3.9×10^{-7}	C. dike	8.2	13.0	PL, TT
AG-13	9.0	0.0	3.78	2.5	23.1	20.5	5	2843	3.9×10^{-7}	C. dike	10.7	13.3	TP
AG-09	9.0	1.0	3.04	2.5	23.2	21.0	5	2490	3.9×10^{-7}	C. dike	8.8	13.8	PL, TT
AG-08	12.0	0.0	3.94	2.5	23.5	20.0	5	3113	3.9×10^{-7}	Cone sheet	12.1	22.4	PL, TT
AG-06	12.0	0.0	3.52	2.5	22.4	19.8	5	2779	3.9×10^{-7}	Cone-Trans	10.7	17.5	-
AG-14	12.0	0.0	4.20	2.5	23.5	21.0	5	2739	3.9×10^{-7}	Cone-Trans	11.1	16.9	-
AG-15	12.0	0.0	3.65	2.5	23.5	21.1	5	2586	3.9×10^{-7}	Cone-Trans	9.8	17.7	-
AG-16	12.0	0.0	3.77	2.5	23.2	20.5	5	2902	3.9×10^{-7}	Cone-Trans	16.8	17.5	-
AG-10	12.0	1.0	3.55	2.5	22.5	21.0	5	2401	3.9×10^{-7}	Cone sheet	12.0	23.4	PL, TT
AG-05	12.0	1.0	3.58	2.5	23.1	19.7	5	2721	3.9×10^{-7}	Cone sheet	14.3	23.7	TT
AG-17	12.0	1.0	3.95	2.5	23.2	19.7	5	2580	3.9×10^{-7}	Cone sheet	15.2	24.5	TP
AG-19	12.0	1.0	3.80	2.5	23.1	19.0	5	2964	3.9×10^{-7}	Cone sheet	15.3	24.0	TP
AG-18	12.0	2.0	3.90	2.5	23.2	22.0	5	3031	3.9×10^{-7}	Cone sheet	14.5	23.9	TP

537 **Table 1:** Model parameters, observed results, and methods applied in the experiment analysis. The experiments are listed in order of caldera
538 diameter C and offset injection position X. The measured caldera depth D, gelatin concentration Wt.%, thickness of gelatin slab H, time left to cure
539 t, refrigerator temperature T, average Young's modulus E, and injection flux of fluid Q is reported. 'Result' corresponds to the final geometry of the
540 intrusion classified as 'C. dike' (circumferential dike), 'Cone sheet', or 'Cone-Trans' for transitional geometries, and the final depth of bending h, and
541 extent of intrusion d are also reported. The analysis methods used are: Polarized light (PL), vertical tip tracking (TT) and tracer particles (TP).



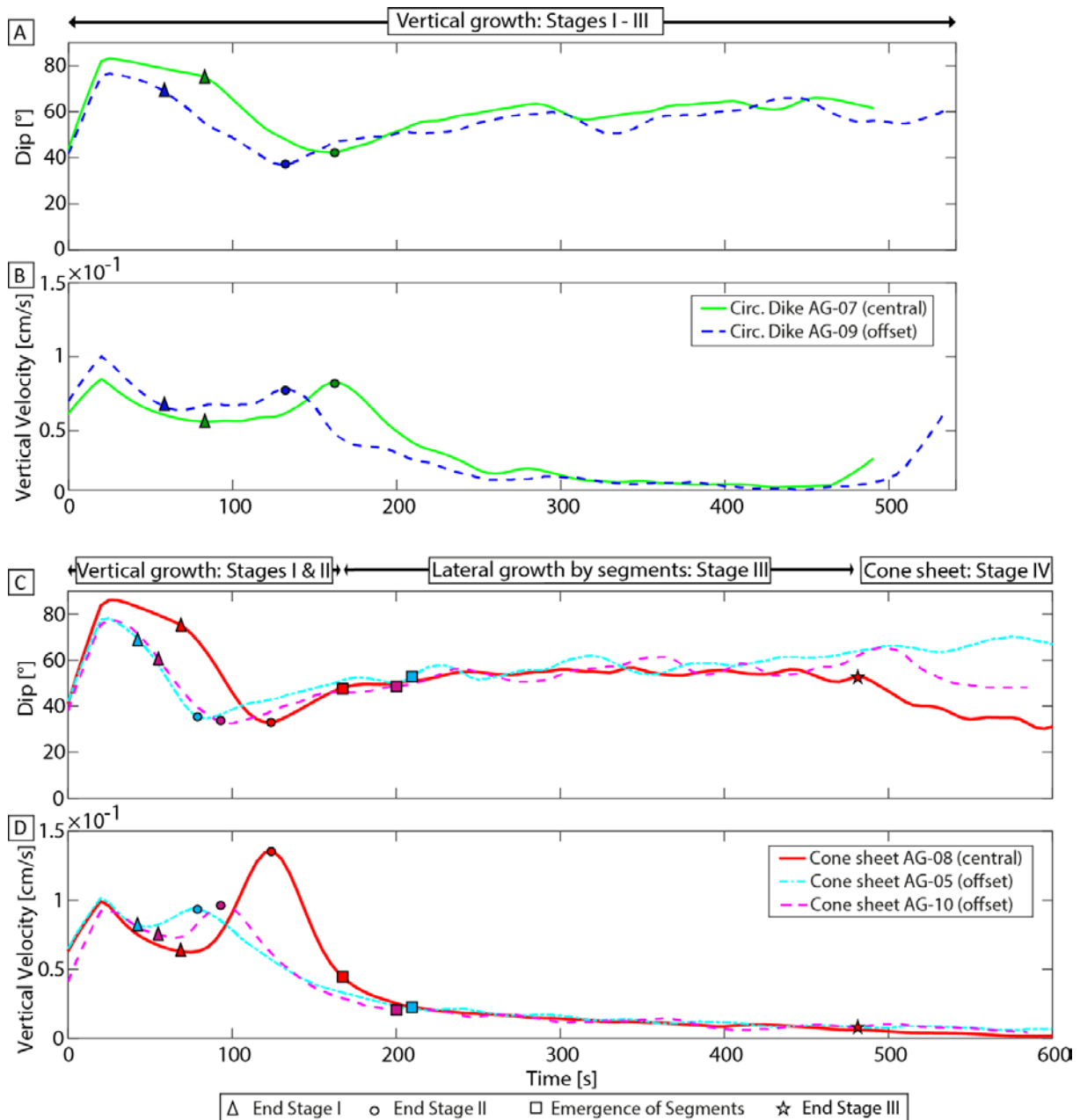
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Figure 1: Schematic diagram of the experimental setups. A) Polarized light experiment: dyed water is injected into the base of a gelatin slab using a peristaltic pump. The gelatin surface is modeled to have a caldera-like topography, and stress in the gelatin is visualized using two parallel polarized sheets attached to the tank walls on the x-z plane and perpendicular to the initial dike profile. Two HD video cameras (not shown) record images the x-z and y-z directions. B) Tracer particle experiment: a high intensity vertical laser sheet illuminates a 2D profile (either x-z plane or y-z plane) through the center of the tank and exciting passive-tracer fluorescent particles in the gelatin. A CCD camera records the illuminated plane at 1 frame per second, synchronized with the laser.

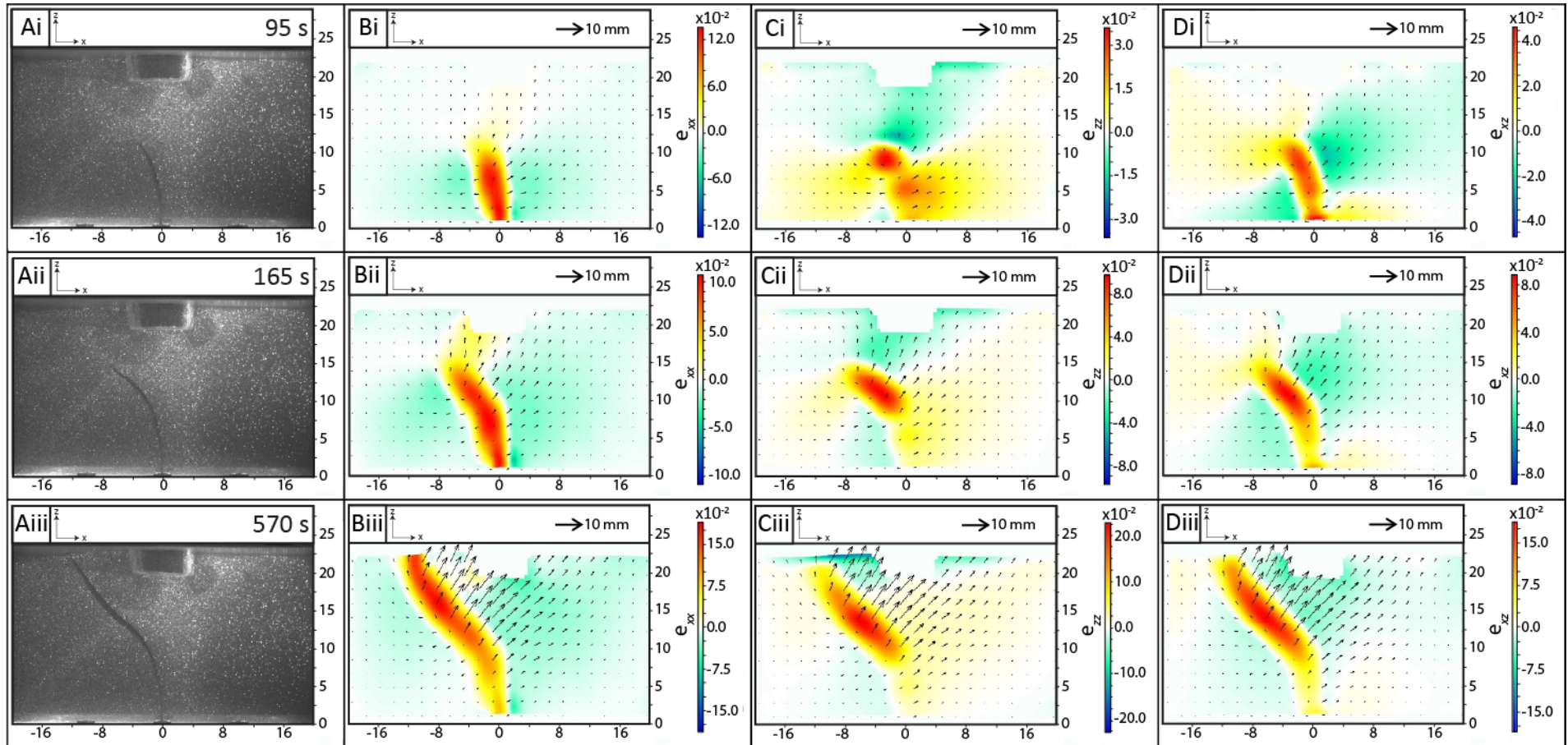


552

553 **Figure 2:** Photographs of circumferential dike development in the presence of a small caldera
 554 (Experiment AG-07, see Table 1): A) Polarized light (x-z plane), and B) artificial light (y-z plane).
 555 i) Pre-injection state, ii) Stage I: sub-vertical dike (95 s), iii) Stage II: inclined sheet (165 s), iv)
 556 Stage III: ascent to eruption (485 s). See also Supplementary Video Figure S1.

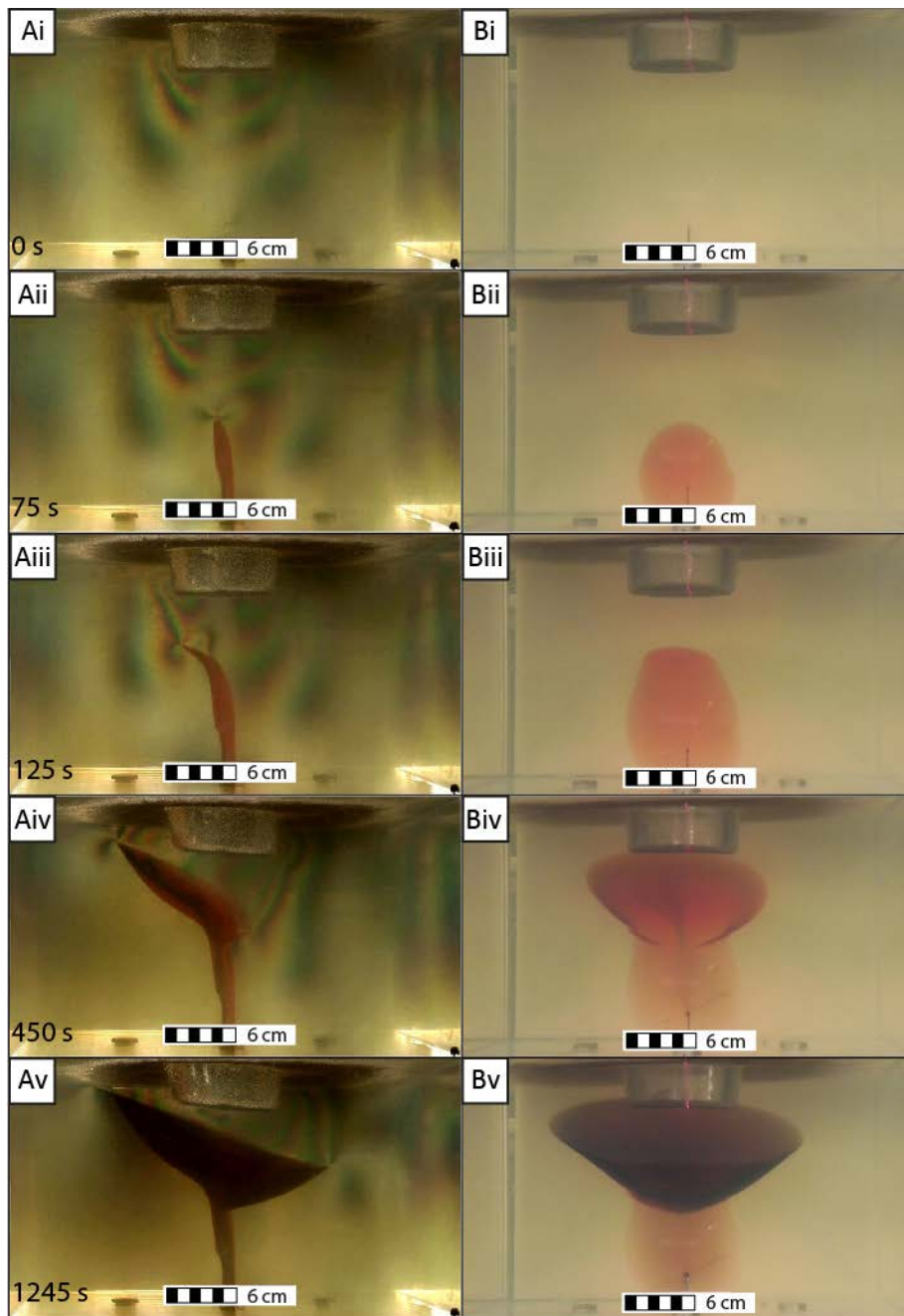


557
 558 **Figure 3:** Three stages of circumferential dike (A-B) and four stages of cone sheet (C-D) growth
 559 shown by changes in Dip angle (°) and velocity (cm/s) of the vertical dike tip in the presence
 560 of the caldera. The approximate timings of stage transitions is indicated at the top of the
 561 graphs (A for circumferential dikes, and C for cone sheets). In the graphs the triangle indicates
 562 the end of Stage I (sub-vertical dike), the circle indicates the end of Stage II (inclined sheet),
 563 and the star indicates the end of Stage III (lateral growth by arcuate segments in cone sheet
 564 emplacement). Stage III shows the ascent to eruption in circumferential dike emplacement.
 565 The Stage III of cone sheet growth produces laterally propagating arcuate segments (the time
 566 of their emergence is indicated by a square) and these join at the start of Stage IV to complete
 567 the geometry.



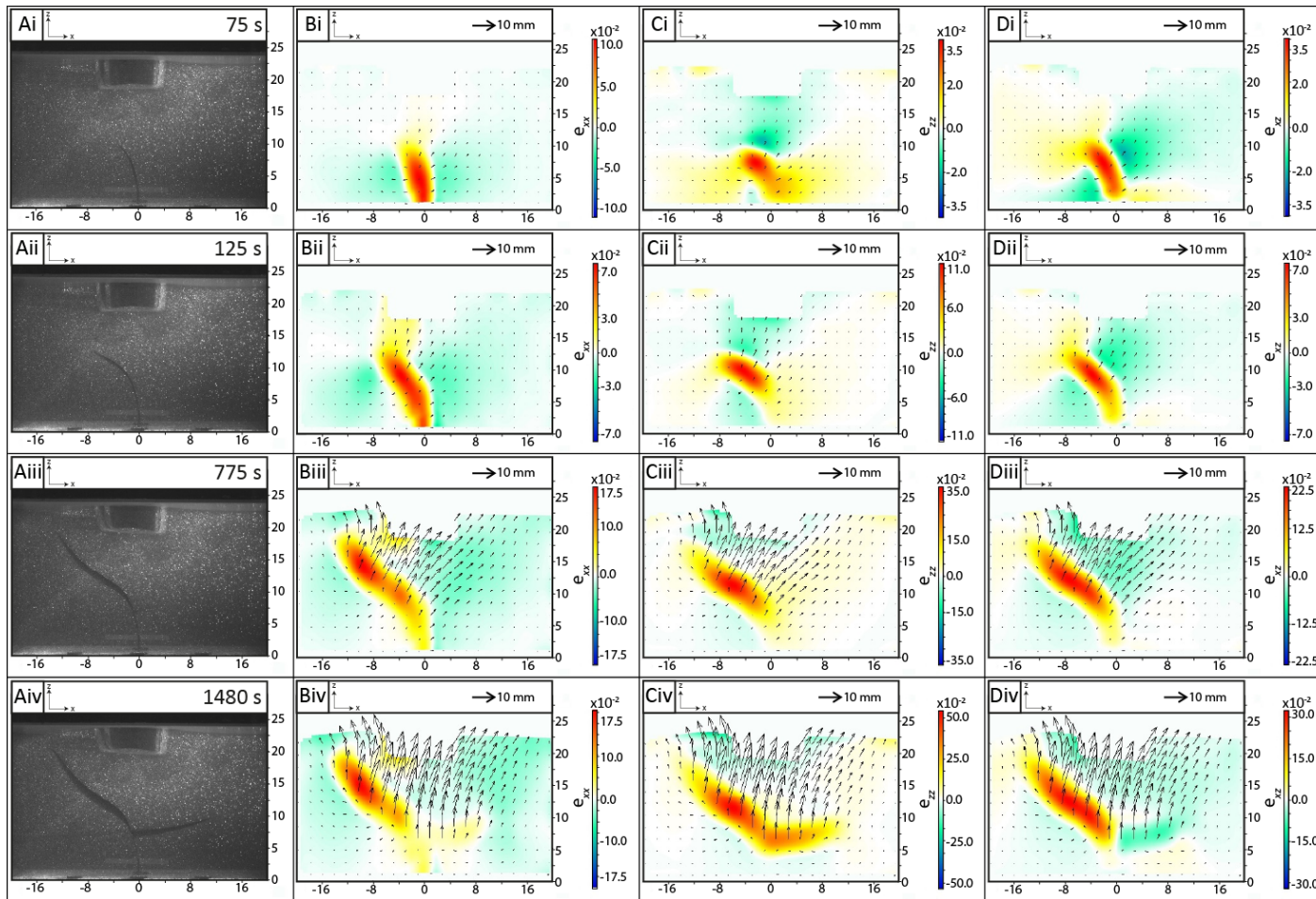
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569 **Figure 4:** Three stages of circumferential dike development in the presence of a small caldera, imaged in the x-z plane, with sub-surface total strain
 570 (color maps) and displacement (vector arrows) calculated using DIC (Experiment AG-13, see Table 1): i) Stage I: initial sub-vertical dike (95 s), ii)
 571 Stage II: inclined sheet (165 s), and iii) Stage III: ascent to eruption (570 s). A) Dewarped experimental images, B) horizontal total normal strain e_{xx} ,
 572 C) vertical total normal strain e_{zz} , and D) total shear strain component e_{xz} are shown. The red color represents extensional deformation in the
 573 normal components and anticlockwise rotational deformation in the shear component. See also Supplementary Video Figure S1.



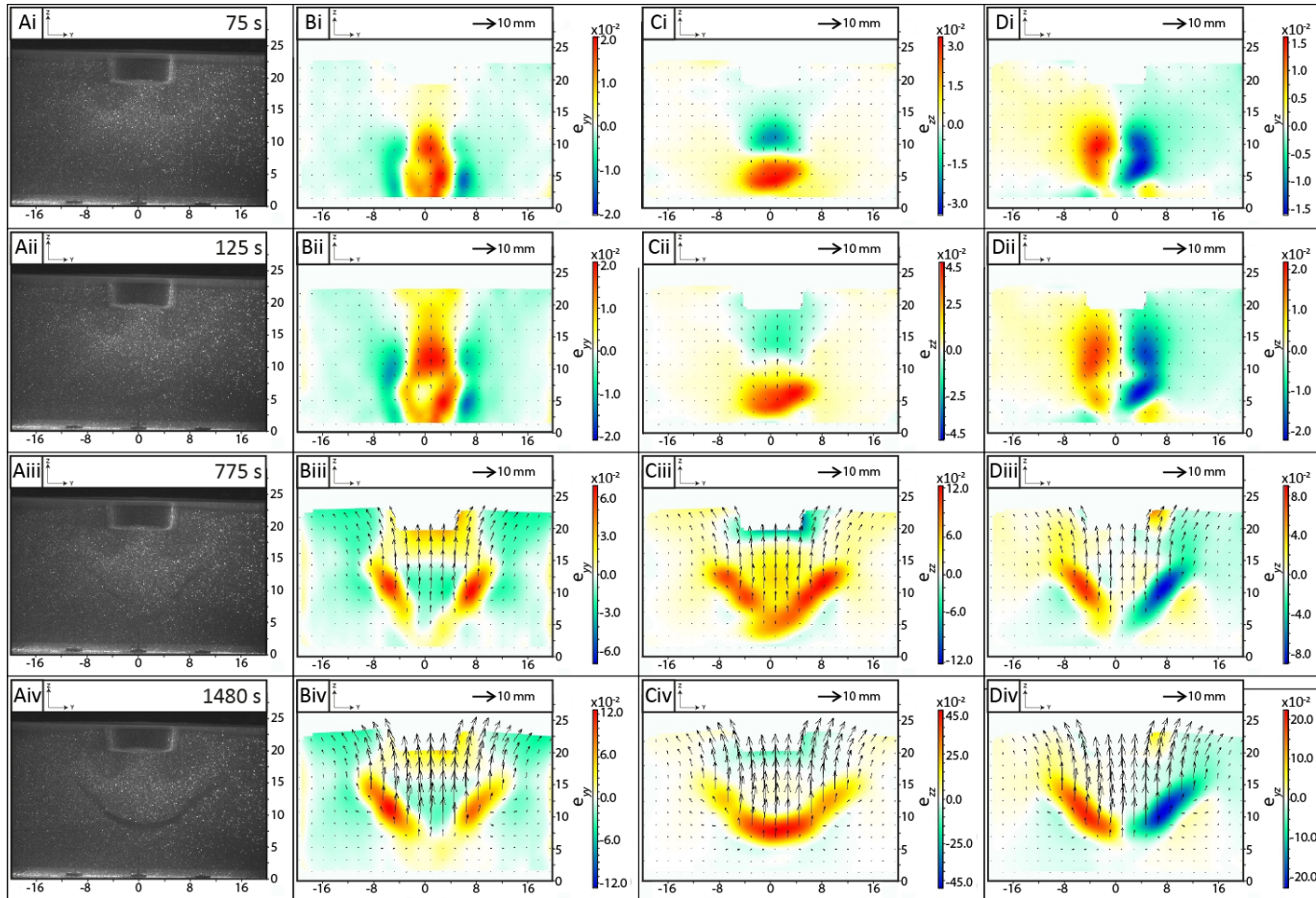
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575 **Figure 5:** Photographs of cone sheet development in the presence of a large caldera
 576 (Experiment AG-08, see Table 1): A) Polarized light (x-z plane), B) artificial light (y-z plane). i)
 577 Pre-injection stress state, ii) Stage I: sub-vertical dike (75 s), iii) Stage II: inclined sheet (125 s),
 578 iv) Stage III: lateral growth by en echelon arcuate segments (450 s), and v) Stage IV: cone sheet
 579 completion with no eruption (1245 s). See also Supplementary Video Figure S2.



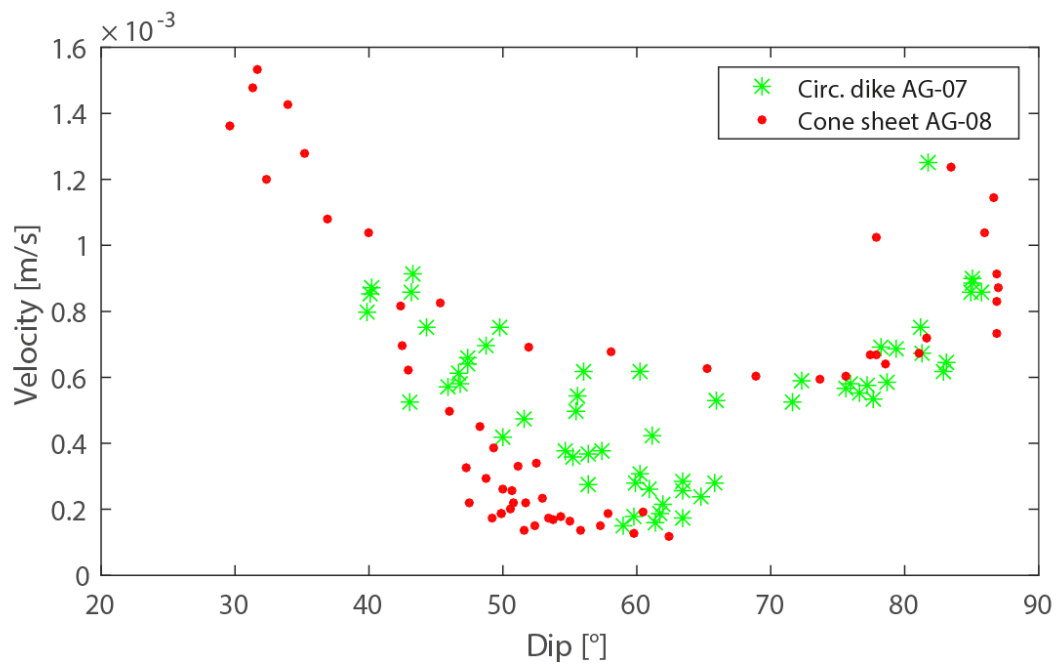
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581 **Figure 6:** Cone sheet development in the presence of a large caldera, viewed in the x - z plane, with sub-surface total strain (color maps) and
 582 displacement (vector arrows) calculated using DIC (Experiment AG-17, see Table 1). Four stages of cone sheet development are shown: i) Stage I:
 583 initial sub-vertical dike (75 s), ii) Stage II: inclined sheet (125 s), iii) Stage III: arrest and increased opening of the inclined sheet (775 s), and iv) Stage
 584 IV: cone sheet geometry completion with no eruption (1480 s). A) Dewarped experimental images, B) horizontal total normal strain e_{xx} , C) vertical
 585 normal strain e_{zz} , and D) shear strain component e_{xz} . The red color represents extensional deformation in the normal components and anticlockwise
 586 rotational deformation in the shear component. See also Supplementary Video Figure S3.

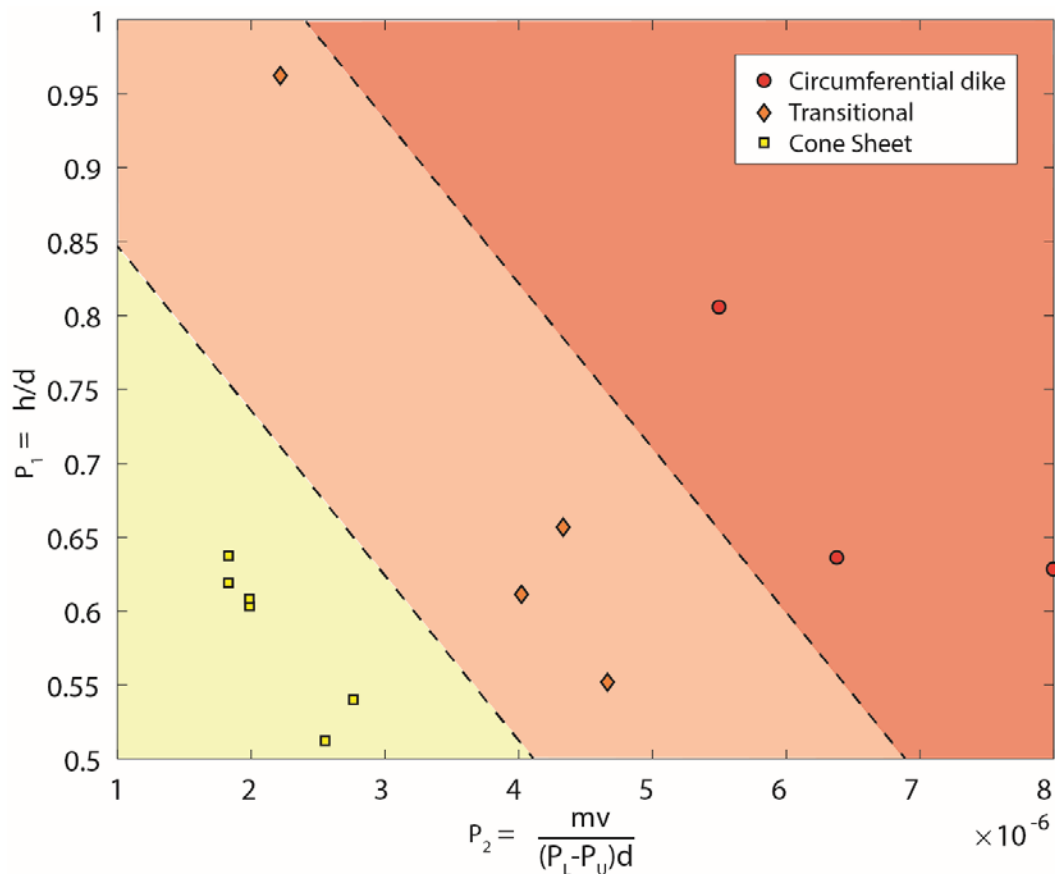


587

588 **Figure 7:** Cone sheet development in the presence of a large caldera, viewed in the y - z plane, with sub-surface total strain (color maps) and
 589 displacement (vector arrows) calculated using DIC (Experiment AG-19, see Table 1). Four stages of cone sheet development are shown: i) Stage I:
 590 initial sub-vertical dike (75 s), ii) Stage II: inclined sheet (125 s), iii) Stage III: arrest and increased opening of the inclined sheet (775 s), and iv) Stage
 591 IV: cone sheet geometry completion with no eruption (1480 s). A) Dewarped experimental images, B) horizontal normal strain e_{yy} , C) vertical normal
 592 strain e_{zz} , and D) shear strain component e_{yz} . The red color represents extensional deformation in the normal components and anticlockwise
 593 rotational deformation in the shear component. See also Supplementary Video Figure S4.



594
 595 **Figure 8:** The local dip angle relative to vertical ascent velocity for circumferential dike (AG-
 596 07) and cone sheet development (AG-08). See Table 1 for experimental conditions.



597
 598 **Figure 9:** Dimensionless phase diagram presenting the range of intrusion geometries formed
 599 in the experiments: circumferential dikes (red circles), Transitional geometries (orange
 600 diamonds) and cone sheets (yellow squares). The dimensionless parameters represent the
 601 model conditions $\Pi_1 = h/d$ and $\Pi_2 = \mu v / (P_L - P_U)d$. The cone sheets and circumferential
 602 dikes plot in distinct fields with transitional geometries formed in the intermediate zone.

	Parameter (units) or Equation	Nature (range)	Nature (preferred value)	Experiments (range)	Experiments (preferred value)	Scaling ratio	
Medium and fluid properties							
	Host medium density ¹	ρ_r (kg m ⁻³)	2300 - 3000	2700	994 – 1002	1002	0.37
	Fluid density ²	ρ_f (kg m ⁻³)	2000 - 2800	2680	990 – 996	996	0.37
	Fluid viscosity ¹⁰	μ (Pa s)	0.1 – 1E+23	100	8.9E-4	8.9E-4	8.9E-6
	Density difference ³	$\Delta\rho = \rho_r - \rho_f$	1 - 300	20	4 - 6	6	0.3
	Poisson's ratio ⁴	ν	0.1 – 0.35	0.25	0.495-0.5	0.499	2
	Fracture toughness ⁵	K_c (Pa m ^{1/2})	3E+8 – 1E+9	1E+9	24 - 80	80	8E-8
	Acceleration due to gravity	g (m s ⁻²)	-	10	-	10	1
Geometry							
	Geometric length	L (m)	-	1E+3	-	0.01	1E-5
	Caldera diameter	C (m)	9E+3 – 12E+3	12E+3	0.09 – 0.12	0.12	1E-5
	Caldera depth	D (m)	3E+3 – 4.5E+3	4E+3	0.03 – 0.045	0.04	1E-5
	Depth of intrusion ¹¹	h (m)	3E+3 – 17E+3	13.5E+3	0.08 – 0.16	0.15	1.1E-5
Scaling expressions							
Lengths							
	Buoyancy length ⁶	$L_b = (K_c / (\pi^{1/2} \Delta\rho g))^{2/3}$	3.2E+3 – 6.6E+4	19965	0.83 – 1.22	0.83	4.1E-5
Stresses							
	Elastic deformation ⁷	$\sigma = Ee$	1E+6 - 4E+7	2E+7	4.5 - 75	60	3E-6
	Lithostatic load	$P_L = \rho_r g h$	6.7E+7 – 5E+8	3.6E+8	779 - 1571	1473	4.1E-6
	Unloading ⁸	$P_U = \rho_r g D$	6.9E+7 – 1.3E+8	1.1E+8	298 – 451	401	3.7E-6
	Young's Modulus ⁹	E	1E+9 - 1E+10	1E+10	300 - 3000	3000	3E-7
Strain							
	Thickness/width	e	1E-3 - 4E-3	2E-3	1.5E-2 - 2.5E-2	2E-2	10

603 **Supplementary Table S1:** Parameters and equations implemented to scale the experiments, including their ranges and the preferred values we
604 have selected in nature and the experiments (¹ Carmichael and Klein, 2018; Di Giuseppe et al., 2009, ² Murase and McBirney, 1973, ^{3,5} Kavanagh et

605 al., 2013; Rivalta et al., 2015; ⁴ Gercek, 2007, ^{6,8,9} Kavanagh et al., 2013; Rivalta et al., 2015, ⁸ Merle, 2015, ¹⁰Rivalta et al., 2015, ¹¹Kennedy et al.,
606 2018).

607

Load	Mass [kg], m	Thickness [m]	Diameter [m], ψ
L1	0.05	0.012	0.025
L2	0.042	0.010	0.025

608 **Supplementary Table S2:** Properties of the two cylindrical brass loads used to measure the Young's modulus.

609 **Video Figure S1:** Experimental circumferential dike formation and propagation (all videos 30
610 frames per second): a)-b) Experiment AG-07 viewed with a) polarized light (x-z plane), and b)
611 artificial light (y-z plane), c)-f) Experiment AG-13 (x-z plane) viewed with laser light (c), and
612 total strain (color maps: horizontal E_{xx} (d), vertical E_{zz} (e), and shear E_{xz} (f) components) and
613 displacement (vector arrows) calculated using digital image correlation. The red color
614 represents extensional deformation in the normal components and anticlockwise rotational
615 in the shear component.

616 **Video Figure S2:** Experimental cone sheet formation and propagation (experiment AG-08, 30
617 frames per second): a) viewed with polarized light (x-z plane), and b) viewed with artificial
618 light (y-z plane).

619 **Video Figure S3:** Experimental cone sheet formation and propagation (experiment AG-17, x-z
620 plane, all videos 30 frames per second): a) Viewed with laser light, b)-d) total strain (color
621 maps: horizontal E_{xx} (b), vertical E_{zz} (c), and shear E_{xz} (d) components) and displacement
622 (vector arrows) calculated using digital image correlation. The red color represents
623 extensional deformation in the normal components and anticlockwise rotational in the shear
624 component.

625 **Video Figure S4:** Experimental cone sheet formation and propagation (experiment AG-19, y-z
626 plane, all videos 30 frames per second): a) Viewed with laser light, b)-d) total strain (horizontal
627 E_{yy} (b), vertical E_{zz} (c), and shear E_{yz} (d) components) and displacement (vector arrows)
628 calculated using digital image correlation. The red color represents extensional deformation
629 in the normal components and anticlockwise rotational in the shear component.

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