Earthquakes as a stress meter of active volcanoes

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The orientation of faulting associated with volcano-tectonic earthquakes follows the stress field there, as with tectonic earthquakes. Therefore, stress changes associated with volcanic activity change fault orientations or focal mechanisms. Zhan et al. (2022) observed temporal changes of focal mechanisms associated with volcanic unrest. They decomposed the stress field into the ambient differential stress, volcano loading, and the stress change by the dike intrusion; they then evaluated their relative contributions to constrain the magnitude of the ambient differential stress that is consistent with the observation. This study indicates that focal mechanisms can be used to monitor the stress state of an active volcano. Combining focal mechanisms with other geophysical observables, such as seismic anisotropy and geodetic measurements, will give us more precise assessments of the stress state, leading to better forecasts of volcanic activity.

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Key Points:

- Zhan et al. (2022) assessed the stress state of an active volcano from temporal changes of focal mechanisms during its unrest.
- A quantitative assessment of temporal changes of focal mechanisms allows us to use them as a stress meter.
- Combining focal mechanisms with other geophysical measurements yields more precise estimates of the stress state of active volcanoes.

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Plain Language Summary

The movement of magmatic fluids induces various types of earthquakes. Among them, a particular type of earthquakes, called volcano-tectonic earthquakes, occurs on faults with favorable orientation according to the maximum and minimum compressional stress field. Although earthquakes tell us about the stress orientation, they do not directly tell us about the magnitude ratio of the maximum to minimum compressional stress. Stress changes due to the movement of magmatic fluids may be used to infer the absolute stress magnitude. Zhan et al. (2022) observed temporal changes of stress orientations from the fault orientations of volcano-tectonic earthquakes; they then evaluated relative contributions of the background stress, volcano loading, and the stress change by an intrusion of magmatic fluids. Then they constrained the magnitude of the ambient differential stress to be consistent with the observation. Combining the fault orientations with other geophysical observables, such as the directional dependence of seismic wavespeeds and surface deformation, gives us a more precise assessment of the stress state of an active volcano, leading to better forecasts of volcanic activity.

Main Text

Monitoring the stress state of an active volcano is crucial to understanding its state and forecasting its eruptions because the transport of magmatic fluids results in stress changes within it. Notwithstanding its importance, measuring the stress state is not straightforward. For example, ground deformation measures stress changes through strain changes (e.g., Biggs & Pritchard, 2017; Poland & Zebker, 2022), but it does not offer any information about the absolute background stress.

Earthquake focal mechanisms have been frequently used to infer the stress state because they reflect the background stress state (e.g., Heidbach et al., 2018; Mariucci & Montone, 2020; Uchide et al., 2022). Let us consider a plane perpendicular to the intermediate stress axis. If the intermediate stress axis is vertical, for example, then the directions of both the maximum and minimum compressional stress axes are horizontal, and the most favorable focal mechanism is a strike-slip on a vertical plane.

Let us consider a stress state of the most compressional stress σ_1 and least compressional stress σ_3 (compression positive) so that an intact rock with cohesion C can cause faulting. Figure 1a shows that a straight line (Line 1) with an intercept of $\tau = C$, where τ is the shear stress, and slope μ, which represents the friction coefficient, intersects at one point, A, in Figure 1a. The angle between the horizontal axis and the line OA in Figure 1a equals $\tan^{-1}(1/\mu)$ and twice the angle between the fault strike and the direction of the maximum principal stress, θ (Figure 1b). If there is no friction, that is $\mu = 0$, the optimum fault plane is 45 degrees from the direction of σ_1, while the optimum fault plane is ~ 29.5 degrees from the direction of σ_1 with $\mu = 0.6$, which is considered reasonable from rock friction experiments (e.g., Byerlee, 1978; Scholz, 2019, p. 53–61).

The existence of preexisting fractures corresponds to the lack of cohesion or $C = 0$. Line 2 in Figure 1a intersects with Mohr's circle at two points at B and C. In this case, faults striking between θ_1 and θ_2 can generate earthquakes, where angles between the horizontal axis and OB and OC in Figure 1b are $2\theta_1$ and $2\theta_2$, respectively.

Non-zero pore pressure can activate faults with various orientations. The corresponding slope intersects at $\sigma_n = p$, where σ_n and p represent the normal stress and pore pressure, respectively. Figure 1b denotes the extreme case where the pore pressure equals the minimum compressional stress. In this case, pre-existing faults striking between 0 and 2θ from the direction of σ_1 can be activated (Figure 1a). In other words, faults with all orientations can be activated if $\mu = 0$ and those striking between 0 and ~ 59 degrees from the direction of σ_1 if $\mu = 0.6$.

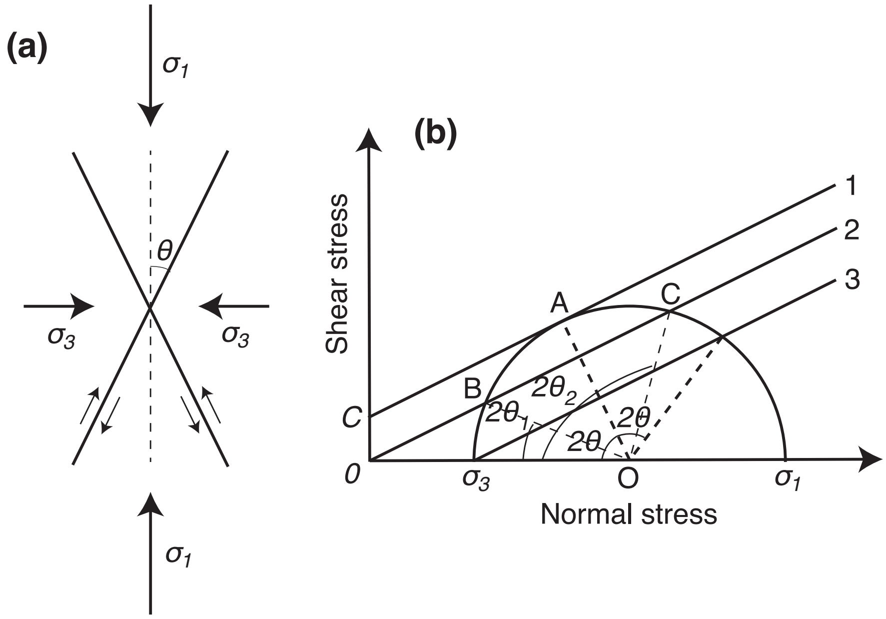

Figure 1. (a) Relation between the direction of the maximum compression (σ_1), minimum compression (σ_3), and the fault orientation. θ denotes the angle of the fault orientation and the direction of σ_1. (b) Mohr's circle, given σ_1 and σ_3. Faulting occurs when a point on each line representing normal (horizontal axis) and shear (vertical axis) stresses is inside the circle. The slope of the lines is the friction coefficient μ. Suppose the stress state is so that faulting in rock with cohesion C occurs only at point A (Line 1). In this case, the orientation of the fault is $\theta = (1/2)\tan^{-1}\mu$ from the direction of σ_1. The fault orientation of a cohesionless rock in the same stress state (Line 2) can be more varied. In the extreme case where the pore pressure equals the minimum compressional stress (Line 3), the orientation of the fault can be between 0 and 2θ ($= \tan^{-1}\mu$) from the direction of σ_1.

The argument above implies that a single focal mechanism cannot constrain the stress orientation, but a collection of focal mechanisms can constrain the stress orientation and its temporal changes. Many studies have investigated the stress field and its temporal changes from a collection of focal mechanisms (e.g., Hardebeck & Michael, 2006; Becker et al., 2018; Yoshida et al., 2019). The basic idea is that the more diverse the observed focal mechanisms are, the smaller σ_3/σ_1 is, or the larger the deviatoric stress (normalized by σ_1) is.

Focal mechanisms can be used to infer the stress field and its temporal changes not only in tectonic but also in volcanic environments. Although volcanic earthquakes are more diverse than tectonic earthquakes (e.g, McNutt, 2005; Kawakatsu & Yamamoto, 2015), which mostly exhibit double-couple focal mechanisms resulting from the shear failure of rocks, we focus on volcano-tectonic earthquakes, which have double-couple focal mechanisms, as with tectonic earthquakes, to infer the stress field.

Volcano-tectonic earthquakes occur either at a distance from the activity center (e.g., White & McCausland, 2016) or at the activity center (e.g., Rubin & Gillard, 1998; Roman & Cashman, 2006). The latter occurs in response to the stress perturbation induced by migrations of magmatic fluids. Many previous studies have detected temporal changes of focal mechanisms by volcanic activity (e.g. Roman & Cashman, 2006; Roman et al., 2006; Vargas-Bracamontes & Neuberg, 2012; Terakawa et al., 2016). Zhan et al. (2022) investigated the temporal changes of focal mechanisms associated with the 2006 unrest of Augustine volcano, Alaska, and modeled the observation by an intrusion of a magma-filled crack, or dike, which is a ubiquitous form as an intrusion of magma with low to intermediate viscosity (Rubin, 1993; Rivalta et al., 2015).

How, then, does dike intrusion change the stress field? The most favorable orientation of dike intrusion is perpendicular to the minimum compressional stress axis to minimize the force to open the dike (E. M. Anderson, 1939; Célérier, 2008). Ziv and Rubin (2000) show that misoriented preexisting fractures do not much affect the orientation of the intruded dike. Let us here suppose the ambient stress state whose both maximum and minimum compressional stress axes strike the horizontal direction (Figure 2a). In other words, the vertical axis represents the intermediate stress axis. Dike intrusion extends the near-tip region and compresses otherwise (Figure 2). Zhan et al. (2022) quantitatively discussed expected focal mechanisms by the dike intrusion. If the dike over-

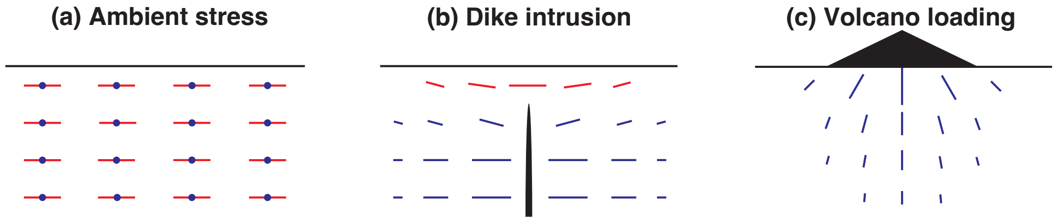

Figure 2. A schematic cross-sectional view of the end member of the stress and stress changes. Focal mechanisms change due to dike intrusions when the stress change by the dike intrusion dominates over the ambient stress and the stress by volcano loading. (a) The ambient stress. Here we assume that both maximum and minimum compressional axes are in the horizontal direction, the maximum (red) and minimum compressional (blue) axes being in-plane and out-of-plane, respectively. (b) Stress changes by an intrusion of a vertical dike. Red and blue lines denote extension and compression, respectively, with their magnitude and direction. A dike intrusion extends near the dike tip but compresses areas perpendicular to the dike plane. (c) Stress by volcano loading. Compressional stress (blue lines) is the largest right below the volcano and fades away from the volcano.

pressure, or the stress perturbation by the dike intrusion, is small enough, the focal mechanism reflects the local stress field, and earthquakes occur only near the dike tip where stress perturbation promotes faulting (Figure 2b). On the other hand, large dike overpressure significantly alters the dike intrusion. The dike-induced stress perturbation makes the stress perpendicular to the dike wall more compressional. If the dike pressure is large enough, the direction perpendicular to the dike call can turn from the minimum compressional stress axis, or σ_3, to the most compressional stress axis, or σ_1.

Zhan et al. (2022) also considered the stress given by the volcano edifice. Loading by a volcanic edifice makes the stress field more isotropic (e.g., Araragi et al., 2015) because it is usually close to axis-symmetric. If both the local deviatoric stress and dike-induced stress perturbation are minor, volcano loading dominates the stress field, leading to the nearly isotropic stress field. Otherwise, the local stress field, dike-induced stress changes, or both dominate the stress field.

Measuring absolute stress is crucial to understanding the state of the volcano but not straightforward. Although hydraulic fracturing is currently the only way to measure the absolute stress directly (e.g., Zoback et al., n.d.), it is too costly to do it in high spatial and temporal resolution. Monitoring temporal changes of focal mechanisms is a way to indirectly measure the absolute stress field because, as discussed above, temporal changes of focal mechanisms can infer the relative magnitude of the local stress to the stress changes, which deformation measurements give, if they are available.

Not only focal mechanisms but also seismic anisotropy carry information about the local stress field. Seismic anisotropy is mainly generated by deviatoric stress and the preferred orientation of minerals. Because the orientation of minerals does not quickly change with time, observed changes in seismic anisotropy are due to stress changes. Indeed, some previous studies found temporal changes of seismic anisotropy associated with volcanic activity (e.g., Miller & Savage, 2001; Gerst & Savage, 2004; Saade et al., 2019). However, the origin of stress changes that caused temporal changes of seismic anisotropy is not always well understood or consistent with observed ground deformation (e.g., Shelley et al., 2014). Numerical methods such as those done by Zhan et al. (2022) might lead to a more precise stress modeling to gain more insights into the origin of stress changes observed as temporal changes of seismic anisotropy.

So far, we have considered only elastic deformation to explain the observations. The transport of hydrothermal fluids, however, might affect the stress field. For example, (Saade et al., 2019) interpreted temporal changes of seismic anisotropy around Mt. Fuji and Hakone volcano, Japan, as due to porosity surge triggered by dynamic stress changes of the 2011 Tohoku-oki earthquake ($M_w = 9.0$). While incorporating such hydrothermal effects adds complexity to numerical modeling, it will lead to a more precise assessment of the stress state.

The stress state and its temporal changes inferred from seismic and geodetic methods do not consider the dynamics of magmatic fluids that generate the seismic and geodetic signals. Therefore, constructing a model to fit the observation and be consistent with the physics of the transport of magmatic fluids at the same time not only makes the model more sophisticated but also might help us forecast volcanic activity in the future. Given this importance, many studies have developed such physics-based models of magma transport in the last decade (e.g., K. R. Anderson & Segall, 2011, 2013; Zhan et al., 2017; Bato et al., 2018; Gregg et al., 2022). While many of these studies construct a model to fit deformation measurements, incorporating other geophysical observations such as the amount and composition of gas emission, seismicity, and focal mechanisms, as Zhan et al. (2022)

investigated, will lead to reducing uncertainties of key model parameters. This development leads to more precise physical models, and better forecasts of the volcanic activity (e.g., Poland & Anderson, 2020).

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