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Buoyancy-driven fracture ascent: Experiments in layered gelatine

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Abstract

Laboratory experiments on air-filled fracture propagation in solidified homogeneous and layered gelatine have been carried out, providing an analogue model for magma-filled dikes ascending in the crust. The effects of layering on fracture velocity and shape have been analyzed in detail. The free surface is found to accelerate approaching fractures. Layering accelerates or decelerates fractures approaching discontinuities of the elastic parameters, depending on the value of the rigidity contrast. The shape of fractures are strongly influenced as they pass from one layer to another. The observed cross-sectional shape when crossing a layer interface and the acceleration with decreasing rigidity can be explained with theoretical models. Our experiments also reproduce the arrest of fractures in proximity of joints and the formation of sills in the layer below the interface. These findings could help in the interpretation of accelerated seismicity and deformation rates observed in volcanic areas.

Keywords: analogue experiments; layered media; fluid-filled fractures; dike propagation; sill

1. Introduction

High contrasts in the elastic parameters are common at shallow depth in volcanic areas or at the crust–mantle transition. Several volcanic edifices lie on very stiff basaltic basements, whereas the edifices themselves are commonly much more compliant, as demonstrated by several tomographic studies (e.g. Patanè et al., 2002; Di Stefano and Chiarabba, 2002). Vertical profiles of elastic parameters are therefore characterized by high rigidity contrasts.

In some areas cold brittle rocks lie on hot viscoelastic materials. This situation is found for example in hot-spot areas, where upwelling plumes influence the rheology of the surrounding materials. Often these situations are manifested through low-velocity layers for shear waves. Although these and other temperature-controlled interfaces may be smooth, a sharp interface approximation may be useful when dikes are considerably longer than the transition zone width.

Numerical and analytical models (Tinti and Armigliato, 1998; Bonafede and Rivalta, 1999a,b; Gud-

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mundsson and Marinoni, 1999) show that such rigidity contrasts are responsible for stress concentrations and changes in fracture shapes. As a result of the interaction between magma-filled fractures and discontinuity surfaces, the enhanced deformation can trigger seismic events.

Gelatine has been used several times in experimental works on fluid-filled fracture propagation (Johnson and Pollard, 1973; Pollard and Johnson, 1973; Takada, 1990, 1994a,b; Heimpel and Olson, 1994; Dahm, 2000b; Menand and Tait, 2002; Ito and Martel, 2002). Laboratory experiments with fluid injections into gelatine are analogous to dike ascent in the crust and provide a 3D analogue model with several advantages for observations: gelatine is transparent, brittle at room temperatures, and the typical length of propagating fractures is of the order of centimeters. Furthermore, the elastic parameters can be controlled by varying the concentration of gelatine in water.

The injection phase, when the fracture is typically penny-shaped, and the propagation stage, when the fracture is arched-door-shaped and moves with constant velocity toward the surface, have already been documented in previous studies. The process is well described by the Weertman model (Weertman, 1971), that provides the fundamental equations governing buoyancy-driven fluid-filled fractures in solid materials and is able to predict the cross-sectional shape of ascending fractures with high accuracy.

In a detailed work Johnson and Pollard (1973) and Pollard and Johnson (1973) studied the growth of Laccolithic intrusions and performed laboratory experiments in layered gelatine. They injected oil or grease of nearly neutral buoyancy directly into the layer interface in order to study the lateral growth and the deformation of the overburden. In contrast to these experiments, our study concentrates on the buoyancy-driven ascent of intrusions and the impact of layer interfaces on ascent velocity and emplacement.

The aim of this work is thus to investigate experimentally how fluid-filled fractures propagate in layered media. We analyze both possible situations:

(1) experiments H2L: the fracture propagates from a high rigidity towards a low-rigidity medium,
(2) experiments L2H: the opposite layering.

We discuss the main influence of the discontinuity with respect to the homogeneous case and the relevance of the rigidity and fracture toughness contrasts. The acceleration or the stopping of fractures can also be observed in the experiments, as well as the formation of horizontal, sill-like intrusions just below the layer interface.

2. Experimental technique

2.1. Laboratory experiments

Gelatine is transparent and at 4 °C brittle for the typical loading times of our experiments (<30 min). Density and bulk modulus are similar to that of water, i.e. $\rho \approx 1000$ kg/m^3 and K=2.2 GPa. The shear modulus is very small, in the range between 50 and 10 000 Pa, depending on the concentration of the gelatine. We used concentrations between 2% and 5% leading to 75 Pa$\leq G \leq$2000 Pa (Table 1). Due to the large Poisson number of $v \cong 0.5$ the relative deformation and the opening-length ratio of fractures is larger than for fractures in rock.

The development of fractures crucially depends on the involved parameters: type and volume of injected viscous fluids, elastic constants and fracture toughness K_C of the two layers. After Weertman (1971), the critical half-length necessary for propagation can be expressed by

$$a_C = \left(\frac{K_C}{\sqrt{\pi} \Delta \rho g} \right)^{\frac{2}{3}} \tag{1}$$

where $\Delta\rho$ is the density difference between the solid (in our case gelatine) and fluid (in our case air) and g the gravity acceleration. We approximate $\Delta\rho$ with ρ_{water}. The fracture toughness K_C is approximately given by $K_C = \sqrt{4\gamma_s G(1+v)} = \sqrt{\gamma_s 6G}$, where γ_s1 J m^{-2} is the surface energy of gelatine (see Menand and Tait, 2002). Typical critical fracture lengths in our experiments were between 2 and 10 cm and the opening-length ratio was between 0.01 and 0.07. For rock and magma-filled dikes the critical dike-lengths are in the order of kilometer having an opening-length ratio of about 0.001.

For the experiments we have used two types of acrylic glass containers: a rectangular one (length=40 cm, width=30 cm, height=50 cm) and a cylindric one