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How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes

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Abstract

To assess the probability of a volcanic eruption during an unrest period, we must understand magma-chamber rupture and dyke propagation to the surface, as well as dyke arrest at depth in the volcano. Dyke propagation and arrest depend strongly on the local stresses in the individual mechanical layers which constitute the volcano. The local stresses are primarily determined by the loading conditions (tectonic stress, magmatic pressure, or displacement) and the mechanical properties of the layers. In the absence of stress monitoring of volcanoes, the local stresses must be inferred from models, either analytical or numerical. This paper reviews many analytical and numerical models of local stresses around magma chambers, as well as analytical models and numerical examples of dyke-injection and eruption frequencies.

Most analytical models of magma chambers ignore the mechanical properties of the individual layers and their contacts, assume the volcano to behave as a homogeneous, isotropic, elastic half space or a semi-infinite plate, and are of two main types: nuclei of strain and cavities. The best-known nucleus of strain is the point-source Mogi model, used to explain surface deformation as a result of either increase or decrease in magma pressure in a chamber whose depth is also inferred from the surface data. The model explains stresses and displacements far away from the chamber, but neither the stress concentration around the chamber, which determines if and where chamber rupture and dyke injection take place, nor the shape, size, and likely tectonic evolution of the chamber.

In the cavity or (two-dimensional) hole model the magma chamber has a finite size. Thus, the local stresses at, and away from, the boundary of a chamber can be calculated. For various loading conditions, an analytical cavity model gives a crude indication of the local stresses in a volcano and its surface deformation. However, variation in mechanical properties, and contacts, between layers are ignored. The analytical cavity model thus cannot be used for detailed analyses of the local stresses in a composite volcano.

The numerical models presented here show that the local stresses in a volcano depend strongly on the magma-chamber geometry and the mechanical properties of its layers which are often contrasting, particularly at shallow depths. For example, lava flows, welded pyrolastic units, and intrusions may be very stiff (with a high Young's modulus), whereas young and non-welded pyroclastic and sedimentary units may be very soft (with a low Young's modulus). Consequently, the local stresses may change abruptly from one layer to the next; for example, one layer may favour dyke propagation while an adjacent layer favours dyke arrest. No dyke-fed eruption can occur if there is any layer along the potential path of the dyke to the surface where the stress field is unfavourable to dyke propagation. If such a layer occurs, the dyke normally becomes arrested and an eruption is prevented. The present results indicate that during unrest periods composite volcanoes commonly develop local stresses that arrest dykes and prevent eruptions, in agreement with field observations. These results underline the need for in situ stress monitoring of volcanoes to assess the probability of dyke-fed eruptions.

Keywords: volcanic eruption; dyke injection; magma chamber; crustal stress; layered crust; volcanotectonic modelling

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1. Introduction

In recent decades, there has been considerable progress in the general understanding of the hazards involved once an eruption has started. The improved understanding applies, in particular, to the dynamics of eruptive columns (Sparks et al., 1997) and the formation and mechanics of transport of pyroclastic rocks (Fisher and Schmincke, 1984; Cas and Wright, 1987; Freundt and Rosi, 2001; Schmincke, 2004). But there has also been considerable advancement in the general knowledge of the evolution of basaltic lava flow fields such as those that occur worldwide at the surfaces of mantle plumes and other basaltic provinces (Walker, 1991; Kilburn and Lopes, 1991; Self et al., 1996; Rossi, 1996; Calvari et al., 2003).

Most volcanic unrest periods, however, do not result in an eruption (Newhall and Dzurisin, 1988). Even those unrest periods where magma-driven fractures (dykes or inclined sheets) are known to be injected from a shallow magma chamber do not normally result in an eruption (Pollard et al., 1983; Lister and Kerr, 1991; Rubin, 1995; Bonafede and Rivalta, 1999; Pinel and Jaupart, 2000; Gudmundsson, 2002, 2003; Acocella and Neri, 2003; Stewart et al., 2003, 2005; Rivalta et al., 2005).

Since nearly all volcanic eruptions are supplied with magma through dykes and inclined sheets, it follows that for an eruption to occur a dyke or a sheet must be able to propagate from a magma chamber to the surface. The initiation of a dyke and its eventual propagation to the surface or, alternatively, arrest at some depth in the volcano, depend on the state of stress in the volcano. This stress state is controlled, first, by the mechanical properties of the rocks that constitute the volcano and the associated crustal segment and, second, by the shape, depth, and loading conditions of the source magma chamber or chambers. In solid mechanics, "load" is a word that normally means the forces, stresses, or pressures applied to a body and external to its material (Benham et al., 1996). Accordingly, in this paper "loading conditions" refer to the stresses and magmatic pressures applied to the magma chambers in the analytical and numerical models.

To understand and assess the hazard during an unrest period, we must know the state of stress in the volcano and, in particular, the stress concentration around the magma chamber or chambers that supply magma to its eruptions. Mechanically, partly or completely solidified magma chambers (plutons) that have properties different from those of the host rock are analogous to inclusions in an elastic body; completely molten chambers are analogous to cavities. In two-dimensional models, cavities are referred to as holes. All cavities and inclusions in an elastic body disturb the stress field of that body and give rise to stress concentrations (Fig. 1).

Stress concentrations around magma chambers are responsible for their ruptures and dyke or sheet injections during periods of unrest. As a result of stress concentration, a local stress field develops around the chamber and in its vicinity. This local field determines whether an injected sheet intrusion becomes a sill, an inclined sheet, or a subvertical dyke (Fig. 2). In this paper the word "dyke" is used mostly as a generic term, covering both proper dykes and inclined sheets. When necessary, however, a distinction is made between subvertical dykes and inclined sheets. Also, when discussing results applicable to composite volcanoes it is implied that the same results may apply to composite rift zones.

To understand the mechanics of a composite volcano (central volcano, stratovolcano) one must know the stress fields associated with its source magma chamber. Some authors have modelled the host rock of the chamber as viscoelastic (Bonafede et al., 1986; Folch et al., 2000). Here, however, the focus is on host-rock behaviour that can be described to a first approximation as elastic. When the rock hosting the chamber is

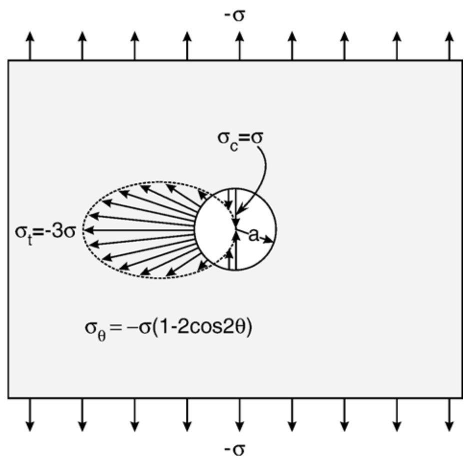

Fig. 1. Any hole or cavity in a solid material subject to loading gives rise to stress concentration. The same applies to inclusions with material properties different from those of the hosting solid material (the matrix). For a circular hole subject to tensile stress $-\sigma$ the stress at its boundary is given by the equation $\sigma_\theta=-\sigma(1-2\cos 2\theta)$ where the maximum tensile stress at its boundary is $\sigma_t=-3\sigma$ (cf. Eq. (16) with $b=c$) and occurs at the transverse diameter ($\theta=\pm 90°$). For the longitudinal diameter ($\theta=0°$, 180°) there is compressive stress of magnitude $\sigma_c=\sigma$. Mechanically, fluid magma chambers are analogous to holes (two-dimensional models) or cavities (three-dimensional models), whereas partially molten chambers are analogous to inclusions (modified from Boresi and Sidebottom, 1985).