Experimental modelling of shallow magma emplacement: Application to saucer-shaped intrusions

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ABSTRACT

Saucer-shaped dolerite and sandstone intrusions are common in sedimentary basins world-wide. We have conducted a series of scaled experiments simulating the process of magma emplacement in sedimentary basins, with particular attention on the formation of saucer-shaped sills. The model materials were (1) cohesive fine-grained silica flour, representing brittle crust; and (2) molten low-viscosity oil, representing magma. The experiments were performed in both homogeneous and layered models. In all the experiments, oil injection resulted in doming of the surface. In the homogeneous models, the injected oil formed cone sheets and sub-vertical dykes. Cone sheets formed for shallow injection (∼1–3 cm), and vertical dykes formed for deeper injection (∼4–5 cm). In layered models, the injected oil always formed saucer-shaped intrusions. Our experimental results show that (1) sill intrusion results in the formation of a dome, with melt erupting at the rim; (2) layering controls the formation of sills and saucer-shaped sills; (3) saucer-shaped sills are fed from the bottom and the fluid flows upward and outward; and (4) the diameter of saucer-shaped sills increase with increasing emplacement depth. The systematic relation between domes and sills and the depth-dependence of sill diameters show that saucer-shaped intrusions result from the interaction between a growing flat-lying shallow sill and doming of the free surface. We conclude that saucer-shaped intrusions represent fundamental geometries formed by shallow magma intrusion in stratified basins.

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1. Introduction

Transport and emplacement of magma in the Earth’s crust are processes with great significance for the evolution of our planet. Magmatic intrusions are common in many sedimentary basins, and field observations show that they mostly consist of sheet intrusions, such as sills and dykes. It has recently been realized that the intrusion of sills into sediments may have very important implications for (1) global climate by the release of large volumes of greenhouse gases from metamorphic aureoles around the sills (Svensen et al., 2004, 2007), (2) organic matter by the release of large volumes of greenhouse gases from metamorphic sediments may have very important implications for (1) global climate (Svensen et al., 2004, 2007), (2) organic matter by the release of large volumes of greenhouse gases from metamorphic sediments may have very important implications for (1) global climate observations show that they mostly consist of sheet intrusions, such as cone sheets and sub-vertical dykes. Cone sheets formed for shallow injection (∼1–3 cm), and vertical dykes formed for deeper injection (∼4–5 cm). In layered models, the injected oil always formed saucer-shaped intrusions. Our experimental results show that (1) sill intrusion results in the formation of a dome, with melt erupting at the rim; (2) layering controls the formation of sills and saucer-shaped sills; (3) saucer-shaped sills are fed from the bottom and the fluid flows upward and outward; and (4) the diameter of saucer-shaped sills increase with increasing emplacement depth. The systematic relation between domes and sills and the depth-dependence of sill diameters show that saucer-shaped intrusions result from the interaction between a growing flat-lying shallow sill and doming of the free surface. We conclude that saucer-shaped intrusions represent fundamental geometries formed by shallow magma intrusion in stratified basins.

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(Trude et al., 2003; Shoulders and Cartwright, 2004; Thomson and Hutton, 2004; Hansen and Cartwright, 2006b,a; Thomson, 2007a) and anomalies of magnetic susceptibility data (AMS; Polteau et al., 2008b) support the latter model. In such models, the saucer-shaped sills are the result of a mechanical interplay between the growing sills and their deforming overburden (Pollard and Johnson, 1973; Pollard and Holzhausen, 1979; Fialko, 2001; Malthe-Sørenssen et al., 2004; AMS; Polteau et al., 2008b). However, it is still debated whether the structures overlying the sills are domes or volcanoes (Hansen and Cartwright, 2007; Thomson, 2007b). Thus, the emplacement mechanisms of saucers and their geological implications are still poorly constrained, and many fundamental questions remain to be answered. What controls the saucer evolution of sills? What is the nature and origin of the overlying structures? If they are domes, what is the effect of doming? What controls the inner sill-to-inclined sheet transition?

In order to answer such questions, we resorted to scaled laboratory experiments, in which a vegetable oil, simulating magma, was injected into cohesive Coulomb silica flour, simulating the brittle upper crust. Our objectives were to simulate the emplacement of saucer-shaped intrusions and to understand the physical processes governing the saucer-shape evolution of sills.

2. Experimental setup and scaling

2.1. Model materials and scaling

We used fine-grained crystalline silica flour as an analogue for the brittle crust, and a low-viscosity vegetable oil for the magma. The flour is produced by Sibelco, in Belgium, and sold under the name M400. The grain size is ~15 µm. It fails according to a Mohr–Coulomb criterion, and we measured its cohesion and friction coefficient at 369±44 Pa and 0.81±0.06, respectively, using a Hubbert shear box, as described for example by Hubbert (1951), Schellart (2000) and Galland et al. (2006). This value is within errors the same as that used by Galland et al. (2006). This yields an angle of internal friction ~39°. According to Galland et al. (2006), the tensile strength of the silica flour is ~100 Pa. The vegetable oil is produced by Unilever and sold in France under the name Végétaline. It is solid at room temperature but melts at ~31 °C.
The viscosity of the oil is poorly temperature-dependant (Galland et al., 2006), and we injected it at −50 °C, where its viscosity is ∼2×10^{-2} Pa.s.

The scaling and the suitability of the model materials have been described in detail by Galland et al. (2006). In such settings, the scaling is challenging because (1) the ranges of geological settings and viscosities of magmas are very broad, and (2) the experiments aim to simulate both the flow of low-viscosity magma and the deformation of the country rocks. The principle is to define selected dimensionless numbers, which characterize the kinematics and the kinetics of the simulated processes. The scaling procedure is based on the standard similarity conditions as developed by Hubbert (1937) and Ramberg (1981), and used for example by Merle and Borgia (1996).

The principal geometric input variable is the thickness of the overburden (D). Output geometrical variables are the sill length (l) and thickness (h). Material properties are the densities of the magma (ρm) and the country rock (ρc), the angle of internal friction (ϕ) and the cohesion (C) of the country rock, and the viscosity of the magma (η). The only external force is due to the gravity (g). The injection flow rate is Q. The magma flow velocity (U) can be calculated from the sill length and thickness, and the flow rate. Notice that the length and the radius of the intrusion are results of the experiments, and not a parameter known a priori. However, they need to be taken into account in the dimensional analysis in order to analyse the viscous stresses into the intrusions.

According to the Buckingham-II theorem (e.g. Barenblatt, 2003), ten variables minus three variables with independent dimensions lead to seven independent dimensionless numbers that characterize the system. The experiments are similar to nature if these seven numbers have the same values in nature and in experiments. Our experiments aim to simulate basin-scale phenomena, so that we chose a model to nature scale ratio of 10^{-5}, i.e. 1 cm in experiments represents 1 km in nature.

The first dimensionless parameters are the geometric ratios of the considered system:

\[
\Pi_1 = h/l, \quad \Pi_2 = l/D. \tag{1}
\]

\(\Pi_1\) expresses the strain associated with the sill emplacement. In nature, sill diameter is typically 10–20 km, whereas their thickness ranges between 20 and 200 m. Thus, \(\Pi_1\) is typically of the order of 10^{-2}. In experiments, saucer radii were typically between 5 and 10 cm, whereas their thicknesses ranged between 1 and 3 mm. Thus, \(\Pi_1\) was also of the order of 10^{-2}, i.e. in the same range as natural saucers. In nature, saucer-shaped sills have been emplaced at depths of a few kilometres. Thus, \(\Pi_1\) is between 1 and 5. In our experiments, \(\Pi_1\) ranged between 1 and 1.7 (see Fig. 6 and Table 2). Therefore, the geometry of model intrusions approximately matched with natural intrusions.

The first dimensionless parameter to scale the brittle country rock is the angle of internal friction:

\[
\Pi_3 = \phi. \tag{2}
\]

\(\Pi_3\) expresses the strain associated with the intrusion of magma into the rock is controlled by a balance between the sill flow velocity (U) and the deformation of the country rock. In elastic-plastic materials such as rocks and cohesive granular media, the material deforms both elastically and plastically. The angle of internal friction is well known, its elastic properties are in turn challenging to estimate and difficult to scale properly. Therefore, we use the cohesion to scale the strength of the rock. Thus, the dimensionless number \(\Pi_3\) to scale the viscosity of magma is the ratio of viscous pressure drop within the fluid along the intrusion to the cohesion (i.e. strength) of the country rock. For lammar flow of a Newton fluid of viscosity η flowing at a velocity U, the viscous pressure drop along a fracture of length \(l\) and thickness \(h\) is \(\Delta P_v = \eta U l / h^2\) (e.g. Lister and Kerr, 1991; Kavanagh et al., 2006). Thus, the expression of \(\Pi_3\) is:

\[
\Pi_3 = \frac{\eta U}{h^2C}. \tag{4}
\]

If we assume that 20- to 200-meter thick sills are fed by a 1-meter thick dyke, in which magma velocity U ranges between 0.1 and 1 m s^{-1}, the estimated magma velocity in sills is expected to range between 5×10^{-4} and 5×10^{-2} m s^{-1} (Table 1). The viscosity range of magmas is very large, from 1 Pa.s for wet crystal-poor mafic magma, to 10^{10} Pa.s for dry crystal-rich felsic magma (e.g. Dingwell et al., 1993; Peacock, 1993; Romano et al., 2003). However, we only consider common magma types such as basaltic to rhyolitic magma, for which the viscosities range between 100 Pa.s to 10^{10} Pa.s. In basins, saucer-shaped sill radii are typically ∼5 km. Therefore, \(\Pi_3\) in nature ranges from 6.3×10^{-11} to 6.3×10^{-1} (Table 1), so that viscous stresses are negligible compared to the strength of the country rock. In experiments, the injection flow rate was 40 ml min^{-1}, within fractures of typical radii about 7 cm and typical thickness 1–3 mm; the viscosity of the oil is 2×10^{-2} Pa.s at 50 °C (Galland et al., 2006). Thus, the values of \(\Pi_3\) in experiments are 4.23×10^{-10} to 1.2×10^{-2} (Table 1). Such values are in the range of \(\Pi_3\) in nature and much smaller than 1, which means that viscous stresses are negligible with respect to the cohesion of the country rock. This is a major difference from experiments of lithospheric deformation where the stresses in the ductile crust must be of the same order of magnitude as those in the brittle crust (e.g. Davy and Cobbold, 1991).

### Table 1

<table>
<thead>
<tr>
<th>Definition of parameters</th>
<th>Field</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>C Cohesion of brittle material</td>
<td>10^{1} → 10^{4}</td>
<td>370</td>
</tr>
<tr>
<td>D Thickness of overburden</td>
<td>1000 → 5000</td>
<td>0.01 → 0.05</td>
</tr>
<tr>
<td>g Acceleration due to gravity</td>
<td>9.81</td>
<td>9.81</td>
</tr>
<tr>
<td>h Intrusion thickness</td>
<td>20 → 200</td>
<td>1×10^{-1} → 3×10^{-3}</td>
</tr>
<tr>
<td>t Intrusion radius</td>
<td>−7000</td>
<td>0.1</td>
</tr>
<tr>
<td>U Magma flow velocity</td>
<td>5×10^{-6} → 5×10^{-2}</td>
<td>4.72×10^{-4} → 3×10^{-3}</td>
</tr>
<tr>
<td>ϕ Angle of internal friction</td>
<td>25 → 45</td>
<td>39</td>
</tr>
<tr>
<td>pm Density of magma</td>
<td>2500 → 2700</td>
<td>892</td>
</tr>
<tr>
<td>rν Density of country rock</td>
<td>2500</td>
<td>1050</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Definition of dimensionless ratios</th>
<th>Field</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Pi_1) Intrusion thickness/length</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>(\Pi_2) Intrusion length/depth</td>
<td>1 → 2</td>
<td>1 → 10</td>
</tr>
<tr>
<td>(\Pi_3) Angle of internal friction</td>
<td>25 → 45</td>
<td>39</td>
</tr>
<tr>
<td>(\Pi_4) Gravitational stress/cohesion</td>
<td>2.4×10^{-1} → 12.3</td>
<td>2.8×10^{-1}</td>
</tr>
<tr>
<td>(\Pi_5) Viscous stresses/cohesion</td>
<td>6.3×10^{-11} → 6.3×10^{-1}</td>
<td>4.3×10^{-8} → 1.2×10^{-2}</td>
</tr>
<tr>
<td>(\Pi_6) Inertial/viscous forces</td>
<td>2.5×10^{-6} → 270</td>
<td>1.4×10^{-2} → 1.3×10^{-1}</td>
</tr>
<tr>
<td>(\Pi_7) Magma/country rock densities</td>
<td>0.08 → 0</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Average dimensionless ratios \(\Pi_7\) for nature and experiments.

| Symbols, units, and values of the mechanical variables in nature and experiments |
|----------------------------------|------------------|
| Cohesion of brittle material (C) | Pa |
| Thickness of overburden (D) | m |
| Acceleration due to gravity (g) | m s^{-2} |
| Intrusion thickness (h) | m |
| Intrusion radius (t) | m |
| Magma flow velocity (U) | m s^{-1} |
| Angle of internal friction (ϕ) | |
| Density of magma (ρm) | kg m^{-3} |
| Density of country rock (ρc) | kg m^{-3} |

An average density for natural rocks is about 2500 kg m^{-3}; their cohesion spans between 10^{7} to 10^{10} Pa (Schellart, 2000). Sills are usually emplaced at a few kilometres depth, so that we choose D ranging from 1 to 5 km. Therefore, \(\Pi_4\) in nature yields values ranging from 0.24 to 12.3 (Table 1). Because the model to nature scale ratio is 10^{-5}, we varied D in experiments between 1 and 5 cm. The density of the silica flour was controlled at ∼1050 kg m^{-3}, and the cohesion was ∼370 Pa (Table 1). Therefore, \(\Pi_4\) in experiments yields a value of 0.28, which is towards the lower bound of the range of \(\Pi_4\) in nature (Table 1).

The experiments aim to simulate the transport of viscous fluid into a deforming Coulomb material of cohesion C. The propagation of magma into the rock is controlled by a balance between the flow of magma and the deformation of the country rock. In elastic-plastic materials such as rocks and cohesive granular media, the material deforms both elastically and plastically. If the cohesion of the silica flour is well known, its elastic properties are in turn challenging to estimate and difficult to scale properly. Therefore, we use the cohesion to scale the strength of the rock. Thus, the dimensionless number \(\Pi_3\) to scale the viscosity of magma is the ratio of viscous pressure drop within the fluid along the intrusion to the cohesion (i.e. strength) of the country rock. For lammar flow of a Newton fluid of viscosity η flowing at a velocity U, the viscous pressure drop along a fracture of length l and thickness h is \(\Delta P_v = \eta U l / h^2\) (e.g. Lister and Kerr, 1991; Kavanagh et al., 2006). Thus, the expression of \(\Pi_3\) is:

\[
\Pi_3 = \frac{\eta U}{h^2C}. \tag{4}
\]
The flow regime of magma within intrusions (laminar versus turbulent) is predicted by the Reynolds number, which is the ratio between inertial and viscous forces:

\[ \Pi_6 = \frac{Re}{\eta} = \frac{\rho_m h U}{\eta}. \]  

(5)

The density of magma is 2500 to 2700 kg m\(^{-3}\) for felsic to mafic magma, respectively. Therefore, \(\Pi_6\) in nature ranges between \(2.5 \times 10^{-6}\) and 270 (Table 1). Thus, usually inertial forces are negligible and magma flow is laminar. However, in cases of very fluid magma flowing at high velocity in narrow sills, some local turbulence may occur (Kavanagh et al., 2006; Menand, 2008). In experiments, \(\Pi_6\) ranges between 1.4 \times 10^{-2} and 1.3 \times 10^{-1}, so that inertial forces are also negligible.

The final dimensionless number is the ratio of hydrostatic forces to lithostatic forces, corresponding to the buoyancy of the magma, which can be expressed by:

\[ \Pi_7 = 1 - \frac{\rho_m}{\rho_l}. \]  

(6)

If \(\Pi_7<0\), the magma is heavier than the country rock, and locally negatively buoyant; in contrast if \(\Pi_7>0\), the magma is lighter than the country rock, so that the magma is locally buoyant. In nature, \(\Pi_7\) ranges between \(-0.08\) and \(0\), so that magma is neutrally buoyant to negatively buoyant. In contrast in experiments, \(\Pi_7=0.15\), so that the oil is positively buoyant (Table 1). Therefore, there is a discrepancy between the experiments and geological systems. However, as sills are sub-horizontal conduits, the effect of the buoyancy is very small, as discussed by Lister and Kerr (1991), Kavanagh et al. (2006) and Menand (2008). We will show below that the buoyancy is indeed negligible in both nature and experiments, and is thus not a critical parameter.

2.2. Experimental setup

Our apparatus is a modified version of that developed by Galland et al. (2003, 2006, 2007). The models lay in a square box, 40 cm wide and with variable thickness (Fig. 2). The model rock consisted of a pack of compacted silica flour. The preparation procedure consisted of measuring a mass of flour that we compacted using a high frequency compressed-air shaker sold by Houston Vibrator (model GT-25). Such a procedure allows a homogeneous, repeatable, and fast compaction of the flour.

We want to take into account the mechanical layering to simulate the sedimentary strata. Galland (2005) simulated layering by introducing cohesionless layers made of fine-grained silica spheres into the cohesive silica flour. However, the high frequency shaking mixes the spheres and the flour, so that the layers are not preserved. In the present set of experiments, we simulated layering by introducing a flat flexible net into the flour, of grid size \(\sim 2\) mm. The net simulated a weak layer as it reduced the contacts between the flour grains. In all the experiments, the net was a 30 \times 30 cm square. The advantage of using a net is that the oil can cross it easily, in contrast with a film that prevents the oil from crossing. It is difficult to quantify the heterogeneity associated with the net, and we suspect that it is rather high. Nevertheless, cohesion contrasts in sedimentary basins can sometimes be very important, i.e. several orders of magnitude (e.g. Hoek et al., 1998; Schellart, 2000). Therefore, we consider that introducing a net is reasonable for our purpose. Finally, the net was much larger than the diameters of the intrusions, and the shape of the net (square) was different to those of the intrusions (circular). We thus infer that the boundaries of the net had no influence on the transport of the oil, i.e. there was no boundary effect.

To prepare the experiments with the net, we poured a first layer of flour; then we shook the box to flatten the surface of the flour. Subsequently, we placed the net and a second layer of flour. We shook the box a second time until the density of the upper layer was 1050 kg m\(^{-3}\). Such a procedure induced a density contrast of less than 5% between the lower and upper layers. We consider this difference negligible.

There are two stages in the emplacement of saucer-shaped sills: (1) the emplacement of a planar sill from a feeder, and (2) the evolution of that sill to saucer-shape. In this work, we focussed on the latter stage and we did not consider the feeder-to-sill transition. We therefore located the net right at the top of the inlet, so that the oil formed a sill from the initial stage of intrusion. In nature, feeder structures can be either planar dykes or circular pipes or plugs. The shape of intrusions would obviously depend on the feeder shape. For technical reasons, we chose a circular inlet of 1 cm diameter.

Each experiment typically lasted for a minute, during which we measured the evolution of the oil overpressure (Fig. 3e). After the end of the experiments, the oil solidified within about half an hour. Then, the intrusion was excavated (Fig. 3d), and its top surface digitalized using a moiré projection technique developed by Brèque et al. (2004).

3. Results

Here we present two series of experiments. In the first series (series H), the models were homogeneous, made of pure silica flour. In contrast, in the second series (series L), the models were heterogeneous, with a flexible net simulating layering. In both series, the injection
Fig. 3. Photographs of typical model surface evolution and some excavated model intrusions. a. Initial flat surface. b. After the oil has started intruding, the surface lifts up, forming a dome. c. Eruption of oil. In all the experiments, the oil erupted at the rim of the dome. The dashed line locates the following cross-section. d. 3D view of the cross-section of a model after the end of the experiment. The grey solid body comprises the intrusion itself and an oil percolation aureole in the silica flour. The intrusion exhibits a V-shape in cross-section. The excavated part of the intrusion exhibits a cone shape. e. Plot of typical oil overpressure evolution with time during experiments L3, L4 and L5. The overpressure initially builds up until the intrusion is initiated, and then drops following a hyperbolic trend. This evolution is typical of hydraulic fracturing, as discussed by Murdoch (1993a,b, 2002), Galland (2005) and Galland et al. (2007). Notice that the overpressure is larger than 1000 Pa. f. Experiment H2. The intrusion is a cone-sheet, with its centre corresponding to the inlet position. g. Experiment H4. The intrusion is a sub-vertical dyke. Beneath the surface, it branches to an elongated cone-sheet. h. Experiment L2. The intrusion is a saucer-shaped sill. A small inner sill branches outward to inclined sheets. i. Experiment L4. The intrusion is a saucer-shaped sill. As in experiment L2, it consists of an inner sill and inclined sheets.
depth \((D)\) was a variable parameter, ranging from \(~1\ \text{cm}\) to \(~5\ \text{cm}\) (Table 2). In all experiments, the evolution of the oil overpressure was similar, with a short initial pressure build up to \(5000–10000\ \text{Pa}\), followed by a hyperbolic pressure drop down to \(1000–2000\ \text{Pa}\) (Fig. 3e).

3.1. Homogeneous models (series H)

In the H experiments the flow rate of injection was constant at \(40\ \text{ml min}^{-1}\). During injection, the surface of the models locally lifted up, resulting in smooth circular doming (Fig. 3). Subsequently, the oil reached the surface at the rim of the domes (Fig. 3). The experiments terminated when the oil erupted. The resulting sheet intrusions were a few millimetres thick. This geometry is typical of dykes and sills in nature (Lister and Kerr, 1991; Rubin, 1995).

The model intrusions exhibited various shapes with respect to the injection depth. In experiments H1 to H3, the inlet was shallow \((1.4\ \text{to} \ 3.4\ \text{cm}; \text{Table 2})\), and the intrusions were axi-symmetric inward dipping sheets, converging towards the inlet (Figs. 3d–f and 4a). This geometry is typical of cone-sheets, as commonly observed at central volcanoes (e.g. Ancochea et al., 2003; Klausen, 2004; Pasquare and Tibaldi, 2007). We analysed the intrusion shapes by averaging a series of radial profiles, as described in Fig. 4c–d. Outward dip variations were sometimes visible, as in experiment H3: the intrusion dipped \(45–50^\circ\) near the inlet, whereas it became gentler close to the surface \((\sim 30^\circ); \text{Figs. 4 and 5a})\). In addition, the deeper the injection, the later the eruption occurred (10 s to 28 s; Table 2; Fig. 6a) and the larger the map area of the intrusion \((26\ \text{cm}^2 \text{ to} \ 60\ \text{cm}^2; \text{Fig. 6c})\).

In contrast, in experiments H4 and H5, the inlet was deeper \((4.5\ \text{and} \ 5.5\ \text{cm}, \text{respectively})\) and the resulting intrusions were sub-vertical dykes (Fig. 3g). In experiment H5, at \(1–2\ \text{cm}\) depth the dyke branched to a cone sheet much smaller than those formed in experiments H1 to H3. Consequently, in H4 and H5 the oil moved to the surface more quickly \((5\ \text{s} \text{ to} \ 24\ \text{s}; \text{Table 2; Fig. 6a})\) and the eruption occurred at an earlier stage than in H1–H3. In addition, the map areas of intrusions were also much smaller \((5\ \text{cm}^2 \text{ to} \ 24\ \text{cm}^2; \text{Fig. 6c})\).

3.2. Layered experiments (series L)

In the L experiments the net simulated a layer. The injection flow rate was \(40\ \text{ml min}^{-1}\) also in these experiments. As in the H experiments oil injection resulted in doming; again, the oil erupted along the rim of the domes (Fig. 3). Excavated intrusions exhibited sheet-like bodies a few millimetres thick.

The shapes of the intrusions were a bit more complex than in the H experiments (Figs. 3–5). Their three-dimensional geometry was axially symmetric. Close to the inlet, the oil formed a circular horizontal inner

<table>
<thead>
<tr>
<th>Experiment Type</th>
<th>Injection depth/mm</th>
<th>Intrusion shape</th>
<th>Intrusion duration/s</th>
<th>Area of intrusion/cm²</th>
<th>Diameter of inner sill/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1 Homogeneous</td>
<td>14</td>
<td>Cone sheet</td>
<td>10</td>
<td>26</td>
<td>–</td>
</tr>
<tr>
<td>H2 Homogeneous</td>
<td>25</td>
<td>Cone sheet</td>
<td>26</td>
<td>60</td>
<td>–</td>
</tr>
<tr>
<td>H3 Homogeneous</td>
<td>34</td>
<td>Cone sheet</td>
<td>28</td>
<td>58</td>
<td>–</td>
</tr>
<tr>
<td>H4 Homogeneous</td>
<td>45</td>
<td>Dyke</td>
<td>5</td>
<td>5</td>
<td>–</td>
</tr>
<tr>
<td>H5 Homogeneous</td>
<td>55</td>
<td>Dyke (+cone sheet)</td>
<td>24</td>
<td>24</td>
<td>–</td>
</tr>
<tr>
<td>L1 Layered</td>
<td>10</td>
<td>Saucer</td>
<td>5</td>
<td>17</td>
<td>1.7</td>
</tr>
<tr>
<td>L2 Layered</td>
<td>20</td>
<td>Saucer</td>
<td>17</td>
<td>29</td>
<td>2.1</td>
</tr>
<tr>
<td>L3 Layered</td>
<td>31</td>
<td>Saucer</td>
<td>24</td>
<td>91</td>
<td>5.3</td>
</tr>
<tr>
<td>L4 Layered</td>
<td>41</td>
<td>Saucer</td>
<td>42</td>
<td>117</td>
<td>6.6</td>
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<tr>
<td>L5 Layered</td>
<td>50</td>
<td>Saucer</td>
<td>83</td>
<td>189</td>
<td>7.1</td>
</tr>
</tbody>
</table>

In every experiment, the injection flow rate was \(40\ \text{ml min}^{-1}\).

![Fig. 4. 3D diagrams of the upper surface of typical model intrusions. a. Experiment H3. The intrusion exhibits a typical axi-symmetric cone-sheet shape. b. Experiment L5. The intrusion exhibits a typical axi-symmetric saucer shape, with a flat basal sill, steep inclined sheets, and flat outer sills. c. Map view of the intrusion of experiment L5. The scale is in millimetres. The radial white lines locate serial topographic profiles. The origin of the profiles is centre of the basal sill. d. Plots of the serial radial sections (light gray) of the intrusion of experiment L5. The average profile (red) gives the whole shape of the intrusion.](image-url)
sill that propagated along the net. Subsequently, the inner sill turned into steeply inclined sheets (60°), whose inclinations became gentler towards the surface and sometimes ended in sub-horizontal outer sills (Figs. 4 and 5). The inner sill-to-inclined sheet transition controlled the final shape of the inner sill. In all L experiments the inner sills were close to circular (Figs. 4 and 5). Although the saucer-shaped intrusions in the experiments were axi-symmetric, the centre of the inner sill was not systematically consistent with the location of the inlet (Fig. 5). In L3, the inlet was even next to the rim of the inner sill.

The variable parameters in the L experiments were the depth $D$ of the inlet and the depth of the net, varying between 1 and 5 cm (Table 2). The model intrusions all exhibited similar saucer shapes (Fig. 5); nevertheless the deeper the injection, the wider the inner sills (Table 2; Figs. 5 and 6). The ratio of the inner sill diameter to the emplacement depth ($W/D$) was close to constant about 1.5 in all experiments (Fig. 6c). Positive correlations between the depth of emplacement and intrusion duration, the map area of the intrusions and the diameter of the inner sills illustrate a depth-dependence of the intrusions (Fig. 6).

4. Discussion

4.1. Validity of the scaling

4.1.1. Viscous stresses

A major assumption in the experiments is that the viscous stresses are negligible with respect to the strength of the country rock. This assumption can be verified if the fluid overpressure is larger than the viscous dissipation along the fracture. In the experiments, the measured oil overpressure was larger than 1000 Pa (Fig. 3e), whereas the viscous dissipation along the crack, calculated from $\Delta P_v \sim \eta U/h^2$, is relatively small.
Therefore, the viscous dissipation in the experiments was indeed negligible with respect to the driving overpressure, and so to the strength of the host material. In nature, the estimates of magma driving overpressure within magma conduits range from a few MPa to a few tens MPa (e.g. Pollard and Segall, 1987; Rubin, 1995; Hogan et al., 1998). Considering 20- to 200-meter thick sills with \( \eta \) between 100 and 10 \textsuperscript{7} Pa, \( l \) being 5 km, and \( U \) between \( 5 \times 10^{-4} \text{ m s}^{-1} \) and \( 5 \times 10^{-2} \text{ m s}^{-1} \) (Table 1), the viscous drag along the sills is \( 6.3 \times 10^{-3} \text{ Pa} \) to 6 MPa. Therefore, as in experiments, the viscous drop along sills in usual cases is also negligible with respect to the magma driving overpressure. However, this assumption is not true for very viscous magma flowing at high velocity in narrow sills.

4.1.2. Buoyancy forces

A second critical assumption is the negligible effect of buoyancy on the emplacement of saucers. The buoyancy forces (i.e. hydrostatic forces \( \Delta \rho g h \)) of an intrusion of thickness \( h \) is given by \( \Delta \rho g h \), where \( \Delta \rho = \rho_m - \rho_s \). As discussed by Lister and Kerr (1991), because sills are sub-horizontal intrusions, \( h \) is very small and the buoyancy forces are likely to be negligible. In experiments, \( h \) was typically 1 to 3 mm and \( \Delta \rho \) was \( -158 \text{ kg m}^{-3} \), so that the buoyancy forces of the magma within the intrusions ranged between 1.5 Pa and 4.5 Pa. Thus, as the oil driving overpressure was larger than 1000 Pa, the buoyancy of the intrusion was negligible compared to the driving pressure. In addition, we even observed significant downward flow of the oil in the models below the sills, although the oil is lighter than the surrounding silica flour. This confirms that the buoyancy forces are indeed negligible in the experiments. In nature, sills are often considered to have emplaced along the level of neutral buoyancy (e.g. Francis, 1982; Lister and Kerr, 1991). However, observations show that this assumption is not obvious because heavy magma can rise through lighter rocks such as sediments. In addition, the formation of domes overlying sills and the formation of inclined sheets show that the magma is able to lift up its overburden and to keep rising after being emplaced into sills, so that it is over-pressed. Indeed, the magma driving overpressure results from the local buoyancy integrated along the whole magmatic system, so that the driving pressure of a heavy magma intruding through lighter rocks can be very high (Lister and Kerr, 1991; Hogan et al., 1998; Gerya and Burg, 2007). Usual estimates of the driving overpressure range from \( 10^6 \) to \( 10^8 \) Pa (e.g. Pollard and Segall, 1987; Rubin, 1995; Hogan et al., 1998). In contrast, the buoyancy of a 20- to 200-meter thick sills ranges from \( -3 \times 10^5 \text{ Pa} \) to zero Pa. Thus, usually, in sills as well as in our experiments, the buoyancy forces are negligible with respect to the magma driving overpressure and have negligible effect on the inner sill-to-inclined sheet transition.

In nature and in experiments, the dip angles of the inclined sheets strongly differ. In both case, the dip angle of the inclined sheets is acquired during the very early stage of inclined sheet formation, i.e. when they are very small. In such a configuration, the buoyancy forces are also negligible. Thus, we infer that the difference in the dip angles of the inclined sheets in nature and experiments is not due to differences in buoyancy forces. Nevertheless, we cannot rule out that in the later stages of saucer-shaped sill emplacement where the inclined sheets can be up to 1000 m high, buoyancy forces can be significant.

4.2. General considerations

The overall intrusion geometries in our experiments match major features of intrusions observed in nature. Our homogeneous experiments reproduced sub-vertical dykes and cone sheets, as observed at central volcanoes. Our layered experiments reproduced the three-dimensional shape of saucer-shaped intrusions with a horizontal inner sill along a horizontal weakness, a sharp transition from the inner sill to steep inclined sheets, and a progressive transition from inclined sheets to flatter outer sills (Figs. 4 and 5). Furthermore, the experiments simulate dome formation above the intrusions; the geometrical relationship between dome rims and the inclined sheets was striking (Figs. 1 and 3). In addition, our 3D experimental results also match results from 2D numerical simulations of saucer-shaped sill formation (Malthe-Sørensen et al., 2004). We thus suggest that our experiments simulate well the processes governing the emplacement of saucer-shaped sills in sedimentary basins. In addition, our results suggest that dome-like structures overlying sills are forced folds as proposed by Hansen and Cartwright (2006a, 2007).

The geometry of intrusions is a good indicator of the processes that govern the emplacement of magma. In our experiments, the intrusions formed horizontal sheets with a thickness to width aspect ratio of \(-0.02\). Such aspect ratios are characteristic of dykes and sills formed by hydraulic fracturing in nature (Hubbert and Willis, 1957; Lister and Kerr, 1991; Clemens and Mawer, 1992; Rubin, 1993, 1995). In previous experiments, also using vegetable oil and fine-grained silica flour, Galland et al. (2007) showed that the oil intruded into the silica flour by hydraulic fracturing.

4.3. Emplacement of the inner sill

The rheological properties of the host rock are important parameters that control the emplacement of magma. In experiments with a weak layer, the oil initially intruded along the layer and formed a sill (Figs. 4 and 5). In contrast, in experiments without a layer, oil injection always resulted in the formation of cone sheets or sub-vertical dykes (Figs. 3 and 5). Therefore, the experiments strongly suggest that the formation of flat-lying sheets require layering in the country rock. In nature, sills mostly form in sedimentary basins where strata typically represent strong mechanical layering (e.g. Hoek et al., 1998; Schellart, 2000). Our experiments suggest that the inner sill forms by following a sedimentary layer. This conclusion is supported by previous experimental modelling (Pollard and Johnson, 1973; Hyndman and Alt, 1987; Rivalta et al., 2005; Kavanagh et al., 2006; Menand, 2008), and numerical calculations (Gudmundsson and Brenner, 2001).

The geometrical relationship between the sills and their feeders provide important constraints on the mechanisms of sill emplacement. In our layered experiments, the oil was always connected to the inner sills, although it was not systematically at the centre (Fig. 5). Therefore, the intrusions were always fed from the inner sills and the oil flowed upward and outward within the inclined sheets and the outer sills (Fig. 5). Several models propose that saucer-shaped sills in nature result from feeding from the outer sills or from the inclined sheets, followed by buoyancy-controlled downward flow of the magma to the inner sills (Bradley, 1965; Francis, 1982; Chevallier and Woodford, 1999). However, the models of sills fed from the sides are not consistent with recent AMS (Polteau et al., 2008b) and seismic (e.g. Thomson and Hutton, 2004; Hansen and Cartwright, 2006b; Thomson, 2007a) data, which suggest that magma flows outward and upward in saucer-shaped sill complexes and that the outer parts of the saucers are fed from the inner sills. Our 3D experimental results support the model of saucers fed from the inner sill, and are consistent with previous 2D models (Pollard and Johnson, 1973; Malthe-Sørensen et al., 2004).

4.4. Inner sill-to-inclined sheet transition

The sharp inner sill-to-inclined sheet (IS-ISH) transition is the most characteristic feature of saucer-shaped intrusions. In our experiments, the IS-ISH transition documents the transition between (1) the emplacement of the inner sill following a layer and (2) the emplacement of the inclined sheet propagating away from the layer. Former models of sill intrusion in layered media also reproduced similar sharp transitions (Johnson and Pollard, 1973; Malthe-
correlated (Fig. 6), and (3) the inclined sheets always formed directly underneath the rims of the domes (Fig. 3). Such systematic relationships imply that the formation of the domes and the inclined sheets is genetically linked. In nature, saucer-shaped intrusions exhibit similar three-dimensional shapes, depth-dependence trends, and geometrical links with overlying domes (Fig. 1; Hansen et al., 2004a; Malthe-Sørenssen et al., 2004; Polteau et al., 2008a), suggesting that the layering plays a major role in sill emplacement.

In our experiments (1) the IS-ISH transitions exhibited sub-circular shapes similar to those of the overlying domes (Figs. 4 and 5), (2) the emplacement depths and the diameters of the inner sills are positively correlated (Fig. 6), and (3) the inclined sheets always formed directly underneath the rims of the domes (Fig. 3). Such systematic relationships imply that the formation of the domes and the inclined sheets is genetically linked. In nature, saucer-shaped intrusions exhibit similar three-dimensional shapes, depth-dependence trends, and geometrical links with overlying domes (Fig. 1; Hansen et al., 2004a; Malthe-Sørenssen et al., 2004; Polteau et al., 2008a).

The detailed processes governing the IS-ISH transition and the role of the overlying dome are poorly understood. In our experiments, we cannot observe the in situ evolution of the structures because the silica flour is opaque. We have demonstrated earlier that the buoyancy forces are negligible both in nature and in our experiments, so that the IS-ISH transition is not controlled by the buoyancy of the magma. Former work has addressed similar processes in relationship to growing cracks interacting with a free surface (Johnson and Pollard, 1973; Pollard and Johnson, 1973; Pollard and Holzhausen, 1979; Fialko, 2001; Bunger and Detournay, 2005; Bunger et al., 2005). That suggests that the layering controls the formation of sharp inner sill-to-inclined sheet transitions. In nature, field observation show that such sharp IS-ISH transitions occur (e.g. Chevallier and Woodford, 1999; Polteau et al., 2008a), suggesting that the layering plays a major role in sill emplacement.

In our experiments, we infer the following scenario for the emplacement of saucer-shaped intrusions (Fig. 7): (1) a shallow sill grows and spreads along a layer parallel to the surface, (2) the sill deforms its overburden by doming (Fig. 7a), (3) shear stresses at the edges of the dome result in asymmetric stresses at the crack tip (Fig. 7b; Malthe-Sørenssen et al., 2004), and (4) when the sill reaches a diameter of approximately 1.5 times the thickness of the overburden in our experiments (Fig. 6c), an inclined sheet is initiated (Fig. 7c). Malthe-Sørenssen et al. (2004) suggested that such a transition occurs when the asymmetric stresses reach a critical value and deflect the crack tip upward.

The deformation mode of the overburden may play a major role for the location of the IS-ISH transition (Fig. 7). In our experiments, the silica flour was an elasto-plastic material (Galland et al., 2006; Galland et al., 2007), and plastic deformation, i.e. faulting, was likely to occur at the rim of the domes and to trigger the formation of inclined sheets. In contrast, previous works considered an elastic overburden, and control of the IS-ISH transition by elastic stresses (Johnson and Pollard, 1973; Pollard and Johnson, 1973; Pollard and Holzhausen, 1979; Fialko, 2001; Fialko et al., 2001; Malthe-Sørenssen et al., 2004; Bunger and Detournay, 2005; Bunger et al., 2005; Goulty and Schofield, 2008). In nature, seismic data sometimes show that the seismic reflectors are offset at the rims of overlying domes (Fig. 1c; Hansen and Cartwright, 2006a), suggesting that plastic deformation plays a significant role in the IS-ISH transition (Galland, 2005). The role of plastic deformation of the country rock has important implications for the emplacement of shallow sills in very weak unconsolidated sediments. In such sediments, magma does not intrude by hydraulic fracturing and the resulting intrusions are likely to exhibit lobate shapes (e.g. Hallot et al., 1996). In addition, the thermal effect of sills on such water-rich sediments often leads to the formation of perorites (e.g. Busby-Spera and White, 1987; Skilling et al., 2002; Galerne et al., 2006).

The rheological architecture of the country rock may also play a major role on the formation of inclined sheets. In our experiments, where sill overburden was homogeneous, the inner sill diameter to emplacement depth aspect ratio (W/D) was 1.5 (Figs. 4 and 5) and the dip angles of the inclined sheets were 40°–50°. In contrast, in sedimentary basins where sill overburden is typically layered, the W/D ratios for natural sills are larger (3-4; Fig. 8; Malthe-Sørenssen et al., 2004; Polteau et al., 2008a), and the dip of the inclined sheets is gentler (10°–30°) than in our experiments. As we demonstrated above, the buoyancy of the magma is negligible in both nature and experiments, so that such a discrepancy cannot be inferred from a buoyancy effect. In contrast, Galland (2005, Chapter 5) suggested that the mechanical layering of the overburden plays a major role in the formation of the IS-ISH transition. In the experiments of Galland (2005, Chapter 5), experiments with strong homogeneous overburden resulted in small inner sills with steep inclined sheets, whereas experiments with thin weak layers resulted in wider inner sills and gentler inclined sheets. Such a difference comes from the different elastic stiffness of the overburden, where a homogeneous
medium is elastically much stiffer than a multilayered one (e.g. Pollard and Johnson, 1973; Galland, 2005). Thus, we infer that a growing sill may spread easily underneath a low stiffness layered overburden, like in a sedimentary basins, whereas a stiff homogeneous overburden will prevent the sill from spreading, like in our experiments.

4.5. Geological implications

The understanding of the emplacement of saucer-shaped sills has important implications for oil exploration (Hansen and Cartwright, 2006a). Indeed, the emplacement of large sills into organic-rich layers can trigger or enhance the maturation of organic matter (e.g. Galushkin, 1997; Svensen et al., 2004; Fjeldskar et al., 2008). In addition, the domes overlying saucer-shaped sills represent potential traps for hydrocarbons (Trude et al., 2003; Hansen and Cartwright, 2006a; Tulipan sill, Møre Basin; Polteau et al., 2008a). Thus, the systematic association of saucer-shaped sills and overlying domes may generate local petroleum prospects.

In this study, we have shown that saucer-shaped sills result from a fundamental interaction between intruding shallow sills and doming of the overburden in sedimentary basins. The understanding of such processes also has wide implications for the understanding of sub-volcanic systems. Intrusions similar to saucer-shaped sills are observed in active and exhumed volcanoes (e.g. O’Driscol et al., 2006; “Cup-shaped intrusions” of Mathieu et al., 2008). Those intrusions are often associated with deformation structures of the volcanic edifices, including doming (Chang et al., 2007; Mathieu and Van Wyk de Vries, 2005) and caldera collapse (e.g. Walter and Troll, 2001; Troll et al., 2002). Thus, flat-lying and saucer-shaped intrusions are likely to play a major role in the volcanological and deformation histories of volcanic systems. In addition, we suspect that sill intrusions represent more realistic magma reservoir geometry than the usually assumed spherical or elliptical magma chambers (e.g. Gudmundsson, 1998, 2006; Gudmundsson and Philipp, 2006). Our results show that experimental modelling is a very useful method to understand magmatic and sub-volcanic systems.

5. Conclusions

In this paper, we have described the results of experimental modelling of shallow magma intrusion in sedimentary basins. The model magma (molten vegetable oil) was injected at a constant flow rate into a model crust (cohesive silica flour). Our main experimental results are the following.

1. The oil injection systematically induced doming of the surface of the models right above the intrusions. The domes were sub-circular with a few millimetres of relief. The oil always erupted at the rim of the domes.
2. The oil intruded by hydraulic fracturing and resulted in sheet intrusions (dykes, cone sheets, and saucer-shaped sills).
3. In homogeneous experiments, intrusions were cone sheets and resulted in sheet intrusions (dykes, cone sheets, and saucer-shaped sills).
4. In layered experiments, the sills developed three-dimensional structures, including doming (Chang et al., 2007; Mathieu and Van Wyk de Vries, 2005) and caldera collapse (e.g. Walter and Troll, 2001; Troll et al., 2002). Thus, flat-lying and saucer-shaped intrusions are likely to play a major role in the volcanological and deformation histories of volcanic systems. In addition, we suspect that sill intrusions represent more realistic magma reservoir geometry than the usually assumed spherical or elliptical magma chambers (e.g. Gudmundsson, 1998, 2006; Gudmundsson and Philipp, 2006). Our results show that experimental modelling is a very useful method to understand magmatic and sub-volcanic systems.