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How caldera collapse shapes the shallow emplacement and transfer of magma in active volcanoes

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ABSTRACT

Calderas are topographic depressions formed by the collapse of a partly drained magma reservoir. At volcanic edifices with calderas, eruptive fissures can circumscribe the outer caldera rim, be oriented radially and/or align with the regional tectonic stress field. Constraining the mechanisms that govern this spatial arrangement is fundamental to understand the dynamics of shallow magma storage and transport and evaluate volcanic hazard. Here we show with numerical models that the previously unappreciated unloading effect of caldera formation may contribute significantly to the stress budget of a volcano. We first test this hypothesis against the ideal case of Fernandina, Galápagos, where previous models only partly explained the peculiar pattern of circumferential and radial eruptive fissures and the geometry of the intrusions determined by inverting the deformation data. We show that by taking into account the decompression due to the caldera formation, the modeled edifice stress field is consistent with all the observations. We then develop a general model for the stress state at volcanic edifices with calderas based on the competition of caldera decompression, magma buoyancy forces and tectonic stresses. These factors control: 1) the shallow accumulation of magma in stacked sills, consistently with observations; 2) the conditions for the development of circumferential and/or radial eruptive fissures, as observed on active volcanoes. This top-down control exerted by changes in the distribution of mass at the surface allows better understanding of how shallow magma is transferred at active calderas, contributing to forecasting the location and type of opening fissures.

1. Introduction

The dynamics of magma storage, transport and eruption are thought to be controlled by both bottom-up (e.g., magma supply rate, volume and composition; e.g., Poland et al., 2012; Galland et al., 2014) and top-down processes (e.g., the effect of edifice load on magma ascent; e.g., Pinel and Jaupart, 2000; Muller et al., 2001). Understanding the state of stress within a volcanic edifice is one of the key ingredients to improve our ability of forecasting magma propagation and eruption. Most polygenetic volcanoes are formed over long time scales by deposition and compaction of volcanic products that create a time-evolving stress state within the edifice. The stress field may be later modified by diffuse fracturing, diking or redistribution of surface mass (e.g. landslides), and by changes in the mechanical properties of the rock layers themselves as the layers tend to become stiffer with time. The simple assumption of a gravitationally loaded volcano may, therefore, be very far from reality for most volcanoes around the world. Important clues into the stress state of a volcano come from the orientation of dikes and fissures observed in the field, as they tend to orient perpendicularly to the direction of the minimum compressive stress, $\sigma 3$ (Anderson, 1951) and be controlled by stress gradients (buoyancy, edifice and regional stresses).

Calderas are sub-circular topographic depressions created by the yielding of a magma chamber, drained by large intrusions, effusive or explosive eruptions (Lipman, 2000; Cole et al., 2005). Post-caldera volcanism is commonly fed by regional, circumferential and radial dikes (e.g., Acocella and Neri, 2009). Regional dikes are often sub-vertical and aligned orthogonal to the regional tectonic $\sigma 3$, as observed along the axis of rift zones, both within and outside the calderas. Dikes that propagate within the volcanic edifice are likely to be controlled by the local stress field (Gautneb and Gudmundsson, 1992). These dikes may be arranged as centrally-inclined sheets (e.g., cone sheets), which are com-

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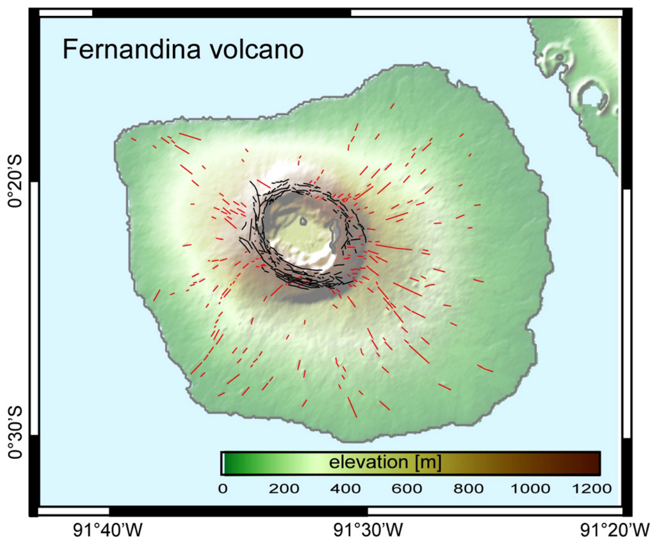

Fig. 1. Shaded relief map of Fernandina with colorcoded elevation (digital elevation model from SRTM V2_1). Circumferential and radial fissures (Chadwick and Howard, 1991) are highlighted by the black and red solid lines, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

monly circular or elliptical in map view, and/or have a radial distribution in alignment with the axis of the edifice (e.g., Acocella and Neri, 2009). Although their orientation at the surface may mimic that of ring faults (i.e., shear fractures), inclined sheets are magma-filled extensional fractures. Both radial dikes and inclined sheets have been observed at several eroded volcanoes, with the latter also possibly associated to shallow viscous magma (Galland et al., 2014). In particular, inclined sheets have been identified in Scotland (e.g. Burchardt et al., 2013), the Canary Islands (e.g., Ancochea et al., 2003), Japan (Geshi, 2005), and Iceland (e.g. Burchardt and Gudmundsson, 2009). Their surface expression as circumferential eruptive fissures is, on the other hand, relatively rare, and has only been observed around calderas in the western Galápagos Archipelago (Fernandina, Wolf, Darwin, Alcedo, Sierra Negra and Cerro Azul; Chadwick and Howard, 1991) and, to lesser extent, in Iceland at Krafla, Grimsvotn (Thordarson and Self, 1993) and Askja calderas (Hartley and Thordarson, 2012), Dolomieu (Piton de la Fournaise, La Réunion; Carter et al., 2006), Rano Kau (Easter Island; Vezzoli and Acocella, 2009); and other planets (Venus, Tharsis Province on Mars; e.g., Montési, 2001) calderas. The rare and selective distribution of circumferential eruptive fissures suggests that most inclined sheets stall at depth, without reaching the surface, and that formation of these fissures is favored, but not guaranteed, by the presence of a caldera. This may imply a specific stressing mechanism active at volcanoes with a caldera, competing with other stressing factors.

Some of the best-developed circumferential fissures are found at Fernandina (Galápagos; Fig. 1; Chadwick and Howard, 1991), which hosts a ∼1 km deep and ∼6.5 × 4 km wide caldera resulting from several collapses testified by old benches and a ∼350 m drop of the SE caldera floor in 1968 (Simkin and Howard, 1970; Howard, 2010). Several models have been proposed to explain the formation of circumferential fissures at Fernandina, considering the effect of: a) caldera faults capturing and channeling magma to the caldera rim (Nordlie, 1973; Browning and Gudmundsson, 2015); b) caldera walls unbuttressing re-orienting the minimum compressive stress perpendicular to them (Simkin, 1984; Munro and Rowland, 1996); c) stress perturbations due to the pressurization of a magma chamber (Chadwick and Dieterich, 1995; Chestler and Grosfils, 2013) or d) a previous intrusion (Bagnardi et al., 2013). The caldera fault model was excluded based on observing: i) no displacement in layers adjacent to circumferential dikes; ii) circumferential dikes crosscutting caldera faults; and iii) circumferential fissures located well downslope from the caldera rim (Chadwick and Dieterich, 1995). The edifice unbuttressing model fits well with the orientation of circumferential fissures at the surface but is inconsistent with intrusions starting as sills (Chadwick et al., 2011; Bagnardi et al., 2013). The most accredited models now appeal to the inflation of magma reservoirs of various shapes. For example, the inflation of a diapir-shaped source plus the uniform surface load due to the emplacement of lava flows applied from the caldera wall outward produce a stress field consistent with proximal circumferential dikes and distal radial dikes (Chadwick and Dietrich, 1995).

Recent crustal deformation studies have revealed previously unknown features of magma transport beneath Fernandina. Modeling of InSAR data showed that the dike feeding the 2005 eruption started as a sub-horizontal sill that curved upward and erupted through proximal circumferential fissures (Chadwick et al., 2011; Bagnardi et al., 2013). The magma injection feeding the subsequent 2009 eruption also started as a sub-horizontal sill that, propagating laterally, turned into a dike with dip angle increasing from 33° to 50°, indicating a progressive twisting about a radial axis (Bagnardi et al., 2013). Radial fissures present on the volcano flanks result therefore from shallow dipping dikes intersecting the volcano topography (Jónsson et al., 1999; Bagnardi et al., 2013). While former interpretations and models on the mechanics of magma transport were constrained only by the eruptive fissure distribution at the surface, current robust constraints on the 3D sub-surface intrusion geometry now allow us to test previous and new models.

Analytical and numerical models of local stresses around magma chambers have been used to infer dike propagation paths to the surface, as well as their arrest at depth (e.g., Gudmundsson, 2006). Chestler and Grosfils (2013) calculated the stress pattern due to the inflation of an oblate reservoir, as there is a widespread geological, geophysical and modeling evidence that these are the most common shapes for magma reservoirs (e.g., Petford et al., 2000). The authors focus on the conditions necessary to generate radial dikes, inclined sheets and sills twisting into radial dikes based on rupture orientation at the chamber wall as well as orientation of $\sigma 3$ within the edifice with specific application to Fernandina. This study revealed that radial dikes can initiate at the reservoir wall only for mildly oblate reservoirs (with aspect ratio around 1.3) however such reservoirs are difficult to reconcile with the flat-topped reservoir geometry imaged for Fernandina (Chadwick et al., 2011; Bagnardi and Amelung, 2012). For more oblate reservoirs (i.e., aspect ratio >2), intrusions are expected to initiate as sills at the chamber wall. Then depending on the chamber aspect ratio and based on the orientation of $\sigma 3$, different magma paths and dike geometries are derived but none of them is consistent either with a sill bending into an upward propagating dike (with an upward concavity) to feed a circumferential fissure or with a radially propagating dike reaching the surface in the flank area, since $\sigma 3$ is always in plane in the upper 1.5–2.0 km beneath the surface. Moreover, magma reservoirs depressurize while injecting a sill or a dike (e.g., Gudmundsson, 2006) reducing the magnitude of the induced stress perturbation. Simultaneously, as the dikes elongate the stress concentration at their tip will intensify, resulting in a decrease of the role played by the other contributions (magma chamber or unloading).

The orientation and location of the eruptive fissures at Fernandina was related to the stress perturbation from earlier intrusions (Bagnardi et al., 2013). For example, the 2005 intrusion was found consistent with the stress perturbation due to the intrusion of a sill with geometry, location and displacement derived for the preceding 1995 intrusion. This model may explain both the location and orientation of the fissures and the alternation between circumfer-