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The mechanics of sill inception, propagation and growth: Experimental evidence for rapid reduction in magmatic overpressure

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ABSTRACT

A model of magma propagation in the crust is presented using a series of analogue experiments, where dyed water is injected at a constant flux into layers of solidified gelatine. The gelatine layers are transparent and, when intruded, deform in an almost ideal-elastic manner under the experimental conditions (low gelatine concentration: 2.5 or 3 wt%, and low temperature: 5–10 °C). The upper gelatine layer was 1.0 to 1.5 times stiffer than the lower layer, with either a 'weak' or 'strong' interface strength between the gelatine layers. The gelatine is seeded with 20–50 μm-diameter PMMA-RhB neutrally buoyant particles that are fluoresced by a pulsed, vertical laser sheet centred on the injection point. Digital image correlation (DIC) is used to calculate incremental strain and finite strain in the deforming host material as it is intruded. This is mapped in 2D for the developing experimental volcanic plumbing system that comprises a feeder dyke and sill. Since the gelatine deforms elastically, strain measurements correlate with stress. Our results indicate that, for constant magma flux, the moment of sill inception is characterised by a significant magmatic pressure decrease of up to ∼60%. This is evidenced by the rapid contraction of the feeder dyke at the moment the sill forms. Sill propagation is then controlled by the fracture properties of the weak interface, with fluid from the feeder dyke extracted to help grow the sill. Pressure drops during sill inception and growth are likely to be important in volcanic systems, where destabilisation of the magmatic plumbing system could trigger an eruption.

1. Introduction

The mechanisms through which magma is stored and transported through the crust have important implications for the development of volcanic plumbing systems and the construction of the continental crust. Magma propagates through the crust within fractures; these are called dykes if discordant with stratigraphic layering, or sills if concordant. Successive sill emplacement at depth has been linked to the formation of large igneous bodies such as laccoliths, magma chambers and plutons (Cruden and McCaffrey, 2001; Leuthold et al., 2012; Menand, 2008). Volcanic plumbing systems comprise a series of dykes, cone sheets and sills that connect source magma reservoirs with volcanic conduits to feed eruptions at the surface (e.g. Geshi et al., 2010). Placing constraints on the factors that influence dyke and sill formation and growth may improve our understanding of eruption processes, and so is significant when appraising volcanic hazards. Magma intrusions also merit economic considerations, as they have been shown to improve the petroleum prospects of sedimentary basins by providing heat to help mature organic materials (e.g. Malthe-Sørenssen et al., 2004), can be important reservoirs for diamonds via kimberlite magma (e.g. Gernon et al., 2012; Kavanagh and Sparks, 2011; White et al., 2012) and they act as conduits and traps for Ni-sulphide ore deposits (Naldrett, 2011; Saumur et al., 2015).

Several mechanisms for sill formation have been hypothesised. The magma buoyancy hypothesis suggests the magma intrudes at its neutral buoyancy level (Francis, 1982; Taisne and Jaupart, 2009). Reorientation of local or regional stresses can also cause a vertically propagating dyke to turn and intrude horizontally as a sill (Menand et al., 2010; Valentine and Krogh, 2006). Crustal heterogeneities can be important in controlling where a sill forms (Galland et al., 2009; Magee et al., 2013a; Thomson and Schofield, 2008), for example by the presence of a weak interface between rock layers (Kavanagh and Pavier, 2014; Maccaferri et al., 2011), modifications in pore fluid pressure (Gressier et al., 2010) or where

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there are rigidity (Kavanagh et al., 2006; Rivalta et al., 2005) or strength (Gudmundsson, 2011) contrasts between layers.

Much of our understanding of the dynamics of magma transport in the crust comes through studying ancient, solidified systems using a combination of field and geophysical techniques (Daniels et al., 2012; Magee et al., 2013a; Muirhead et al., 2014; Schofield et al., 2012; Thomson and Hutton, 2004). Substantial insights have been gained from voluminous sill complexes that intruded sedimentary basins (e.g. Magee et al., 2013b; Svensen et al., 2012). Using these observations to comment on dynamical processes is however not straightforward. Imaging and monitoring active magma intrusion is also problematic, potentially relying on opportunistic placement of geophysical equipment or satellites (e.g. Gudmundsson et al., 2014; Sigmundsson et al., 2014) and the interpretation of signals with multiple possible origins. Analogue and numerical models have therefore proved to be important additional tools to help study magma intrusion in the crust, and to aid the interpretation of surface and sub-surface signals of their propagation (see Rivalta et al., 2015 for a review). In particular, the mechanics of the dyke-to-sill transition (e.g. Galerne et al., 2011; Johnson and Pollard, 1973; Pollard and Johnson, 1973; Valentine and Krogh, 2006) and the associated sub-surface and surface deformation signals, such as strain and stress changes, are not well constrained.

To model the emplacement mechanics of magmatic intrusions and links with volcanic activity, gelatine analogue experiments were carried out to characterise the dynamics of dyke propagation, sill inception and sill propagation. We first present a characterisation of the gelatine crustal analogue, followed by a description of the experimental setup and results that can be extracted using digital image correlation (DIC).

2. Analogue modelling

2.1. Crustal analogue characterisation

Gelatine is a visco-elastic material whose properties are sensitive to concentration, temperature and pH (Kavanagh et al., 2013). Previous work has shown that at low temperature (between 5 and 10 °C) and low concentrations (2 to 5 wt%), gelatine is a suitable analogue material for modelling magmatic intrusions in the crust (Kavanagh et al., 2013).

To fully characterise the deformation behaviour and stress-strain relations of the gelatine during the analogue experiments, a series of tests were carried out using a Haake MARS III rotational rheometer (Fig. 1). Gelatine mixtures were prepared following the procedures of Kavanagh et al. (2013). During cooling, gelatine mixtures undergo a curing process whereby a macromolecular network develops. This curing process can be monitored by a rotational rheometer. Oscillation tests were carried out using a 35 mm parallel-plate head geometry, and imposing a shear stress of 1 Pa at a frequency of 10 rad/s for a specified temperature (5 °C or 10 °C). During curing, the energy storage of the gelatine evolves such that the shear storage modulus (G') significantly increases compared to the shear loss modulus (G'') (Fig. 1A). Once the complex shear modulus $G^* = G' + iG''$ has stabilised (Metzger, 2013) the material is considered to have cured. For rheometer tests at the specified conditions, the curing time of 2.5 wt% gelatine mixtures at 5 °C was approximately 1 h (3600 s) (Fig. 1A). Previous work has shown that the curing time of forty litres of the same concentration gelatine cooled in a refrigerator set at 5 °C is on the order of 100 h (Kavanagh et al., 2013). Amplitude sweep rheological experiments were then carried our to measure the stress imposed by a logarithmically increasing rotational stress (0.01–10,000 Pa at 10 rad/s; Fig. 1B) with an estimated error of <3% (Thermo Fisher). At these conditions the gelatine deforms as an almost ideal elastic material, with yielding occurring at approximately 1000 Pa stress and strain of 1 (Fig. 1B). The gelatine has Poisson's ratio of 0.5 (see papers in Kavanagh et al., 2013).

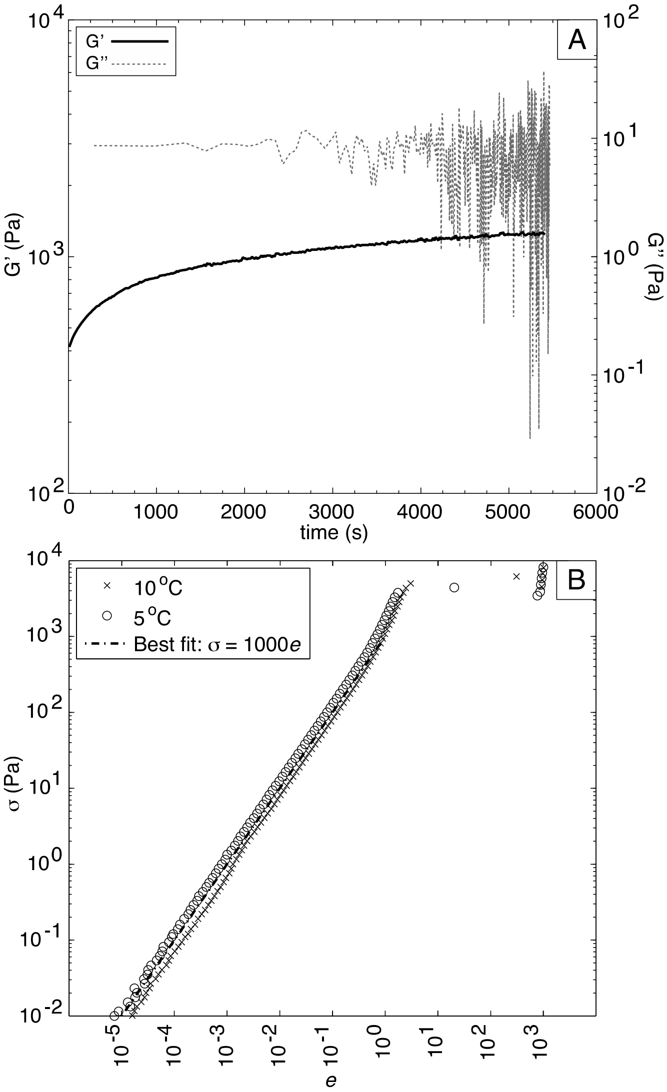

Fig. 1. Mechanical properties of gelatine at the conditions of the analogue experiments. A) Shear storage modulus G' and shear loss modulus G'' plotted against time for 2.5 wt% gelatine mixtures at 5 °C. Note the log axes. The gelatine curing time is reached after approximately 1 h (3600 s). Data were obtained via an oscillation test using a rotational rheometer. B) Positive linear correlation of stress σ (Pa) and strain e for cured 2.5 wt% gelatine mixtures at low temperature (5 °C and 10 °C). A linear model is fitted for strains up to 1 in the region where the material deforms elastically: $\sigma = 1000e$ ($R^2 = 0.99$). Data were obtained via an amplitude sweep test using a rotational rheometer.

2.2. Experimental setup

The analogue experiments were carried out in a 30 × 40 × 40 cm^3 clear-Perspex tank (Fig. 2) filled with a mixture of pigskin gelatine (20 Mesh, 260 Bloom; Gelita UK) and almost boiling distilled water. Before setting, the gelatine solution was seeded with 20–50 μm-diameter PMMA-RhB fluorescent spheres (peak excitation wavelength ∼540 nm); stirring the mixture until it cooled to the gel-point (21 °C) ensured even distribution within the gelatine solid.

Experiments were designed to have either a 'weak' or 'strong' interface strength between the gelatine layers. The strength of the interface depends on the amount of welding that occurs during the preparation of the experiment as the upper gelatine layer