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Solidification effects on sill formation: An experimental approach

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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.

1. Introduction

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

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

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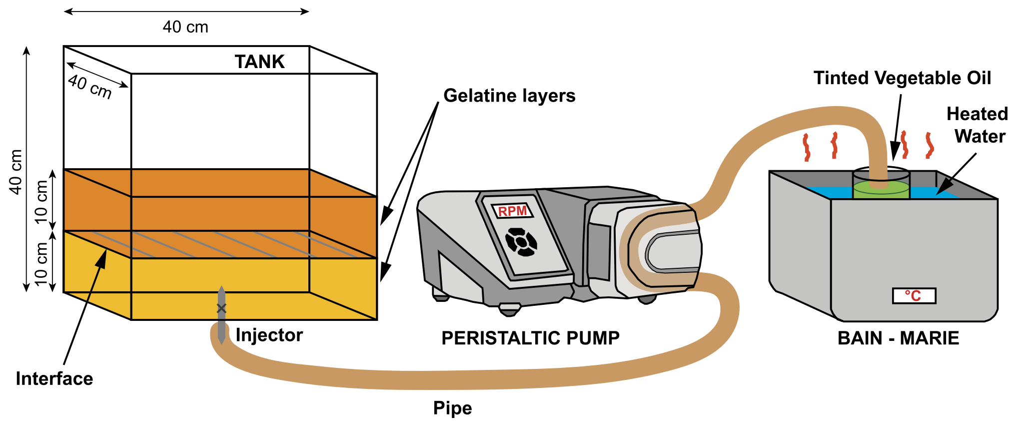

Fig. 1. Experimental apparatus. The gelatine solid has two layers of different stiffness, to create a priori favourable conditions to form sills. Vegetable oil is heated with a bain-marie and injected at a constant rate with a peristaltic pump in the layered gelatine solid.

All experimental and numerical studies on sill intrusions have therefore been carried out under isothermal conditions and have neglected the potential effect of magma solidification on sill formation and propagation. In fact, very few studies have dealt with cooling and solidification effects on intrusions. Theoretical studies (e.g. Bolchover and Lister, 1999; Lister, 1999) are limited to two dimensions, and so provide only a limited understanding of solidification effects because intrusions such as dykes and sills are inherently three-dimensional objects (e.g. Taisne and Tait, 2009, 2011). To our knowledge, Taisne and Tait (2011) are the only ones to have investigated experimentally solidification effects on intrusion propagation, focusing on dykes. They found that solidification effects have a strong impact on dyke dynamics: when solidification effects are important, dykes display an intermittent, stepwise mode of propagation, during which dykes momentarily stop propagating and then swell without advancing, before resuming their propagation when the incoming fluid that is stored in the fissure is able to fracture both the surrounding solid and the frozen crust that has developed within the fissure. Without solidification, dyke propagation operates continuously. Additionally, solidification affected the propagating dyke by focusing fluid flow in its central portion, hence limiting its horizontal dimension, and by adding a more complex geometry owing to the successive and intermittent outbreaks of fluid that occurred around the dyke periphery and sometimes away from its tip. These findings raise naturally the question of the effects that solidification could potentially have not only on the geometry and the dynamics of sills, but also on their formation.

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

2. Experimental approach

2.1. Experimental apparatus

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

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

2.2. The gelatine

The gelatine used is a 260 bloom, 20 mesh, pig-skin derived gelatine powder prepared in two batches to obtain a final solid with two layers of the same volume but different stiffness. The upper layer has to possess a higher stiffness than the lower layer, in order to create mechanically favourable conditions to form sills (Kavanagh et al., 2006). A higher gelatine concentration leads to a higher rigidity. The first batch of gelatine was poured in the tank, which was then placed in a fridge at a temperature of $\simeq 5\,^{\circ}\mathrm{C}$ for $\simeq 24$ h. Once the gelatine was solid, the second batch was poured in the tank, which was then placed back in the fridge and kept at the same temperature for another $\simeq 72$ h before running an experiment.

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