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1 Solidification effects on sill formation: an experimental approach

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6 **Abstract**

Sills represent a major mechanism for constructing continental Earth's crust because these intrusions can amalgamate and form magma reservoirs and plutons. As a result, numerous field, laboratory and numerical studies have investigated the conditions that lead to sill emplacement. However, all previous studies have neglected the potential effect magma solidification could have on sill formation. The effects of solidification on the formation of sills are studied and quantified with scaled analogue laboratory experiments. The experiments presented here involved the injection of hot vegetable oil (a magma analogue) which solidified during its propagation as a dyke in a colder and layered solid of gelatine (a host rock analogue). The gelatine solid had two layers of different stiffness, to create a priori favourable conditions to form sills. Several behaviours were observed depending on the injection temperature and the injection rate: no intrusions (extreme solidification effects), dykes stopping at the interface (high solidification effects), sills (moderate solidification effects), and dykes passing through the interface (low solidification effects). All these results can be explained quantitatively as a function of a dimensionless temperature θ , which describes the experimental thermal conditions, and a dimensionless flux ϕ , which describes their dynamical conditions. The experiments reveal that sills can only form within a restricted domain of the (θ, ϕ) parameter space. These experiments demonstrate that contrary to isothermal experiments where cooling could not affect sill formation, the presence of an interface that would be a priori mechanically favourable is not a sufficient condition for sill formation; solidification effects restrict sill formation. The results are consistent with field observations and provide a means to explain why some dykes form sills when others do not under seemingly similar geological conditions.

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7 *Keywords:* sill formation, solidification, rigidity contrasts, analogue modelling

8 **1. Introduction**

9 Sill intrusions are a major mechanism for constructing continental crust. Indeed, the amalga-
10 mation of repeated pulses of magma, many of them in the form of sills, can lead to the formation of
11 magma reservoirs (John, 1988) and plutons as confirmed by geophysical data (Benn et al., 1999),
12 theoretical models (Annen and Sparks, 2002; Menand, 2008), field studies and geochronological
13 data (Miller et al., 2011; Horsman et al., 2010; Leuthold et al., 2012). Interconnected sill com-
14 plexes have also been proposed as viable and efficient pathways for magma transport in the crust
15 (Cartwright and Hansen, 2006; Muirhead et al., 2012). Thus sills could both lead to magma storage
16 or its transport in the crust.

17 Different models of sill formation have been proposed based on field observations, laboratory
18 experiments or numerical simulations: buoyancy could force sills to form at crustal levels where
19 magmas become neutrally buoyant (Corry, 1988), or could help develop magma overpressures
20 that are large enough to generate sills along specific horizons (Taisne and Jaupart, 2009); rigidity
21 anisotropy in the crust could favour sill formation along those interfaces that separate an upper stiff
22 layer from a softer lower one (Kavanagh et al., 2006; Burchardt, 2008; Maccaferri et al., 2010); rhe-
23 ology contrast between a ductile rock layer and a brittle one, or between adjacent layers where one
24 is much more ductile than the other, would favour sill inception between these layers or within the
25 weakest ductile zones (Parsons et al., 1992; Miller et al., 2011); and stress anisotropy would favour
26 sill formations in crustal regions with high, horizontal, compressive deviatoric stress (Menand et al.,
27 2010). An analysis of these different mechanisms suggests that crustal heterogeneities, and their
28 mechanical or rheological anisotropies, would play a dominant role in controlling whether and
29 where sills could form (Menand, 2011). However, all these studies have overlooked the potential
30 effect of magma cooling and solidification.

31 All experimental and numerical studies on sill intrusions have therefore been carried out under
32 isothermal conditions and have neglected the potential effect of magma solidification on sill for-

33 mation and propagation. In fact, very few studies have dealt with cooling and solidification effects
34 on intrusions. Theoretical studies (e.g. [Bolchover and Lister, 1999](#); [Lister, 1999](#)) are limited to two
35 dimensions, and so provide only a limited understanding of solidification effects because intrusions
36 such as dykes and sills are inherently three-dimensional objects (e.g. [Taisne and Tait, 2009, 2011](#)).
37 To our knowledge, [Taisne and Tait \(2011\)](#) are the only ones to have investigated experimentally
38 solidification effects on intrusion propagation, focusing on dykes. They found that solidification
39 effects have a strong impact on dyke dynamics: when solidification effects are important, dykes
40 display an intermittent, stepwise mode of propagation, during which dykes momentarily stop prop-
41 agating and then swell without advancing, before resuming their propagation when the incoming
42 fluid that is stored in the fissure is able to fracture both the surrounding solid and the frozen crust
43 that has developed within the fissure. Without solidification, dyke propagation operates continu-
44 ously. Additionally, solidification affected the propagating dyke by focusing fluid flow in its central
45 portion, hence limiting its horizontal dimension, and by adding a more complex geometry owing
46 to the successive and intermittent outbreaks of fluid that occurred around the dyke periphery and
47 sometimes away from its tip. These findings raise naturally the question of the effects that solidifi-
48 cation could potentially have not only on the geometry and the dynamics of sills, but also on their
49 formation.

50 To address this issue, we present laboratory experiments that involved the injection of hot veg-
51 etable oil (a magma analogue) which solidified during the propagation of an experimental dyke
52 in a colder and layered solid gelatine (a host rock analogue). The gelatine solid had two layers
53 of different stiffness, to create a priori favourable conditions to form sills. We investigated ex-
54 perimentally the effect of solidification on the formation of sills, and quantified how solidification
55 can restrict sill formation. The experimental approach is introduced in section 2, before presenting
56 the experimental observations and results in section 3. We discuss their geological implications in
57 section 4 and then conclude in section 5.

58 **2. Experimental approach**

59 *2.1. Experimental apparatus*

60 The experiments described here involved the injection of hot vegetable oil (magma analogue)
61 in a colder gelatine solid inside a tank of $40 \times 40 \times 40$ cm made of PMMA. The tank had circular
62 openings of 1 cm diameter at its base to make injections (Fig. 1). The gelatine had two layers with
63 different stiffness, the upper layer being stiffer than the lower one, to create a priori favourable
64 conditions to form sills (Kavanagh et al., 2006). The solidification temperature of the vegetable oil
65 is higher than that of gelatine, which allows the analogue intrusion to partially solidify during its
66 propagation depending on injection conditions.

67 The injection temperature and the injection flux were controlled and varied between experi-
68 ments in order to observe the effects of solidification on sill formation. The vegetable oil was
69 heated with a bain-marie to the desired temperature. This temperature had to be higher than the
70 solidification temperature of the vegetable oil, which is 31°C (Galland et al., 2006). The gelatine
71 was first incised at the base of the tank through the injection point in order to obtain a preferred
72 orientation for the development of a dyke (the incision was typically 5 cm high). The hot oil was
73 then injected in the cold gelatine solid through a metal tube of 4 mm diameter that was inserted into
74 the incision made, and connected to a pipe fed by a peristaltic pump. This pump allowed us to both
75 control and maintain constant the volumetric injection flux Q throughout each experiment. The
76 temperature of the gelatine (host rock) and the injection temperature of the vegetable oil (magma),
77 measured at the point of injection in the gelatine solid, were continuously recorded throughout the
78 experiments with thermocouples while the experiments were recorded by a video camera in front
79 of the tank.

80 *2.2. The gelatine*

81 The gelatine used is a 260 bloom, 20 mesh, pig-skin derived gelatine powder prepared in two
82 batches to obtain a final solid with two layers of the same volume but different stiffness. The
83 upper layer has to possess a higher stiffness than the lower layer, in order to create mechanically

84 favourable conditions to form sills (Kavanagh et al., 2006). A higher gelatine concentration leads
 85 to a higher rigidity. The first batch of gelatine was poured in the tank, which was then placed in a
 86 fridge at a temperature of $\simeq 5^\circ \text{C}$ for $\simeq 24$ hours. Once the gelatine was solid, the second batch
 87 was poured in the tank, which was then placed back in the fridge and kept at the same temperature
 88 for another $\simeq 72$ hours before running an experiment.

89 Before running an experiment, measurements of the elastic properties of the gelatine solid were
 90 performed. The Young's modulus was calculated by applying a cylindrical known-weight load on
 91 the upper layer of the solidified gelatine and measuring the deflection caused by this load. The
 92 measured deflection is directly linked to the Young's modulus E_{upp} of the upper layer (Timoshenko
 93 and Goodier, 1970):

$$E_{upp} = \frac{Mg(1 - \nu^2)}{Dx} \quad (1)$$

94 where M is the mass of the applied load in kg; $g = 9.81 \text{ m.s}^{-2}$ is the gravitational acceleration;
 95 $\nu = 0.5$ is the Poisson's ratio of the gelatine (Crisp, 1952; Richards Jr and Mark, 1966); D is the
 96 diameter of the cylindrical load applied on the gelatine in m; x is the deflection in m; E_{upp} is the
 97 Young's modulus of the upper layer in Pa.

98 To calculate the Young's modulus, the gelatine is assumed to be semi-infinite. To avoid base
 99 effects and side-wall effects when the load is applied on the gelatine in the tank, the diameter of
 100 the load needs to be $\leq 10\%$ of the horizontal dimension of the tank (Kavanagh et al., 2013). In
 101 these experiments, the applied load measured 29.99 mm in diameter and so represented 7.5% of
 102 the tank size. The stress variation with depth induced by a load applied to the surface can also be
 103 calculated. According to Timoshenko and Goodier (1970), the largest stress component induced
 104 by a load σ_0 applied on top of a semi-infinite elastic body is the vertical component σ_z , which can
 105 be expressed as:

$$\sigma_z = \sigma_0 \left[1 - \frac{8z^3}{(1 + 4z^2)^{\frac{3}{2}}} \right] \quad (2)$$

106 where z is the depth normalized by the load's diameter. The thickness of the gelatine layer was 100

107 mm, so $z = 3.33$. Consequently, $\sigma_z/\sigma_0 = 3.3 \%$. The vertical stress generated by the surface load
 108 at 10 cm depth in a semi-infinite elastic medium would be only 3.3 % of the surface load. This
 109 allowed us to assume that the base and side-wall had negligible effects, and to consider the upper
 110 gelatine layer as a semi-infinite medium, and equation (1) to be valid.

111 The formation of a sill requires that the Young's modulus of the upper layer E_{upp} is higher
 112 than the Young's modulus of the lower layer E_{low} . It is not possible to directly measure E_{low} , but
 113 the Young's modulus ratio between the two layers can be easily calculated as a first approximation
 114 from the Young's modulus ratio at infinite time, $\Delta E = E_{upp}/E_{low}$, provided the gelatine layers
 115 are left long enough to solidify. Indeed, the Young's modulus of the gelatine increases with time
 116 before reaching a plateau E_∞ after about 48 hours, although the exact amount of time depends on
 117 the gelatine concentration and volume (Kavanagh et al., 2013). Therefore, the gelatine layers were
 118 left long enough before running an experiment to ensure they had reached their Young's modulus
 119 plateaus $E_{upp\infty}$ and $E_{low\infty}$ (72 to 96 hours) and that the Young's modulus ratio had reached the
 120 constant value:

$$\Delta E = \frac{E_{upp\infty}}{E_{low\infty}} = \frac{\alpha w_{upp} + \beta}{\alpha w_{low} + \beta} = \frac{w_{upp} - 1.3}{w_{low} - 1.3} \quad (3)$$

121 where w is the concentration by weight of the upper and lower layers; the numerical constants α
 122 and β have been estimated to be $\alpha = 6000$ and $\beta = -7800$ (Kavanagh et al., 2013). This ratio
 123 allows the value E_{low} of the lower layer to be calculated once E_{upp} has been determined. This
 124 measurement method for the Young's modulus has the added advantage of ensuring that the time
 125 between the preparation of the two layers is kept to a minimum, which helps to create an interface
 126 between the two that is as strong as possible.

127 Our experiments were designed to investigate and quantify the potential effect fluid solidifica-
 128 tion could have on sill formation when mechanically favourable conditions are already met. As
 129 shown by Kavanagh et al. (2006) isothermal experiments, sills should always occur when the rigid-
 130 ity contrasts $\Delta E > 1.1$. We therefore ran all our experiments in this mechanical condition and
 131 deliberately chose as narrow a ΔE range as possible to isolate and quantify the effect of solidifica-

132 tion. The rigidity contrast ΔE in our experiments lied between 1.4 and 3.9.

133 2.3. *Experimental limitations*

134 Several assumptions were made in the experiments reported here. One limitation concerns
135 a parameter that is unknown and uncontrolled in the experiments: the strength of the interface,
136 i.e. how strongly welded the interface is. If an interface is weak or even not welded, it will
137 necessarily force the creation of a sill, regardless of the rigidity contrast. This parameter will
138 affect the formation of sills. In the experiments reported here, the interface is considered welded
139 and relatively strong, but how strong is not known. This difficulty is inherent to an experimental
140 approach, and quantifying the impact of interface strength on sill intrusions is more likely to be
141 resolved by numerical studies.

142 Also, gelatine has an elastic behaviour and cannot act as an analogue material to simulate non-
143 elastic behaviour of the crust. However, restricting our investigation to the elastic case, enabled
144 us to focus on the effect solidification could have on sill formation, and to be able to compare our
145 results with previous studies, which were also elastic. Moreover, even though rocks of the Earth's
146 crust are fractured and heterogeneous, the elastic approximation has been shown to be appropriate
147 to first order ([Delaney and Pollard, 1981](#)).

148 Finally, the state of stress is considered lithostatic (or "gelistatic"), so these experiments are not
149 applicable to different stress environments (e.g. tectonic stresses, stresses induced by the load of a
150 volcanic edifice, ...).

151 2.4. *Data processing*

152 To analyse the experiments, we follow the experimental analysis of [Taisne and Tait \(2011\)](#) and
153 define two dimensionless parameters. One describes the thermal conditions of the experiments at
154 the injection point (dimensionless temperature θ) and the other describes their dynamical condi-
155 tions (dimensionless flux ϕ).

156 The dimensionless temperature θ is defined as:

$$\theta = \frac{(T_s - T_g)}{(T_i - T_g)} \quad (4)$$

157 where T_s is the solidification temperature of vegetable oil, $T_s = 31^\circ \text{C}$ (Galland et al., 2006); T_g
 158 is the gelatine temperature during the injection, typically between 5 and 7°C ; T_i is the injection
 159 temperature of vegetable oil. We note that θ can only be defined mathematically if the three tem-
 160 peratures differ from one another. This will not be the case if the injection temperature is equal to
 161 the gelatine ambient temperature as this would amount to having also the solidification tempera-
 162 ture equal to the two other temperatures. In this particular case, trying to define a dimensionless
 163 temperature theta would therefore be meaningless.

164 The dimensionless flux ϕ is defined as the ratio between the heat advected by vegetable oil and
 165 the heat lost by conduction in the gelatine. ϕ describes the competition between the heat advected
 166 along the intrusion over a time Δt to increase the temperature by an amount ΔT and the heat
 167 lost by conduction over a distance δ and the same time Δt . The advected heat A is defined by
 168 $A = \rho H L B C_p \frac{\Delta T}{\Delta t} = Q \rho C_p \Delta T$ where ρ is the density of the intrusion; H is the thickness, L the
 169 length, and B the breadth of the intrusion; C_p is the heat capacity of the intrusion; $Q = V/\Delta t$
 170 is the flux, or volumetric rate of flow of the intrusion where $V = H L B$ is its volume. The heat
 171 lost by conduction C is defined by $C = \rho H L B C_p \frac{\Delta T}{\Delta t}$ which diffuses over a distance δ in a time
 172 $\Delta t = \delta^2/\kappa$ where κ is the thermal diffusivity. In the experiments presented here, the heat lost by
 173 conduction is considered to be over a distance similar to the thickness of the intrusion, i.e. $\delta \simeq H$.
 174 Therefore: $C = \frac{\rho H L B C_p \Delta T \kappa}{H^2} = \frac{\rho L B C_p \Delta T \kappa}{H}$. And we get the dimensionless flux:

$$\phi = \frac{A}{C} = \frac{QH}{\kappa LB} \quad (5)$$

175 To find H/LB , a pressure balance is used (Taisne and Tait, 2011) between the buoyancy
 176 pressure P_b , that drives the intrusion, and the elastic pressure P_e , which allows the dyke to deform
 177 the host rock:

$$P_b = P_e \Rightarrow \Delta \rho g L = \frac{E}{2(1-\nu^2)} \frac{H}{B} \Leftrightarrow \frac{H}{LB} = \frac{2(1-\nu^2)}{E} \Delta \rho g \quad (6)$$

178 where $\Delta \rho$ is the density difference between the host rock and the intrusion; $g = 9.81 \text{ m.s}^{-1}$ is
 179 the gravitational acceleration; E and ν are the Young's modulus and the Poisson's ratio of the host
 180 rock.

181 The same formula as in [Taisne and Tait \(2011\)](#) is found for the dimensionless flux of a dyke:

$$\phi = \frac{3Q\Delta\rho g}{2E\kappa} \quad (7)$$

182 where Q is the flux of injection in $\text{m}^3 \cdot \text{s}^{-1}$; $\Delta\rho$ is the difference of density between the gelatine
 183 and the vegetable oil - from [Galland et al. \(2006\)](#), $\rho_{vegetableoil} = 892 \text{ kg} \cdot \text{m}^{-3}$ and $\rho_{gelatine} = 1000$
 184 $\text{kg} \cdot \text{m}^{-3}$ (considered the same as that of water) therefore $\Delta\rho = 108 \text{ kg} \cdot \text{m}^{-3}$; E is the Young's
 185 modulus of the lower layer (through which the dyke propagates); $\nu = 0.5$ is the gelatine Poisson's
 186 ratio; κ is the thermal diffusivity (assumed to be identical to that of water), $\kappa = 1.4 \times 10^{-7} \text{ m}^2 \cdot \text{s}^{-1}$;
 187 $g = 9.81 \text{ m} \cdot \text{s}^{-2}$ is the gravitational acceleration.

188 T_s and T_g were essentially the same for all experiments so θ varied only with T_i the injection
 189 temperature. Likewise, $\Delta\rho$, g , κ were all kept constant. Consequently, ϕ varied between experi-
 190 ments with the injection flux Q and the Young's modulus E_{low} of the lower layer. θ and ϕ were
 191 maintained constant during an experiment (T_i , E_{low} and Q were maintained constant), and were
 192 varied systematically between experiments to quantify their respective influence on the formation of
 193 sills.

194 θ varies between 0 and 1 and ϕ varies between 0 and ∞ . [Table 1](#) summarises the behaviour of
 195 θ and ϕ .

$\theta \rightarrow 1$	$T_i \rightarrow T_s$	solidification operates rapidly
$\theta \rightarrow 0$	$T_i \gg T_s$	almost no solidification
$\phi \rightarrow 0$	low Q values	solidification operates rapidly
$\phi \gg 1$	high Q values	almost no solidification

Table 1: Behaviour of the dimensionless temperature θ and dimensionless flux ϕ .

196 2.5. Experimental strategy

197 The flux ϕ and the temperature θ are dimensionless. These values are thus scale-independent,
 198 and can be compared between experiments and with values in nature.

199 Regarding θ , in the Earth's crust, values of 300° C at $\simeq 10\text{ km}$ depth and 450° C at $\simeq 15\text{ km}$
200 depth are obtained (using a thermal gradient of $30^\circ\text{ C.km}^{-1}$) for the temperature of the host rock
201 (T_g). Magmatic injection and solidification temperatures will depend on magma composition: for
202 a basalt, reasonable values are $T_i \simeq 1200^\circ\text{ C}$ and $T_s \simeq 900^\circ\text{ C}$ while for a rhyolite, $T_i \simeq 800^\circ\text{ C}$
203 and $T_s \simeq 775^\circ\text{ C}$. Using equation (4), the range of natural values obtained for θ is:

- 204 • $\theta = 0.67$ (basalt) to $\theta = 0.95$ (rhyolite) at 10 km depth;
- 205 • $\theta = 0.60$ (basalt) to $\theta = 0.93$ (rhyolite) at 15 km depth.

206 Regarding ϕ , Taisne and Tait (2011) used as natural values $E \simeq 10\text{ GPa}$, $\kappa \simeq 10^{-6}\text{ m}^2.\text{s}^{-1}$ and
207 $\Delta\rho \simeq 100\text{ kg.m}^{-3}$. The range of magmatic flux Q is quite large, but values between 1 and 100
208 $\text{m}^3.\text{s}^{-1}$ seem to be typical of many volcanoes, including Piton de la Fournaise Volcano, La Réunion
209 Island, France (Traversa et al., 2010). Of course, these values could be extended. Indeed, magmatic
210 fluxes can reach values higher than $1000\text{ m}^3.\text{s}^{-1}$, i.e. an order of magnitude higher, as has been
211 observed at the Mauna Loa in Hawaii or during the 1783 Laki eruption in Iceland (Macdonald and
212 Finch, 1950; Thordarson and Self, 1993). However this is rather an exception, and values between
213 1 and $100\text{ m}^3.\text{s}^{-1}$ seem more reasonable. Using equation (7), the range of natural values obtained
214 for ϕ is:

- 215 • $\phi = 0.15$ ($Q \simeq 1\text{ m}^3.\text{s}^{-1}$) to $\phi = 16$ ($Q \simeq 100\text{ m}^3.\text{s}^{-1}$).

216 In order to scale experiments correctly, the range of experimental injection temperatures and fluxes
217 were chosen to ensure they cover these ranges of natural values for θ and ϕ . The experiments
218 focused on the formation of sills in experiments involving solidification. Therefore θ and ϕ were
219 varied systematically between experiments to identify whether these values affected conditions for
220 the formation of sills and the type of the intrusions (feeder dykes or sills).

221 2.6. Scaling

222 If the experiments reported here represent a good analogue of natural intrusions, they should be
223 correctly scaled so that their geometry, kinematics and dynamics are similar to those in nature. The

224 scaling procedure for analogue intrusions defined in [Kavanagh et al. \(2013\)](#) is followed. Different
 225 scale ratios between experimental parameters and natural parameters are defined:

$$L^* = \frac{L_l}{L_n}; \quad T^* = \frac{T_l}{T_n}; \quad U^* = \frac{U_l}{U_n}; \quad E^* = \frac{E_l}{E_n} \quad (8)$$

226 where the subscript l means laboratory and the subscript n means nature, so that $*$ is the ratio
 227 between the value measured in laboratory experiments and the natural value. L is a length scale, T
 228 is a time scale, U is a velocity scale and E is a Young's modulus scale.

229 The characteristic length scale of a dyke is the buoyancy length L_b ([Taisne and Tait, 2011](#)).
 230 It is the length, for which the buoyancy pressure (allowing the ascent of the dyke) is balanced by
 231 resistance from rock fracture, and defined as:

$$L_b = \left(\frac{K_c}{\Delta\rho g} \right)^{\frac{2}{3}} \quad (9)$$

232 K_c is the fracture toughness; $\Delta\rho$ is the density difference between the host rock and the fluid;
 233 $g = 9.81 \text{ m.s}^{-2}$ is the gravitational acceleration.

234 By introducing the reduced gravity scale $g' = \Delta\rho/\rho_{solid}$ where ρ_{solid} is the density of the host
 235 rock, a characteristic time scale T and a characteristic velocity scale U can be defined:

$$T = \sqrt{\frac{L_b}{g'}}; \quad U = \frac{L_b}{T} \quad (10)$$

236 To obtain a characteristic Young's modulus scale, a balance between the buoyancy pressure
 237 ($\Delta\rho g L_b$) and the elastic pressure $\left(\frac{E}{2(1-\nu^2)} \frac{H}{L_b} \right)$ that occurs in the head region of the dyke is used,
 238 yielding the following scale:

$$E = 2(1-\nu^2) \Delta\rho g L_b \frac{L_b}{H} \quad (11)$$

239 where H is the thickness of the dyke head; E is the Young's modulus of the surrounding solid,
 240 and ν its the Poisson's ratio ([Kavanagh et al., 2013](#)). Moreover, $\nu = 1/2$ for gelatine and $\nu = 1/4$

241 - 1/3 for rocks therefore $2(1 - \nu^2)$ does not vary much between the laboratory and nature. From
 242 these expression we obtain:

$$L^* = \left(\frac{K_c^*}{\Delta\rho^*} \right)^{\frac{2}{3}} \quad (12)$$

$$243 \quad T^* = (\rho_{solid}^*)^{\frac{1}{2}} (K_c^*)^{\frac{1}{3}} (\Delta\rho^*)^{-\frac{5}{6}} \quad (13)$$

$$244 \quad U^* = (\rho_{solid}^*)^{-\frac{1}{2}} (K_c^*)^{\frac{1}{3}} (\Delta\rho^*)^{\frac{1}{6}} \quad (14)$$

$$245 \quad E^* = \Delta\rho^* L_b^* \left(\frac{L_b}{H} \right)^* \quad (15)$$

246 In our experiments, $E_{l_{mean}} \simeq 5000$ Pa implying a fracture toughness $K_c \simeq 100$ Pa.m^{1/2}
 247 (Kavanagh et al., 2013). These values give us an experimental buoyancy length $L_b \simeq 22$ cm.

248 In nature, K_c varies between 10⁶ to 10⁸ Pa.m^{1/2} depending on whether the value is measured
 249 in the field or in the laboratory (Delaney and Pollard, 1981). $K_c \simeq 10^7$ Pa.m^{1/2} seems to be a
 250 representative value. The ratio between thickness and length H/L_b for a dyke varies in nature
 251 between 10⁻⁴ and 10⁻³ (Kavanagh and Sparks, 2011; Gudmundsson, 2011), while it is $\simeq 10^{-2}$ -
 252 10⁻¹ in gelatine. The magnitude of $\Delta\rho$ in nature is 100 kg.m⁻³, i.e. the same as in gelatine. Finally,
 253 we take a value for ρ_{solid} of 2800 kg.m⁻³ in nature and 1000 kg.m⁻³ in gelatine. Consequently:

$$254 \quad \bullet L^* = 4.6 \times 10^{-4}$$

$$255 \quad \bullet T^* = 1.3 \times 10^{-2}$$

$$256 \quad \bullet U^* = 3.6 \times 10^{-2}$$

$$257 \quad \bullet E^* = 10^{-5} - 10^{-7}$$

258 With experimental values $L_l = L_b \simeq 22$ cm, $T_l \simeq 80 - 400$ s, $U_l \simeq 7$ mm.s⁻¹ and $E_l = E_{l_{mean}} \simeq$
 259 5000 Pa, these give:

$$260 \quad \bullet L_n = 480 \text{ m, which seems reasonable;}$$

$$261 \quad \bullet T_n = 2 - 9 \text{ h, which seems also reasonable;}$$

- 262 • $U_n = 0.2 \text{ m.s}^{-1}$, which is consistent with velocity of dykes between 0.1 and 0.5 m.s^{-1}
 263 ([White et al., 2011](#));
- 264 • $E_n = 10^9 - 10^{11} \text{ Pa}$, which are typical natural values.

265 These calculations confirm that the experiments are correctly scaled.

266 In addition to the scale ratios determined by [Kavanagh et al. \(2013\)](#), we define an additional
 267 characteristic dynamic flux scale. A natural flux scale is:

$$Q = HL_bU \quad (16)$$

268 and applying the same pressure balance between the buoyancy pressure and the elastic pressure in
 269 the dyke head region as before - equation (11) - yields the following expression for the thickness
 270 H :

$$H = \Delta\rho g (L_b)^2 \frac{2(1-\nu^2)}{E} \quad (17)$$

271 Consequently:

$$Q^* = \Delta\rho^* (L^*)^3 (E^*)^{-1} U^* \\ \Rightarrow Q^* = 10^{-7} - 10^{-5} \quad (18)$$

273 Experimental fluxes Q_l have typical values of 10^{-7} to $10^{-5} \text{ m}^3.\text{s}^{-1}$, which would correspond
 274 to natural values $Q_n = 0.01 - 100 \text{ m}^3.\text{s}^{-1}$, which are similar to natural values for volcanic systems
 275 (e.g. [Traversa et al., 2010](#)). We note that this range of natural flux Q_n is deduced directly from
 276 a scaling argument and therefore it does not include any considerations of the thermal evolution
 277 of the intrusion. It is thus independent from the range of flux considered to calculate the range
 278 of dimensionless fluxes ϕ in section 2.5. The range of fluxes in the experiments thus correctly
 279 represent the dynamics of natural intrusions (Q_n), and their thermal evolution (ϕ).

280 **3. Results**

281 Fifteen experiments were performed with different injection temperatures and injection fluxes
 282 (Tab. 2). For each experiment, θ and ϕ were calculated. ϕ quantified the dyke dynamical conditions
 283 in the lower layer, and thus whether conditions for sill formation could be met.

Exp	w_{upp}	w_{low}	$T_g(C)$	$T_i(C)$	$E(Pa)$	$Q(m^3.s^{-1})$	θ	ϕ	$\frac{\sigma_\theta}{\theta}$	$\frac{\sigma_\phi}{\phi}$	Result	Symbols
1	5	3	7.00	45.78	10164	1.38E-06	0.62	1.54	0.03	0.08	Sill	●
2	5	3	7.02	46.02	10164	2.50E-06	0.62	2.79	0.03	0.07	Crossing dyke	△
3	3	2	7.56	42.65	996	1.38E-06	0.67	15.68	0.04	0.07	Crossing dyke	△
4	3	2	5.73	44.08	3159	3.75E-06	0.66	13.48	0.03	0.06	Crossing dyke	△
5	4	2	5.87	38.35	2930	2.50E-06	0.77	9.69	0.04	0.06	Sill	●
6	4	2	6.24	34.81	2882	2.50E-06	0.87	9.85	0.04	0.06	Blocked dyke	□
7	4	2	6.24	34.81	2882	4.00E-06	0.87	15.77	0.04	0.06	Sill	●
8	4	2	6.64	32.44	1828	2.25E-06	0.94	13.98	0.04	0.06	Blocked dyke	□
9	4	2	6.64	32.44	1828	7.51E-07	0.94	4.66	0.04	0.09	No intrusion	★
10	5	4	6.66	37.72	12903	1.50E-05	0.78	13.21	0.04	0.06	Sill	●
11	5	4	6.66	37.72	12903	1.00E-06	0.78	0.88	0.04	0.08	No intrusion	★
12	4	2	6.57	43.34	3003	2.50E-06	0.66	9.96	0.04	0.15	Sill	●
13	4	2	6.57	43.34	2851	1.38E-06	0.66	5.48	0.03	0.07	Sill	●
14	4	2	6.57	40.89	2851	3.75E-07	0.71	1.42	0.03	0.06	Blocked dyke	□
15	4	2	6.48	37.07	3003	2.00E-06	0.80	7.57	0.04	0.07	Sill	●

Table 2: Experimental data for investigation of sill formation.

θ is calculated from equation (4) with $T_s = 31^\circ C$. ϕ is calculated from equation (7) with $\Delta\rho = 100$, $g = 9.81 m.s^{-1}$, $\kappa = 1.4 \times 10^{-7} m^2.s^{-1}$. E of the lower gelatine layer is determined and calculated from equation (3). The uncertainties σ_θ and σ_ϕ were calculated according to the principles of the "Propagation of Errors" (Bevington and Robinson, 2003).

284 In all experiments, a dyke was first generated in the lower layer. All experiments were pre-
 285 pared in such a way that the interface between the two gelatine layers was a priori mechanically
 286 favourable for the formation of sills ($\Delta E > 1.1$ - Kavanagh et al., 2006). However, contrary to
 287 what has been observed in previous isothermal experimental studies (e.g. Kavanagh et al., 2006),
 288 sill formation did not systematically occur. Instead, different types of intrusion were observed:

289 dykes blocked at the interface, dykes passing through the interface, and sills. Each type of intru-
290 sion could be linked to distinct θ and ϕ fields.

291 *3.1. Types of intrusions*

292 The initial dyke could be blocked at the interface (Fig. 2A). It stopped its vertical propagation
293 there and propagated laterally, underneath the interface, until the end of the injection (Fig. 3C).
294 These dykes were particularly thick with a thickness to length ratio greater than 10^{-1} .

295 When a sill formed (Fig. 2B) it took place at the interface between the two layers. Initially, the
296 feeder dyke propagated in the same way as a dyke blocked at the interface before fracturing and
297 propagating parallel to the interface, forming a sill (Fig. 3D). During the propagation of a sill, the
298 upper layer was deformed and the interface bulged slightly towards the surface.

299 The dyke could also pass through the interface (Fig. 2C). It propagated initially in the same way
300 as a dyke blocked at the interface before piercing the interface and propagating into the upper stiffer
301 layer (Fig. 3E). The dyke made a pause before penetrating the interface and taking a triangular
302 shape along strike above the interface. These dykes had a thickness to length ratio of $\simeq 10^{-1}$ (the
303 length used is the total vertical length of the dyke in the lower and upper layer).

304 *3.2. Morphologies of intrusions*

305 Different morphologies of intrusions were observed, all similar to those observed in nature.
306 The experimental dykes had sometimes a smooth surface, but were usually very irregular. Plumose
307 structures were commonly observed (Fig. 4A). Additionally, many discontinuities could be seen at
308 the leading edges of the experimental dykes as en-echelon segments (Fig. 4B) or lobes (Fig. 4C).
309 These en-echelon segments did not always have the same orientation. The discontinuities observed
310 on our experimental dykes are similar to those observed in [Taisne and Tait \(2011\)](#) and they are
311 linked to solidification processes. We observe that for dykes and sills as solidification effects
312 become more important, the number of discontinuities usually increases as well. Additionally,
313 these discontinuities are not limited to the propagating tip of the fissure but are also initiated at
314 the margins (e.g. Fig. 4C), which corroborates the observations of [Taisne and Tait \(2011\)](#). In

315 comparison, the experimental sills had generally very smooth surfaces with few asperities filled
316 with gelatine (Fig. 4D). The surface of the sills were smooth probably because they did not really
317 need to fracture the gelatine in order to propagate along the interface. However, as for dykes,
318 discontinuities were also observed at the edge of some (Fig. 4E).

319 3.3. Result analysis

320 The results of the experiments, that is blocked dykes, crossing dykes, sills and cases when fluid
321 could not intrude the gelatine, are all summarised on a graph showing θ as a function of ϕ (Fig. 5).
322 Solidification effects increase as $\theta \rightarrow 1$ and $\phi \rightarrow 0$. Four areas are clearly identified:

- 323 • when the dimensionless temperature is relatively high and the dimensionless flux is very low
324 ($\theta \simeq 0.75 - 0.95$ and $\phi < 6$), there is no propagation (Fig. 5, stars). Solidification effects are
325 so important that vegetable oil freezes and solidifies in the tube and no intrusion is observed;
- 326 • when the dimensionless temperature is high and for larger dimensionless fluxes ($\theta \simeq 0.7 -$
327 0.95 and $\phi < 15$), dykes are blocked at the interface between the two gelatine layers (Fig.
328 5, squares). Solidification effects are important and the dyke partially solidifies at its walls
329 during its propagation and development. Solidification at the upper tip of the dyke blocks
330 its propagation, and prevent its piercing of the interface and subsequent propagation in the
331 upper stiffer layer or its spreading along the interface as a sill;
- 332 • when the dimensionless temperature has intermediate values ($\theta \simeq 0.60 - 0.90$ and $\phi < 16$),
333 sills are created (Fig. 5, disks). Solidification effects are smaller. Consequently, the feeder
334 dyke propagates as a sill by spreading at the interface between the two layers;
- 335 • finally, when the dimensionless temperature is low ($\theta \simeq 0.60 - 0.70$ and $\phi > 2$), dykes
336 passing through the interface are created (Fig. 5, triangles). Dykes do not create sills but
337 instead pierce directly the interface to propagate in the upper layer, easily fracturing the
338 gelatine presumably because of their high temperature: higher input of hot vegetable oil at the
339 tip of the feeder dyke leads to lower solidification effects and presumably easier fracturation;

340 the injection flux seemed to have less of an effect. However, solidification along the walls of
341 the dyke seem to prevent the fluid from intruding the interface between the gelatine layers.

342 These results are consistent and systematic over the narrow range of rigidity contrasts ΔE used
343 in the experiments ($1.4 \leq \Delta E \leq 3.9$).

344 4. Discussion

345 4.1. Sill Formation

346 The first important result of our experiments is the difference with isothermal experiments
347 (using water as the injected fluid) where there is no effect of solidification. Indeed, in these ex-
348 periments (Kavanagh et al., 2006), sill formation occurred systematically when the upper gelatine
349 layer was stiffer than the lower one. With solidification effects, the rigidity contrast alone is not
350 sufficient anymore to ensure sill formation. The conditions that are required for the formation of
351 sills are reduced: it becomes more difficult to form sills when solidification of the flowing fluid
352 occurs. At a given intermediate value of the dimensionless temperature θ , dykes passing through
353 the interface are created for higher values of the dimensionless flux ϕ whereas sills are created
354 with lower ϕ values (i.e. lower injection flux Q). In the same way at a comparatively higher value
355 of θ , sills are created for higher values of ϕ and dykes blocked at the interface are created at ϕ
356 comparatively lower ϕ values.

357 Each type of intrusion corresponds to a well defined area in Fig. 5, and so to a specific range of
358 θ and ϕ values. The limits of each area appear well defined by the following linear relationships:

359 • (b): $\theta = 0.019\phi + 0.68$ ($R^2 = 0.99$);

360 • (c): $\theta = 0.0039\phi + 0.61$ ($R^2 = 0.89$).

361 These two equations (b) and (c) delimit the upper and lower ranges, respectively, of thermal (θ) and
362 dynamical (ϕ) conditions for the formation of sills. It seems that there is also a separation between
363 the "no propagation" area and the "dyke blocked at the interface" area (dashed line on Fig. 5),

364 but this separation (a) is only qualitative. Sill formation depends on the thermal and dynamical
365 conditions of the injected fluid. The thermal conditions (θ) depends essentially on the injection
366 temperature T_i whereas the dynamical conditions (ϕ) depends not only on the injection flux Q
367 but also on the rigidity of the intruded solid. Therefore, the formation of sills in our experiments
368 depends mainly on three parameters: the rigidity of the rocks intruded below a potential interface,
369 the injection temperature T_i , and the injection flux Q .

370 4.2. Geological Applications

371 These experiments were carried out under dimensionless conditions (θ and ϕ) identical to those
372 present in nature. The experimental results can therefore be extended to natural conditions. These
373 results imply that because of solidification effects, even if mechanical conditions are favourable
374 (upper layer stiffer than the lower one), above some injection magmatic flux (equation (c), Fig. 5),
375 sills are no longer created, and dykes passing through the interface are expected instead, which
376 could lead to an eruption.

377 The experimental results provide also a means to explain why some dykes form sills when
378 other dykes do not under seemingly similar geological conditions. If one considers a dyke that
379 encounters an interface with favourable mechanical conditions (rigidity contrast with $\Delta E > 1.1$),
380 different scenarios can be envisaged depending on its dynamical and thermal conditions (Fig. 5).
381 If conditions for sill formation were met (favourable injection temperature and flux), a sill would
382 be created. However, a recharge in magma (e.g. the arrival of a new magma batch) or a new
383 dyke propagating with a higher flux would change the dynamical and thermal conditions owing to
384 increased magmatic flux and/or injection temperature. The conditions for sill formation would no
385 longer be met and the dykes would now be able to cross the interface. In the same way, if a dyke
386 was blocked at an interface because conditions for sill formation were not met (too low injection
387 temperature or flux) a sill could subsequently form because of a recharge in magma, which would
388 lead to a temperature and flux increase. Similarly, if a dyke crossed the interface because of a large
389 injection temperature or flux, this dyke could later turn into a sill along a subsequent favourable
390 mechanical interface. As magma flows, it cools down and its injection flux will likely decrease as

391 magma is withdrawn from the source: thermal and dynamical conditions will change and increase
392 the likelihood for sill formation further away.

393 These results are consistent with field observations. Indeed, sills are not created each time there
394 is a suitable rigidity contrast (upper layer stiffer than the lower one) as illustrated in Fig. 6 where a
395 feeder dyke crosses several interfaces in the same rock unit, and thus characterised by presumably
396 similar rigidity contrast, before spreading as a sill at one of them. Solidification effects could be a
397 plausible explanation for this behaviour.

398 Our experiments explored a limited range of dimensionless fluxes ϕ when extremely-high-flux
399 dykes do sometimes occur in nature, with ϕ values perhaps as high as 200. Extrapolating the results
400 summarised in Fig. 5 to high values suggests that dykes with extremely-high dimensionless flux
401 would have a greater propensity for crossing interfaces and thus for getting closer to the surface.
402 Although this makes sense, our results might not necessarily hold for such extreme events, and
403 additional work should clarify the behaviour of these extremely-high-flux dykes.

404 Additionally, some issues could not be addressed with our experiments. First, these experi-
405 ments assume the deformation of the host rock is elastic. If materials are not consolidated (pyro-
406 clastic flows, hyaloclastites, shales, ...), deformation can be ductile, which would affect the forma-
407 tion of sills (very weak interface because of very soft material, premature arrest of the feeder dyke
408 ...). These interactions with non-elastic materials are expected to be more important for intrusions
409 close to the surface because crustal heterogeneities are likely to be more important there.

410 Another issue is that these experiments study the effects of solidification on the magma but
411 neglect the potential effect on the host rocks. The temperature difference between the host rock and
412 the intrusion and the heat advected by the intrusion during its propagation may affect the rheology
413 of the host rock. For example, if an intrusion is taking place near an area of magma storage, the
414 crust heated by this presence could possess a different rheology, likely to be more ductile than
415 elastic.

416 Also, the vegetable oil used as a magma analogue here has a single solidification temperature.
417 Magma in nature will have a range of solidification temperature between its liquidus and solidus.

418 This temperature range depends widely on its composition, which evolves as the magma solidifies.
419 Likewise, the experimental temperature at the injection point T_i was maintained constant during an
420 experiment whereas magma temperature is likely to change during an intrusive event. In nature the
421 thermal conditions θ are thus likely to change, which is not accounted for in these experiments. In
422 the same way, ϕ remains constant during an experiment because Q is maintained constant whereas
423 natural magma fluxes are likely to wax and wane during the same injection of magma.

424 5. Conclusions

425 The purpose of this study was the quantification of the effects of solidification on the formation
426 of sills by means of analogue laboratory experiments. They involved the injection of hot vegetable
427 oil, a magma analogue that solidifies during its injection, in a layered colder solid gelatine, a host
428 rock analogue. The injection temperature T_i and the injection flux Q were systematically varied
429 between experiments. The experiments were carried out under dimensionless conditions (temper-
430 ature θ and flux ϕ) identical to those present in nature, and are correctly scaled geometrically,
431 dynamically, kinematically, and thermally. The results are consistent with field observations and
432 provide a means to explain why some dykes form sills where other dykes do not under similar
433 geological conditions.

434 Several types of intrusions were observed: dykes stopping at the interface, dykes passing
435 through the interface and sills. These different shapes demonstrate that contrary to isothermal
436 experiments (no temperature effect able to block sill formation), a rigidity contrast between two
437 layers is not a sufficient condition to create a sill. When solidification effects are significant (low
438 Q and T_i slightly higher than T_s), the created dyke partially solidifies on the walls during its prop-
439 agation, which prevents its piercing of the interface and propagation in the upper stiffer gelatine
440 layer, or its spreading along the interface as a sill. When solidification effects are lower (range
441 of medium Q and T_i higher than T_s), the feeder dyke can propagate as a sill by spreading at the
442 interface between the two layers. When solidification effects are low (range of medium and high
443 Q and T_i higher than T_s), the constant input of hot vegetable oil at the dyke tip allows it to pierce

444 the interface and propagate in the upper layer of gelatine.

445 Thus, solidification effects restrict sill formation at an interface with a favourable rigidity con-
446 trast (upper layer stiffer than the lower one). Sill formation occurs only for a specific range of
447 dimensionless temperatures θ and fluxes ϕ : $\theta_{min} \leq \theta \leq \theta_{max}$, where $\theta_{min} = 0.0039\phi + 0.61$
448 and $\theta_{max} = 0.019\phi + 0.68$. The thermal conditions (θ) depend on injection temperature T_i , and
449 dynamical conditions (ϕ) depend on injection flux Q and rigidity contrast of the intruded solid.
450 Therefore, in our experiments, sill formation along an interface depends on three critical param-
451 eters : the injection temperature T_i , the injection flux Q , and the rigidity of the rocks below this
452 interface.

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Captions of figures and tables

FIGURE 1: Experimental apparatus.

The gelatine solid has two layers of different stiffness, to create a priori favourable conditions to form sills. Vegetable oil is heated with a bain-marie and injected at a constant rate with a peristaltic pump in the layered gelatine solid.

FIGURE 2: Experimental intrusions.

(A) Experimental dyke blocked at the interface, experiment 11, three-quarter view. (B) Experimental sill, experiment 1, side view. (C) Experimental dyke passing through the interface, experiment 2, three-quarter view. The dyke takes a triangular shape above the interface.

FIGURE 3: Schematic diagram illustrating the formation of experimental intrusions.

(A) Initial circular dyke, front view. (B) The dyke stops at the interface between the two layers and propagation continues laterally beneath the interface, front view. (C), (D) and (E) are the final shapes of the three different intrusions observed in the experiments. (C) Final shape of the dyke stopping at the interface, front view. (D) The dyke fractures the gelatine at the interface and creates a sill, side view. (E) The dyke pierces the interface, propagates into the upper layer of gelatine and creates a dyke passing through the interface, front view. The dyke takes a triangular shape above the interface.

FIGURE 4: Morphologies of intrusions.

(A) Plumose structures on the feeder dyke, experiment 7, front view. (B) En-echelon segments at the upper tip of the dyke, experiment 14, top view. (C) Lobes on the side of the dyke, experiment 14, side view. (D) Smooth surface and asperity filled by gelatine on a sill, experiment 1, top view. (E) Discontinuities at the edge of the sill, experiment 5, side view.

FIGURE 5: Dimensionless temperature θ as a function of dimensionless flux ϕ .

Gray area shows natural ranges of values for θ and ϕ as defined in 2.5. Stars represent experiments where no propagation occurred; squares are dykes blocked at the interface; disks are sills; triangles are dykes passing through the interface. Lines (a), (b) and (c) delimit the areas for each type of intrusions. The dashed line (a) is only qualitative whereas the continuous lines (b) and (c) can be determined reliably. See text for details.

FIGURE 6: Sill with its feeder dyke in the Henry Mountains, Utah, USA, modified from Menand (2011).

The view is from the East. The sill, its feeder dyke (both outlined by dashed white lines) and the intruded layered sandstone (continuous white lines) have all been rotated almost 90° . The feeder dyke crosses several similar interfaces before spreading as a sill.

TABLE 1: Behaviour of the dimensionless temperature θ and dimensionless flux ϕ .

TABLE 2: Experimental data for investigation of sill formation.

θ is calculated from equation (4) with $T_s = 31^\circ \text{C}$. ϕ is calculated from equation (7) with $\Delta\rho = 100$, $g = 9.81 \text{ m.s}^{-1}$, $\kappa = 1.4 \times 10^{-7} \text{ m}^2.\text{s}^{-1}$. E of the lower gelatine layer is determined and calculated from equation (3). The uncertainties σ_θ and σ_ϕ were calculated according to the principles of the "Propagation of Errors" (Bevington and Robinson, 2003).

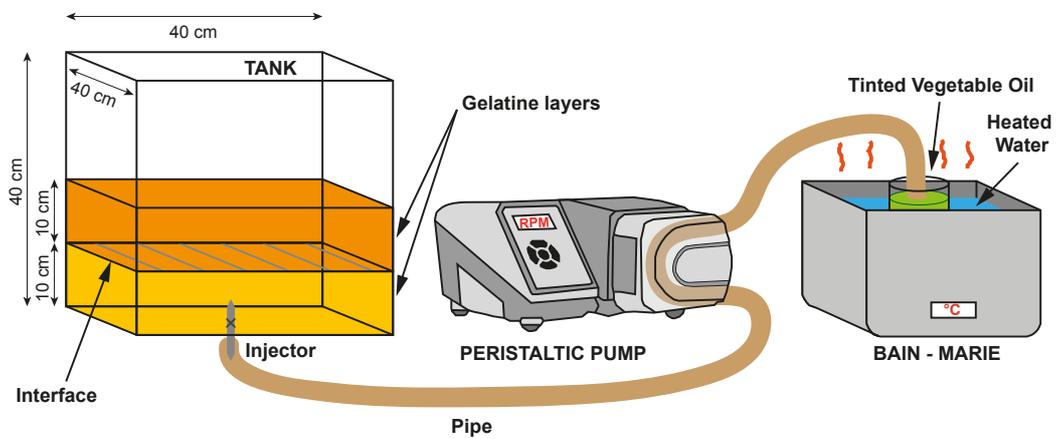


Figure 1: Experimental apparatus.

The gelatine solid has two layers of different stiffness, to create a priori favourable conditions to form sills. Vegetable oil is heated with a bain-marie and injected at a constant rate with a peristaltic pump in the layered gelatine solid.

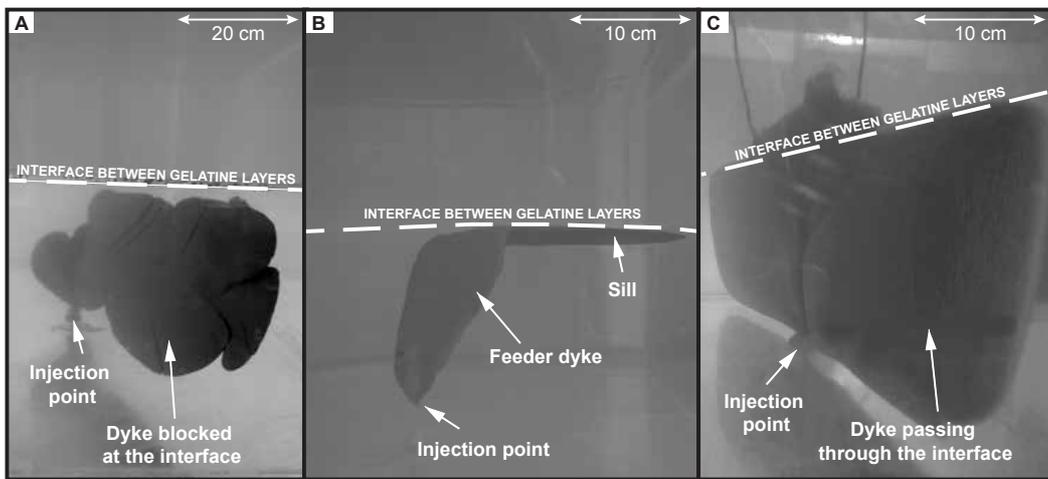


Figure 2: Experimental intrusions.

(A) Experimental dyke blocked at the interface, experiment 11, three-quarter view. (B) Experimental sill, experiment 1, side view. (C) Experimental dyke passing through the interface, experiment 2, three-quarter view. The dyke takes a triangular shape above the interface.

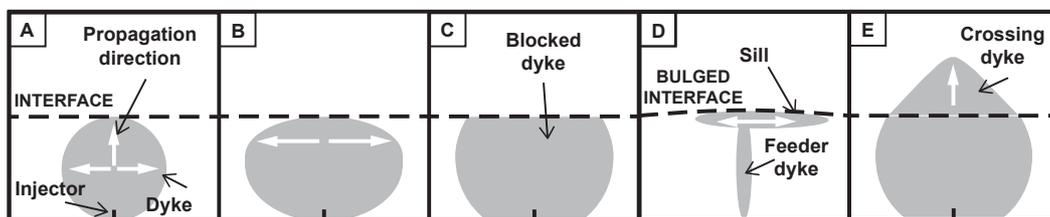


Figure 3: Schematic diagram illustrating the formation of experimental intrusions.

(A) Initial circular dyke, front view. (B) The dyke stops at the interface between the two layers and propagation continues laterally beneath the interface, front view. (C), (D) and (E) are the final shapes of the three different intrusions observed in the experiments. (C) Final shape of the dyke stopping at the interface, front view. (D) The dyke fractures the gelatine at the interface and creates a sill, side view. (E) The dyke pierces the interface, propagates into the upper layer of gelatine and creates a dyke passing through the interface, front view. The dyke takes a triangular shape above the interface.

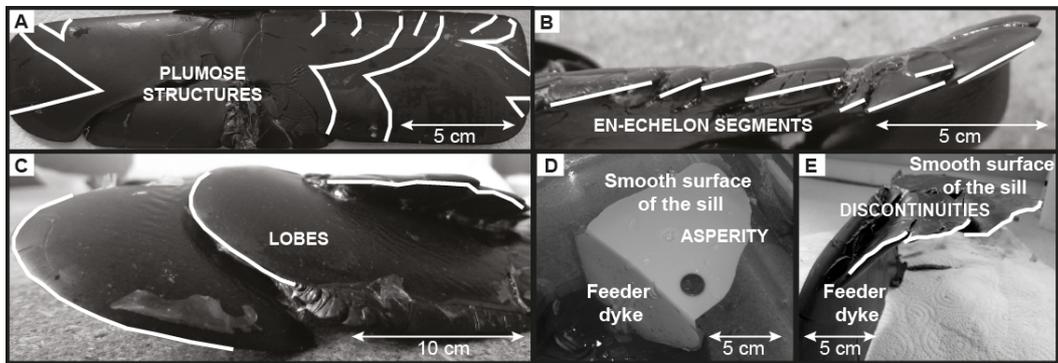


Figure 4: Morphologies of intrusions.

(A) Plumose structures on the feeder dyke, experiment 7, front view. (B) En-echelon segments at the upper tip of the dyke, experiment 14, top view. (C) Lobes on the side of the dyke, experiment 14, side view. (D) Smooth surface and asperity filled by gelatine on a sill, experiment 1, top view. (E) Discontinuities at the edge of the sill, experiment 5, side view.

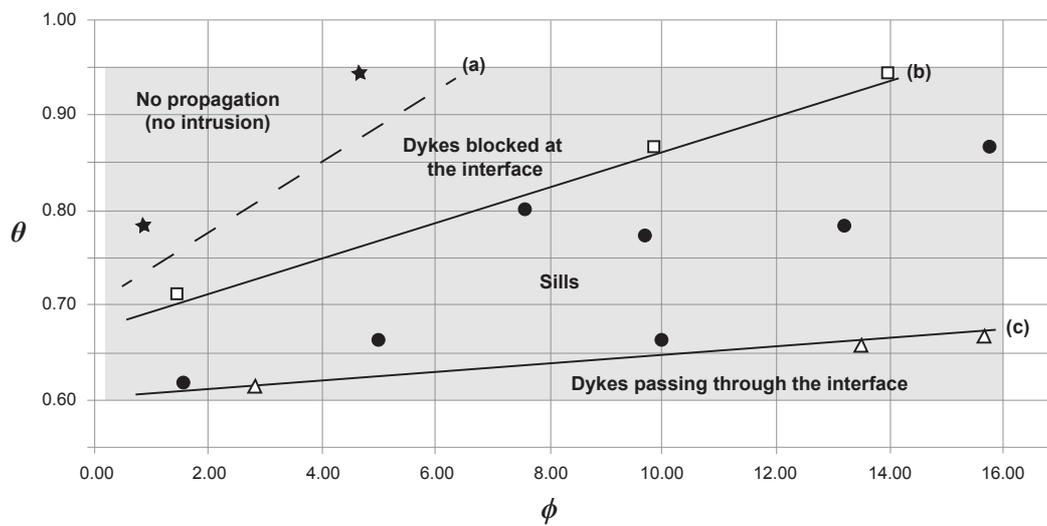


Figure 5: Dimensionless temperature θ as a function of dimensionless flux ϕ .

Gray area shows natural ranges of values for θ and ϕ as defined in 2.5. Stars represent experiments where no propagation occurred; squares are dykes blocked at the interface; disks are sills; triangles are dykes passing through the interface. Lines (a), (b) and (c) delimit the areas for each type of intrusions. The dashed line (a) is only qualitative whereas the continuous lines (b) and (c) can be determined reliably. See text for details.



Figure 6: Sill with its feeder dyke in the Henry Mountains, Utah, USA, modified from [Menand \(2011\)](#).

The view is from the East. The sill, its feeder dyke (both outlined by dashed white lines) and the intruded layered sandstone (continuous white lines) have all been rotated almost 90° . The feeder dyke crosses several similar interfaces before spreading as a sill.