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Stress evolution during caldera collapse

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ABSTRACT

The mechanics of caldera collapse are subject of long-running debate. Particular uncertainties concern how stresses around a magma reservoir relate to fracturing as the reservoir roof collapses, and how roof collapse in turn impacts upon the reservoir. We used two-dimensional Distinct Element Method models to characterise the evolution of stress around a depleting sub-surface magma body during gravity-driven collapse of its roof. These models illustrate how principal stress orientations rotate during progressive deformation so that roof fracturing transitions from initial reverse faulting to later normal faulting. They also reveal four end-member stress paths to fracture, each corresponding to a particular location within the roof. Analysis of these paths indicates that fractures associated with ultimate roof failure initiate in compression (i.e. as shear fractures). We also report on how mechanical and geometric conditions in the roof affect pre-failure unloading and post-failure reloading of the reservoir. In particular, the models show how residual friction within a failed roof could, without friction reduction mechanisms or fluid-derived counter-effects, inhibit a return to a lithostatically equilibrated pressure in the magma reservoir. Many of these findings should be transferable to other gravity-driven collapse processes, such as sinkhole formation, mine collapse and subsidence above hydrocarbon reservoirs.

1. Introduction

Extraction of material from a sub-surface body commonly causes the overburden to subside or collapse. Perhaps the most extreme instances occur with drainage of a sub-surface magma body. This can cause subsidence of many 100's or 1000's of metres within a few weeks or days (Geshi et al., 2002; Michon et al., 2007; Wilson and Hildreth, 1997), to form enclosed topographic depressions called pit-craters (diameter <1 km) or calderas (diameter 1–100 km). A similar, smaller-scale natural phenomenon is sinkhole formation induced by karst-rock dissolution (Gutierrez et al., 2008). Man-made phenomena include ground subsidence or collapse induced by sub-surface mining (Walters, 1978; Whittaker and Reddish, 1989), water extraction (Arkin and Gilat, 2000) or hydrocarbon recovery (Nagel, 2001; Odonne et al., 1999). In all cases, removal of material from the sub-surface body causes deformation and stress changes within the surrounding host-rock. The host-rock eventually fails through to the surface, with often dramatic and adverse consequences for buildings, equipment, infrastructure and human safety. Characterisation of the host-rock stress field during depletion or extraction of material from below the Earth's surface is hence of multidisciplinary interest.

The mechanical (i.e. stress-related) attributes of caldera collapse, which are the focus of this paper, have been subject of a long-running debate. Several unresolved questions include:

(1) How does the stress field arising from magma reservoir depletion evolve with progressive deformation and fracturing during the reservoir roof's collapse?
(2) What are the modes of fracturing in the host rock around the reservoir and which of these is associated with ultimate roof failure?
(3) How are the evolutions of stress and fracturing in the reservoir roof coupled to pressure conditions in the reservoir?

Answers to these questions inform the interpretation of geodetic, seismic and other geophysical data collected before, during and after a collapse event (Ekstrom, 1994; Fichtner and Tkalcic, 2010; Massin et al., 2011; Michon et al., 2011; Shuler et al., 2013). They are hence important for deformation monitoring and hazard assessment at not only volcanoes, but also other natural or man-made instances of depletion-induced subsidence (Cesca et al., 2011; Dahm et al., 2011; Lenhardt and Pascher, 1996; Segall, 1989).

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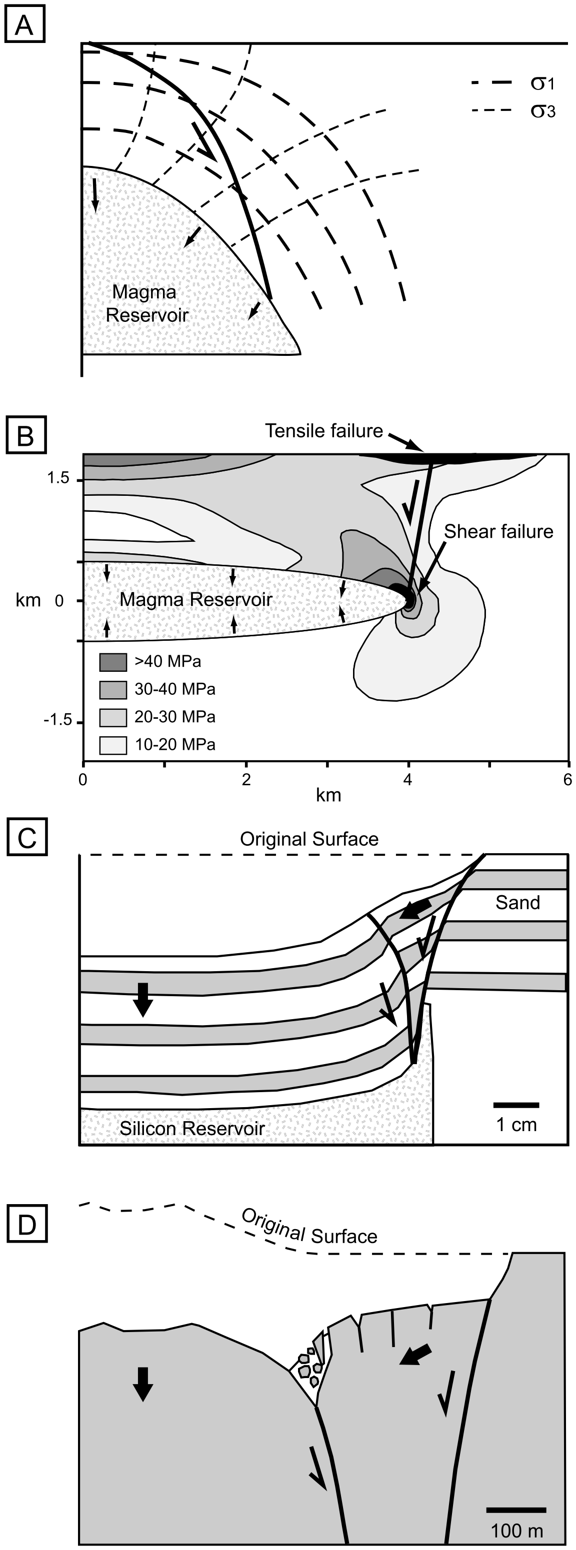

Fig. 1. Stress and faulting during caldera collapse. The upper two half-section sketches show existing hypotheses on the relationship of stress to faulting upon failure of a magma reservoir roof. The lower two show fault geometries observed in analog models and in the field. **(A)** An analysis of principal stress orientations predicting initial failure along an outward-inclined reverse fault (modified from Anderson, 1936). **(B)** An analysis of differential stress patterns predicting initial failure along an inward-inclined normal fault (modified from Folch and Marti, 2004). **(C)** Analog model showing development of both outward-inclined reverse and inward-inclined normal faults in that order (modified from Roche et al., 2000). **(D)** Interpretation of field and geodetic data for the 2000 collapse of Miyakejima caldera showing development of both outward-inclined reverse and inward-inclined normal faults (modified from Geshi et al., 2002).

For caldera collapse, these answers are clouded by differing observations or interpretations of primary field or geophysical data, as well as by inconsistency of past modelling approaches or results. For example, some past analytical or numerical studies of stresses arising from reservoir depletion conclude that initial roof failure should occur along a reverse fault inclined outward from the reservoir centre (Anderson, 1936; Holohan et al., 2013; Sanford, 1959) (Fig. 1A), whereas others conclude or assume that it should occur along a normal fault inclined toward the reservoir centre (Gudmundsson, 1998; Gudmundsson et al., 1997; Robson and Barr, 1964) (Fig. 1B). This discrepancy arises in part because continuum-based analytical and numerical approaches cannot simulate the large discontinuous (i.e. fault-related) strains characteristic of caldera collapse. Analogue models (Marti et al., 1994; Roche et al., 2000) of caldera collapse can do so and produce both fault orientations (Fig. 1C). Although these models are consistent with field and geophysical evidence from some well-exposed or well-monitored calderas (Clough et al., 1909; Fichtner and Tkalcic, 2010; Geshi et al., 2002; Holohan et al., 2009; Massin et al., 2011) (Fig. 1D), they have not yielded information on how fracturing relates to stress. One consequence is an inconsistency in the literature about how the orientations of principal stresses and caldera faults relate to each other, e.g. (Roche et al., 2000) vs. (Lavallee et al., 2004) vs. (Michon et al., 2009).

Here we characterise the evolution of stress around a depleting sub-surface body from the onset of roof subsidence through to the roof's failure and collapse. We do so with two-dimensional Distinct Element Method (DEM) models (Cundall and Strack, 1979) in which rock is represented by an assemblage of bonded particles (Potyondy and Cundall, 2004). The relatively-new DEM approach readily simulates the formation and growth of large-displacement fracture systems, such as those formed during caldera collapse (Hardy, 2008; Holohan et al., 2011), and so can reveal their relationship to evolving stress-states. Moreover, our model formulation is such that roof stresses and fracturing are coupled to the reservoir's loading-unloading history. This enables relationships between roof fracturing, reservoir depletion and reservoir 'under-pressure' to be ascertained throughout the course of roof subsidence. While the model results primarily pertain to stress evolution during collapse into a depleting magma body, many of them should be transferable to other extraction-induced subsidence scenarios.

2. Numerical methods and model set-up

Our starting point for modelling caldera collapse is the following geological scenario. A dyke intrusion has begun to laterally drain a magma reservoir (e.g. Geshi et al., 2002; Hildreth and Fierstein, 2000; Michon et al., 2007). Pressure in the reservoir has returned to a 'lithostatically-equilibrated' value, as the dyke's propagation and the onset of any associated eruption has expended any related 'over-pressure' (Druitt and Sparks, 1984; Roche and Druitt, 2001). (Note: "lithostatic" or "magmastatic" here describe the origins of stress or pressure, as derived from the weight of overlying rock or magma, respectively. 'Lithostatically-equilibrated' thus refers to a reservoir pressure equal to that expected from the combined lithostatic and magmastatic loads.) Thereafter, magma withdrawal continues through the open dyke, even as the reservoir becomes 'under-pressured' relative to its lithostatically-equilibrated state and the roof eventually collapses without any eruption through it. Detailed observations of recent collapses at several volcanoes (Geshi et al., 2002; Michon et al., 2007; Sigmundsson et al., 2015; Staudacher et al., 2009) support this scenario's plausibility.

We address this collapse scenario numerically by using the two-dimensional DEM software PFC2D (Itacsa Consulting Group Inc., 2004). This simulates the motion of rigid disk-like particles that