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Experimental modelling of ground deformation associated with shallow magma intrusions

Olivier Galland

Physics of Geological Processes (PGP), University of Oslo, Norway

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ABSTRACT

Active volcanoes experience ground deformation as a response to the dynamics of underground magmatic systems. The analysis of ground deformation patterns may provide important constraints on the dynamics and shape of the underlying volcanic plumbing systems. Nevertheless, these analyses usually take into account simplistic shapes (sphere, dykes, sills) and the results cannot be verified as the modelled systems are buried. In this paper, I present new results from experimental models of magma intrusion, in which both the evolution of ground deformation during intrusion and the shape of the underlying intrusion are monitored. The models consisted of a molten vegetable oil, simulating low viscosity magma, injected into cohesive fine-grained silica flour, simulating the brittle upper crust; oil injection resulted is sheet intrusions (dykes, sills and cone sheets). The initial topography in the models was flat. While the oil was intruding, the surface of the models slightly lifted up to form a smooth relief, which was mapped through time. After an initial symmetrical development, the uplifted area developed asymmetrically; at the end of the experiments, the oil always erupted at the steepest edge of the uplifted area. After the experiment, the oil solidified, the intrusion was excavated and the shape of its top surface mapped. The comparison between the uplifted zone and the underlying intrusions showed that (1) the complex shapes of the uplifted areas reflected the complex shapes of the underlying intrusions, (2) the time evolution of the uplifted zone was correlated with the evolution of the underlying intrusion, and (3) the early asymmetrical evolution of the uplifted areas can be used to predict the location of the eruption of the oil. The experimental results also suggest that complex intrusion shapes (inclined sheet, cone sheet, complex sill) may have to be considered more systematically in the analyses of ground deformation patterns on volcanoes.

1. Introduction

During the last decades, geodetic measurements such as Interferometric Synthetic Aperture Radar (InSAR) imaging and GPS measurements have become very useful tools for monitoring the evolution of active volcanoes (Fig. 1; Cayol and Cornet, 1998; Froger et al., 2001, 2007; Fukushima et al., 2005, 2010; Pedersen and Sigmundsson, 2006; Masterlark, 2007; Sigmundsson et al., 2010). Some techniques allow continuous monitoring through time, such as GPS (e.g., Bonforte et al., 2008; Cervelli et al., 2002; Letourneur et al., 2008; Peltier et al., 2010), tiltmeters and extensiometers (e.g., Battaglia and Bachèlery, 2003; Bonaccorso, 1998; Peltier et al., 2006), but their spatial resolution is limited. In contrast, other techniques provide data with high spatial resolution, such as Photogrammetry (e.g., Cayol and Cornet, 1998) and InSAR (e.g., Sigmundsson et al., 2010; Wright et al., 2006), but the temporal resolution is low.

Ground movements in active volcanoes can be triggered, among others, by (1) deep magma movement and resulting pressure redistribution at depth, or (2) emplacement of shallow intrusions such as dykes or sills. Such ground movements may range from a few millimetres (e.g., Froger et al., 2007) to hundreds of metres (Donnadieu and Merle, 1998, 2001). The analysis of ground movement and deformation may provide important constraints on the dynamics and shape of the volcanic plumbing systems. Such analyses are based on analytical or numerical modelling of ground deformation due to a pressure source (intrusion) of a prescribed shape, such as point source (Masterlark, 2007; Mogi, 1958), magma chamber (e.g., Froger et al., 2007; McTigue, 1987; Peltier et al., 2008), dyke (Fukushima et al., 2005, 2010; Grandin et al., 2010a,b; Wright et al., 2006) or sill (Amelung et al., 2000; Battaglia et al., 2006; Chang et al., 2007; Fialko and Simons, 2001; Fialko et al., 2001; Pedersen and Sigmundsson, 2004, 2006; Sigmundsson et al., 2010; Vasco et al., 2007; Woo and Kilburn, 2010). The principle of the analysis is to find the shape, depth and pressure parameters of the pressure source that give the best fit between the measured and the modelled ground deformation (Fig. 1).

E-mail address: olivier.galland@fys.uio.no.

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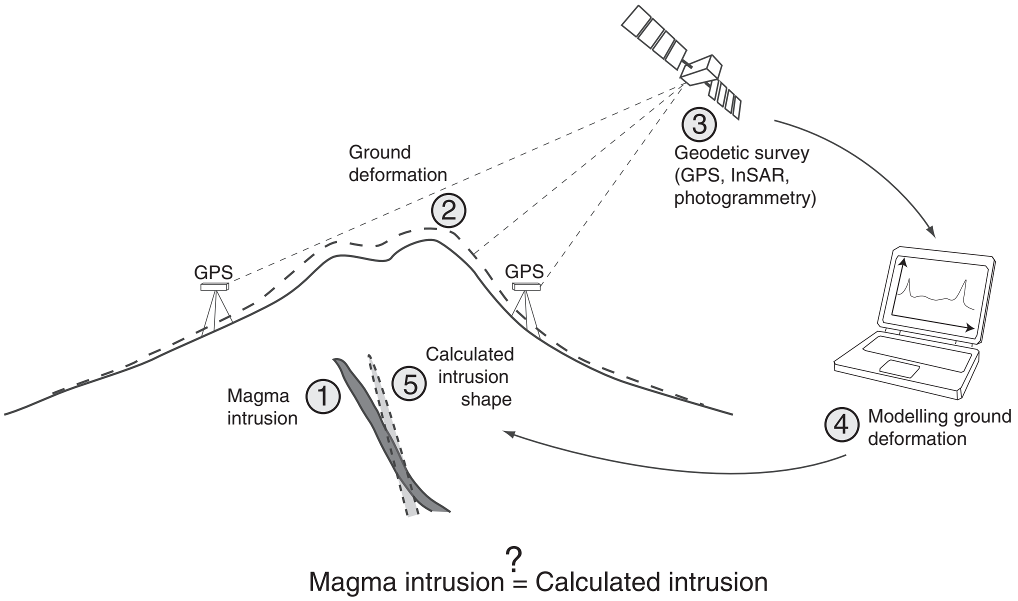

Fig. 1. Schematic diagram illustrating the principle of ground deformation analyses on active volcanoes. Numbering gives the succession of the stages of the analyses. 1. Magma intrudes in volcano, feeding magma reservoir or forming a sheet intrusion (dark grey intrusion). 2. Magma intrusion triggers ground deformation at surface, leading to modified topography (dashed line). 3. Topography variation is measured by geodetic techniques (GPS, InSAR, Photogrammetry, etc.). Note that GPS technique detects ground movements earlier than InSAR. 4. Geodetic data are compared with modelling of ground deformation due to various intrusion shapes. 5. The best fit between models and ground deformation data provides a calculated intrusion shape (light grey dashed intrusion) responsible for the measured ground deformation. Nevertheless, the calculated intrusion shape is not a unique solution, and no direct observation is available to validate the calculation results.

Nevertheless, these techniques have several limitations. (1) The modelled pressure sources have only simple shapes. Field observations show that natural magma intrusions exhibit much more diverse and complex shapes, such as e.g. cone sheets (Anderson, 1936; Klausen, 2004; Phillips, 1974), or saucer-shaped sills (Galerne et al., 2011; Hansen and Cartwright, 2006; Hansen et al., 2011; Polteau et al., 2008). (2) Though the numerical models take into account simple shapes, they require important computational power and skills. (3) As the volcanic plumbing systems are by definition buried, modelling results cannot be validated by direct observations. (4) Many models only take into account the elastic response of the host rock, while plastic deformation, such as faulting, may play a major role in nature, notably so in rift zones (Bianco et al., 1998).

In order to quantify the physical processes that produce ground deformation and to validate the modelling of ground deformation patterns in active volcanic systems, one needs to use a physical system in which both the shape of the volcanic plumbing system and the resulting ground deformation pattern are known.

In this paper, I present a new quantitative experimental modelling approach, in which both the final 3D shape of shallow sheet intrusions and the resulting ground deformation patterns are measured. This experimental work allowed (1) periodic monitoring of the evolution of ground deformation during the emplacement of magma, and (2) comparing the resulting complex ground deformation with the shape of the underlying intrusion. This study shows how the evolution and the morphology of the ground deformation pattern reflect the complex evolution and shape of the underlying intrusions. This experimental approach can be of considerable support for interpreting ground deformation data in volcanic systems. Here I focus on the experimental method, and the application of these models to natural volcanoes will be discussed in future papers.

2. Experimental procedure

Fine-grained crystalline silica flour is an analogue for the brittle crust, and low-viscosity vegetable oil is an analogue for the magma. The grain size of the flour is ~15 μm. It fails according to a Mohr–Coulomb criterion, and its cohesion (C) and friction coefficient are 369 ± 44 Pa and 0.81 ± 0.06, respectively (Table 1; Galland et al., 2009). This yields an angle of internal friction $\Phi \sim 39°$. The tensile strength of the flour is $T \sim 100$ Pa (Galland et al., 2006). The vegetable oil is produced by Unilever and sold in France under the name Végétaline. Its melting temperature is ~31 °C, so that it solidifies at room temperature. The viscosity of the oil is poorly temperature-dependant (Galland et al., 2006). Its temperature during injection is ~50 °C, where the viscosity is $\sim 2 \times 10^{-2}$ Pa s.

The scaling and the suitability of the model materials were described in details by Galerne et al. (2011) and Galland et al. (2006, 2009). 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 standard similarity conditions as developed by Hubbert (1937) and Ramberg (1981), and used, for example, by Merle and Borgia (1996). Here, experiments aim to simulate basin- or volcanic-scale phenomena, so that I chose a model-to-nature scale ratio of 10^{-5}, i.e. 1 cm in experiments represents 1 km in nature. In addition, the models aim to simulate the flow of low viscosity magma, from basalt (10^2 Pa s) to rhyolite (10^8 Pa s; Table 1). The detailed discussion of the scaling is described in the Supplementary material.

Table 1
Symbols, units, and values of the mechanical variables in nature and experiments.

	Definition of parameters	Field	Experiment	Dimension
C	Cohesion of brittle material	$10^7 \rightarrow 10^8$	350	Pa
D	Thickness of overburden	$1000 \rightarrow 5000$	$0.03 \rightarrow 0.05$	m
g	Acceleration due to gravity	9.81	9.81	$m\ s^{-2}$
h	Thickness of intrusion	$1 \rightarrow 100$	$2 \times 10^{-3} \rightarrow 3 \times 10^{-3}$	m
Φ	Angle of internal friction	$25 \rightarrow 45$	39	
η	Magma viscosity	$10^2 \rightarrow 10^8$	2×10^{-2}	Pa s
ρm	Density of magma	$2500 \rightarrow 2900$	~900	$kg\ m^{-3}$
ρr	Density of country rock	$2000 \rightarrow 2500$	1050	$kg\ m^{-3}$