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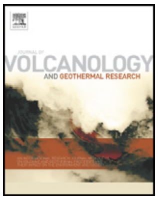

# Consequences of volcano sector collapse on magmatic storage zones: Insights from numerical modeling

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ABSTRACT

Major volcano flank collapses strongly affect the underlying magmatic plumbing system. Here, we consider the magma storage zone as a liquid pocket embedded in an elastic medium, and we perform numerical simulations in two-dimensional axisymmetric geometry as well as in three dimensions in order to evaluate the consequences of a major collapse event. We quantify the pressure decrease induced within and around a magma reservoir by a volcano flank collapse. This pressure reduction is expected to favor replenishment with less evolved magma from deeper sources. We also estimate the impact of the magma pressure decrease, together with the stress field variations around the reservoir, on the eruptive event associated with the edifice failure. We show that, for a given magma reservoir geometry, the collapse of a large strato-volcano tends to reduce the volume of the simultaneous eruption; destabilization of large edifices may even suppress magma emission, resulting in phreatic eruptions instead. This effect is greater for shallow reservoirs, and is more pronounced for spherical reservoirs than for vertically-elongated ones. It is reduced for compressible magmas containing a large amount of volatiles. Over a longer time scale, the modification of pressure conditions for dyke initiation at the chamber wall may also explain an increase in eruption rate as well as an apparent change of magma storage location.

## 1. Introduction

Large flank collapses have been recognized as common phenomena in the long-lived evolution of volcanic edifices. A large number of studies focus on the causes of, and/or triggers for, these destabilization events. They show that the origin of the destabilization can be related to exogenous processes such as weathering, but in most cases volcanic activity itself is involved (Mc Guire, 1996). In particular, the ability of magmatic intrusions to favor large flank collapse either during vertical dyke emplacement or during sill formation has been observed in the field (Famin and Michon, 2010), and investigated through modeling (Paul et al., 1987; Iverson, 1995). Siebert (1992) emphasized the potential hazards represented by sector collapses, which fully justify studies investigating volcano stability (Voight and Elsworth, 1997; Borselli et al., 2011). From a risk assessment perspective, the direct impact of a sudden and drastic sector collapse is also investigated through studies or modeling related to the volume and extension of the associated debris avalanche deposits (Borselli et al., 2011).

Another field of study encompasses describing and quantifying the consequences of such an event on the magmatic plumbing system evolution. The long-term history of volcanic edifices reveals that partial destruction of an edifice is usually followed by a change in eruption rate and/or magma composition (Presley et al., 1997; Hildenbrand et al., 2004; Hora et al., 2007; Longpré et al., 2010; Boulesteix et al., 2012). For oceanic volcanoes, this observation has usually been related to an increase in decompression melting subsequent to collapse (Presley et al., 1997; Hildenbrand et al., 2004), although Manconi et al. (2009) also evoked the depressurisation of a magmatic storage zone. For continental volcanoes, Pinel and Jaupart (2005), using an analytical elastic model for the two-dimensional plane strain approximation, quantified the pressure decrease induced within a magmatic reservoir by the partial destruction of an edifice. They also detailed the influence of such an event on the volume of magma erupted during the failure event.

Meanwhile, other surface load variations, occurring over a larger time scale, have been proven to have a significant impact on eruptive behavior. In particular, a temporal correlation is observed between ice retreat induced by climate warming and volume of magma erupted, with an increase of eruption rates during postglacial periods (Jellinek et al., 2004; Sinton et al., 2005). The effect of ice retreat on both magma melting and storage has been investigated (see Sigmundsson et al., 2010 for a review). More recently, new modeling has shown that magma propagation within the upper crust is also affected by ice unloading, with an increased likelihood of magma storage within the crust during transport towards the surface. This

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is in good agreement with some geodetic observations performed around Vatnajökull ice cap in Iceland (Hooper et al., 2011).

In this study, we calculate the pressure reduction induced by a sudden flank collapse event within and around a magma storage zone located beneath a volcanic edifice. We only consider one-shot catastrophic flank collapses, rather than the effects of large, progressive landslides. We then quantify how the flank collapse affects the volume of erupted magma during the associated eruption, resulting from the storage zone withdrawal. Results are derived from numerical simulations incorporating the equation of elasticity, performed with the commercial software COMSOL both in axisymmetric geometry and in three dimensions. We also discuss the potential impact of large flank collapses on the long-term eruptive history, based on petrological observations.

## 2. Pressure decrease induced by a volcano flank collapse

Broadly speaking, a major sector collapse is equivalent to a surface unloading event. In reality, the edifice portion which fails is not removed from the Earth's surface, but is redistributed over a larger area. As previously shown by Pinel and Jaupart (2005), using analytical solutions, and by Albino et al. (2010), using numerical models in axisymmetric geometry, an unloading event always induces a pressure decrease within the underlying crust. This pressure reduction is of the same order of magnitude as the load removed from the surface.

### *2.1. A conical load removed over an elastic half-space*

If we consider the crust to be an elastic, homogeneous medium characterized by its Young's modulus, $E$, and Poisson's ratio, $\nu$, the stress changes induced at depth by a conical load can be derived by integration of the point load solution. At the axis, the vertical stress due to a cone of radius, $R_e$, and maximum height, $H_e$, as a function of depth below the surface, $z$, is given by:

$$\sigma_{zz} = P_e\left[1 - \frac{z}{\sqrt{R_e^2+z^2}}\right], \tag{1}$$

with $P_e = \rho_c g H_e$, where $\rho_c$ is the load density. The horizontal components are equal and given by Pinel and Jaupart (2000):

$$\begin{aligned} \sigma_{rr} = \sigma_{\theta\theta} &= \frac{P_e}{2}\left[(1+2\nu) - 2(1+\nu)\frac{z}{R_e}ln\left(\frac{R_e+\sqrt{R_e^2+z^2}}{z}\right) + \frac{z}{\sqrt{R_e^2+z^2}}\right] && \text{for z} > 0 \\ \sigma_{rr} = \sigma_{\theta\theta} &= \frac{P_e}{2}(1+2\nu) && \text{for z} = 0. \end{aligned} \tag{2}$$

It follows that the pressure, $P$, defined as one third on the stress tensor trace, induced by a conical load, is equal to:

$$\begin{aligned} P &= \frac{2P_e}{3}(1+\nu)\left[1 - \frac{z}{R_e}ln\left(\frac{R_e+\sqrt{R_e^2+z^2}}{z}\right)\right] && \text{for z} > 0 \\ P &= \frac{2P_e}{3}(1+\nu) && \text{for z} = 0. \end{aligned} \tag{3}$$

Stress and pressure reduction induced by the removal of conical load are shown in Fig. 1. The stress component most affected by the load is, as expected, the vertical one $\sigma_{zz}$. The amplitude of the perturbation is greatest at the surface, and is directly related to the height of the load removed. The pressure reduction decreases with depth and becomes negligible at depths greater than three times the radius of the load.

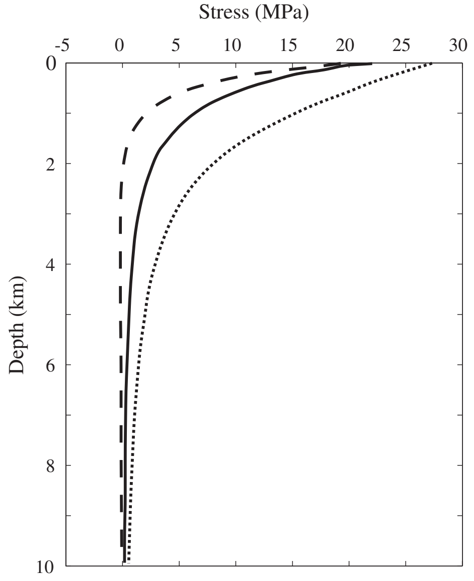

**Fig. 1.** Stress reduction under the center of a conical load (2 km radius, 1 km height, density of 2800 kg/m$^3$) which is removed from the surface. Calculation is for an elastic half-space with Poisson's ratio equal to 0.25. The dotted line is for the vertical component of the stress tensor, $\sigma_{zz}$, the dashed line is for the horizontal components, $\sigma_{rr} = \sigma_{\theta\theta}$, and the solid line is for the pressure reduction, $P = (1/3)(\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz})$.

### *2.2. A conical load removed from above a magmatic reservoir*

Most tomographic studies performed on volcanoes (Monteiller et al., 2005; Prôno et al., 2009) reveal that the crust is far from being homogeneous around a magmatic system. In particular, shallow magma storage zones have been detected in many locations by either petrologic, seismic or geodetic studies (Gardner et al., 1995; Sturkell et al., 2006; Peltier et al., 2008). The pressure reduction induced by an unloading event within these magma pockets will depend both on the crustal deformation and on the equation of state of the melt embedded in the crust. Here we consider an ellipsoidal magmatic reservoir filled with fluid, embedded in a homogeneous elastic crust. Initially the liquid has the same density as the surrounding crust and is characterized by its bulk modulus, $K$. We only deal with the perturbation induced by a conical load removed from the Earth's surface, on which the initial stress field has no influence.

Within the magma reservoir the pressure change, $\Delta P$, is related to the reservoir volume change, $\Delta V$, through the bulk modulus definition:

$$\Delta P = -K\frac{\Delta V}{V}, \tag{4}$$

with $V$ being the initial volume of the reservoir.

The change in reservoir volume is also a function of the chamber wall displacement, which depends on both the conical load and the magma pressure change. This volume change is calculated numerically, using the equations of elasticity with the commercial software COMSOL. The domain of calculation is a $100*100$ km square box with a mesh of about 100 000 triangular units that is refined around the volcanic edifice and magma reservoir. No displacement perpendicular to the boundary is allowed at the basal and lateral boundaries; the upper boundary is considered as being a free surface. The load is modeled with a normal stress applied at the upper surface, and a normal stress equal to the magma overpressure is applied at the reservoir walls. Numerical solutions have been validated using well-known analytical solutions as detailed in Albino et al. (2010). Pressure reduction within and around the magma reservoir induced by a conical load of 2 km radius, 1 km height, and density