

Shape of plutons in crustal shear zones: A tectono-magmatic guide based on analogue models

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2 **models**

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21 **Abstract**

22 Plutons in crustal shear zones may exploit inherited structures, interfere with strain localizing or be
23 deformed passively. To constrain the relative timing of such tectono-magmatic constellations in
24 natural settings is not always straight-forward. We here present sandbox-type analogue model
25 experiments simulating magma emplacement into simple and transtensional crustal shear zones to
26 test the diagnostic potential of pluton shape with respect to timing and setting. Observations based
27 on surface deformation and intrusion shape exemplify the interplay between evolving and inherited
28 tectonic structures and magma uprising. We observe markedly asymmetric intrusions in association
29 with dikes reflecting the regional stresses, fault pattern and finite strain field. At the same time, the
30 presence of an intrusion modifies the tectonic evolution, but only transiently, resulting in short-lived
31 faults, reactivation and inversion. Diagnostic attributes include the pluton's aspect ratio, its
32 orientation and amplitude as well as dike association. Accordingly, syn-tectonic intrusions show the
33 highest pluton amplitudes and intermediate elongation oriented parallel to between Riedel shears in
34 simple shear, and compression in transtension. Post-tectonic intrusions are least elongated but
35 relatively high and exploit Riedel shears. Pre-tectonic intrusions are characterized by low amplitudes
36 and high aspect ratios parallel to the finite elongation direction. Intrusions in transtensional shear
37 zones are generally of lower amplitude than those in simple shear zones. Experimental results are
38 tested against observations from natural examples validating the diagnostic potential of pluton
39 shape for the timing and the tectonic setting of the emplacement.

40 **1 Introduction**

41 The spatial association of plutons and shear zones has long been recognized. Revealing their
42 temporal and spatial relation as a key to understand the mechanisms of tectono-magmatic
43 interaction, is a matter of research since. The interactions of tectonic and magmatic processes are
44 often ambiguous and hard to interpret (Paterson and Schmidt, 1999; Paterson and Tobisch, 1992).
45 It is generally recognised that both inherited structures and active faults represent key features in

46 crustal-scale magma transport and emplacement (Hutton, 1988; Hutton and Reavy 1992;
47 Vigneresse 1995; Román-Berdiel et al., 1997; Petford et al., 2000; Handy et al., 2001; Rosenberg,
48 2004; Corti et al., 2005; Galland et al., 2006; Galland et al., 2007b). Likewise, the presence of
49 magma in actively deforming crust may control fault localization and structural evolution (e.g.
50 Holohan et al., 2008; Dooley and Schreurs, 2012; Gomes et al., 2019). The delineated scenarios of
51 pre-, syn- and post-tectonic magmatism and the mechanisms involved remain poorly understood
52 taking also into account that gathering information from the field could be rather challenging. Beside
53 the limited outcrops in some areas, observations are, in most cases, restricted to the final stage of
54 magma emplacement which is often overprinted. In addition, the deformed upper crustal layers that
55 once hosted the magmatic chamber are in most cases subject to erosion and therefore missing from
56 the field. Consequently, the information on the incremental and finite deformation has to be inferred
57 with much effort from structural indicators and the processes taking place at depth must be
58 extrapolated (Vigneresse, 1995).

59 Modelling can help in overcoming some of the restrictions of field analysis and guide researchers
60 by identifying key observables and testing hypothesis. While all kinds of modelling have tackled
61 tectono-magmatic interaction, including analytical (e.g. Mandal and Chakraborty, 1990) and
62 numerical modelling (e.g. Burov et al., 2003), analogue models were used in particular for the
63 typically cross-scale and four-dimensional problems posed by tectono-magmatic processes (see
64 e.g. review by Galland et al., 2015). Amongst them, studies on syn-tectonic magma emplacement
65 prevail: a) in compressional settings (Galland et al., 2003, 2006, 2007; Mazzarini et al., 2010;
66 Montanari et al., 2010); b) in strike-slip settings (Román-Berdiel et al., 1997; Corti et al., 2005;
67 Mazzarini et al., 2010; Gomes et al., 2019); c) in transpressional settings (Benn et al., 1998); d) in
68 transtensional settings (Román-Berdiel et al., 2000; Corti et al., 2003) and finally e) in extensional
69 settings (Román-Berdiel et al., 1999; Mazzarini et al., 2010; Corti et al., 2003).

70 With a few exceptions (Holohan et al., 2008; Dooley and Schreurs, 2012; Gomes et al., 2019),
71 previous works were focused on syn-tectonic intrusion scenarios. However, little evidence exists

72 from analogue modelling regarding crustal shearing of pre- tectonic intrusion scenarios. Similarly,
73 the post-tectonic intrusion system is very poorly studied, where exploitation of inherited structures
74 from the uprising intrusion is still under debate. In this paper, we aim at closing this knowledge gap
75 and test the diagnostic potential of pluton shape for relative timing with a new set of analogue model
76 experiments simulating magma emplacement within the upper brittle crust rising from a basal ductile
77 shear zone. We conduct a systematic series of magma emplacement scenarios in simple shear and
78 transtensional regime (Fig. 1). To cover the full range of relative timing, we realize pre-tectonic, syn-
79 tectonic and post-tectonic intrusion scenarios (Table 1).

80 In contrast to earlier analogue modelling studies with a similar goal (e.g. Román-Berdiel et al., 1997;
81 Corti et al., 2005; Holohan et al., 2008; Mazzarini et al., 2010), we do not use a Riedel-type
82 experiment with a linear velocity discontinuity at the base but a more realistic distributed basal shear
83 zone (e.g. Dooley and Schreurs, 2012, and references therein). The viscous-weak body, in contrast
84 to previous work (Holohan et al., 2008; Dooley and Schreurs, 2012; Gomes et al., 2019) is not lying
85 parallel to the shear zone, but it is introduced vertically and in direct contact to the shear zone. In
86 addition, in previous work the tectonic deformation of the magmatic chamber and the brittle crust,
87 induced by the vertical upraising of the viscous – body, prior to and following the tectonic
88 deformation, is not recorded. In the present study the magmatic chamber is not represented as an
89 igneous pocket, but it is injected vertically, deforming this way the sand layers (no topography has
90 been added in this study) before, during and after the tectonic deformation. In addition, the weak
91 body appears with a fixed radius = 2cm, since the focus of the study is on the progressive
92 interference with the brittle crust, for all emplacement scenarios. For this reason and in contrast to
93 previous studies (Dooley and Schreurs, 2012; Zwaan and Schreurs, 2017) the intrusion geometry
94 and its initial orientation (angular position) relative to the shear zone are not evaluated.

95 Using state of the art kinematic monitoring techniques (Digital Image correlation – DIC; Structure-
96 from-Motion – SfM), the full 3D surface deformation over time (i.e. 4D deformation) and the final
97 intrusion three-dimensional shapes are captured digitally at high resolution and accuracy. Based on

98 this experimental data set, which is openly available (Michail et al., 2020), we verify existing
99 diagnostic features (e.g. pluton aspect ratio, orientation) and new attributes (pluton amplitude, dike
100 association) of pluton shape and validate them against selected field examples. The presented
101 models appear as a guide to the interpretation of necessarily incomplete and limited field
102 observations. **(Figure 1 here)**

103 **2 Methods and materials**

104 *2.1 Experimental setup*

105 The experimental setup consists of two mobile plastic plates on a 1 by 1 m wide solid steel support
106 platform. The mobile plates are moved by linear actuators, controlled by stepper motors, in opposite
107 direction (Fig. 1). A 40-mm wide gap between the two 700 mm long and 7 mm thick mobile plates
108 is filled with viscous material (silicone oil) to allow the formation of a distributed basal shear zone,
109 similar to natural lower crustal shear zones (Fig. 1a-b). Two kinematically distinct experimental
110 series, representing two different tectonic regimes, namely simple shear (reference model RS and
111 models of group A; Fig. 1c,e) and transtension (reference model RT and models of group B; Fig.
112 1d,f) are presented (Table 1).

113 For the simple shear regime, the gap between the mobile plates is oriented parallel to the plates'
114 motion (Fig. 1c,e), while in the transtensional configuration, they are oriented with an angle, α , of
115 15° (Fig. 1d). Relative plate velocity is fixed to 1 mm/min, for all experiments, which corresponds to
116 a simple shear rate of $4.2 \cdot 10^{-4} \text{ s}^{-1}$ across the width of gap resulting in a final relative displacement of
117 the two sides of the shear zone of 60 mm for all experiments. A low shear rate, together with a
118 viscous fluid, rough inner edges of the mobile plates and polished and lubricated surface of the
119 metal base, result in a well distributed deformation within the gap although minor localization of
120 shear and extension at the shear zone boundaries is unavoidable. Simple shear and transtensional
121 models are run under dextral and sinistral senses of shear, respectively, in order to ease their
122 distinctness. **(Table 1 here)**

123 A 40-mm thick, sieved quartz sand layer representing the brittle upper crust (Fig. 1a-b) covers the
124 mobile plates and the basal shear zone. On top of each mobile plate, fixed, motion-parallel sidebars
125 confine the sand layer laterally and helps in model preparation (Fig. 1a,e). In the centre of the basal
126 shear zone, a motor-controlled piston pushes silicone oil up through a pipe (with 40 mm diameter)
127 placed beneath the experiment's foundation, to simulate the magma ascending from the lower crust
128 into the upper-crustal shear zone (Fig. 1e-f). The piston moves at a velocity of 1 mm/min, which
129 translates into an injection rate of 21 mm³/s for all experiments (Table 1). All the experiments are
130 performed under air-controlled ambient conditions (23°-25°C, 50% humidity).

131 2.2 Analogue materials

132 The viscous analogue material used for both the intrusion and the basal ductile layer is a silicone oil
133 (Polydimethylsiloxane PDMS, G30M by K. Obermeier GmbH). It has a density of 965 kg m⁻³ and a
134 Newtonian viscosity of 22.4 kPa s at laboratory strain rates below 10⁻² s⁻¹ (Rudolf et al., 2016; see
135 Table 2). Earlier studies showed that similar material is a suitable analogue for ductile lower crust
136 and, at reduced viscosity, for low density-high viscosity (i.e. granitic) magmas simulation (e.g.
137 Román-Berdiel et al., 1997; Benn et al., 1998, 2000; Galland et al., 2015). We here use one material
138 for simulating both the ductile lower crust and the magma in order to reduce rheological complexity
139 but also due to practical reasons, i.e. to avoid gravitational flow of the material at the end of the
140 experiment and to allow manual excavation of the ductile shear zone and the intrusion.

141 Sieved dry quartz-sand (G12) functions as brittle analogue of the upper crust. The sand is a well-
142 sorted, well-rounded and fine-grained (<400 µm) sand of fluvial origin (Klinkmüller et al., 2016;
143 Rosenau et al., 2018). When sieved, a bulk density $\rho \sim 1600$ kgm⁻³ is reached and the sand layer
144 is characterized by internal friction coefficients μ of 0.69, 0.62, 0.55 (static, reactivated, sliding) and
145 a cohesion C in the order of 50 - 110 Pa (Table 1). The localization behaviour of sand produces
146 shear zones several grain diameters wide rather than idealized infinitely narrow faults. However, we
147 here use the term "faults", to describe the small-scale shear zones, evolving in the analogue model
148 because of the generally close dynamic similarity (Ritter et al., 2016). With the term "shear zone" in

149 contrast we refer to the regional deformation zone composed of several faults evolving on top of the
150 basal ductile shear zone.

151 2.3 *Scaling and Similarity*

152 The experiments are scaled following the principles of geometric, kinematic and dynamic similarities
153 to the natural prototype (Hubbert, 1937; Ramberg, 1981; Weijermars and Schmeling, 1986).
154 Accordingly, for a brittle-viscous sandbox model under normal gravity, the stress scaling dictates
155 the length and time scaling. In the pressure-dependent brittle regime and under normal gravity, the
156 length scale L^* can be delineated from densities and cohesion in the model and prototype following
157 the scaling law:

$$158 \quad L^* = C^* / \rho^* \quad (i)$$

159 where the asterisks denote the model/prototype ratios known as the scaling factors (i.e. $C^* =$
160 $C_{model}/C_{prototype}$). Inserting numbers for the scaling factors for density and cohesion of our brittle
161 analogue rock material ($C_{model} \sim 10\text{-}100 \text{ Pa}$, $\rho_{model} = 1600 \text{ kg/m}^3$) and typical upper crustal rocks
162 ($C_{prototype} = 10 \text{ MPa}$, $\rho_{prototype} = 2600 \text{ kg/m}^3$) yields a length scaling factor of L^* in the order of 0.6-
163 6×10^{-6} , i.e. 1 cm in the model equals 0.6-6 km in nature (Table 2). Consequently, our model
164 represents an intrusion into the upper 2-20 km thick crust. For our models, due to dimensional
165 identity, the stress scale is also fixed by the choice of cohesion to $\sigma^* = 1\text{-}10 \times 10^{-6}$.

166 In the strain-rate dependent viscous regime the time-scale T^* can be delineated, based on
167 dimensional arguments, from the viscosities η in the model and in nature using the formerly set
168 stress scale and following the scaling law

$$169 \quad T^* = \eta^* / \sigma^*. \quad (ii)$$

170 With the viscosity of the silicone oil ($\eta_{model} \sim 10^4 \text{ Pas}$) and considering a typical viscosity range for
171 magma ($\eta_{prototype} = 10^4\text{-}10^{10} \text{ Pas}$), this scaling yields highly unsuitable laboratory time scales, that
172 require running the experiments at even lower rates than in nature. This dilemma has already been
173 noticed by Ramberg (1981) who stated that magma cannot be properly scaled because even the

174 most viscous (low water content, high silica) magma would require an analogue fluid, which is even
175 less viscous than water and which does not exist. **(Table 2 here)**

176 To solve this dilemma, we here consider the rising magmatic body not as a homogenous melt with
177 low viscosity but as a succession of rapid melt injections into the crust over millions of years. This
178 is in accordance to the general view that plutons grow transiently over the Ma timescale fed by
179 magma that transits through lower crustal shear zones episodically on the hundreds to thousands
180 of years timescale (e.g. Handy et al., 2001, Patterson et al., 2011, Brown, 2013). The resulting
181 magmatic system has therefore an effective bulk viscosity much higher than that of the individual
182 melt components and which is more similar to ductile lower (quartz-feldspatic/andesitic) crust at
183 typical regional tectonic strain rates ($\eta_{prototype} > 10^{20}$ Pas at $< 10^{-14} \text{s}^{-1}$, e.g. Shinevare et al., 2015). Such
184 an alternative interpretation of the analogue model is not only consistent with modern views of
185 episodic pluton growth but considers at the same time, though highly simplified, thermal aspects of
186 the emplacement process (i.e. cooling and crystallization between injection episodes; Gomes et al.,
187 2019). Following this reasoning and considering a Million-year time scale of pluton growth, we derive
188 the time scale by relating the filling times of our model pluton (ca. $10^{-8} \text{ m}^3/\text{s}$) to mean natural rates
189 of $10^2 \text{ km}^3/\text{Ma}$ (e.g. Patterson et al., 2011). Accordingly, we arrive at $T^* = 10^{-13}$ (1 second in the lab
190 corresponds to ca. 30.000 years, Table 2). According to this timescale the applied velocity of 1
191 mm/min scales to ca. 0.5 mm/a in nature and a corresponding shear rate of ca. 10^{-17}s^{-1} .

192 2.4 Monitoring and Analysis

193 We use state-of-the-art digital image correlation techniques for kinematic monitoring of the model
194 surface deformation (Particle Image Velocimetry, PIV) and for deriving the surface topography and
195 intrusion shape (Structure-from-Motion, SfM). All digital data generated in this study are published
196 open access in Michail et al. (2020).

2.4.1 Particle Image Velocimetry (PIV)

A stereoscopic pair of charge-coupled device (CCD) cameras (11 MPx, 14bit, LaVision Imager ProX) monitor the model surface during the experimental run at a frequency of 0.3 Hz (Fig. 2a). Digital image correlation, using a least square minimization technique (as implemented in LaVision Davis 8), allows a quasi-continuous quantitative monitoring of the topographic evolution and surface deformation at high spatio-temporal resolution according to the principles of PIV (Adam et al., 2005). We derive 3D incremental and cumulative surface deformation pattern (i.e. velocity fields, strain fields and topography) at the sub-millimetre resolution.

From the surface velocity field, we produce surface strain maps which show the incremental shear strain E_{xy} (the unit of which is millistrain, mS), highlighting active faults and their kinematics. Positive values (red colors in all Figures) indicate a clockwise rotation or dextral shear sense and negative values (blue colors in all Figures) indicate anti-clockwise rotation or sinistral shear. The final shear strain is computed as the cumulative (or finite) displacement field indicating the relative importance of individual faults in accommodating deformation over the full experimental range.

2.4.2 Structure-from-Motion (SfM)

To obtain the 3D model reconstruction of the final topography (digital elevation model, DEM) and the final intrusion shape (digital intrusion model, DIM) at high resolution we rely on the Structure-from-motion (SfM) technique (Westoby et al., 2012) using digital images taken at the end of every experiment with a customer grade DSLR camera (NIKON D80, 10 MPx). Images including perspective views of both the final model surface and the model intrusion after excavation taken from various angles are used for the 3D model reconstruction achieved by using Agisoft PhotoScan (Professional Edition). For visualization coloured DIM-contours have been extracted from the models.

The intrusion's geometry (pluton shape) is quantified using various dimensionless parameters derived from the DIM:

222 First, its normalized amplitude

$$223 \quad A_{intrusion} = H_{intrusion} / H_{sand\ layer} \quad (iii)$$

224 where $H_{intrusion}$ is the intrusion height above the initial surface of the ductile layer and $H_{sand\ layer}$ is the
225 thickness of the sand layer (i.e. 40 mm). Second, the aspect ratio

$$226 \quad r = L/W \quad (iv)$$

227 calculated based on the length L and width W of the ellipse that fits to the DIM perimeter at a given
228 contour level.

229 Third, the orientation of the intrusion, that is described by Θ , defined as the angle between the long
230 axis L of the fitted ellipse and the strike of the basal shear zone. Θ is counted counter clockwise.

231 Aspect ratio and angle of intrusion are derived for each contour level allowing the analysis of the
232 shape as a function of height.

233 **3 Experimental results**

234 Nine experiments in total are presented and discussed in the following sections (Table 1): i) three
235 reference experiments (Group R); ii) three models of intrusion under (dextral) simple shear (Group
236 A) and iii) three models of intrusion under (sinistral) transtension (Group B). Pre-, syn and post-
237 tectonic intrusion scenarios are presented for the Groups A and B. Group R consists of a static
238 intrusion without applied shear (R0), a simple shear (RS) and a transtensional experiment (RT),
239 both without intrusion. Rates of intrusion and deformation are kept constant in all experiments as
240 well as the thickness of the brittle layer.

241 **3.1 Reference models (Group R)**

242 The surface evolution of the reference experiments, namely the static intrusion model (R0, Fig. 2a-
243 c), the simple shear model (RS, Fig. 2d-f) and the transtension model (RT, Fig. 2g-i) is summarised
244 in Fig. 2. In the R0 model, a circular sand dome starts to form above the intrusion as soon as the

245 injection has started ($V_{inj} = 3.2$ ml; Fig. 2a). Gradually, the sand layer forms an elongated rectangular
246 domal uplift preserved until the latest intrusion stage, bound by lateral reverse faults, parallel to the
247 basal ductile layer (Fig. 2b-c). The uplift rate decreases with time. **(Figure 2 here)**

248 For the reference experiments under simple shear (RS) and transtensional (RT) deformation the
249 surface evolution shows a typical sequence of structures consistent with previous studies using a
250 distributed basal shear zone and dry sand layers (Román-Berdiel et al., 1997; Corti et al., 2005;
251 Dooley and Schreurs, 2012). In the very early evolution stage of the RS model ($d_{rel} = 5.0$ mm) a
252 diffuse belt starts to form above the basal ductile shear zone (Fig. 2d). With increasing displacement,
253 early en-échelon synthetic Riedel shears (R) develop with a trend of $\sim 20^\circ$ to the trace of the basal
254 shear zone ($d_{rel} = 16.1$ mm; Fig. 2e). Lower-angle synthetic shears develop between the overlapping
255 R shears, having a strike of $\sim 15^\circ$ (Fig. 2e). The final deformation surface pattern ($d_{rel} = 38.3$ mm) is
256 characterised by the formation of an active and continuous master fault (MF), as a result of the
257 linkage of the individual early shear structures, parallel to the basal shear zone, along which less
258 active anastomosing minor faults which define shear lenses and pop-up structures ($d_{rel} = 38.3$ mm;
259 Fig. 2f). The final surface width of the shear zone (ca. 50 mm) is larger than the basal shear zone
260 (40 mm; Fig. 2f).

261 The transtensional reference experiment (RT) shows an early evolutionary history similar to the
262 simple shear experiment with the formation of a diffuse shear zone above the basal ductile shear
263 zone (Fig. 2g-i). Linkage of early right-stepping and overlapping R shears occur along lower angle
264 structures (Y, P shears) causing a deformation localization in the central part and forming a through-
265 going master fault from early on ($d = 11.1$ mm; Fig. 2g-h). During the final stage, the deformation
266 partitions between lateral faults and fault-bounded rhomboidal basin structures (Fig. 2i). In this
267 stage, the pull-apart basin structure is cut short by strike-slip faults that continue to propagate
268 towards the dominating parallel boundary faults. This results in lengthening and narrowing of the
269 pull-apart basin in a direction parallel to the displacement vector. The final surface width of the shear
270 zone is larger (ca. 60 mm) than the basal shear zone (44.4 mm; Fig. 2i).

271 3.2 Simple shear intrusion models (Group A)

272 3.2.1 Effect of intrusion on fault pattern

273 The three models presented in this group show the evolution of deformation with the presence of
274 analogue magma injection that predates (A1, pre-tectonic model), coincides (A2, syn-tectonic
275 model) and post-dates (A3 post-tectonic model) the applied simple shear deformation. Our
276 observations focus on the interactions taking place between faulting and intrusion and how they
277 affect the fault pattern evolution and the final intrusion geometry.

278 The pre-tectonic intrusion experiment, model A1 (Fig. 3), consists of two parts: during the first half
279 of the experiment, static intrusion takes place ($V_{inj} = 37.3$ ml) causing a domal uplift ($\Delta h_{init} = 7$ mm,
280 Fig. 3a) as described for the R0 model (Fig. 2a-c). In the second half of the experiment, following
281 the static intrusion, dextral shearing is applied. Accordingly, in the early intrusion stage there is no
282 obvious fault formation (Fig. 3a). Once shearing started diffuse deformation occur in a spindle-like
283 surface area ($d_{rel} = 11.4$; Fig. 3b) forming a wider shear domain bound by transpressional faults. At
284 a later stage of shearing ($d_{rel} = 22.2$ mm; Fig. 3c) a system of strike-slip faults consisting of two
285 lateral and one central fault is cutting through the uplifted domain. The finite fault pattern (Fig. 3d-f)
286 is, in contrast to the model RS, characterized by a wider strike-slip system encompassing the
287 intrusion area and external transpressional faults which have been active mainly during early stages
288 of deformation. **(Figure 3 here)**

289 The fault pattern in the syn-tectonic intrusion experiment, model A2 (Fig. 4), initially evolves in a
290 similar fashion as in model A1. In the early deformational stage ($d_{rel} = 3.9$ mm; $V_{inj} = 4.9$ ml; Fig. 4a)
291 a diffuse spindle-like shear zone occurs encompassing the uplifting centre. With ongoing shearing
292 and intrusion ($d_{rel} = 6.7$ mm; $V_{inj} = 4.9$ ml; Fig. 4b) transpressional faults localize at the periphery of
293 the spindle-like area embracing the intrusion domain as well as Riedel shear in the centre. In the
294 late stage ($d_{rel} = 27.8$ mm; $V_{inj} = 35.0$ ml; Fig. 4c) deformation localizes into a narrow strike-slip fault
295 system cutting the intrusion area. This set of parallel, locally transtensional faults cause the
296 depressing of the uplifted central domain (Fig. 4e). The finite fault pattern (Fig. 4d-f) shares

297 characters of the reference model RS (a central strike-slip fault system; Fig. 2d-f) and the pre-
298 tectonic model A1 (early stage transpressional faults swinging around the intrusion area; Fig. 3b).
299 **(Figure 4 here)**

300 The post-tectonic experiment, model A3 (Fig. 5) consists again of two parts: In the first half, the
301 experiment follows according to the observations documented for the RS model ($d_{rel} = 30\text{mm}$; Fig.
302 2d-f) resulting in a system of strike-slip faults (Fig. 5a) at the start of intrusion. In the second half of
303 the experiment, static intrusion causes formation of new lateral faults (in the “south” of the intrusion)
304 but also the reactivation of inherited, lateral faults (in the “north” of the intrusion; $V_{inj} = 12.6\text{-}32.2\text{ml}$;
305 Fig. 5b-c). Importantly, active faults in opposite corners of the intrusion show a synthetic sense
306 including dextral and sinistral shear (Fig. 5b-c). Consequently, dextral displacement across inherited
307 faults acquired in the first half of the experiment is now partly inverted. The finite fault pattern (Fig.
308 5d-f) is a composite of partly re-activated strike-slip faults similar to the reference model R0 (Fig.
309 2h-i) and new reverse faults embracing a central domal uplift. **(Figure 5 here)**

310 3.2.2 *Effect of deformation on intrusion shape*

311 Among the three emplacement scenarios there is a significant variation regarding the final
312 geometrical features of the intrusion described by the intrusion’s absolute height (H) and normalized
313 amplitude (A), its aspect ratio ($r = \text{length}/\text{width}$) and the orientation of its long axis (angle θ). The
314 intrusion models appear strongly deformed and asymmetric, revealing the tectonic impact during
315 their emplacement, and have a systematic generic relation to the regional stress and finite strain
316 fields (Fig. 6).

317 The intrusion of Model A1 (pre-tectonic, Fig. 6a-d), which has been passively deformed is
318 characterized by low height and amplitude ($H_{A1} = 15\text{ mm}$, $A_{A1} = 0.38$), compared to intrusions from
319 other scenarios. Its asymmetry is related to displacement along the crosscutting faults developing
320 late in the experiment. The lower part of the intrusion represented e.g. by the contour level $c_1 = 3\text{mm}$
321 shows a relatively high aspect ratio ($r_1 = 2.7$) with the long axis of the intrusion forming a low angle
322 of $\theta_1 = 12^\circ$ to the shear zone. At higher contour levels the intrusion progressively elongates ($r > 3$)

323 and rotates antithetic (i.e. anticlockwise) with respect to the dextral simple shear (e.g. $\theta_2 = 34^\circ$ at c_2
324 =12mm) becoming subparallel to the elongation direction of the finite strain tensor (Fig. 7; A.2). The
325 intrusion roof is sculpted by one central and two lateral dikes that represent silicone oil intruding
326 upwards along the master fault (MF) and the lateral faults, obviously during the post-intrusion stage
327 of the experiment. **(Figure 6 here)**

328 The intrusion Model A2 (syn-tectonic, Fig. 6e-h) is characterized by an acute roof resulting in a
329 significant height and amplitude ($H_{A2} = 24\text{mm}$; $A_{A2} = 0.6$; Fig. 6e-f) compared to intrusions from other
330 scenarios. It shows a strong asymmetric wing shape with opposing orientation to the intrusion model
331 A1. At lower levels, the intrusion has a high aspect ratio (e.g. $r_1 = 2.5$) with the long axis almost
332 parallel to the shear zone ($\theta_1 = 1^\circ$). Upwards, the intrusion progressively rotates synthetically into
333 the orientation of Riedel shears (e.g. $\theta_2 = -10^\circ$ at $c_2 = 20\text{mm}$) while keeping its aspect ratio rather
334 constant (Fig. 7; A.3). Lateral dikes flank the central upheaval with all of them exploiting faults formed
335 during intrusion. The wing shape of the intrusion in association with scissor tailed and offset apoph-
336 yses appears unique to this scenario. **(Figure 7 here)**

337

338 The intrusion Model A3 (post-tectonic, Fig. 6 i-l) is characterized by a more domal shape with inter-
339 mediate height and amplitude ($H_{A3} = 22\text{ mm}$; $A_{A3} = 0.55$). It appears sub-circular to gently elongated
340 ($r < 2$) and largely subparallel to the shear zone with no systematic change of aspect ratio and orien-
341 tation with height (Fig. 7; A.4). The roof is rounded and sculpted by a central dike ($r_2 = 1.9$ at $c_2 =$
342 19mm) and two lateral dikes exploiting inherited structures (Fig. 6i-j).

343 3.3 *Transtensional intrusion models (Group B)*

344 3.3.1 *Effect of intrusion on fault evolution*

345 Transtensional intrusion experiments demonstrate, similarly to Group A, ongoing interactions
346 developing between the intrusion and the fault pattern evolution for all three scenarios.

347 In the first half of the pre-tectonic intrusion experiment, model B1, static intrusion takes place ($V_{inj} =$
348 37.7 ml), deforming the initially flat topography and causing a domal surface uplift ($\Delta h_{init} = 7$ mm;
349 Fig. 8a) above the centre. In the second half of the experiment, transtension is applied and a diffuse
350 spindle-like shear zone occurs ($d_{rel} = 5.6$ mm; Fig. 8b) similar as in the pre-tectonic simple shear
351 model A1. With ongoing transtension, lateral oblique normal faults and oblique Riedel shears
352 localize deformation ($d_{rel} = 16.7$ mm; Fig. 8c) causing subsidence along the shear zone. The initial
353 central dome is crosscut by a fault system (P and Y-shears) that links the “northern” and “southern”
354 boundary faults, which remain active until the end of the experiment (Fig. 8c-f). Similar to the
355 reference model (RT, Fig. 2g-i), Riedels form an en-echelon array of oblique normal faults within
356 the basin (Fig. 8d). The finite deformation pattern of the surface is characterised by a well-defined
357 elongated pull-apart basin (Fig. 8d-f). The domal uplift, caused by the initial intrusion, is overprinted
358 and appears as a remaining gentle uplift in the centre (Fig. 8e). Notably, the topographic expression
359 of the pre-tectonic intrusion is much less than in the corresponding simple shear model A1 (Fig. 3e).
360 **(Figure 8 here)**

361 The early stage of the syn-tectonic intrusion experiment, model B2, is characterized by diffuse shear
362 and Riedel shear formation ($d_{rel} = 1.2$ mm; $V_{inj} = 1.5$ ml; Fig. 9a). At an intermediate stage ($d_{rel} = 8.3$
363 mm; $V_{inj} = 10.5$ ml) and along with subsidence, the linkage of these Riedel shears form a dominant
364 fault zone that diverges from the strike of the basal shear zone to form a releasing stepover centred
365 on the intrusion domain (Fig. 9b). At a late stage ($d_{rel} = 16.7$; $V_{inj} = 21$; Fig. 9c) oblique normal faults
366 bound the outer basin margins and curve towards the centre (Fig. 9c). As the master fault continues
367 to propagate, it crosscuts and deforms the evolving basin. The finite fault pattern (Fig. 9d-e) is, in
368 contrast to the reference model (RT, Fig. 2g-i), characterised by a more segmented and curved
369 faults bounding the elongate basin with the deep central graben flanked by horst blocks. **(Figure 9**
370 **here)**

371 The post-tectonic intrusion experiment, model B3 (Fig. 10), is divided again into two parts: the first
372 transtension as described for model RT model (Fig. 2g-i), resulting in a fault-controlled, spindle-

373 shaped pull-apart basin ($d_{rel} = 30\text{mm}$; Fig. 10a, d). Then static intrusion ($V_{inj} = 13\text{ ml}$) starts to form
374 a domal uplift, triggering the re-activation of the pre-existing faults (Fig. 10b). Similarly as observed
375 in model A3, inherited faults are reactivated and partly inverted (Fig. 10b-c). The master fault is re-
376 activated in sinistral sense while dextral displacement occurs along inverted boundary faults ($V_{inj} =$
377 18.6 ; Fig. 10c). The finite topography (Fig. 10d-e) directly reflects the intrusion at depth within the
378 basin system (Fig. 10d-e). **(Figure 10 here)**

379 3.3.2 *Effect of deformation on intrusion geometry*

380 The intrusion Model B1 (pre-tectonic, Fig. 11a-d) is like the corresponding Model A1 characterized
381 by low height and amplitude and enhanced by post-emplacment flattening in the transtensional
382 regime ($H_{B1} = 5\text{ mm}$; $A_{B1} = 0.13$). The intrusion's aspect ratio shows characteristic high values but
383 with no systematic change with height (Fig. 12; A.5), varying from 1.8 at $c_1 = 1\text{mm}$ (Fig. 11c) to 1.9
384 at $c_2 = 3\text{mm}$ (Fig. 11d). The orientation of the intrusion, similar to A1, rotates from the base to the
385 top antithetic (i.e. clockwise) with respect to the sinistral sense of transtensional shear to become
386 subparallel to the finite strain tensor (e.g. $\theta_2 = 42^\circ$; Fig. 12). The intrusion's flat roof is sculpted by
387 lateral dikes exploiting faults developing during the post-emplacment deformation. **(Figure 11**
388 **here)**

389
390 The intrusion Model B2 (syn-tectonic; Fig. 11e-h) similarly to model A2 is characterised by an acute
391 shape ($H_{B2} = 22\text{ mm}$; $A_{B2} = 0.6$). The intrusion's base shows an intermediate aspect ratio of $r_1 = 1.7$
392 with the long axis subparallel to the shear zone boundary (e.g. $\theta_1 = -10^\circ$; Fig. 11g). Upwards, the
393 intrusion rotates synthetically towards the maximum horizontal stress orientation, σ_{Hmax} (Fig.11h;
394 Fig. 12; A.6). This model bears a smooth roof top and lateral dikes flanking the central upheaval.
395 The asymmetric wing shape marked by a scissor tail apophyses that trails behind the intrusion are
396 similarly observed for model A2 (Fig. 6e-h). **(Figure 12 here)**

397 Finally, the intrusion Model B3 (post-tectonic, 11j-l) is a sub-circular to slightly elongated intrusion
398 of domal shape ($H_{B3} = 20\text{ mm}$; $A_{B3} = 0.5$). At lower contour levels, the intrusion shows an aspect

399 ratio of $r_1 = 1.4$ with the long axis parallel to the shear zone like model A3 (Fig. 11k; Fig. 12; A.7).
400 The intrusion has an asymmetric roof of carrying a central dike ($r_2 = 1.7$ at $c_2 = 18\text{mm}$) and two
401 lateral dikes (Fig.11l). The latter exploits inherited faults ($\theta_2 = -11^\circ$; Fig. 7).

402 **4 Discussion of experimental results**

403 We here present sandbox-type analogue model experiments simulating magma emplacement into
404 simple and transtensional crustal shear zones to test the diagnostic potential of the finite pluton
405 shape with respect to timing and setting of its emplacement. Observations based on surface
406 deformation and intrusion shape illustrate strong interactions between evolving and inherited
407 tectonic structures and magma uprising, plus constitute an important contribution in defining the
408 diagnostic potential of pluton shape for the timing and the tectonic setting of the emplacement.

409 *4.1 Synthesis and comparison of experimental results*

410 *4.1.1 Controlling parameters on pluton emplacement*

411 In this study the timing of the magmatic emplacement with respect to the regional tectonic
412 deformation is inferred as a controlling parameter on the finite pluton geometry and emplacement
413 mode. Parallely, the shape of the produced intrusions, based on the timing of their emplacement,
414 is suggested as an effective diagnostic feature. Notably, the findings of this work extend the results
415 of previous studies which observed and described experiments restricted under reference conditions
416 (static, shear deformation) and processes of syn-tectonic magmatic emplacement.

417 Based on our observations, the pluton emplacement is directly controlled by the syn-active evolving
418 faults, for both groups in pre- and syn-tectonic scenarios. At the same time, strain localization on
419 the weak body influences the upward fault propagation. Post-tectonic models are influenced and
420 overprinted by the boundary conditions and indirectly by the inherited fault structures during their
421 emplacement. According to our observations and in agreement with previous related studies
422 (Román-Berdiel et al., 1997; 2000; Corti et al., 2005) local interactions between on-going fault
423 propagation and magma uprising induce asymmetric intrusion shapes. In addition, the thickness

424 ratio between the brittle and ductile band, influence the interactions between the intrusive analogue
425 magma and the developing model surface fault pattern. In our case, the ratio between the ductile
426 band (7mm) and the brittle layer thickness (40mm) is fixed at 0.175. This ratio allows us to observe
427 the overburden deformation without the fault pattern being completely overprinted by deformations
428 induced by piercement of the surface.

429 Román-Berdiel et al. (2000) pointed out the importance of the divergence angle, α , in deformation
430 styles of both surface and magma models, suggesting that for low values (i.e. $\alpha = 15^\circ$) under
431 transtension the fault pattern is similar to pure simple shear kinematics, therefore resulting in similar
432 geometries for the syn-tectonic intrusions. The fault structures observed in the reference
433 experiments (RS and RT), during which no intrusion takes place, are very similar to those described
434 in previous experiments (e.g. Tchalenko, 1970; Wilcox et al., 1973; Naylor et al., 1986). Moreover,
435 for $\alpha < 30^\circ$, the deformation is mainly located in the central part of the model and the localization of
436 brittle deformation is very high (Román-Berdiel et al., 1999; 2000).

437 Previous studies have shown that variations in the displacement velocity and the intrusion rate
438 control the final geometry and orientation of the syn-tectonic magmatic body emplaced in the upper
439 crustal layer (Román-Berdiel et al., 1997; Corti et al., 2005). According to these studies, high
440 horizontal-displacement or low intrusion rates resulted in normal pluton asymmetry with the pluton's
441 long axis parallelising the velocity discontinuity (VD) zone, whereas low horizontal-displacement or
442 high intrusion rates, generated plutons with reverse asymmetry (magmatic emplacement controlled
443 by tensional faults). In this study the variation of the ratio between tectonic displacement rate and
444 intrusion rate is constant. However, by varying the time of emplacement we also captured
445 observations on the pluton's asymmetry. Both pre-tectonic models show normal pluton asymmetry,
446 with the long pluton axis forming with the shear zone angles of $\theta = 28^\circ$ (Model A1, Fig. 6c-d) and θ
447 $= 42^\circ$ (Model B1, Fig. 11c-d) and stretched to the extension direction. In the contrary, syn- and post-
448 tectonic models, from both experimental groups, show reverse asymmetry with their long axis
449 stretched to the compression direction, forming low angles with the shear zone (Fig. 6, Fig. 11f,i).

4.1.2 *Interactions between deformation and pluton emplacement*

The significant geometrical differences of the finite intrusions' shape observed among the emplacement scenarios (Fig. 6, Fig. 11) reveal strong interactions between deformation and intrusion emplacement (Román-Berdiel et al., 1997; Corti et al., 2005; Galland et al., 2007a; Montanari et al., 2010; Gomes et al., 2019). Our experimental results, in both simple and transtensional shear settings, show that pre- and syn-tectonic scenarios produce more elongated and fault-controlled intrusions in comparison to the less deformed post-tectonic intrusions characterised by low aspect ratios. The presence of intrusion causes regional surface uplift above the injection point and interferes with the fault structure evolution during their propagation. Regarding the reference models, with no intrusion presence, fault-controlled pull-apart basin system and of high subsidence rate occur for the transtensional group. The simple shear deformation results in a low angle main deformed linear zone formed by low angle shears and anastomosing shear lenses. Exception to this topography is Model A2 that resulted in narrow pull-apart system divided and displaced by the MF (Fig. 4e).

In accordance to the study of Gomes et al. (2019), this study illustrates that the shear zone deformation can be significantly modified by rheological heterogeneities by looking at the shear zone perturbation effect arising from passive (pre-tectonic) viscous-weak bodies. The pre-tectonic plutons, A1 and B1, with the gradual evolution of the post-emplacement shearing start to accumulate strain deformation in a ductile manner acquiring a sigmoidal (initially circular) shape of high aspect ratio and the lowest amplitude among all models (Fig. 6a-d, Fig. 11 a-d). This is very well shown from the shape analysis, where the lower levels of these intrusions are subparallel to the shear zone while the highest levels follow the finite stretching direction (Fig. 6c-d, Fig. 11c-d). The surface structures observed only for this model are acting separately over the domal uplift and not as one master fault (Fig. 3f). These above results seem compatible with the inferred observation on caldera collapse modelling and the case of strike-slip deformation of brittle layer containing a passive magmatic chamber (Holohan et al., 2008), where the magmatic chamber showed a NE-SW pluton

476 axis orientation, stretched approximately parallel to the extensional direction (in accordance to
477 current study Models A1 and B1). The limitation of pre-tectonic models, by the fault structures
478 developing subparallel to the boundary of the shear zone is an observation that is only attributed to
479 the variations on the overburden thickness (Román-Berdiel et al., 1997). The presence of the weak
480 body delays the upward propagation of the synthetic Riedel shears and results in a wider shear
481 zone, in respect to its reference model (Fig. 2f, Fig. 3f). Fact that is inferred from the deformational
482 response and the delay of the shear zone formation on the brittle surface, in comparison to the
483 reference models (Fig. 2, Fig. 3, Fig.8).

484 In the case of the syn-tectonic intrusions, direct and strong interactions are developing among fault
485 propagation and magma ascent. Faults control and confine the emplacement of the intrusions,
486 resulting in narrow and acute pluton shape that follows the highly active master fault (e.g. Román-
487 Berdiel et al., 1997; Corti et al., 2005; Mazzarini et al., 2010). Syn-tectonic models in simple shear
488 deformation show the highest pluton amplitude among all models ($A_{A2} = 0.6$; Table 3). From the
489 shape analysis of the excavated intrusions is inferred local fault control on the intrusions' boundaries
490 and orientation. Models A2 and B2, are initially orientated subparallel to the shear zone (intrusions'
491 lower level), with very low long axis angles. The deviation of their deformational is registered at their
492 highest levels when Model A2 seems to follow the Riedel orientation (Fig. 6h) while Model B2 is
493 oriented subparallel to S_{Hmax} .

494 The post-tectonic intrusions, Models A3 and B3, ascend without being exposed to the stress field,
495 besides the push from below during their ascent. The shape analysis reveals a characteristic
496 subcircular intrusion of an intermediate amplitude ($A_{A3} = 0.55$; $A_{B1} = 0.5$; Table 3) and with an
497 analogous axis orientation to the syn-tectonic models (Fig. 6k-l, Fig. 11k-l). Only from the strain
498 analyses it is inferred that in both settings, the uprising intrusions interferes and reactivates the pre-
499 existing brittle structures (Fig. 5c, Fig. 10c).

500 As a second order feature, the dike system overprinting the intrusions, is observed and analysed
501 upon excavation. Diking occurs locally and along fault structures and for all models, is developing

502 either on the intrusion's flat roof top, as in the cases of pre- and post-tectonic emplacement models
503 (Fig. 6a-b; i-j, Fig. 11a-b; i-j) or as a form of a sheared tail intrusion's extension, as in the case of
504 the syn-tectonic A2 and B2 Models (Fig. 6e-f, Fig 11e-f).

505 Our models have shown that the pluton's geometry functions as an excellent first order discriminator
506 for the timing of the intrusion with respect to tectonic activity. In addition, this study offers information
507 on the surface deformation, often limited during field work due to the occurrence of natural (e.g.
508 erosion) and tectono-magmatic processes. The diagnostic attributions are summarized in Table 3.

509 **(Table 3 here)**

510 *4.2 Model boundary conditions, simplifications and limitations*

511 *Effect of the basal ductile shear zone on the emplacement process*

512 We use a ductile homogenous shear zone as a basal kinematic boundary condition, which mimics
513 a natural mid-crustal shear zone. Apart from distributing deformation, the ductile material also
514 influences the emplacement mechanisms as reported in previous studies (Román-Berdiel et al.,
515 1997, 2000; Corti et al., 2005; Montanari et al., 2010; Mazzarini et al., 2010). In those models, the
516 presence of a widespread ductile layer is a pre-requisite to allow lateral flow and emplacement in
517 laccolith style. It is suggested that for the syn-intrusive deformation the rheological stratification
518 caused a deeper level of emplacement with respect to purely brittle models and thus controls the
519 timing of magma emplacement. For our experiments, instead of a widespread ductile layer, we
520 introduced a basal ductile band. Intrusions are allowed within the ductile band and above the fixed
521 injection tube. The effects described previously is similarly active in our setup with lateral intrusion
522 aided by the ductile material.

523 *Ignoring thermal and strain-rate dependent effects on rheology.*

524 The deformation in our experiments was accomplished by a quasi-stationary rheology including
525 temperature- and strain rate-insensitive brittle and Newtonian viscous materials. Our modelling
526 faces therefore some limitations regarding rheological principals (Corti et al., 2003). Magma cooling

527 is considered in simplified way by choosing a relatively high viscosity of the model magma (see
528 chapter on scaling and similarity 2.3). Thermal effects caused by the intrusion-related heating on
529 the rheology of the crustal rocks were not taken into consideration for our modelling as for all other
530 models of this type (Román-Berdiel et al., 1997; Corti et al., 2003; Galland et al., 2003, 2006, 2007;
531 Montanari et al., 2010; Mazzarini et al., 2010). At shallow crustal levels as those targeted here,
532 intrusion of rather small amounts of hot material into cold crust has likely a minor effect on the
533 geotherm and thereby on the rheology in general. However, the brittle-ductile transition might be
534 more sensitive to even small fluctuations in the geotherm caused by episodic heat advection by
535 veining and long-term emplacement of the intrusion (e.g. Handy and Streit, 1999; Brown, 2013). Any
536 modification of the rheology around the base of our models including temperature and strain-rate
537 dependent viscosity changes or even switches in the dominant deformation mechanisms (and
538 thereby the geometry of the brittle-viscous transition) is however beyond the scope of this modelling
539 approach. While we consider this drawback of the method more significant at a small scale,
540 numerical modelling might help in verifying the validity of our more stationary approach on a more
541 regional scale.

542 *What drives deformation in the model versus nature?*

543 In our experiments model magma is rising due to two different forces: pressure applied externally
544 and internal buoyancy forces (e.g. Ribe and Davaille, 2013; Wouter et al., 2016). Though qualitative
545 similar mechanisms act in nature the dynamic similarity is hard to verify. Pressure in the model is
546 controlled by the applied intrusion rate and decreases over an experimental run as the intrusion rate
547 is kept constant while the volumetric fraction added to the growing intrusion decreases with $1/t$
548 systematically. Given the geometric and kinematic similarities described above we suspect a
549 realistic de-pressurization scenario in the model. However, given the lack of quantitative
550 observations in nature a conclusion remains elusive. Buoyancy in the model is likely more important
551 than in nature because the density ratio between PDMS and sand is low (1:1.7) while it may be
552 closer to equality (1:1) or even >1 (negatively buoyant) in nature, depending on magma composition.

553 As we observe silicone dikes intruding the overburden in a similar fashion as in nature (e.g. roof
554 dikes, see below), we suspect however, that buoyancy driven intrusion (i.e. diapirism) mimics
555 residual melt injection driven by local pressure anomalies in the prototype.

556 4.3 Comparison with nature

557 Analogue modelling may be characterised by strong limitations and simplifications, mainly related
558 to the inability to reproducing natural thermal and rheological conditions. In addition, limitations on
559 direct comparison among natural and analogue models may be due to restricted exposure of
560 plutons. From our observations, the spatial and temporal relationships between emplacement-
561 related structures and intrusion vary with the level of the exposure. Analogue modelling studies have
562 managed to reproduce models with similar geometrical features of the plutons in the upper crustal
563 levels, for different tectonic settings, supporting the field evidences on tectonic control during pluton
564 emplacement (Castro, 1987; Hutton, 1988) and testifying the reliability of this modelling approach
565 (Román-Berdiel et al., 1997, 2000; Galland et al., 2003; Corti et al., 2005; Gomes et al., 2019).

566 The current analogue modelling approach provides new insights on the reliability of the finite pluton
567 shape as a diagnostic key-feature for constraining the temporal timing (pre-, syn- and post-tectonic)
568 and spatial conditions (tectonic setting) of the shallow crustal level emplacement. To validate our
569 experimental observables, we test them along with some second-order attributes against six cases
570 of well-defined natural examples, emplaced in simple shear and transtensional zones (Fig.13).

571 4.3.1 Natural examples of intrusions along simple shear zones

572 *The pre-tectonic Teixeira Pluton* (Fig. 13a,d) – This elongated ENE-trending batholith (80 km x 25
573 km) is situated in NE Brazil and within a zone that is defined by the E-trending Patos, the So José dos
574 Cordeiros and the Juru shear zones (Fig.13a). The pre-tectonic Teixeira batholith is a leucocratic
575 granite to quartz-syenite in composition that shows a crystallization age of 591 ± 5 Ma (Zircon U/Pb).
576 The batholith fabrics, determined by anisotropy of magnetic susceptibility (AMS) and mineral shape
577 preferred orientation, support a pre-transcurrent batholith emplacement scenario (Archanjo et al.,

578 2008). This natural example carries similar features to the pre-tectonic Model A1 of this study (Fig.
579 6a-d). The pluton is characterised by high aspect ratio ($L/W > 5$), with the long axis orientated
580 subparallel to the extensional direction, forming an angle of $\alpha = 15^\circ$. The Teixeira pluton, on map
581 view, is elongated in a northeast-southwest direction, consistent with the dextral pure strike-slip
582 motion (Fig.13a).

583 Another natural example with similar characteristics to the pre-tectonic model A1 is the granitic
584 Tazenakht Pluton in Morocco. The pluton's deformation follows its emplacement within a left lateral
585 strike slip fault, running along its northern side (Ennih and Liegeois, 2001; Gasquet et al., 2008).
586 The boundaries developing between the fault structure and the intrusion boundaries are sharp. The
587 pluton was probably subject to a minor rotation during the deformational post-intrusion event. This
588 natural example is characterised by high axis ratio ratio ($L/W = 1.6$) and the pluton's long axis forms
589 an angle of $\alpha = 29^\circ$ with the shear zone. The local presence of dykes and the geometrical features
590 of the pluton are similar to those observed for the Model A1.

591 *The syn-tectonic Cabeza de Araya Pluton* (Fig. 13b,e) –The plutons of the Central Extremadura
592 batholith in the Iberian Massif (Fernández and Castro, 1999) is a natural example of syn-tectonic
593 plutonism. This natural example was imposed to tectonic deformation during its emplacement,
594 triggered by a right-lateral shear zone (Vigneresse and Bouchez, 1997; Fernández and Castro,
595 1999; Corti et al., 2005). The emplacement mode of the pluton is coeval with the dextral regional
596 shear zone (Castro, 1985). The pluton shows an aspect ratio of $L/W = 2.7$, with the long axis forming
597 an angle of $\alpha = -45^\circ$ parallel to the compression direction (NW-SE direction, Fig. 13b). Similarly, an
598 intermediate axis ratio is observed for the syn-tectonic Model A2 ($r = 2.5$; Fig. 6g, h). The model's
599 long axis that corresponds to the higher contour levels is orientated with the angle of ($\theta = -10^\circ$),
600 making this natural model a prototype for this emplacement scenario. In addition to this, there are
601 also other important natural examples of syn-tectonic intrusion emplacement scenarios that shows
602 similarities to our observations: 1) *Karawanken pluton* (Visonà and Zanferrari, 2000; Rosenberg,

603 2004); 2) *The Lizio pluton* (Román-Berdiel et al., 1997; Fernandez and Castro, 1999; Corti et al.,
604 2005); 3) *Cases of Syn-tectonic magmatism along the Periadriatic Fault System* (Rosenberg, 2004).
605 *The post-tectonic Vila Pouca de Aguiar pluton* (Fig. 13c,f) – This is a natural example of a post-
606 tectonic granitic intrusion that is emplaced after the main left-lateral shear phase event (Sant’Ovaia
607 et al., 2000). It is suggested that the first to be emplaced and the least evolved granite type (Vila
608 Pouca de Aguiar Granite) upwelled from the local, NE-trending fault-zone, acting as a dike, and
609 formed a thin sill where NE-directed magma flow was dominant. In this case, the pre-existing
610 features exert a major role during emplacement leading to the roughly alignment of the intrusion
611 with the shear zone ($\alpha = -4^\circ$; Fig.13f), with the pluton axis parallel to the compression direction. Even
612 if the pre-tectonic group generated intrusions with the lowest aspect ratios ($r < 1.5$; Fig. 7), the
613 intrusion ellipses corresponding to higher contour levels resulted in a similar aspect ratio ($r = 1.9$)
614 and elongated shape to the *Vila Pouca de Aguiar* pluton (Fig. 6l).

615 Another characteristic natural example of post-tectonic emplacement is the Águas Frias (AF) pluton
616 (Martins et al., 2009; Fig. 13c). This post-tectonic granitic pluton is situated NE from the Vila Pouca
617 de Aguiar pluton, occupying an area of 30 km² and is associated with Penacova-Régua-Verin fault
618 (PRVF) that belongs to the NNE-trending brittle fault system. Its emplacement is fed through a deep
619 conduit located at the centre of the pluton. VPA and AF plutons show similar in mineralogical,
620 chronological and magnetic features. Their feeding zones are located within the NNE-SSW
621 Penacova-Régua -Verin Fault. **(Figure 13 here)**

622 4.3.2 *Natural examples for intrusion into transtensional shear zones*

623 *The pre-tectonic Eğrigöz pluton* (Fig. 13g,j) - This natural example regards a N-S elongated (40x15
624 km) granite body (20.5 ± 1.1 - 18.9 ± 1.2 Ma.; Catlos et al., 2012), situated in the northern Mendere
625 metamorphic core complex and covering an area of 330 Km². Its geometrical features show a high
626 aspect ratio of $L/W = 2.6$ and an axis trend of $\alpha = 46^\circ$ (parallel to the extension direction), analogous
627 to the observations made for the higher contour levels of the strongly deformed pre-tectonic Model
628 B1 ($r = 1.9$; $\theta = 42^\circ$; Fig.11d; Table 3). The 20km-long, NE-striking Gerni shear zone is closely linked

629 to the pulses of magmatic activity and assumed to have propagated immediately following the
630 emplacement of the Eđrigöz pluton. Stress tensor results of the Eđrigöz pluton indicate that the
631 shear zone has been predominant under NE-SW-trending extension. The presence of the aplitic
632 and pegmatitic dikes along the periphery and structurally upper parts of the pluton (Erkül et al., 2017)
633 are rather common and similarly reproduced during the analogue Model B1 experiment (Fig. 11a-
634 b). In addition to this example, more plutons are registered carrying similar diagnostic features of
635 pre-tectonic emplacement mode : 1) *The Totoltepec Pluton* (Kirsch et al., 2013); 2) *The Devonian*
636 *granitoid of Pampa de Achala*, in Central Argentina (Simpson et al., 2001); 3) *The Koyunoba pluton*
637 (Erkül et al., 2017).

638 *The syn-tectonic Monzoni Intrusive Complex* (Fig. 11) – This 4 km-long intrusion situated in the
639 central Dolomites in Italy offers a great occasion for comparison due to its excellent three-
640 dimensional exposure. However and mainly due to contact metamorphism around the pluton and
641 the syn-metamorphic thermally driven fluid circulation, field observations are very limited, and still
642 there is very poor knowledge of kinematic indications. Based on analogue modelling observations,
643 new insights on the shear zone and fault structures, of the missing upper crustal layer that once
644 hosted the emplaced magmatic chamber, is achieved. It is assumed that the pluton's emplacement
645 mode is controlled by the Middle Triassic tectonics, however the time of emplacement (syn-tectonic
646 or indirect post-tectonic emplacement) along the left-lateral shear zone is still under discussion.
647 According to our model observations, this pluton exhibits diagnostic characteristics similar to a syn-
648 to late tectonic intrusion. The pluton's long axis trends with an angle of $\alpha = -14^\circ$, parallel to the
649 compressional field, and shows an aspect ratio of $L/W = 2$ (Fig. 13k). The shape analysis of this
650 pluton shows similarity to the Model B2 ($-10 < \theta < -19^\circ$; $r = 1.7$; Fig. 11g-h). The syn-magmatic dike
651 swarms, cropping out at the intrusion area, appear to cut the deformed sedimentary country rocks
652 and intrude the magmatic edifice (Sloman 1989; Bonadiman et al., 1994; Gianolla et al., 2010; Abbas
653 et al., 2018) while the pluton carries a NE–SW striking apophysis that trails the intrusion at its SW
654 boundary. Similar natural examples of syn-tectonic emplacement mode are: 1) *The Mortagne pluton*
655 (Román-Berdiel et al., 1997); 2) *The Los Pedroches pluton* (Aranguren et al., 1997; Román-Berdiel

656 et al., 2000); 3) *The Jihlava Intrusion* (Verner et al., 2006); 4) *The Hombreiro pluton* (Román-Berdiel
657 et al., 2000); 5) *The Gulf of Aden Ridge* (Corti et al., 2003).

658 *The post-tectonic La Tojiza Pluton* (Fig. 13i,l) - The La Tojiza granite is cropping out in the
659 Mondonedo Nappe Domain (Fig. 13c) and according to geochronological data it consists with a U–
660 Pb age of 295 ± 2 Ma (Fernández-Suárez et al., 2000). This post-tectonic association is composed
661 of granite–granodiorite–tonalite–monzogranite intrusions. The intrusion reactivated the inherited
662 transtensional tectonic structures, leading to the emplacement and formation of a sub-circular pluton
663 of 16 km-diameter (Aranguren et al., 2003). Its thickness is estimated of 1 km and the root zone is
664 located at its eastern border. The pluton shows an axis trend of $\alpha = -6^\circ$ and parallel to the
665 compressional field, with the pluton's aspect ratio $L/W = 1.2$ (Fig. 13l). Most of the observed aplitic
666 dikes are present on the roof of the pluton and oblique to the magnetic lineation. These features are
667 in great accordance to the lower contour levels of the post-tectonic Model B3 ($\theta = 0^\circ$; $r = 1.4$; Fig.
668 11k-l). The *Plasenzuela Intrusion* (Central Extremadura, Spain; Fernandez and Castro, 1999)
669 represents another natural example for this emplacement scenario, characterised by a well-defined
670 rounded pluton shape of low aspect ratio ($L/W \sim 1$).

671 **4 Conclusions**

672 This study provides new insights on the application of the finite pluton shape as a diagnostic indicator
673 for constraining the tectonic setting and the relative timing of magma emplacement versus tectonics.
674 Three scenarios on pluton emplacement (pre-, syn- and post-tectonic) in two different tectonic
675 settings (simple shear, transtension) are tested and analysed. The intrusion shapes (aspect ratio,
676 principal axis trend, amplitude) and the model surface deformation are measured and described,
677 providing useful insights for the understanding of the interactions occurring between tectonics and
678 magmatism. The main insights and conclusions supported by this study are the following:

- 679 1. Incremental strain analysis and final surface deformation reveal a different deformational
680 pattern among the scenarios and strong interactions between tectonics and magma

681 emplacement. Pre-tectonic models accumulate regional strain during shearing, resulting in
682 the delay and diffusion of the brittle structures during their up-ward propagation. Here, the
683 final shear zone appears wider than the respective reference model and crosscut but more
684 than one well-defined fault. Syn-tectonic emplacement causes the major boundary faults to
685 extend and curve towards the centre and the formation of a narrow fault-controlled pull-apart
686 basin overprinted by the master fault. The inverse shear sense, captured in strain maps,
687 caused during intrusion is observed exclusively in the post-tectonic scenario.

688 2. The final shape of the intrusions emplaced along the shear zones with a different timing
689 respect to the tectonic activity show significant deformational variations, delineating its
690 reliability as a diagnostic feature. Observations coming from both tectonic groups (simple
691 shear and transtension) infer parallel deformational pattern and geometrical characteristics
692 for the intrusions of similar timing of emplacement (pre-, syn- or post-tectonic). Based on
693 the analytical shape analysis, the asymmetric and deformed final intrusions reflect the
694 regional stresses and finite strain field. The axis aspect ratio and trend are evolving against
695 the contour level for each model, remaining consistent among those emplaced coevally.

696 3. Among the emplacement scenarios, the pre-tectonic intrusions appear strongly elongated
697 parallel to the extension field with the lowest amplitude and the highest aspect ratios. The
698 intrusion's flat top is cross cut by more post-emplacement shears. Syn-tectonic models are
699 characterised by high amplitude and moderate aspect ratios. They bear acute roofs,
700 oriented parallel to the compression direction, and scissor-tail apophysis that trails the
701 intrusion. The sub-circular post-tectonic models show the lowest aspect ratios and a similar
702 orientation to syn-tectonic models.

703 4. Faults that crosscut the central zone overprint the emplaced or up-lifting intrusion,
704 navigating the intrusions' margins and serving as pathway for diking. The higher levels of
705 the syn- and post-tectonic intrusion boundaries appear parallel to and constrained by the
706 synthetic faults developing on the surface. The lateral expansion of pre-tectonic models is

707 bounded by the major fault structures developing subparallel to the boundary of the shear
708 zone, while their top is overprinted by roof-diking guided by crosscutting shears.

709 5. The obtained diagnostic attributes are tested successfully against natural prototypes,
710 confirming the diagnostic potential and reliability of the intrusion's shape for constraining the
711 time and the tectonic setting of the magmatic emplacement.

712 **Data Availability**

713 Supplementary data to this article can be found online at: [https://dataservices.gfz-](https://dataservices.gfz-potsdam.de/panmetaworks/review/fc4dbaf175809475dea6b59495381e0ba7ae895307bc01b738bdc2c466780604/)
714 [potsdam.de/panmetaworks/review/fc4dbaf175809475dea6b59495381e0ba7ae895307bc01b738b](https://dataservices.gfz-potsdam.de/panmetaworks/review/fc4dbaf175809475dea6b59495381e0ba7ae895307bc01b738bdc2c466780604/)
715 [dc2c466780604/](https://dataservices.gfz-potsdam.de/panmetaworks/review/fc4dbaf175809475dea6b59495381e0ba7ae895307bc01b738bdc2c466780604/)

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- 934

936 **Table 1 Model characteristics and experimental conditions**

Models	Thickness of brittle layer	Thickness of ductile layer	Intrusion rate, I_r	Injected Volume, I_v	Relative displacement rate, D_v	Total horizontal displacement, D_t	Experiment Duration
Reference models (Group R)							
Simple shear RS	40mm	7mm	-	-	1.0 mm/min	30 mm	30 min
Transtension RT	40mm	7mm	-	-	1.0 mm/min	30 mm	30 min
Static Intrusion R0	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	-	-	30 min
Simple shear models (Group A)							
Pre-tectonic intrusion A1	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	60 min
Syn-Tectonic Intrusion A2	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	30 min
Post-tectonic intrusion A3	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	60 min
Transtension models (Group B)							
Pre-tectonic intrusion B1	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	60 min
Syn-Tectonic Intrusion B2	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	30 min
Post-tectonic intrusion B3	40mm	7mm	21.0 mm ³ /s	37.7x10 ³ mm ³	1.0 mm/min	30 mm	60 min

938 **Table 2 Material properties and scaling factors**

Parameters	Models	Nature	Model/ Nature (Scaling factor)
Brittle material	Quartz Sand	Upper Crust	
Length, L	0.01 m	0.6 - 6 km	$0.6 - 6 \times 10^{-6}$
Cohesion, C	10-100 Pa	10 MPa	$1-10 \times 10^{-6}$
Density, ρ	1600 Kg/m	2600 kg/m	0.615
Gravity, g	9.81 m/s	9.81 m/s	1
Viscous material	Silicone oil	Intrusion/ shear zone	
Viscosity, η	3×10^4 Pa s	$>10^{18}$ Pa s	3.0×10^{-14}
Density, ρ	965 kg/m	1600 kg/m	0.603
Time, t	1 sec	30000 yrs	10^{-13}

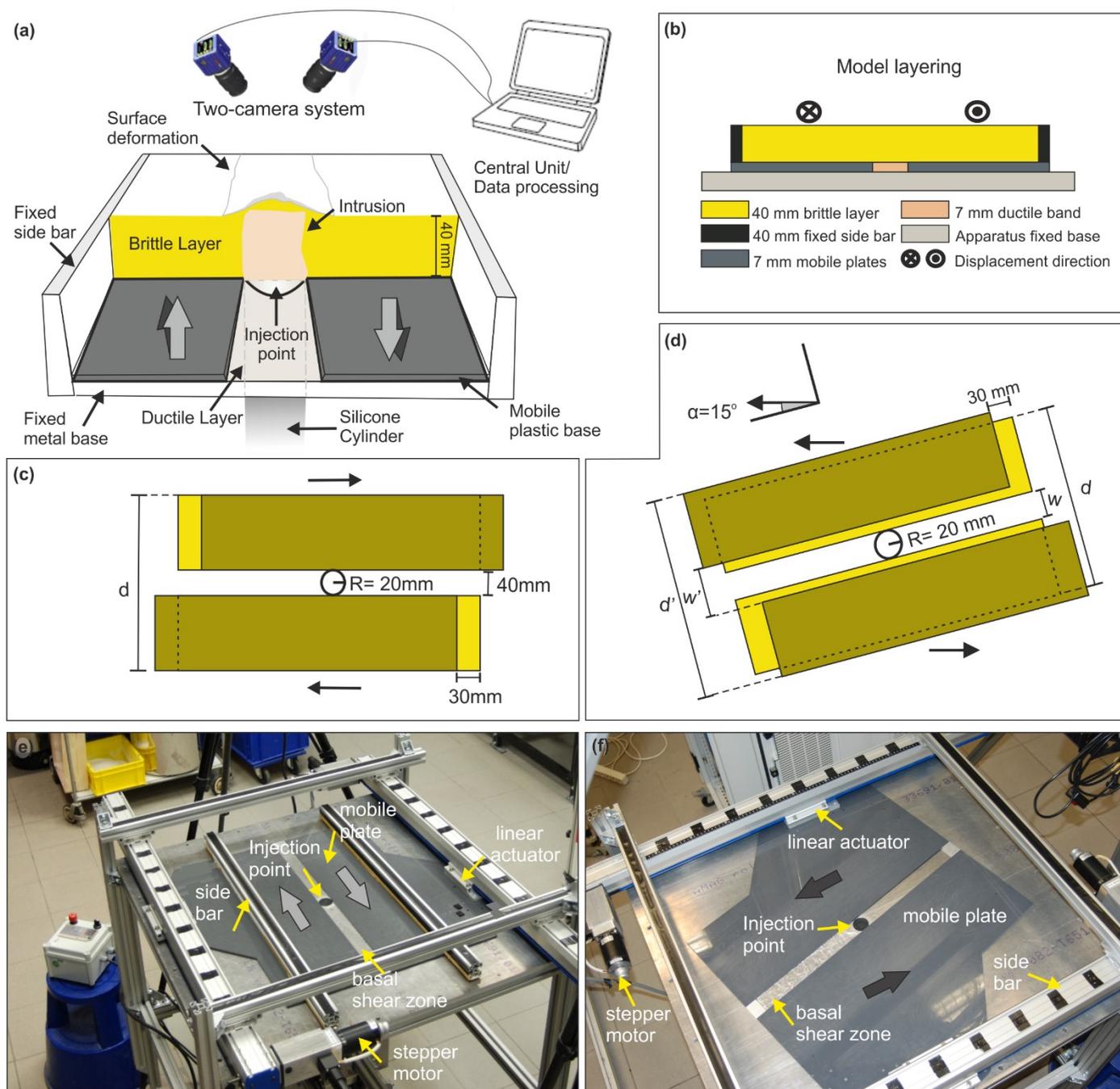
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940 **Table 3 Summarizing table of diagnostic attributes as suggested by the analogue models for the different em-**
 941 **placement scenarios.**

Model	Pluton Elongation ^a		Orientation ^a	Dike system	Pluton Amplitude, A
	Group A	Group B			
Pre-tectonic	High ($r_{A1} > 1.5$)	High ($r_{B1} > 1.5$)	Long axis // extension	Roof	Low
Syn-Tectonic	High ($r_{A2} > 1.5$)	Medium/High ^b ($r_{B2} > 1.5$)	Long axis // compression	Lateral (apophysis)	High
Post-tectonic	Low ($r_{A3} < 1.5$)	Low ($r_{B3} < 1.5$)	Long axis // compression	Roof	Medium

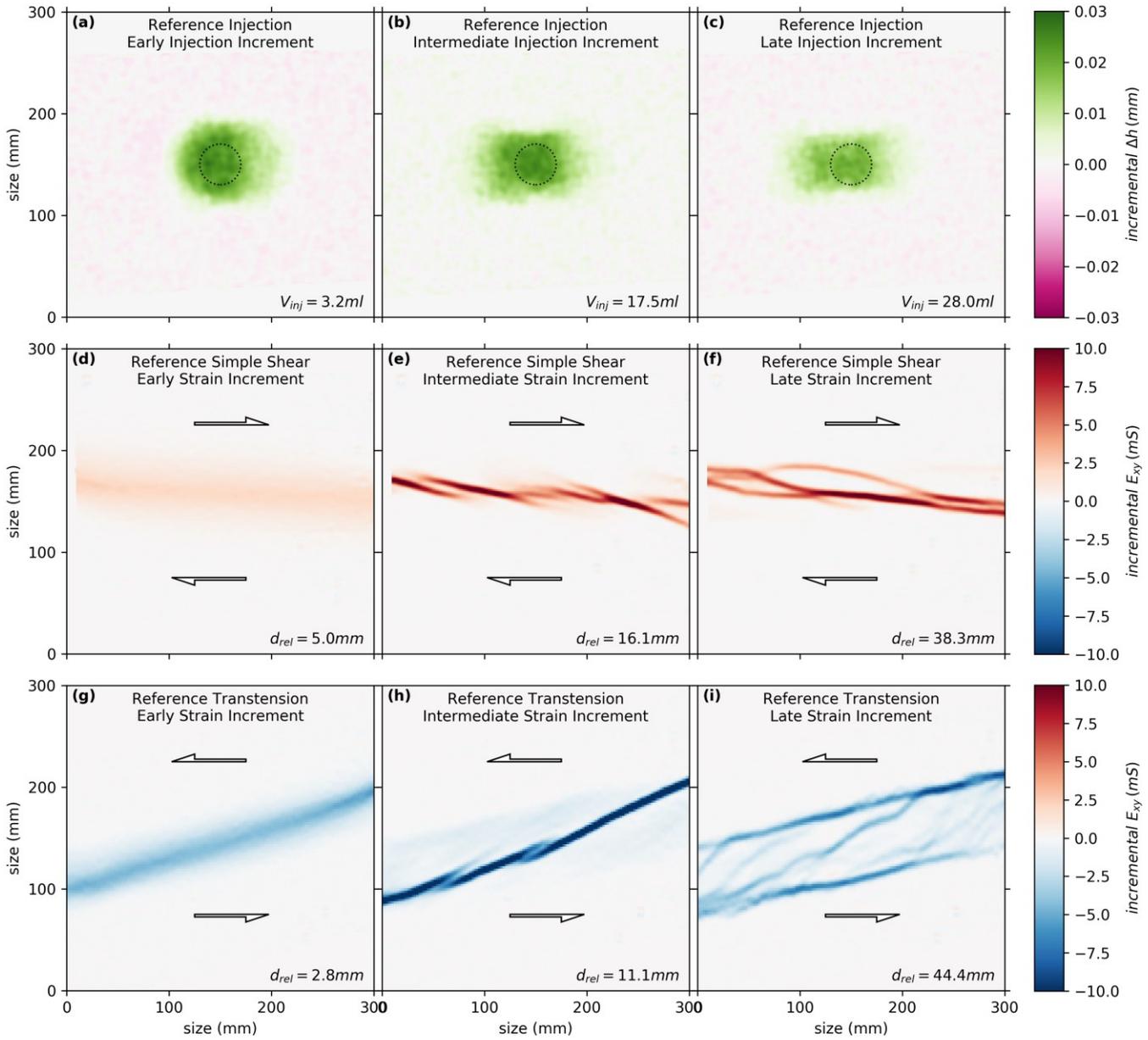
942 ^a Based on an ellipse fitted to the lower (C_1) and higher (C_2) contour level of the intrusion.

943 ^b Based on repetition models (100, 59, 95; see Appendix A.1)



945

946 **Fig. 1** Details of the experimental apparatus. Details of the experimental set-up. (a) Schematic cut-out 3D view
 947 depicting its various components; (b) Model layering; kinematic basal boundary conditions for (c) Sketch of
 948 the experimental setting of the simple shear deformation ($d=310$ mm) and (d) the transtensional deformation
 949 (obliquity $\alpha=15^\circ$) with the initial (yellow) and final (green) positions of the mobile plates ($w=40$ mm, $w'=55.5$
 950 mm, $d=360$ mm, $d'=375.5$ mm); Oblique view of experimental settings for (e) simple shear and (f) transtensional
 951 deformation. Arrows indicate the direction of plate movement.



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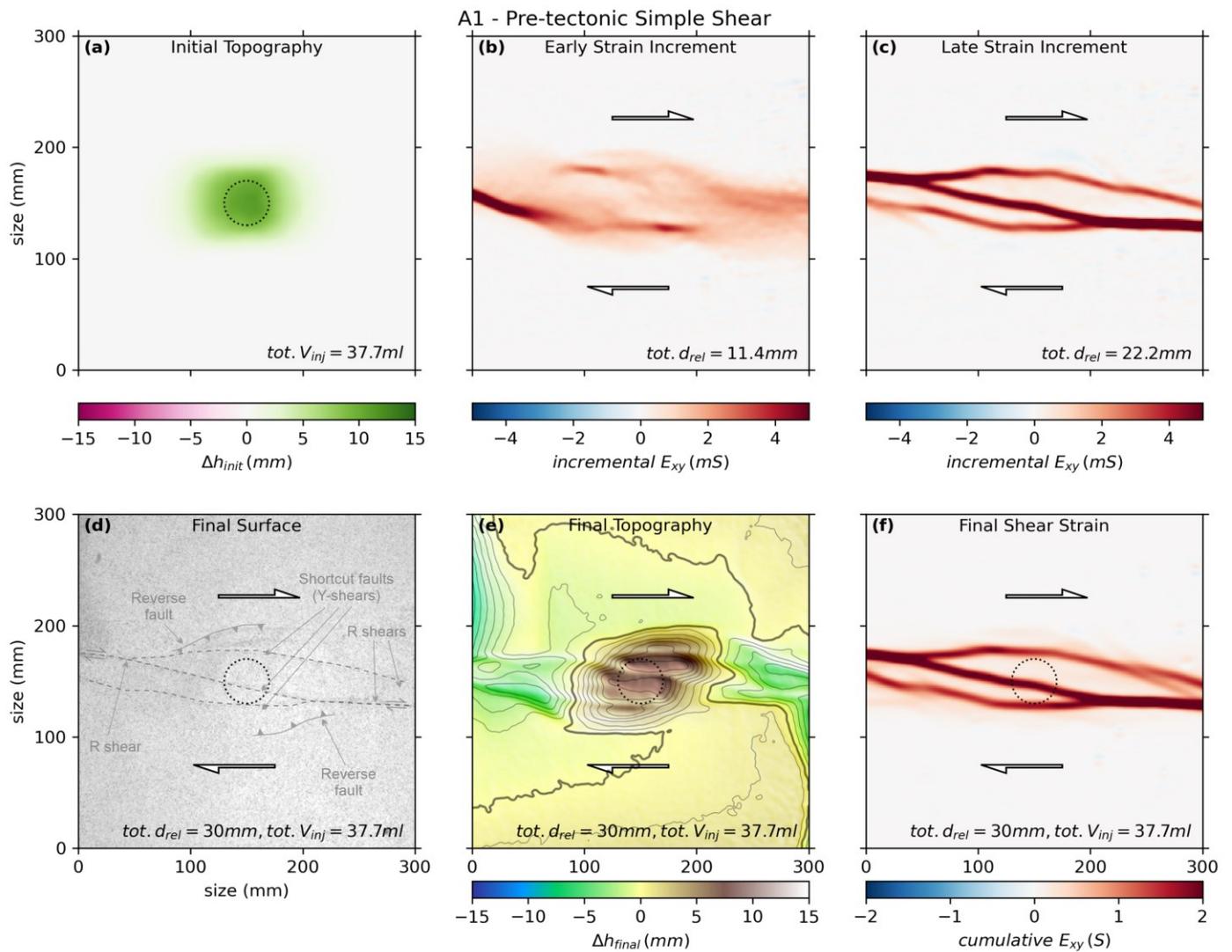
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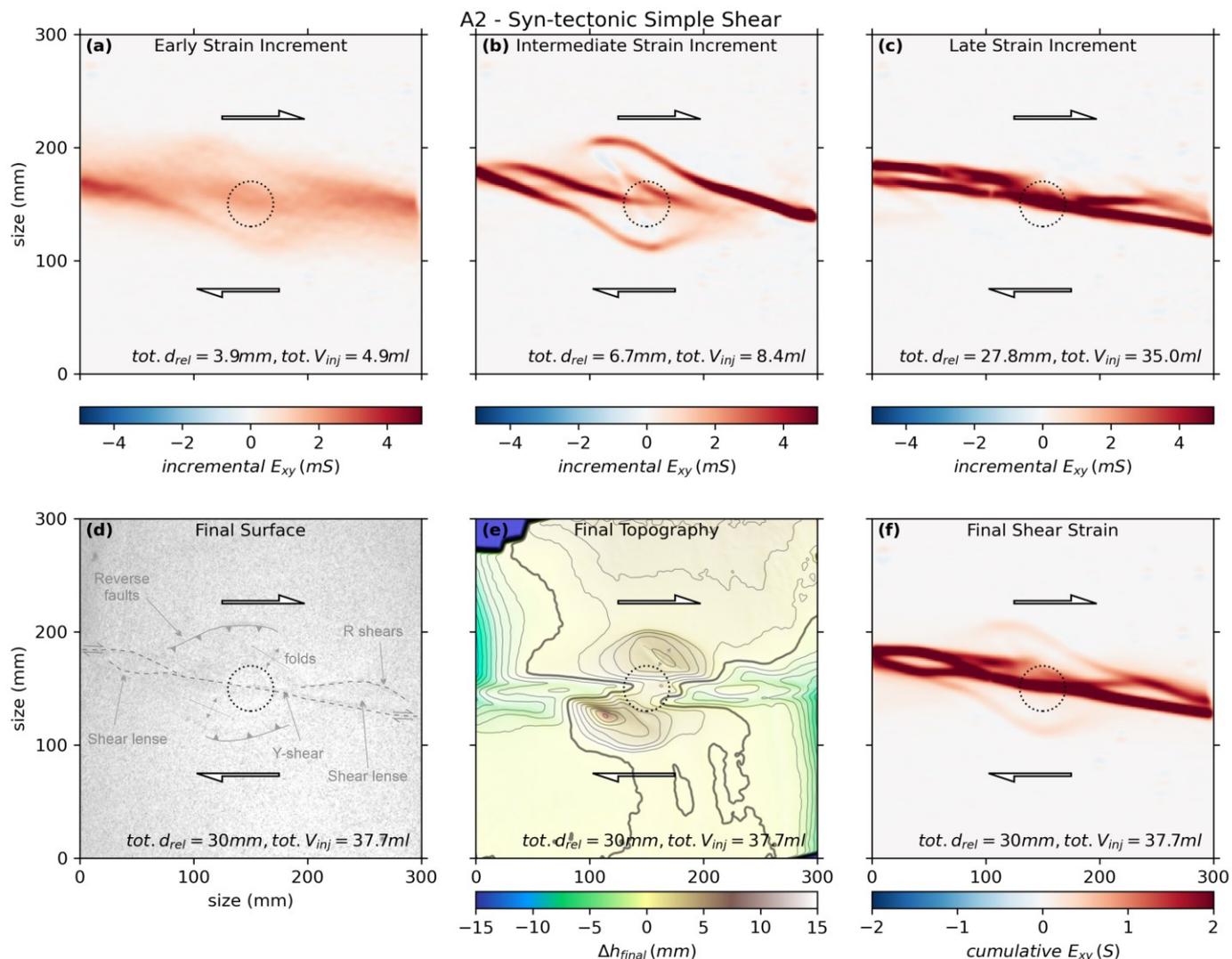
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Fig. 2 Surface evolution and deformational pattern of the reference experiments(Group R): (a-c) representative stages (with $V_{inj} = 3.2, 17.5, 28.0\text{ ml}$) of the topographic evolution (vertical displacement Δh) of the static intrusion model R0; (d-f) representative stages (at $d_{rel} = 5.0, 16.1, 38.3\text{ mm}$) of the strain field (shear strain E_{xy}) of the simple shear model RS and (g-i) representative stages (at $d_{rel} = 5.0, 16.1, 38.3\text{ mm}$) of the strain field (shear strain E_{xy}) of the transtension model RT. Positive values of E_{xy} (in red) indicate a dextral shear sense and negative values (in blue) indicate sinistral shear. Dotted circles indicate the position of the basal injection.



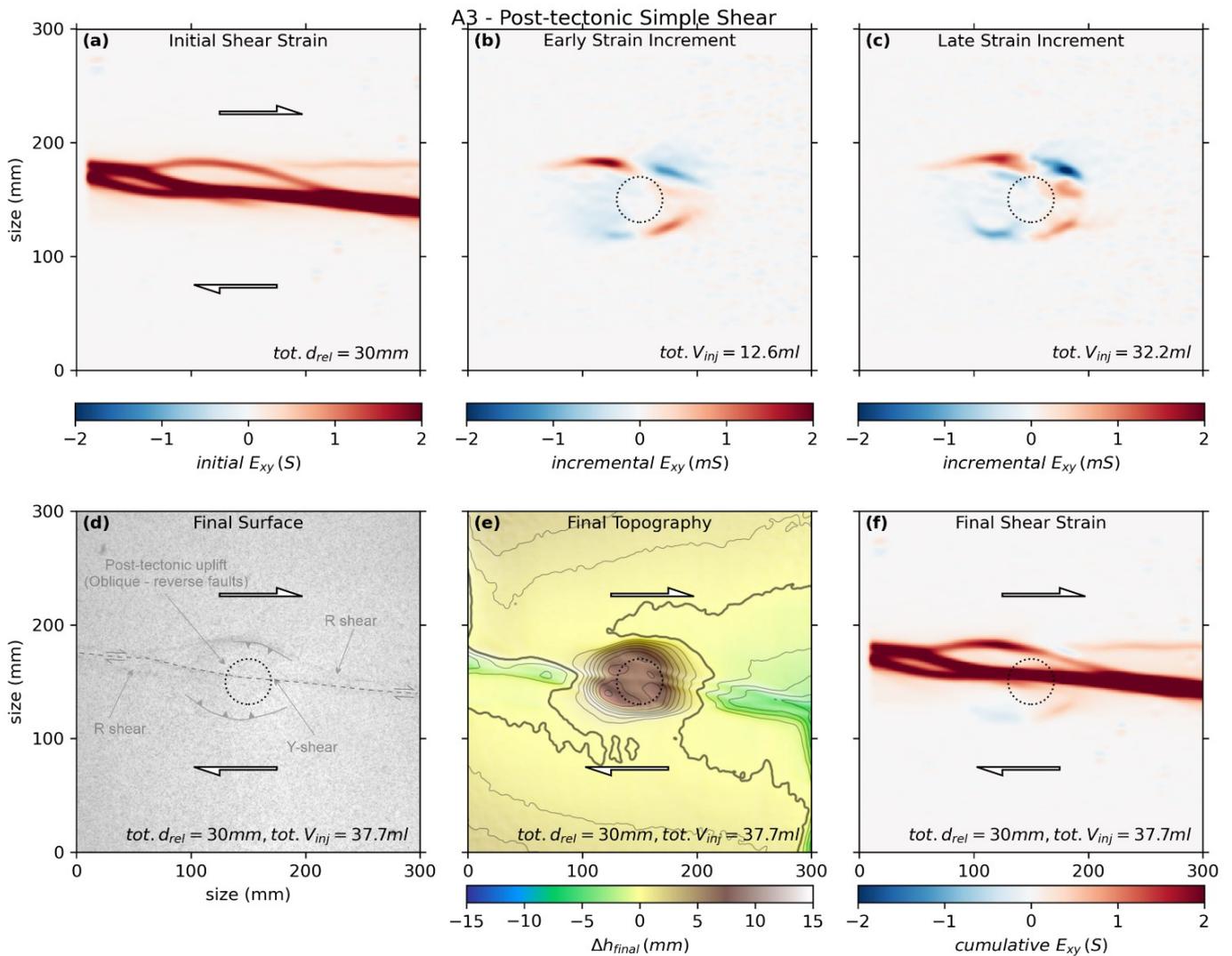
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960 **Fig. 3 Surface deformation of the pre-tectonic intrusion model in simple shear (Model A1). Shown are snapshots**
 961 **of the evolution: (a) Topography the end of static intrusion ($V_{inj} = 37.7 ml$), (b) incremental strain during an early**
 962 **stage of displacement ($d_{rel} = 11.4 mm$), and (c) during a late stage ($d_{rel} = 22.2 mm$). Panels in the second row**
 963 **show the final (cumulative deformation) stage of the model ($d_{rel} = 30 mm$, $V_{inj} = 37.7 ml$): (d) surface image; (e)**
 964 **cumulative vertical displacement ($tot. d_{rel}=30mm$) and (f) cumulative shear strain (E_{xy}). Dotted circles indicate**
 965 **the position of the basal injection.**



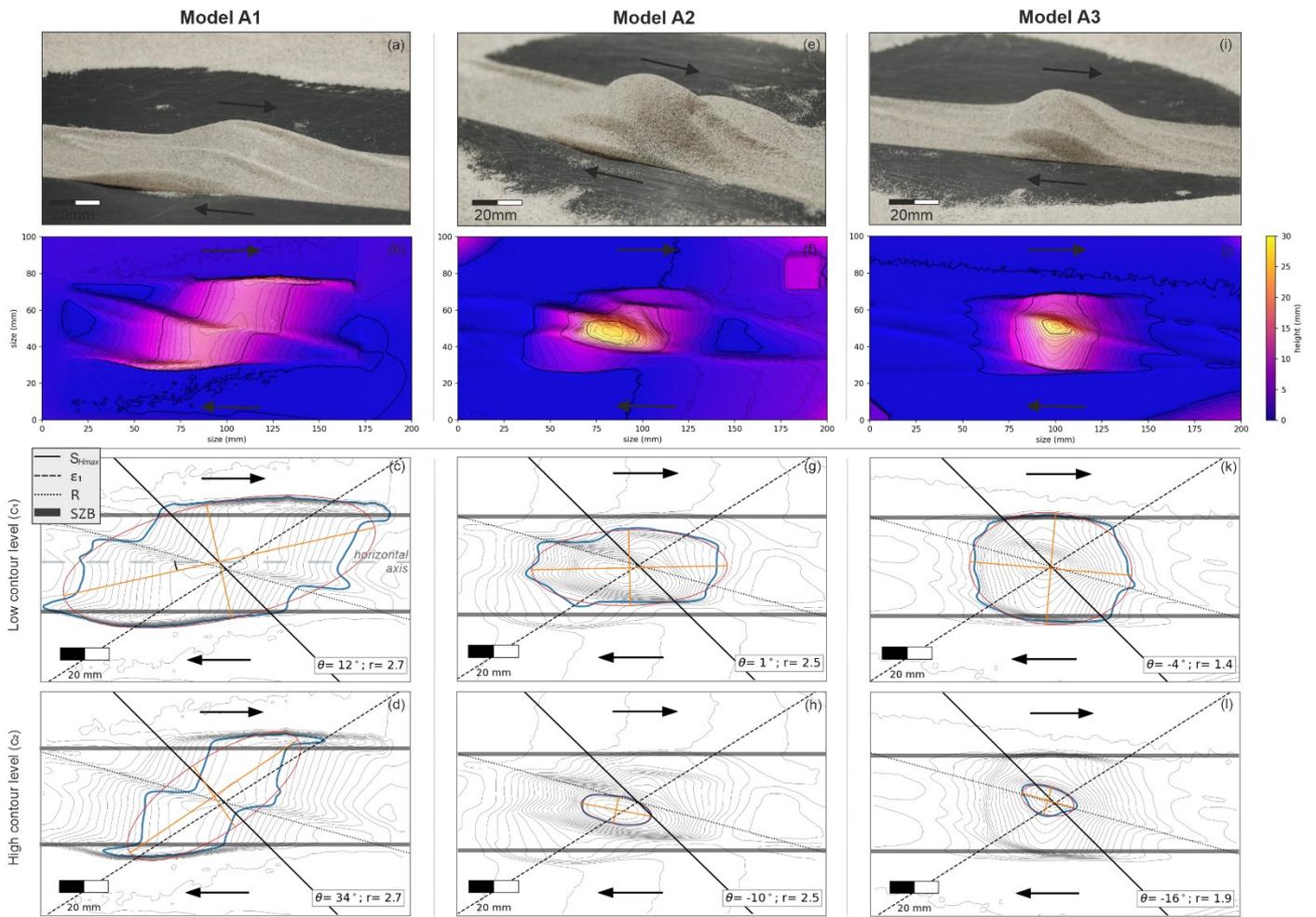
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967 **Fig. 4 Surface deformation of the syn-tectonic intrusion model in simple shear (Model A2). Shown are snapshots**
 968 **of the evolution: Incremental strain during an (a) early ($V_{inj} = 4.9\text{ ml}$ and $d_{rel} = 6.7\text{ mm}$), (b) intermediate ($V_{inj} = 8.4$**
 969 **ml and $d_{rel} = 6.7\text{ mm}$) and (c) late stage ($V_{inj} = 35.0\text{ ml}$ and $d_{rel} = 27.8\text{ mm}$). Panels in the second row show the**
 970 **final (cumulative deformation) stage ($d_{rel} = 30\text{ mm}$, $V_{inj} = 37.7\text{ ml}$): (d) surface image; (e) cumulative vertical**
 971 **displacement (tot. $d_{rel}=30\text{mm}$) and (f) cumulative shear strain (E_{xy}). Dotted circles indicate the position of the**
 972 **basal injection.**



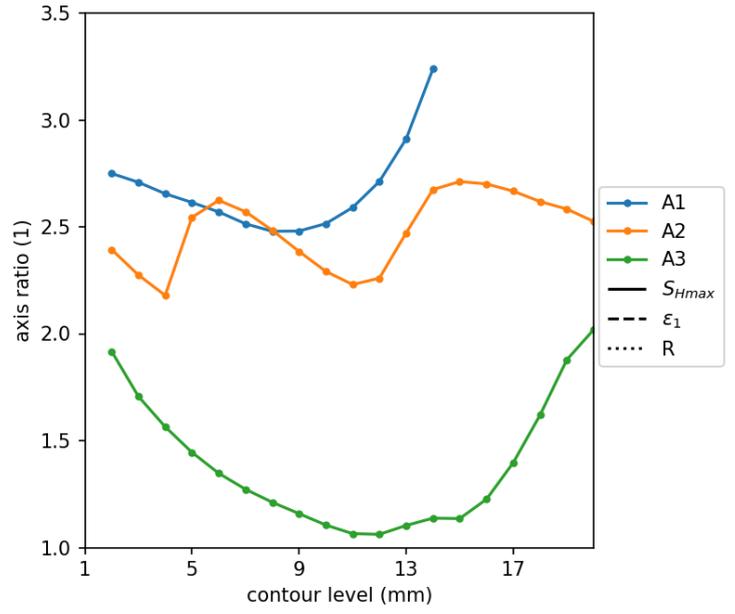
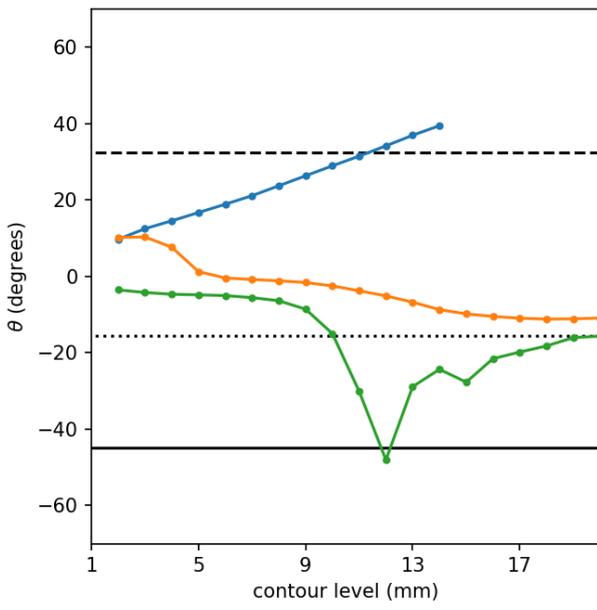
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974 **Fig. 5** Surface deformation of the post-tectonic intrusion model in simple shear (Model A3). Shown are snap-
 975 shots of the evolution: (a) Accumulated strain at the beginning of intrusion ($d_{rel} = 30$ mm), (b) incremental strain
 976 during an early ($V_{inj} = 12.6$ ml) and (c) late stage ($V_{inj} = 32.2$ ml) of intrusion. Panels in the second row show the
 977 final (cumulative deformation) stage ($d_{rel} = 30$ mm, $V_{inj} = 37.7$ ml): (d) surface image; (e) cumulative vertical
 978 displacement (tot. $d_{rel}=30mm$) and (f) cumulative shear strain (E_{xy}). Dotted circles indicate the position of the
 979 basal injection.



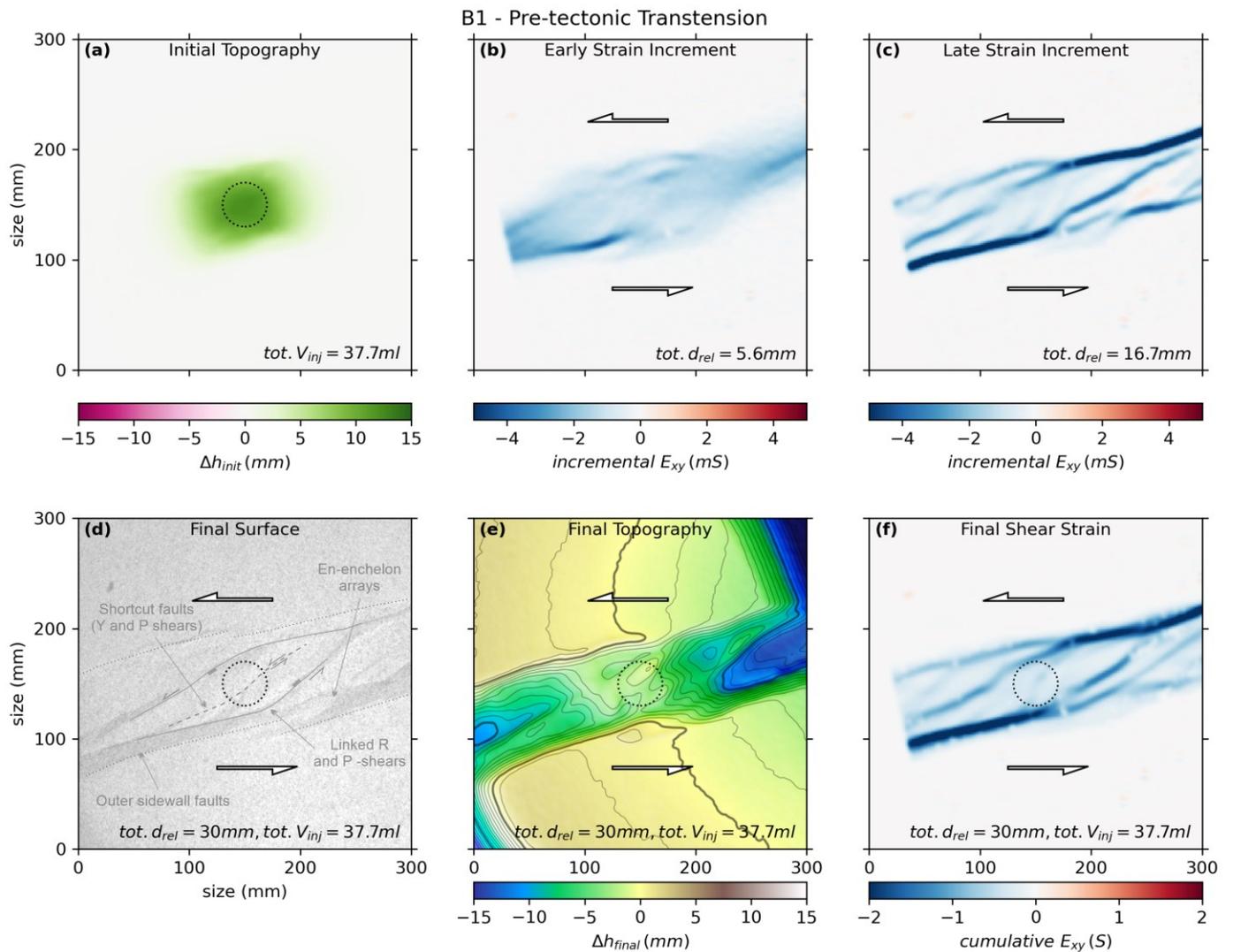
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981 **Fig. 6 Models of the intrusions in the simple shear regime (Group A): Model A1 (a-c); Model A2**
 982 **A3 (g-i). (a, d, g) Oblique views of the excavated intrusions; (b, e, h) Digital Intrusion Models (DIM) coloured and**
 983 **with contour lines; (c, f, i) Orientation and geometry of the intrusion (in map view), where θ = the angle between**
 984 **the long axis (orange) of the fitted ellipse (red) and the strike of the basal shear zone. r is the intrusion's aspect**
 985 **ratio (length-to-width ratio, L/W). Light and dark grey quadrants indicate contraction and extensional quadrants,**
 986 **respectively.**



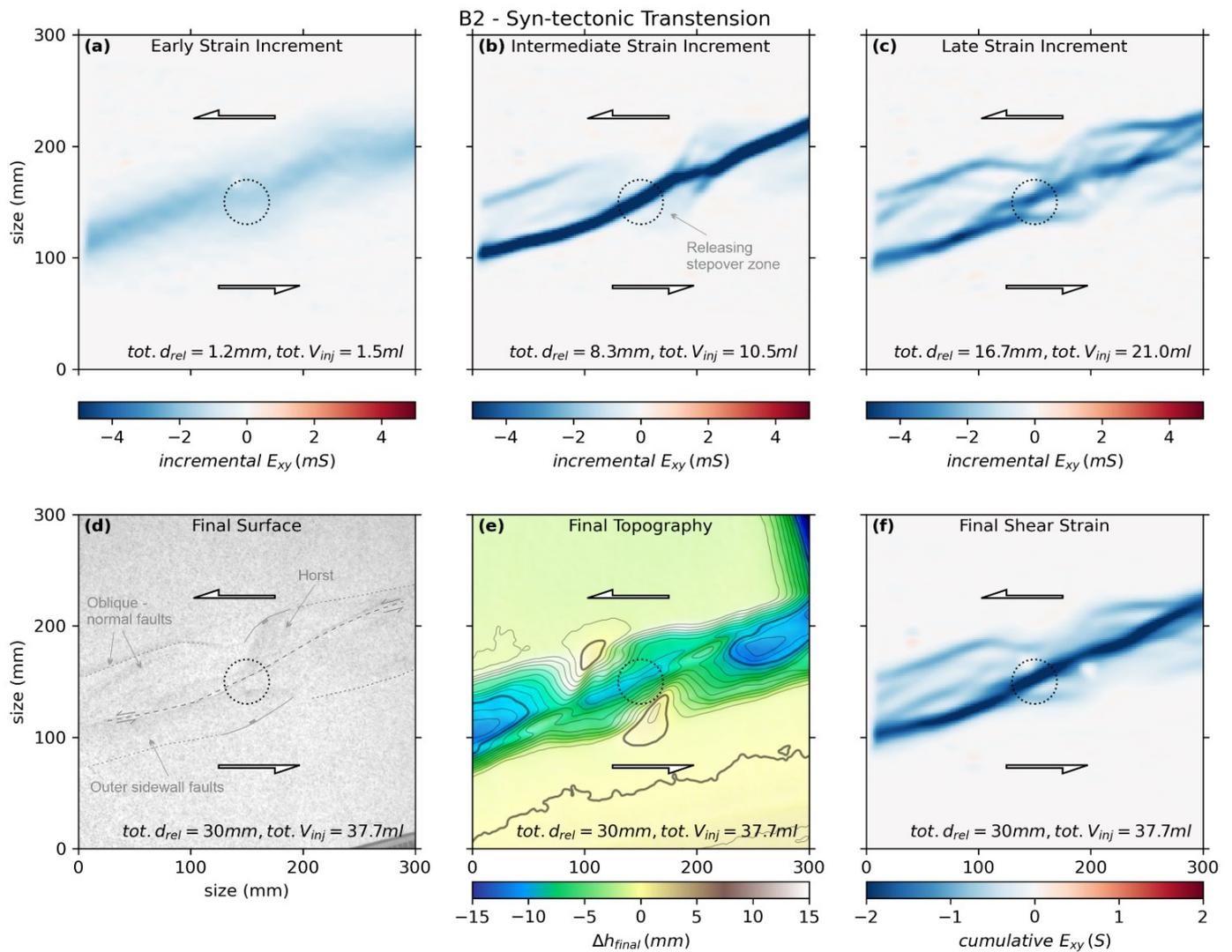
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988 Fig. 7 Series A experimental results expressed in graph of angles and ratios ellipses vs. intrusion contour level.



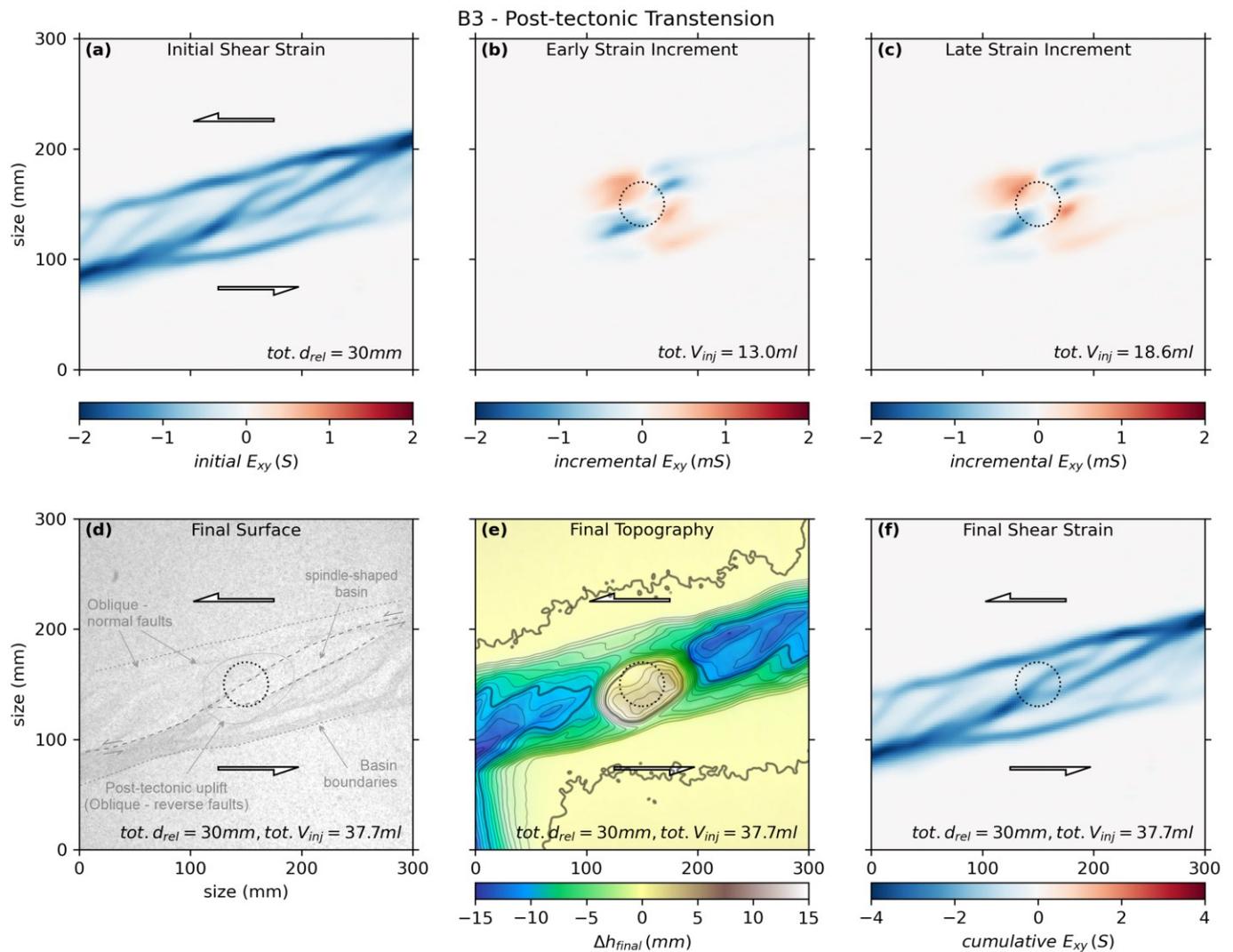
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990 **Fig. 8** Surface deformation of the pre-tectonic intrusion model in transtension (Model B1). Shown are snapshots
 991 representative of the evolution: (a) Topography the end of static intrusion ($V_{inj} = 37.7 ml$), (b) incremental strain
 992 during an early stage of displacement ($d_{rel} = 5.6 mm$), and (c) during a late stage ($d_{rel} = 16.7 mm$). Panels in the
 993 second row show the final (cumulative deformation) stage of the model ($d_{rel} = 30 mm$, $V_{inj} = 37.7 ml$): (d) surface
 994 image; (e) cumulative vertical displacement ($tot. d_{rel}=30mm$) and (f) cumulative shear strain (E_{xy}). Dotted circles
 995 indicate the position of the basal injection.



996

997 **Fig. 9 Surface deformation of the syn-tectonic intrusion model in transtension (Model B2).** Shown are snapshots
 998 representative of the evolution: Incremental strain during an (a) early ($V_{inj} = 1.5\text{ ml}$ and $d_{rel} = 1.2\text{ mm}$), (b) inter-
 999 mediate ($V_{inj} = 10.5\text{ ml}$ and $d_{rel} = 8.3\text{ mm}$) and (c) late stage ($V_{inj} = 21.0\text{ ml}$ and $d_{rel} = 16.7\text{ mm}$). Panels in the second
 1000 row show the final (cumulative deformation) stage ($d_{rel} = 30\text{ mm}$, $V_{inj} = 37.7\text{ ml}$): (d) surface image; (e) cumulative
 1001 vertical displacement (tot. $d_{rel} = 30\text{ mm}$) and (f) cumulative shear strain (E_{xy}). Dotted circles indicate the position
 1002 of the basal injection.



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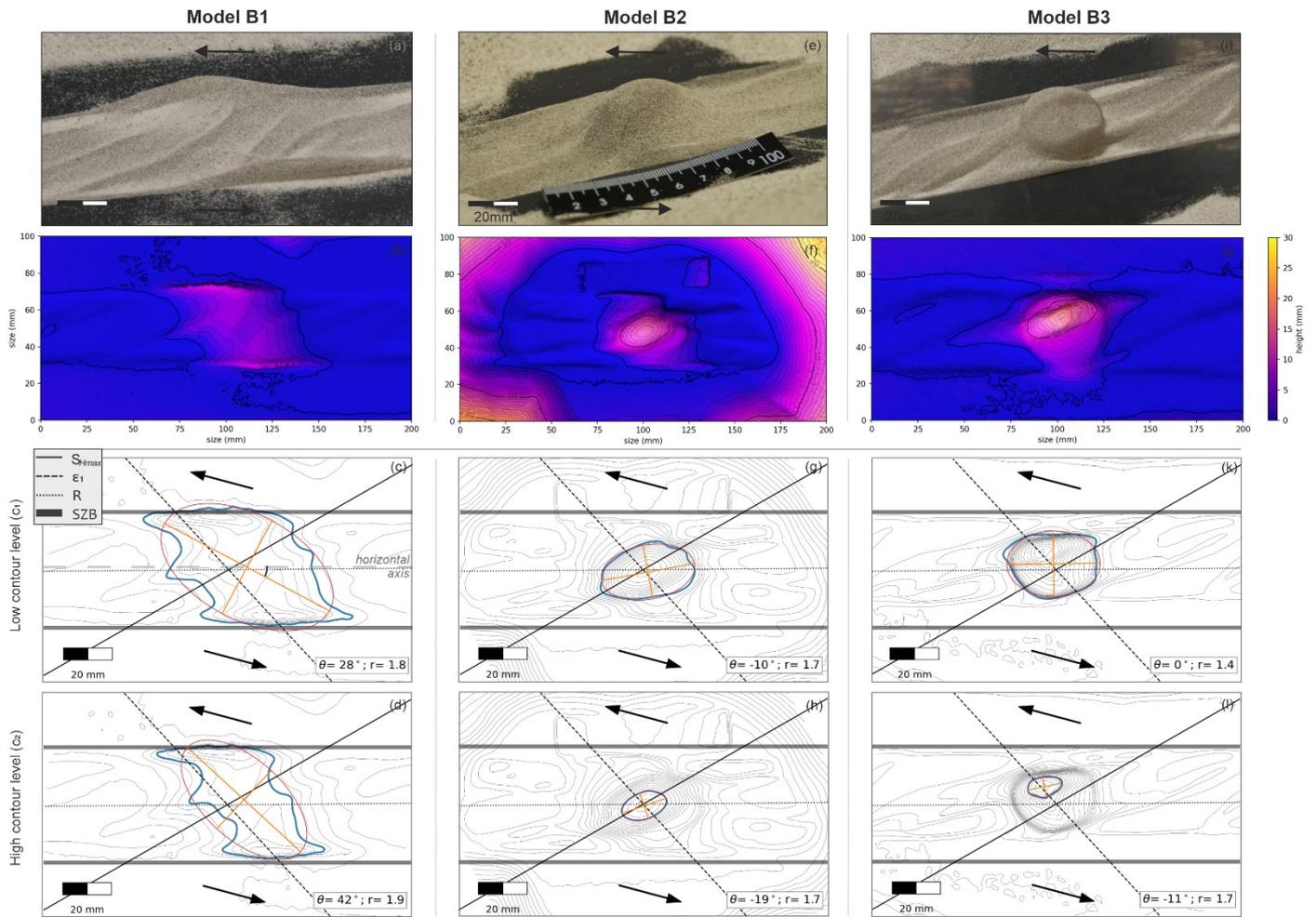
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Fig. 10 Surface deformation of the post-tectonic intrusion model in transtension (Model B3). Shown are snapshots representative of the evolution: (a) Accumulated strain at the beginning of intrusion ($d_{rel} = 30$ mm), (b) incremental strain during an early ($V_{inj} = 13$ ml) and (c) late stage ($V_{inj} = 18.6$ ml) of intrusion. Panels in the second row show the final (cumulative deformation) stage ($d_{rel} = 30$ mm, $V_{inj} = 37.7$ ml): (d) surface image; (e) cumulative vertical displacement ($tot. d_{rel}=30mm$) and (f) cumulative shear strain (E_{xy}). Dotted circles indicate the position of the basal injection.



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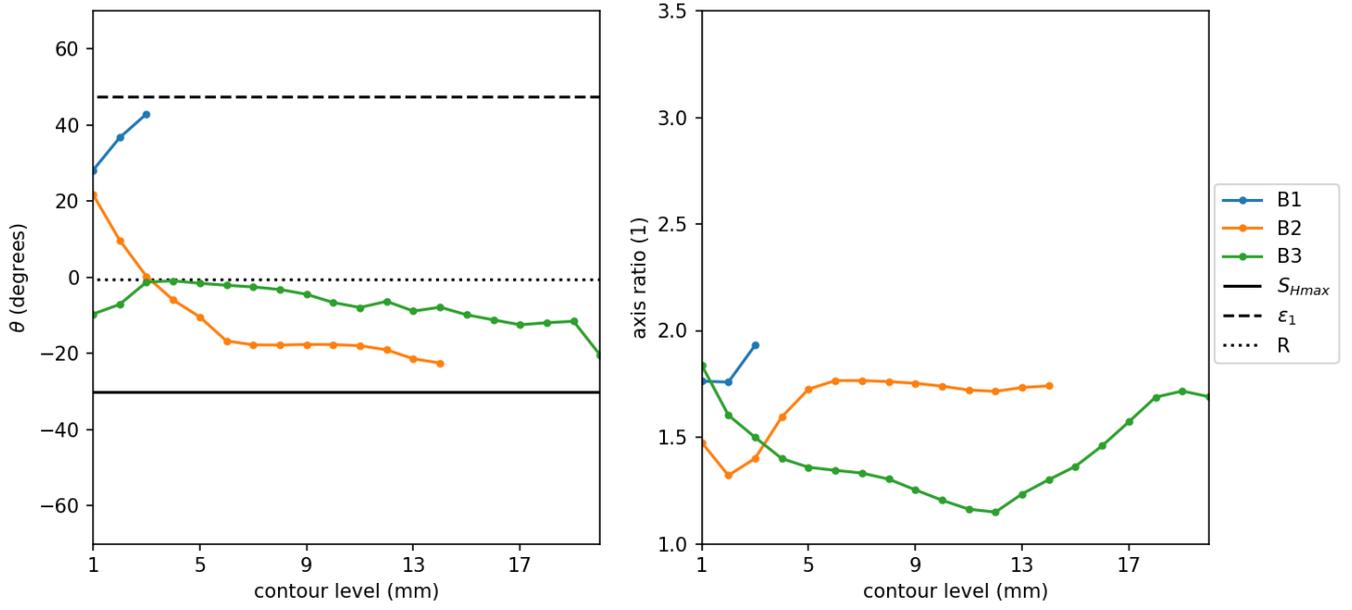
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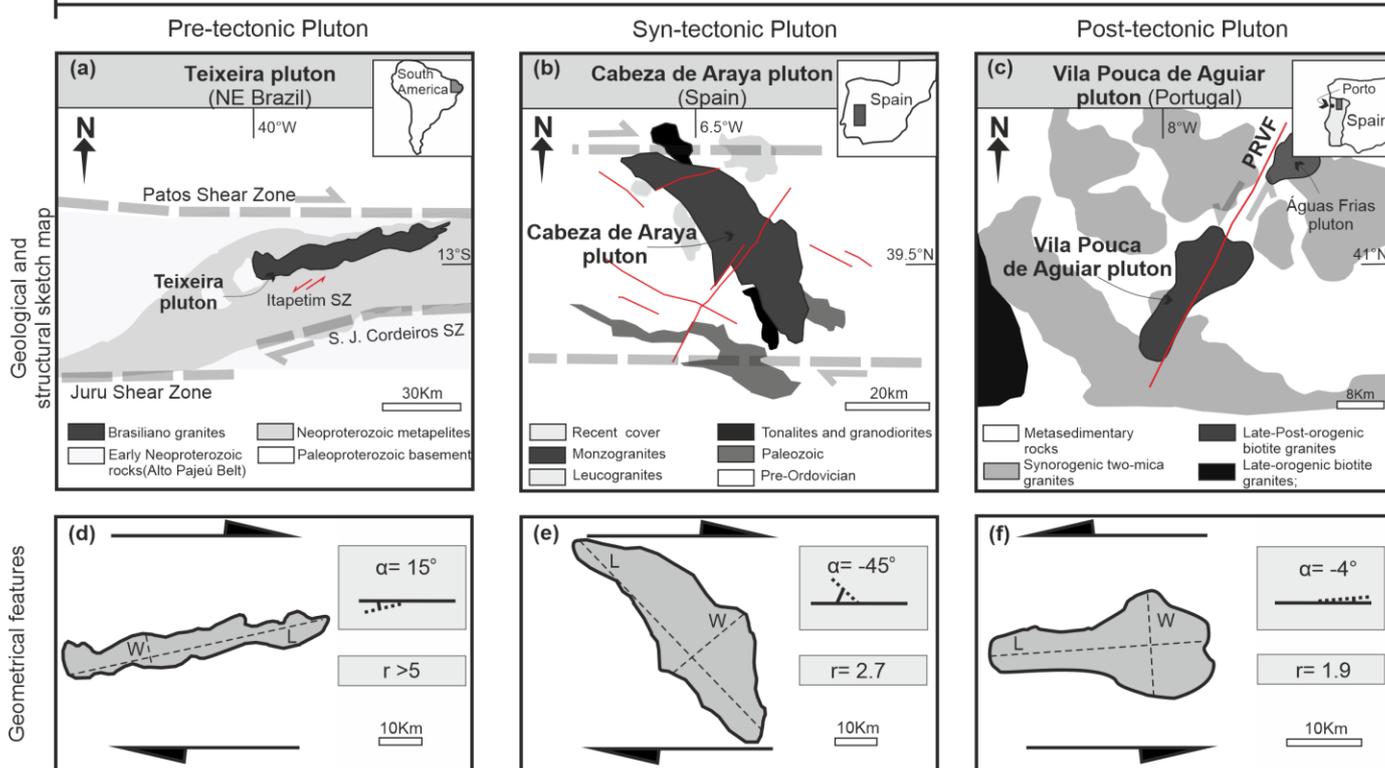
Fig. 11 Models of the intrusions in the transtensional regime (Group B): Model B1 (a-c); Model B2 (d-f) and Model B3 (g-i). (a, d, g) Oblique views of the excavated intrusions; (b, e, h) Digital Intrusion Models (DIM) coloured and with contour lines; (c, f, i) Orientation and geometry of the intrusion (in map view), where θ = the angle between the long axis (orange) of the fitted ellipse (red) and the strike of the basal shear zone. r is the intrusion's aspect ratio (length-to-width ratio, L/W). Light and dark grey quadrants indicate contraction and extensional quadrants, respectively.



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1018 Fig.12 Series B experimental results expressed in graph of angles and ratios ellipses vs. intrusion contour level.

Natural Examples in Simple Shear



Natural Examples in Transtension

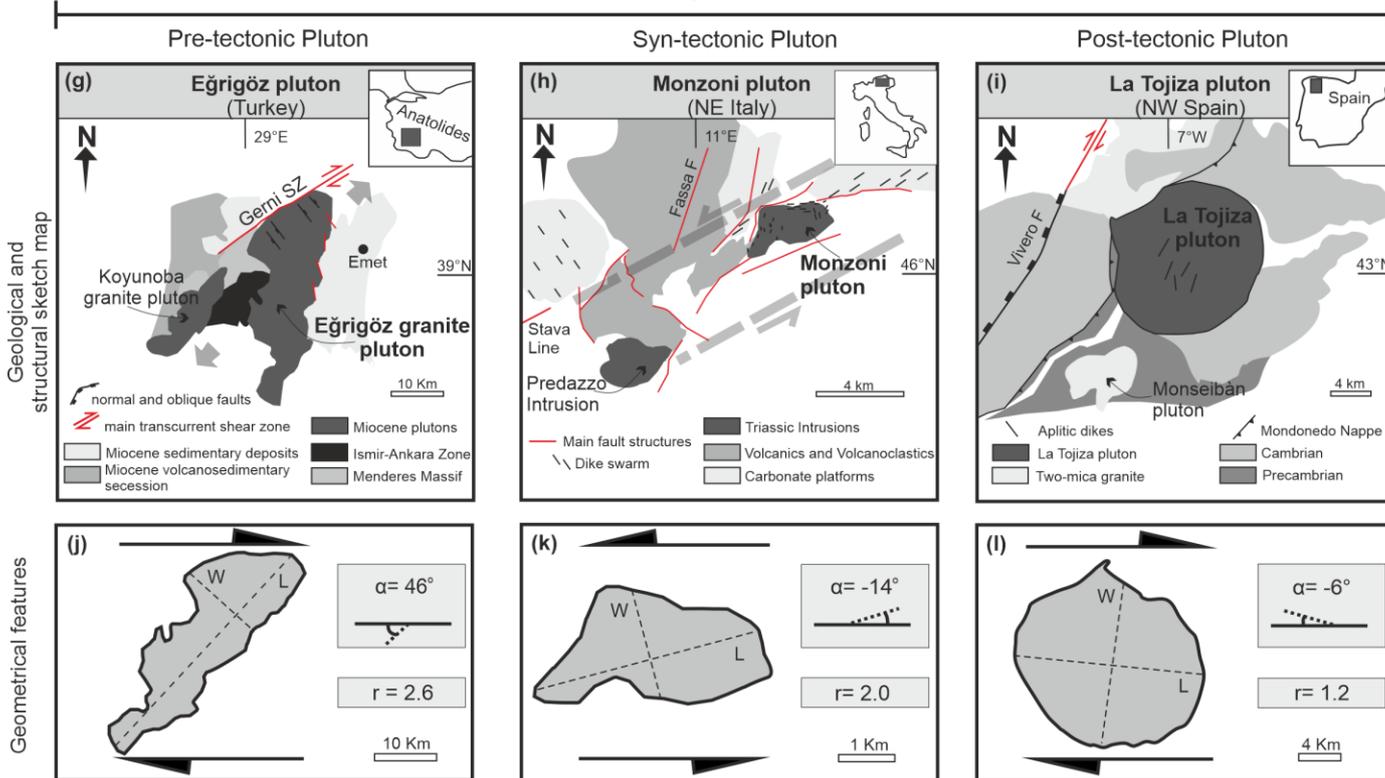
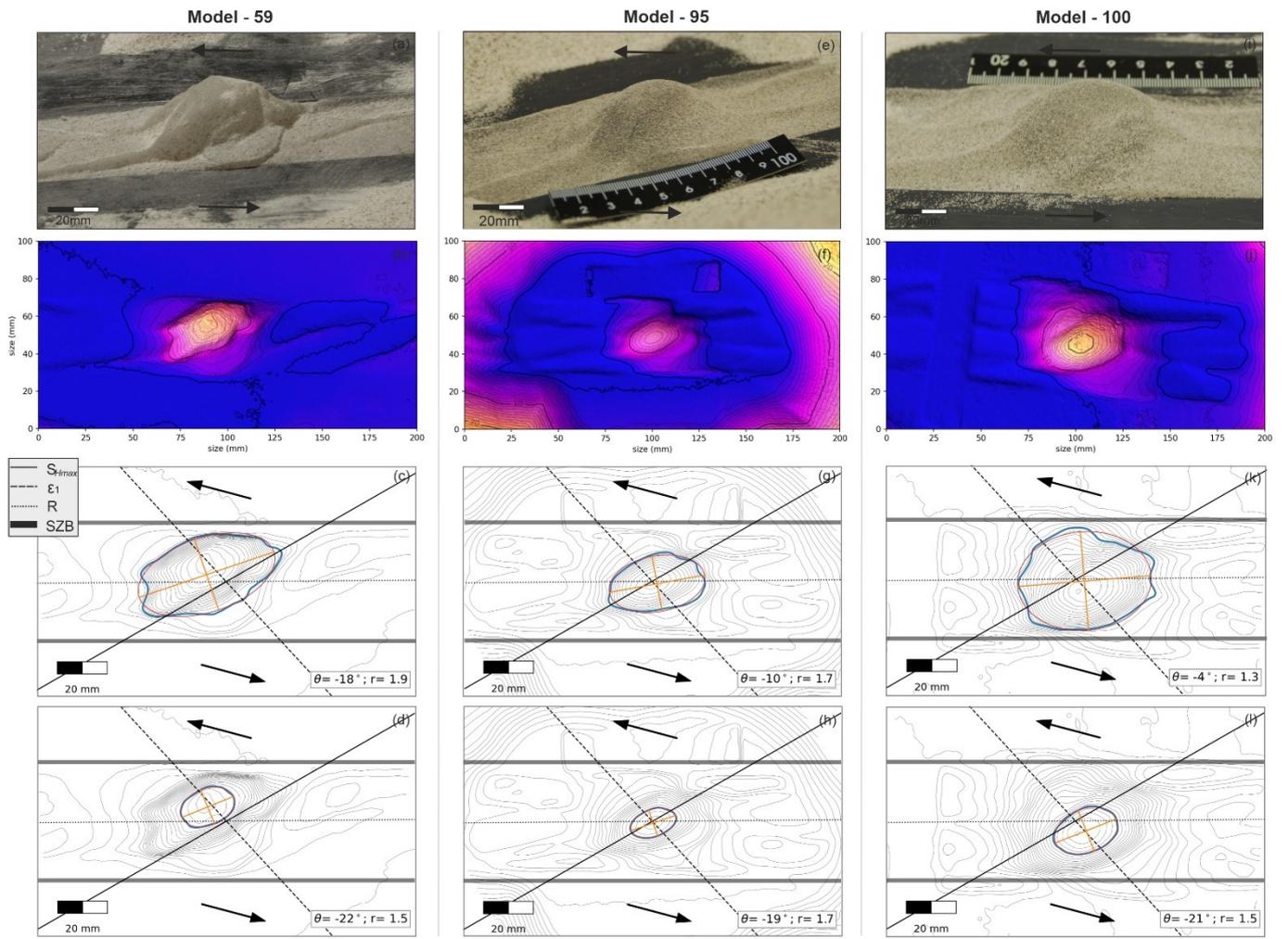


Fig. 13 Simplified geological maps and shapes of natural plutons emplaced in simple shear and transtensional zones: (a, d) The Teixeira pluton (Archanjo et al., 2008); (b, e) The Cabeza de Araya Pluton (Vigneresse and Bouchez, 1997; Fernandez and Castro, 1999; Corti et al., 2005) and (c, f) The Vila Pouca de Aguiar pluton (Sant'Ovaia et al., 2000). Plutons emplaced in transtensional regime: (g, j) The Eğrigöz pluton is a pre-tectonic

1024 intrusion affected by rotation due to the transtensional deformation occurring after the emplacement (Erkül et
1025 al., 2017); (h, k) The Monzoni Pluton developed within a transtensional tectonic environment (Sloman, 1989;
1026 Bonadiman et al., 1994); (i, l) La Tojiza Pluton is a clear example of post-tectonic intrusion only slightly reac-
1027 tivating the previous transtensional tectonic structures (Aranguren et al., 2003).

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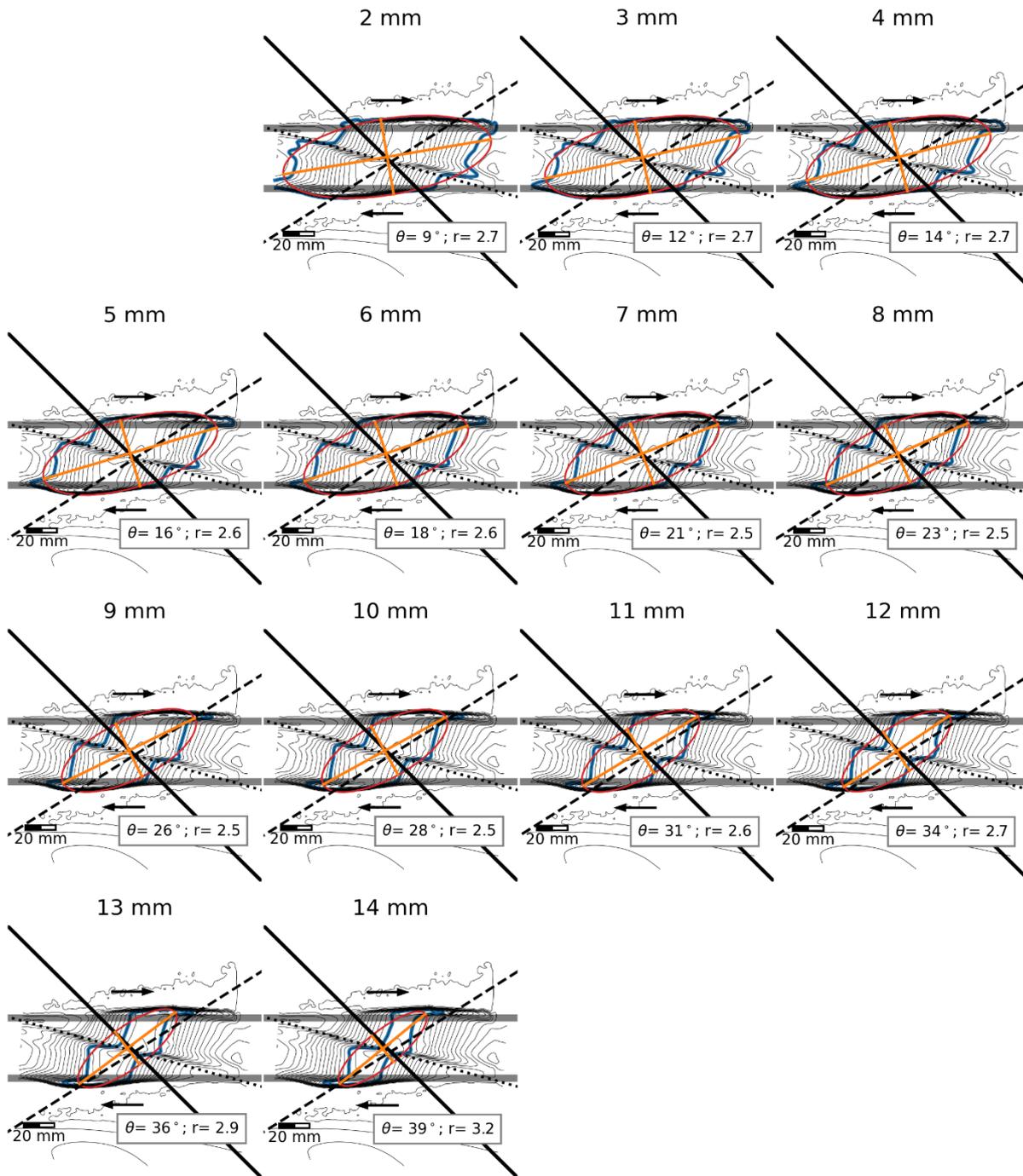


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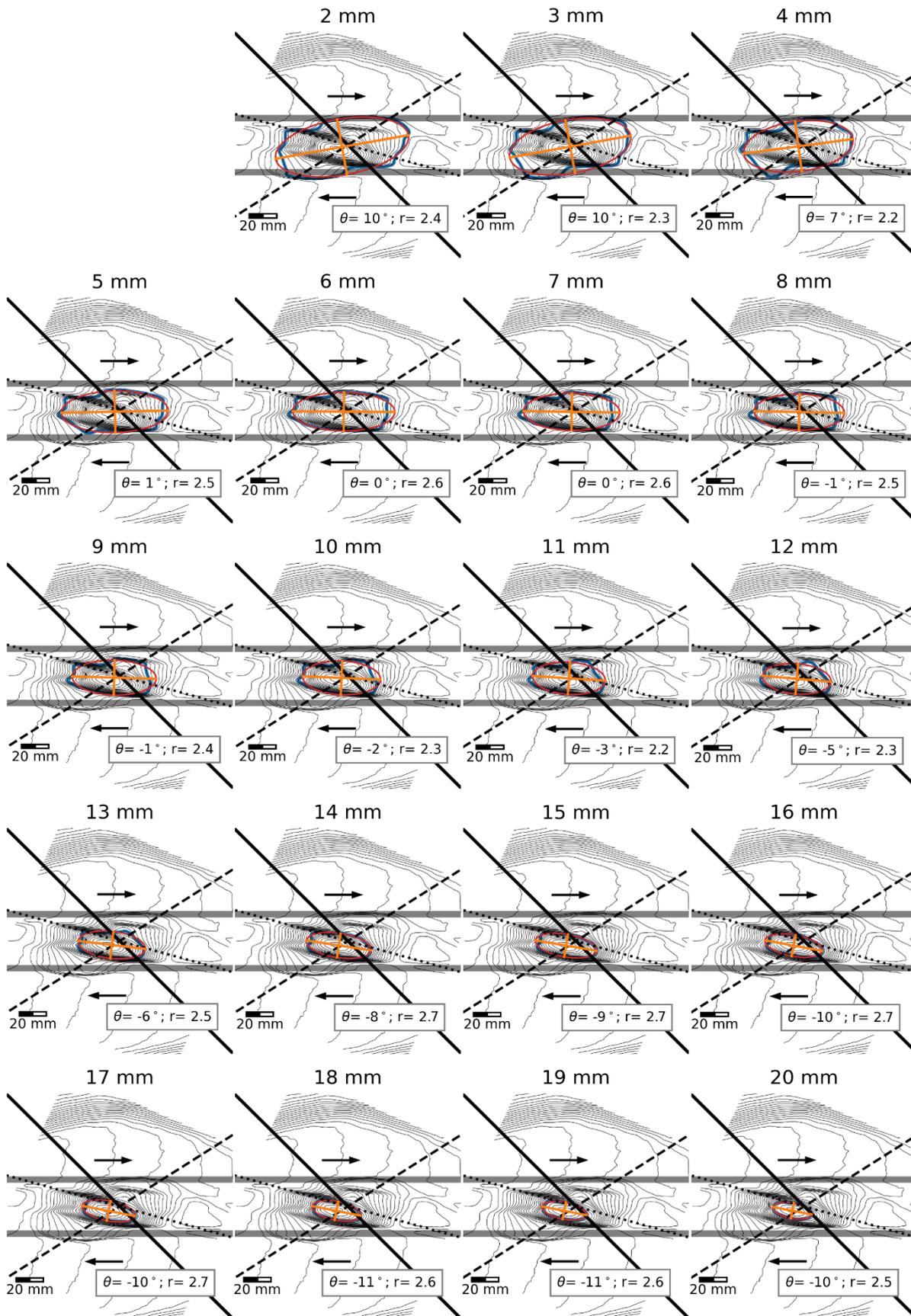
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A.1 Intrinsic variability of intrusion models verified by repeating experiments (Model B2) in syn-tectonic intrusion in transtension.



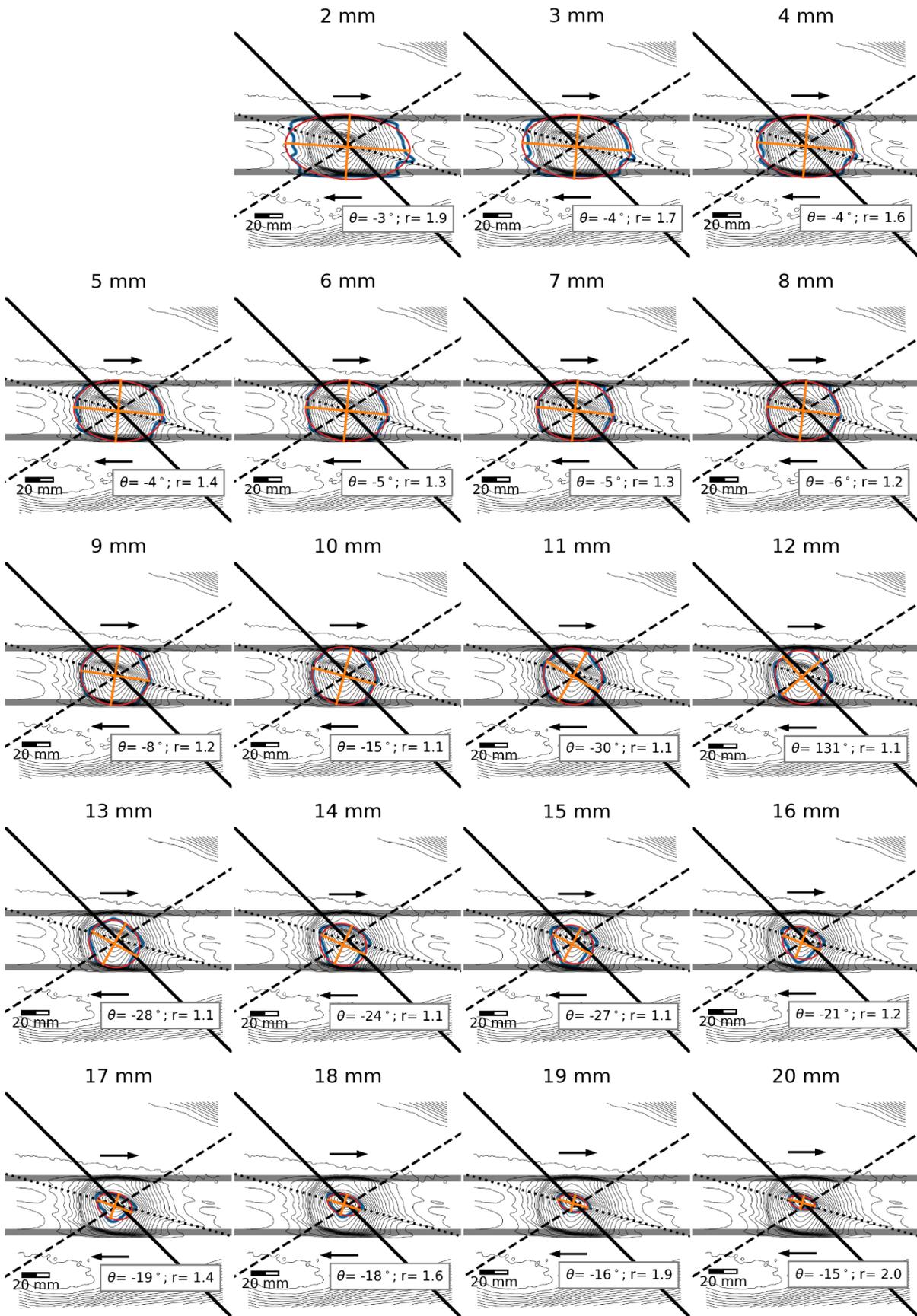
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1034 A.2 Complete contour ellipses analysis of the Model A1 shape as a function of height



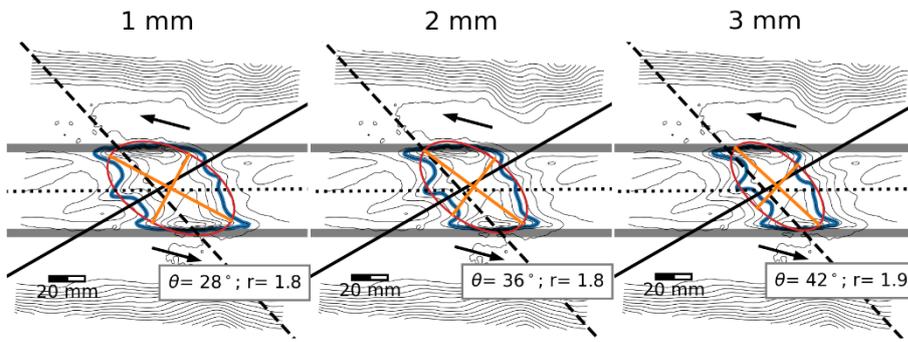
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1036 A.3 Complete contour ellipses analysis of the Model A2 shape as a function of height



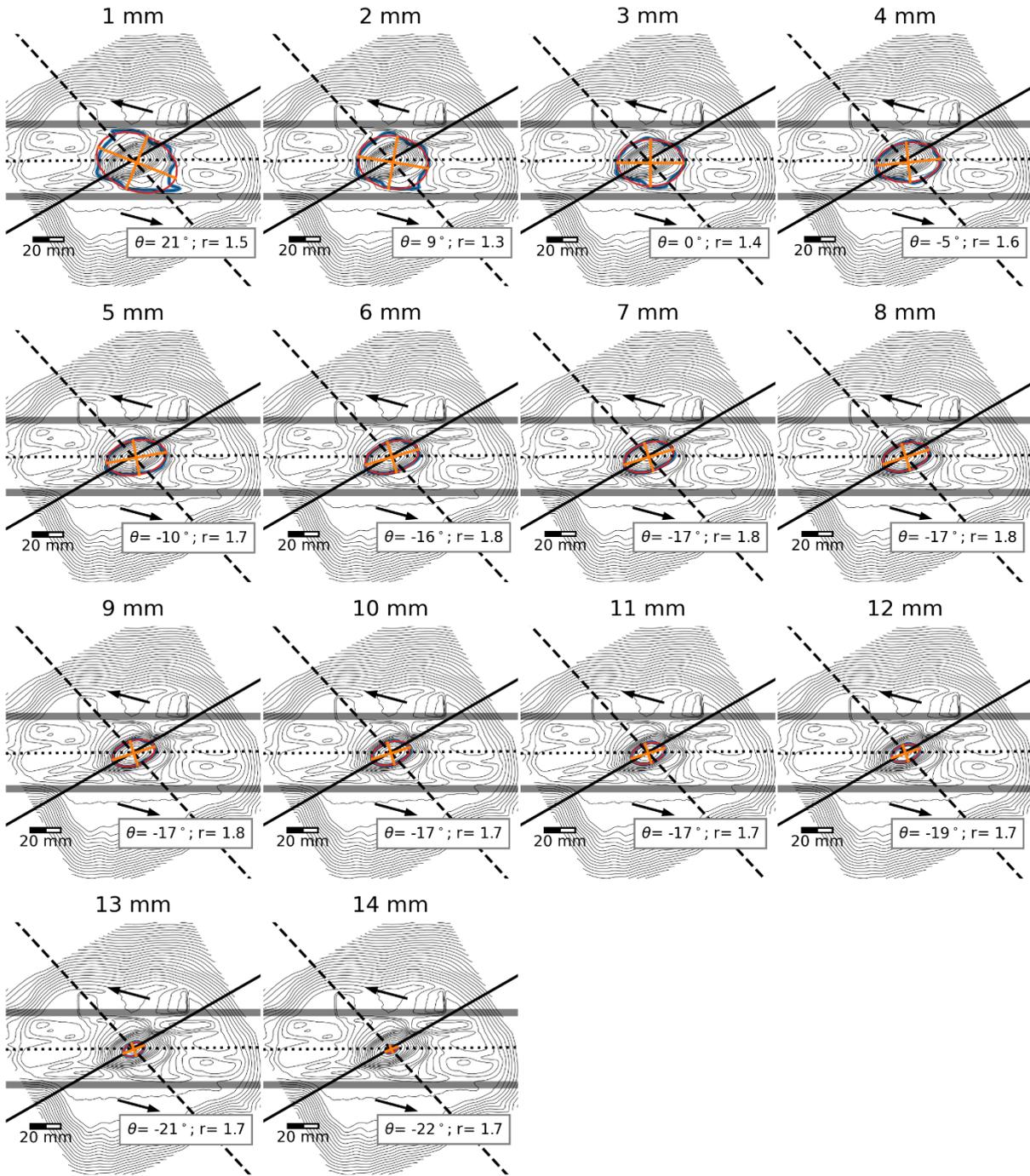
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1038 **A.4 Complete contour ellipses analysis of the Model A3 shape as a function of height**



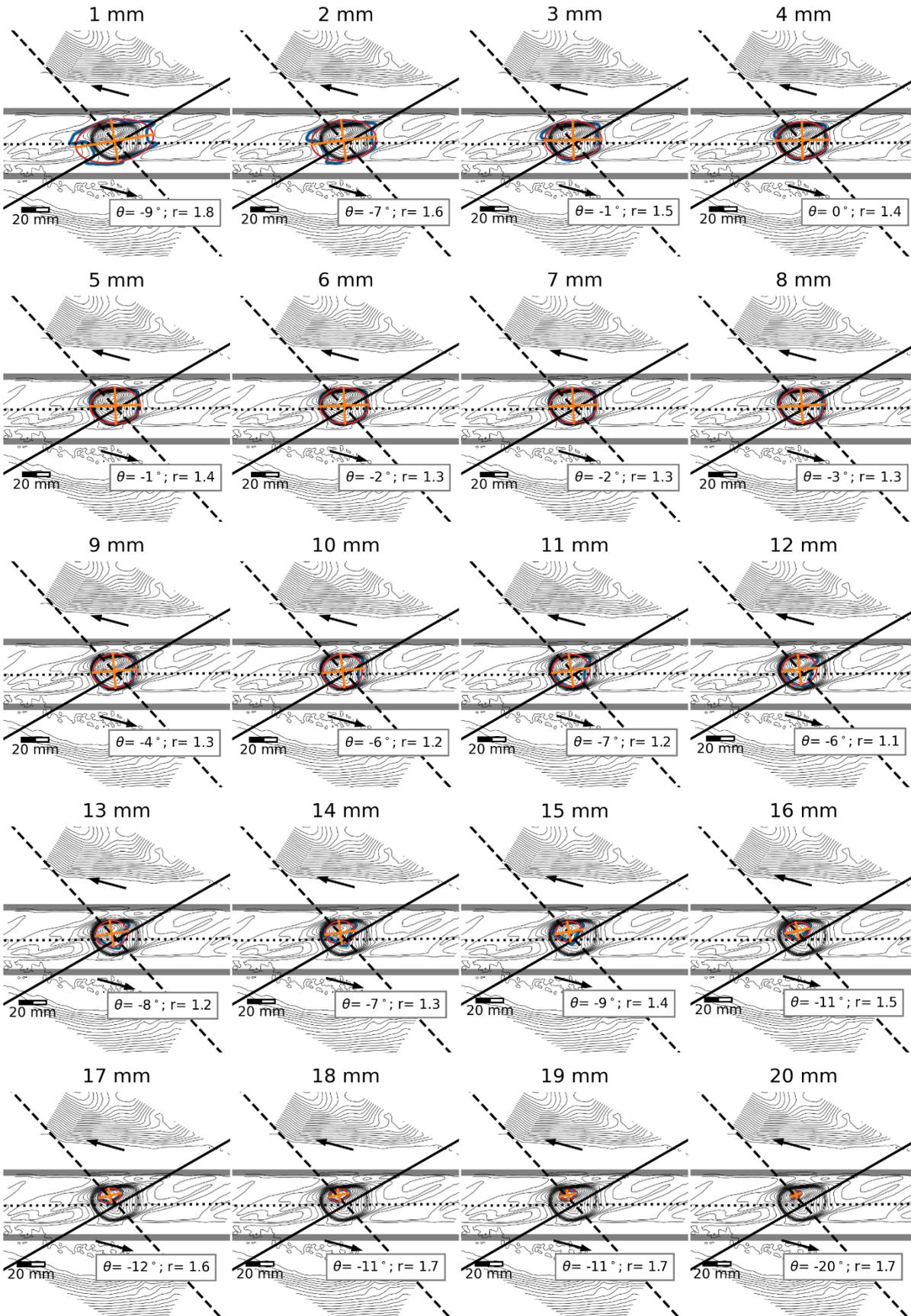
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1040 **A.5 Complete contour ellipses analysis of the Model B1 shape as a function of height**



1041

1042 A.6 Complete contour ellipses analysis of the Model B2 shape as a function of height



1043

1044 A.7 Complete contour ellipses analysis of the Model B3 shape as a function of height