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The effects of solidification on sill propagation dynamics and morphology

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ABSTRACT

Sills are an integral part of the formation and development of larger plutons and magma reservoirs. Thus sills are essential for both the transport and the storage of magma in the Earth's crust. However, although cooling and solidification are central to magmatism, their effects on sills have been so far poorly studied. Here, the effects of solidification on sill propagation dynamics and morphology are studied by means of analogue laboratory experiments. Hot fluid vegetable oil (magma analogue), that solidifies during its propagation, is injected as a sill in a colder layered gelatine solid (elastic host rock analogue). The injection flux and temperature are maintained constant during an experiment and systematically varied between each experiment, in order to vary and quantify the amount of solidification between each experiments. The oil is injected directly at the interface between the two gelatine layers. When solidification effects are small (high injection temperatures and fluxes), the propagation is continuous and the sill has a regular and smooth surface. Inversely, when solidification effects are important (low injection temperatures and fluxes), sill propagation is discontinuous and occurs by steps of surface-area creation interspersed with periods of momentary arrest. The morphology of these sills displays folds, ropy structures on their surface, and lobes with imprints of the leading fronts that correspond to each step of area creation. These experiments show that for a given, constant injected volume, as solidification effects increase, the area of the sills decreases, their thickness increases, and the number of propagation steps increases. These results have various geological and geophysical implications. The morphology of sills, such as lobate structures (interpretation of 3D seismic studies in sedimentary basin) and ropy flow structures (field observations) can be related to solidification during emplacement. Moreover, a non-continuous morphology as observed in the field does not necessarily involve multiple injections, but could instead reflect a continuous, yet complex morphology induced by solidification effects during emplacement. Also, a discontinuous sill propagation induced by solidification effects should be associated with bursts of seismic activity. Finally, our study shows that once a sill has initiated, the dimensionless flux influences the sill thermal state, and in turn its propagation, and final extent and thickness. In restricting the lateral extent of sills, magma cooling and solidification are likely to impact directly the size of plutons constructed by amalgamated sills.

1. Introduction

It is now accepted that large magma bodies are constructed by amalgamation of smaller magmatic intrusions (e.g. Menand et al., 2011, and reference therein). In many cases, these increments are mostly sills, which could then be considered as building blocks for larger magma bodies, and thus as essential for magma transport and storage in the Earth's crust. Moreover, the size of plutons and magma reservoirs depends on the size of the sills that built them, i.e. mainly on their lateral extent (e.g. Horsman et al., 2009) and emplacement rate (Menand et al., 2011; Annen et al., 2015). In turn, the size of reservoirs determines the frequency, size and type of volcanic eruptions (Caricchi et al., 2014), a key question in volcanism. However, we do not know what constrains the lateral extent of sills. Like large magma reservoirs, sills have a very large range of sizes: from less than a meter thick (e.g. Dickin and Jones, 1983, Isle of Skye, Scotland) to covering thousands of square kilometres (e.g. Muirhead et al., 2012, Ferrar sills, Antarctica). Furthermore, a lot of studies deal with the evolution of sills in laccoliths (e.g., Bunger and Cruden, 2011; Michaut, 2011; Horsman et al., 2009; Saint Blanquat et al., 2006; Currier and Marsh, 2015) and with the conditions that turn a dyke

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fissure into a sill (e.g. Kavanagh et al., 2006; Maccaferri et al., 2011) but no model predicts the dynamic and the lateral extent of the sills themselves, and thus that of larger magmatic bodies. The variety of sizes displayed by sills could reflect variations in source conditions such as injected volume, source overpressure or magma composition, although these parameters are not well constrained. An additional challenge is locating the feeders of large sills, which could form as continuous bodies or instead as the amalgamation of several discrete, smaller sills. With the latter interpretation, the growth of large sills would be similar to that of other plutons, and so the dynamics of the smaller sills would be the dominant control. To our knowledge, one aspect of sill dynamics that has never been quantified is the influence of magma cooling and progressive solidification during propagation. These could potentially control the lateral extent of sills.

Even though cooling and solidification are central to magmatism, their effects on intrusion propagation are poorly understood. Nevertheless, some studies have shown that they could have a significant impact. The formation of a solidified crust on lava flows impacts their morphology and dynamics (Griffiths and Fink, 1993; Fink and Griffiths, 1990). Holness and Humphreys (2003) studied the Traigh Bhán na Sgúrra Sill (Isle of Mull, Scotland) and showed that thermal evolution affected its petrography and morphology, and determined where and how long it stayed active. Likewise, the analogue experiments of Taisne and Tait (2011) showed that solidification has important effects on dyke propagation and morphology. This effect could be as important in sills. Chanceaux and Menand (2014) showed that solidification affects sills by restricting the range of favourable conditions for their formation. Theoretical studies show also how a fissure eruption can be locally blocked by solidification, even if there is still a magma supply (Bruce and Huppert, 1989). However, theoretical studies are limited to two dimensions when intrusions are three-dimensional objects. This could explain some discrepancies between theory, which predicts that a dyke cannot resume its propagation once it has solidified and stopped (Bolchover and Lister, 1999), and analogue experiments that show instead how solidification can induce discontinuous dyke propagation with successive momentary arrests interspersed with propagation steps (Taisne and Tait, 2011). Thus, a better understanding of solidification and thermal effects on magma transport in the crust is still needed. This will help refine our interpretations of both field and geophysical data (e.g. radar interferometry of surface deformation, monitoring of seismic activity, or 3D seismic interpretation).

The analogue laboratory experiments presented here were designed to quantify the potential effect fluid solidification could have on both sill propagation dynamics and morphology (including their size) when a sill has already formed, for given initial conditions. Section 2 details our apparatus, procedure and data processing used to analyse our experiments. Section 3 presents our results and observations. We discuss in section 4 their geological implications for the morphology of sills, the dynamics of sills and observed seismicity, and the growth of laccoliths and plutons, before concluding in section 5.

2. Experimental approach

All the parameters used in this paper are summarized in Table 1.

2.1. Experimental apparatus

The experiments described here involved the injection of hot vegetable oil (magma analogue) in a colder gelatine solid (host rock analogue) inside a tank of 40 × 40 × 40 cm made of PMMA.

Table 1

Notation and parameters.

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T_i	Injection temperature	°C
Q	Injection flux	$m^3\,s^{-1}$
E_{upp}	Young's modulus of the upper layer	Pa
E_{low}	Young's modulus of the lower layer	Pa
ΔE	Rigidity contrast between the two layers	–
w_{upp}	Concentration of gelatine in the upper layer	wt.%
w_{low}	Concentration of gelatine in the lower layer	wt.%
θ	Dimensionless temperature	–
T_s	Solidification temperature	°C
T_g	Host temperature	°C
φ	Dimensionless flux	–
H	Thickness of the sill	m
L	Length of the sill	m
κ	Thermal diffusivity	$m^2\,s^{-1}$
V	Injected volume	m^3
m	Elastic stiffness of the host	Pa
t	Time of injection	s
η	Intrusion viscosity	Pa s
E	Young's modulus of the host	Pa
ν	Poisson's ratio of the host	–
S	Area of the sill	m^2
η_i	Viscosity of the injected fluid	Pa s
S_{max}	Final area of the experimental sill	m^2
H_{max}	Maximum thickness of the experimental sill	m
V_{final}	Injected volume of vegetable oil	m^3
P	Number of steps	–
t_{final}	Duration of the experiment	s
S_i	Isothermal area	m^2
H_i	Isothermal thickness	m
t_s	Solidification time of the experimental sill	s
λ	Constant parameter (calculation of t_s)	–
C_e	Crystallisation enthalpy of vegetable oil	J
H_c	Heat capacity of vegetable oil	$J\,kg^{-1}\,K^{-1}$
τ	Dimensionless time	–
ξ	Dimensionless area	–
ψ	Dimensionless thickness	–
$\eta_{adjusted}$	Adjusted viscosities	Pa s

The gelatine had two 10 cm-thick layers. The tank had a circular opening of 1 cm diameter on one side to inject the vegetable oil directly at the interface between the two layers (Fig. 1), with no creation of dykes, in order to study the effects of solidification on dynamics of a sill once it is already formed (the effects of solidification on sill formation have already been investigated in a previous study: Chanceaux and Menand, 2014). The solidification temperature of the vegetable oil is higher than that of gelatine, which allowed the analogue intrusion to partially solidify during its propagation depending on injection conditions. The injection temperature T_i and the injection flux Q were controlled independently and maintained constant during each experiment. These conditions were varied between experiments in order to observe and quantify the effects of solidification on sill propagation.

For each experiments, we carried out the following procedure. The vegetable oil was heated with a bain-marie to the desired temperature. The hot oil was then injected in the cold gelatine solid through a 4 mm-diameter metal tube that was inserted directly at the interface between the two gelatine layers to ensure sill formation (Fig. 1). The metal tube was connected to a pipe fed by a peristaltic pump, which allowed us to both control and maintain the volumetric injection flux Q constant throughout each experiment. Each experiment corresponded to one single sill associated with a single pulse of fluid injected at a constant injection temperature and a constant injection flux directly at the interface between the two gelatine layers. The temperature of the vegetable oil at the injector tip and the temperature of the gelatine solid were continuously recorded throughout the experiments with thermocouples while the experiments were recorded by a video camera situated above the tank.