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Interaction between regional and magma-induced stresses and their impact on volcano-tectonic seismicity

D.M. Vargas-Bracamontes, J.W. Neuberg *

School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom

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ABSTRACT

Recent seismological observations have reported volcano-tectonic (VT) earthquakes with fault-plane solutions exhibiting a change of ~90° in their pressure axes relative to the regional stress field. Interestingly, they are recorded mainly during periods preceding eruptive activity and coexisting with those VTs showing a regional trend. This study explains the occurrence of such trends in VT seismicity and discusses the possible patterns of earthquake locations related to the interaction of regional and magma-induced stresses caused by pressurization or depressurization of magmatic sources. Our analysis shows that in the presence of a dominant regional stress field, faulting will occur on faults whose associated slip direction is close to or in agreement with the background regional stress. Failure on faults with an opposite slip direction is unlikely to occur. As magma pressure starts counter-acting the regional stresses, the likelihood of faults to slip in either a regional or opposite sense of slip relative to regional maximum compression increases, allowing the co-existence of possible failure with both slip tendencies, however the spatial distribution of possible faulting differs. As the pressure is progressively increased, the stress patterns gradually approach those corresponding to the absence of a regional stress field. The presented modeling results have implications for volcanic monitoring routines aiming to detect changes in stress patterns. They will ultimately help to improve the correct interpretation of volcano-tectonic seismicity.

1. Introduction

Among the various types of seismic signals linked to volcanic processes, volcano-tectonic earthquakes (characterized by clear P- and S-waves and dominant frequencies between 5 and 15 Hz (e.g., Lahr et al., 1994)) are often the earliest precursors of volcanic eruptions (e.g., Ida, 1991; Harlow et al., 1996). Their presence reflects faulting in the brittle rock within a volcanic edifice as a consequence of stress perturbations mostly caused by magmatic intrusion. Therefore, these earthquakes can be used to estimate the state of stress in volcanoes from fault-plane solutions (FPS) or from inversions of the stress tensor (e.g., Zobin, 1979; Núñez-Cornú and Sánchez-Mora, 1999; Waite and Smith, 2002; Musumeci et al., 2004; Sánchez et al., 2004). These analyses provide fundamental constraints on the physical processes occurring in a volcano.

Systematic changes in FPS orientation related to episodes of magmatic activity have been documented for several eruptions at various volcanoes. Specifically, such changes consist of an approximately 90° rotation of the P-axis azimuth with respect to regional or background maximum compression (σ_1). For a strike-slip mechanism, this rotation of the P-axis by 90° is equivalent to slip on the same fault in the opposite direction. Hence, an earthquake with right-lateral FPS may be followed by an earthquake with left-lateral motion at the same focus. For instance, the analysis of FPS prior to major eruptive episodes of Mount Etna (Cocina et al., 1996; Patanè and Privitera, 2001) in September–October 1989 and December 1991–March 1993, shows the presence of two distinct seismogenic zones with a prevalence of strike-slip mechanisms, where the deeper zone below 10 km is consistent with the regional stress field, while a rotation in the P-axes distribution at depths shallower than 10 km is observed. At Soufrière Hills volcano, Montserrat, VT earthquakes exhibiting a rotation of the pressure axes by ~90° with respect to the background stress direction have been reported during periods preceding eruptive activity or during changes in eruptive state. In this case, most of the VTs are located in a rather limited depth range and most of the VT events had pure or oblique strike-slip mechanisms (Roman et al., 2006, 2008). Other similar examples showing variability in the focal mechanisms during periods preceding or accompanying significant eruptive activity have been noted at Guagua Pichincha, Ecuador (Legrand et al., 2002), Mount Unzen, Japan (Umakoshi et al., 2001), Popocatépetl, Mexico (Arámbula-Mendoza et al., 2010) and Mount St. Helens, Washington (Lehto et al., 2010). Uprising and intruding magma has been hypothesized as the cause of these major changes in the direction of the pressure axes. In the conceptual model behind this idea (Roman and Cashman, 2006), explicitly stated for strike-slip faulting, the dyke inflates in the direction of regional minimum compression (σ_3), i.e. where it faces the least resistance, generating a local stress field in which induced maximum compression overcomes the regional

* Corresponding author. Tel.: +44 113 343 6769.
E-mail address: J.Neuberg@see.leeds.ac.uk (J.W. Neuberg).

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σ_1 and is perpendicular to it. Stress changes resulting from magma withdrawal from a magmatic reservoir have also been proposed as a cause of posteruptive VT earthquakes associated with a stress regime that is inconsistent with the regional or background stress field (Barker and Malone, 1991).

In a previous study, Roman and Heron (2007) analyzed the effect of interacting regional and volcanically-generated stress fields on patterns of VT seismicity by calculating Coulomb stress changes on faults optimally oriented for failure. They followed the approach used in tectonic applications by King et al. (1994) and King and Cocco (2001); however, in their analysis, the influence of these two interacting stress fields is only considered to determine the orientation of the optimal faults, whereas the stresses acting on these optimal planes are represented only by the magma-induced stress changes. Furthermore, faults optimally oriented for failure may not be present in a volcanic system and are unlikely to arise from stress perturbations accompanying magma ascent (Rubin and Gillard, 1998). Thus, calculation of Coulomb stress changes on pre-existing faults of any orientation (optimal or non-optimal), which combine the background regional stress field with the magma-induced stresses is crucial to interpreting VT earthquake activity in volcanic environments.

This paper presents an analysis of the interaction between a regional stress field and magma-induced stresses caused by pressurization or depressurization of magmatic sources. We consider the effects of these interacting stress fields on faults of any orientation and their implications for volcano-tectonic seismicity. Based on calculations of Coulomb stress changes resulting from these interacting stress fields we assess the potential of pre-existing faults to slip in a right- or left-lateral sense, and present models that can explain observations of volcano-tectonic earthquakes having FPS with P-axes rotated by 90° to regional or background maximum compression.

2. Methodology

We employ the Coulomb failure criterion to assess if a particular stress state is likely to trigger volcano-tectonic seismicity. The potential for slip on a fault will be enhanced or inhibited by a change in Coulomb failure stress, $\Delta\sigma_f$ (or ΔCFS), defined as:

$$\Delta\sigma_f = \Delta\tau + \mu'\Delta\sigma_n \tag{1}$$

where $\Delta\tau$ is the shear stress change (positive in the direction of fault slip), $\Delta\sigma_n$ is the normal stress change (positive if the fault is unclamped), and μ' is the effective (or apparent) friction coefficient (e.g., Stein, 1999; Scholz, 2002). Failure on a fault is encouraged if $\Delta\sigma_f > 0$ and inhibited if $\Delta\sigma_f < 0$. Thus, both increased shear and unclamping of faults promote failure.

Problems involving the calculation of stresses and displacements around cavities have long been studied in rock mechanics and their applications have been of major importance to geosciences. We use the 2D analytical solutions of pressurized circular (Jaeger et al., 2007) and elliptical (Pollard, 1973) cavities in a homogeneous and isotropic elastic material subject to far-field stresses (Fig. 1a) to determine the changes in shear, normal and Coulomb stress (Fig. 1b–c) for given fault planes due to the combined effect of regional and local stress in the vicinity of a magmatic source with elliptical (resembling a dyke parallel to σ_1) or circular (in Supplementary material) geometry. The models incorporate a uniform compressive regional stress of σ_1 (nonzero) along the x-coordinate and internal pressures with values of 0.1, 1, 5 and 10 times σ_1 applied to the cavities. The least compressive stress σ_3 is set to zero. We put an emphasis on explaining the appearance of the rotated VTs, which usually occur during brief periods of time, thus it is reasonable to adopt constant values of the regional stress field while we vary pressure in our models. Additional models where the internal pressure in the cavities is linearly increased are included in the Supplementary material (S3). The spatial patterns of the stress tensor due to the interacting stresses are also provided as auxiliary Figs. S5 and S6.

Since faults of heterogeneous orientations may have developed throughout the course of tectonic and persistent volcanic activity, it is assumed that faults with various orientations already exist within the system. Hence, we select two arbitrary faults with strikes of 45° and 75° (measured clockwise with respect to the y-coordinate) to illustrate the primary results of our modeling. Coulomb stress changes corresponding to right-lateral and left-lateral mechanisms for an intermediate value of the effective coefficient of friction $\mu' = 0.4$ are calculated for these fault planes (Figs. 2 and S1). To enable comparison of the evolving stress patterns as the cavity pressure increases, the limits of the color scale representing stress changes are kept constant through the entire exercise.

Alternation from normal to reverse faulting associated to magmatic intrusions has also been reported in fault-plane solution studies of VT seismicity (e.g., Umakoshi et al., 2001; White et al., 2011). To appropriately study how progressive pressure changes interacting with the background regional stress act to either promote or inhibit such opposing dip-slip styles it is necessary to consider the vertical stress components. The only available analytical solution that provides the stress tensor of the combined effect of the interacting stress fields is the two-dimensional solution we employ in our analysis (Pollard, 1973; Jaeger et al., 2007). Nonetheless, the patterns in Coulomb stress changes for normal and reverse faulting are explored by means of the 3D Okada (1992) sources with a tensile component simulating the injection of magma into a dyke. Results of this modeling exercise which deals only with magma-induced stresses are presented as Supplementary Fig. S7.

3. Results

The results under a prevailing regional stress field, i.e. when $p \ll \sigma_1$ (Figs. 2a, d, S1a, d and S3), show that failure is essentially promoted on all faults with an associated right-lateral sense of slip, more pronounced for a strike of 45° where the P-axis is parallel to σ_1. In contrast, failure is mostly inhibited on faults with a left-lateral mechanism. Zones with positive Coulomb stress changes are present for the plane with a strike of 75° (Fig. S1a and d), although insignificant for the elliptical source (Fig. 2a and d). The observed $\Delta\sigma_f$ amplitude differences for the two fault orientations are due to the proximity of these orientations to the optimal planes, relative to either regional σ_1 or magma-induced compression (see Fig. S2). For $\mu' = 0.4$, a plane with a strike of 56° and right-lateral slip is optimally oriented with respect to regional compression, whereas a plane having a strike of 34° and left-lateral sense of slip would be optimally oriented with respect to the compression induced by the cavity pressurization (e.g., Fossen, 2010). For example, notice that for the faults slipping in a right-lateral sense (Fig. 2a) the highest positive Coulomb stress changes occur for the plane with a strike of 45° which is closest to its corresponding optimally oriented (56° and right-lateral slip). Similarly, it is also apparent that the plane that presents the less negative values of Coulomb stress changes (Fig. 2a) is that with a strike of 75° and a left-lateral slip which is furthest to its companion optimally oriented (34° and left-lateral sense of slip).

As the magnitude of pressure change increases (Figs. 2b, e, S1b, e and S3), shadows of negative Coulomb stress change begin to appear for planes with right-lateral sense of slip, indicating zones where slip is inhibited due to magma-induced stress, and this tendency grows as the magnitude of pressure change further increases (Figs. 2c, f, S1c, f and S3). Still, at the stage where p equals σ_1, failure is promoted to a great extent on right-lateral faulting. For left-lateral faulting, failure remains mainly inhibited everywhere, except for small areas near the edge of the major axis of the ellipse for the plane with a strike of 75° (Fig. 2b and e). The extent of the area affected by the local stress perturbation depends on the applied pressure and on the aspect ratio of the elliptical cavity. It is worth noticing that the stress