

# On the shallow volcanic response to remote seismicity

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## INTRODUCTION

It is a primary goal within the volcano monitoring community to develop improved observational data assessments and early warning for hazardous eruptions. It has become increasingly apparent over the past three decades that volcanic activity may be modulated by large earthquakes (e.g., Hill, et al., 1993), even at great distances. In many cases, the influence has been minor, including the perturbation of hydrothermal systems and expressed by changes in temperature, gas flux, or seismicity (Cox et al., 2015). For a small number (~4%) of large earthquakes ( $M_w > 7$ ), a moderate or large eruption ( $>VEI 2$ ; Volcanic Explosivity Index) may occur (e.g., Linde and Sacks, 1998; Manga and Brodsky, 2006). It is clear that the volcano monitoring community needs to focus on unrest processes related to large remote earthquakes, and how these relationships can be exploited to improve safety. A new contribution by Namiki et al. (p. 67 in this issue of *Geology*), uses analogue and computer simulations to understand the propagation of cracks under the dynamic stress from passing seismic waves. The work utilized a range of edifice aspect ratios, fluid characteristics, and external source excitations to develop an understanding of crack propagation and fluid flow as an analogue to natural volcanic systems. The experimental results demonstrated the importance of external seismic waves as a driver of volcanic edifice resonance and subsequent propagation of variably buoyant cracks. It is useful to outline the relevant mechanisms within shallow volcanic systems, and some of the ways that Namiki et al.'s work could be exploited to promote new research and to enhance volcano monitoring outcomes.

## PRESENT UNDERSTANDING

### Volcanic Systems

Many volcanic systems exist in a delicate state of balance, with the production of hot buoyant magmatic fluids from below being opposed by overlying resistive inertial forces of rock, sea, and atmosphere. If the confining forces are reduced, or if the forces driving magmatic or hydrothermal fluids are increased, an eruption may ensue.

The volcanic environment is often conceptually envisaged to contain a magma supply zone at mantle depths, crustal storage regions including chambers, sill, or dike complexes, and a conduit system that connects these features to the surface. At the shallowest portions of the plumbing system, the conduit will likely include a hydrothermal system, where heat and gas from below interact with the overlying groundwater system. In many cases, the plumbing system is built upon a volcanic edifice, a feature that is commonly linked to the public perception of a volcano.

From a volcano monitoring perspective, there may be a range of observables including seismicity, deformation, gas discharge, and visual features that can be exploited to assess the state of unrest in the system. In general terms, the monitoring observables relate to the aforementioned plumbing system in a reasonably coherent manner. Specific

features include discontinuities, pinch points, and phase transitions that reflect the complexity of the material contrasts that are extant within the conduit system. Discontinuities include layer boundaries with high- and low-permeability zones that may impede and pond fluids. Pinch points include transitions between magma chambers, mush zones, hydrothermal systems, vent funnels, and the conduits that connect them. Phase transitions might include bubble nucleation or crystallization depths, which have attendant impact on the fluid viscosity, density, or acoustic properties. These features are exceptionally important from a monitoring perspective, because they may be a locus of seismicity, a deformation point, or have implications for the characteristics of seismicity and degassing toward the surface. These transition points may be particularly important in a discussion of remote eruption triggering because any external modulation may be expressed by variations in the range of common monitoring observables.

### *Dynamic or Static Stress Modulation in Volcanic Systems*

Relating seismicity to eruptive activity is generally fraught due to the range of potential processes and attendant observation lag times. For small distances between an earthquake source and an eruption vent, mass advection and dynamic or static stress transfer might be plausibly related to eruptive activity, but unique determination of a causal relationship may be ambiguous (Jolly et al., 2018). At greater source-vent distances, advection becomes unlikely, and dynamic or static links may be identified. For large earthquakes, the static stress falls off rapidly ( $1/r^3$ ;  $r$  is distance from epicenter) and for source distances beyond a few hundred kilometers, this influence would be very small. Dynamic stresses decay slowly, by comparison ( $1/r^{1.66}$ ), and have been related to remote triggering (e.g., Manga and Brodsky, 2006; Peng et al., 2018). The link between dynamic stresses from large earthquakes and distant eruptions was first statistically established by Linde and Sacks (1998) but dynamic stress responses have also been inferred from other external modulating factors, such as Earth tides and atmospheric changes (e.g., Sparks, 1981; Neuberg, 2000) which have similar or even lower stress amplitudes.

### *Eruption Mechanisms Related to Dynamic Stress*

Once dynamic stresses are implicated, it becomes reasonable to inquire about the range of mechanisms that may destabilize volcanic systems to the point that they erupt. Several volcano system response mechanisms have been proposed, including magma bubble nucleation, bubble growth, and bubble propagation (e.g., Linde et al., 1994; Hill, et al., 2002; Manga and Brodsky, 2006). These mechanisms could promote and increase excess pressure and positive buoyancy in fluids and promote fluid migration. If the excess pressures exceed the confining pressures, then conduit or vent failure and eruption may take place.

Namiki et al. identified dynamically stressed crack migrations within, and just beneath, an analogue volcanic edifice. Hence, one might focus

on processes within the shallow magmatic storage zones, including the shallow conduit and hydrothermal system, as primary target environments. In systems where shallow magma is always present, even low inherent magma water contents may have two-phase bubbly fluids and strong buoyancy/density contrasts. For systems with robust long-term magmatic degassing profiles, magmatic perturbations might occur within an actively convecting magma system (Kazahaya et al., 1994; Stevenson and Blake, 1998) or within a shallow non-convecting magma plexus.

Within a shallow hydrothermal system, single-phase gas and two-phase bubble/water systems are likely, and fluid over-pressurization may feature as outlined for the magmatic systems above. As an example, spinoidal decomposition (e.g., Favvas and Mitropoulos 2008; Thiéry and Mercury 2009) may be a driving mechanism for volcanic unrest and eruption (e.g., Caudron et al., 2018) at plausible hydrothermal gas ascent times (Jolly et al., 2018). For chemically seal-bound hydrothermal systems (e.g., Christenson et al., 2017), it may be possible for fluids to exist in a metastable state. The new hydrothermal research suggests that such a system could become violently destabilized from rapid pressure or temperature changes at the H<sub>2</sub>O/CO<sub>2</sub> liquid spinoidal critical curve. Hence, the rapid migration of fluids in cracks into an overlying seal-bound hydrothermal system (Namiki et al.) could promote destabilization, seal failure, and eruption. In this context, it might be useful to consider the possible impact of top-down depressurization starting in the hydrothermal system, and cascading into the deeper (and more explosive) magmatic portions of the volcano.

#### Edifice Resonance—Testing the Hypothesis

Namiki et al.'s new work suggests a roadmap for new research whereby the historical catalogues may be re-examined to test the hypothesis of edifice resonance. It would be useful to assess the activity rates for high-aspect-ratio volcanic edifices against low-aspect-ratio equivalents, and use earlier event catalogues (Linde and Sacks, 1998; Manga and Brodsky, 2006). In addition, a rigorous examination of possible crack migration patterns using modern location approaches (e.g., Taisne et al., 2011) could be undertaken on global archive data sets at specific target volcanoes. These might confirm the wider implications of Namiki et al.'s work and improve volcano hazard assessments.

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