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What effects do earthquakes have on volcanoes?

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The interaction between earthquakes and volcanoes intrigues the public and provides a complex and cascading hazard that challenges scientists across a spectrum of disciplines. The key to understanding earthquake-volcano interactions is the response of gas and magma to earthquake-imposed stresses. Avouris et al. (2017, p. 715 in this issue of *Geology*) provide a huge step toward this goal, showing the first correlation between satellite-based volcano degassing and earthquakes. Their data show that when exposed to strong seismic shaking, (1) volcanoes that have open lava lakes release more gas, and (2) volcanoes that are partially plugged release less gas. In this Focus article, I consider this novel data set in the unresolved debate (e.g., Hill et al., 2002) on the roles of viscous (bubbles in liquid magma) and elastic processes (cracks in solid magma) in triggering volcanic eruptions.

Observations regarding the links between earthquakes and volcanoes date back to some of the pioneers of modern science, for example, Pliny the Elder (A.D. 77–79), and Darwin (1840), both observed an association between an earthquake and a volcanic eruption. More recent studies back up these early observations with statistical methods to identify earthquake triggered eruptions (e.g., Marzocchi, 2002, and references therein) and suggest only 0.3%–0.4% of volcanic eruptions are triggered by earthquakes (Linde and Selwyn Sacks, 1998; Manga and Brodsky, 2006; Lemarchand and Grasso, 2007). However, the proportion of triggered eruptions may be an order of magnitude higher in some regions, e.g., in Chile (Eggert and Walter, 2009; Watt et al., 2009) and Indonesia, where 25% of eruptions occur from volcanoes susceptible to earthquake triggering (Bebbington and Marzocchi, 2011). The data of Avouris et al. provide a significant increase in resolution and reveal many previously undetected non-eruptive degassing responses triggered at susceptible volcanoes. This tendency of some volcanoes to be particularly sensitive to earthquakes should make earthquake triggering a crucial component to any volcanic risk analysis.

There are more than 1500 active volcanoes in the world (Simkin et al., 1981) and each requires a range in amount, duration, and direction of critical stress to initiate an eruption (Spieler et al., 2004) or affect degassing. Static stresses from localized crustal movement can reach magnitudes of 10^{-1} MPa (Manga and Brodsky, 2006) and last for months or years (Rojstaczer et al., 1995). Dynamic stresses can reach a few MPa, but are transient (Hill et al., 2002; Manga and Brodsky, 2006). Away from volcanoes, both static and dynamic stresses drive elastic processes that affect fracture permeability (Brodsky and van der Elst, 2014). However, at volcanoes, the presence of magma insists that viscous processes must also be considered. Therefore, the specifics of the volcanic scenario determines whether viscous or elastic processes drive changes in volcano permeability. For example, an open low-viscosity lava lake containing gas bubbles (Fig. 1A) may respond viscously associated with bubble outgassing, whereas a high-viscosity, partially closed lava dome will have a more elastic response as cracks open or close, affecting gas flow (Fig. 1B).

Avouris et al. use a selection of the world's volcanoes as a natural laboratory, and their data clearly distinguishes increased degassing at open systems from decreased degassing at closed systems. The remote sensing analysis compares volcanoes that have experienced similar amounts of shaking. They use the operational OMI SO_2 product obtained from the NASA Goddard Earth Sciences Data and Information Services Center to enable analysis of the actively degassing volcanoes of Ambrym and Gaua (Vanuatu); Bagana, Rabaul, and Ulawun (Papua New Guinea); Fuego and Pacaya (Guatemala); Merapi, Semeru, and Bromo (Indonesia); Turrialba (Costa Rica); and Villarrica (Chile). The data reveal that >50% of >5 KPa shaking events at these volcanoes drive a significant change in degassing. Open system volcanoes where a lava lake has direct access to the atmosphere showed an increase in SO_2. For example, the combined degassing from Ambrym and Gaua volcanoes shows that SO_2 output 5 days after earthquakes consistently increased by ~1 kT per day (an approximate doubling of output). These type of data provide critical temporal and magnitude constraints on the mechanisms responsible. Open system lava lakes consist of low-viscosity magmas that are governed by viscous processes in a magma where bubbles nucleate and rise as magma convects, overturns (Beckett et al., 2014), and sloshes (Namiki et al., 2016) (Fig. 1A). An acceleration in processes such as volatile diffusion (Ichihara and Brodsky, 2006), bubble nucleation (Crews and Cooper, 2014), coalescence (Kennedy et al. 2016), rise (Higginbotham et al., 2017), shaking free of bubbles clinging to individual crystals, and sloshing (Namiki et al., 2016) may all contribute and cascade toward increased rates of convection and degassing. The data cannot distinguish specifically which of these processes dominates, but the time lag of several days and the large magnitude of the changes indicates that a relatively slow but significant cascade of processes is required. This result necessitates further study linking ground based data with other observations to further elucidate the timescales and interactions of these mechanisms.

Statistically, earthquakes are more likely to trigger eruptions at closed system volcanoes than open volcanoes (Eggert and Walter, 2009;

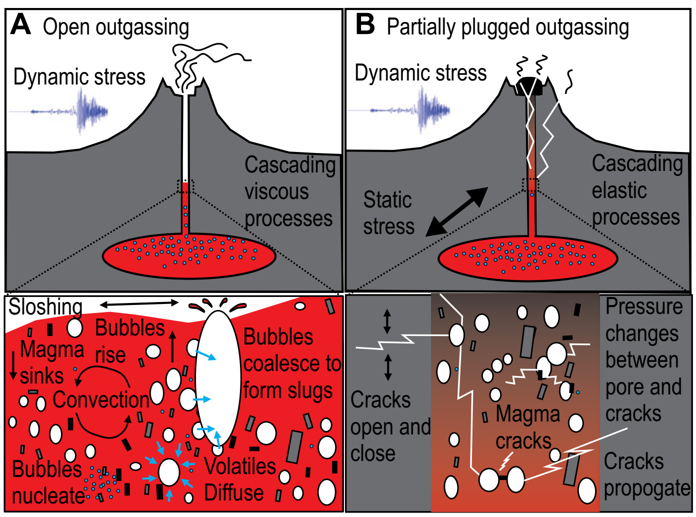

Figure 1. Viscous and elastic processes associated with open and partially closed degassing magma systems. A: Dynamic pressures cause open sloshing and bubble processes that cascade to affect convection and degassing. B: Static and dynamic processes may drive pressure redistribution between cracks and pores that similarly cascade affecting permeability and degassing pathways.

Bebbington and Marzocchi, 2011). Avouris et al. offer a novel explanation for this; they show that degassing reduces following large amounts of shaking at relatively closed volcanoes. Reduced degassing could increase the possibility of pressure build-up inside the volcano. The decreases in degassing measured at plugged volcanoes is difficult to explain by viscous processes and is easier to interpret by evoking elastic processes governing crack controlled permeability (Fig. 1B). Avouris et al. suggest that crack closure in magma that plugs a volcano could be driven by earthquake stresses and explain the decreases in degassing. Crack width, length, and number all affect gas permeability and degassing (Heap et al., 2015) and dominate pore controlled permeability (Heap and Kennedy, 2016). Cracks can open and close in response to both dynamic and static stresses (Bonali et al., 2012; Brodsky and van der Elst, 2014). In a dynamic scenario, fluid within cracks and pores can redistribute and drive changes in the permeability of these structures (Brodsky and van der Elst, 2014) and the data from Avouris et al. suggest that permeability may decrease. This is in contrast to observations of permeability increases in hydrological systems following earthquakes (Brodsky and van der Elst, 2014, and references therein) and suggestions that hydraulic surges may drive crack propagation in volcanoes (Hill et al., 2002). One possible mechanism to explain this could be earthquake-triggered ductile compaction to reduce permeability in magmas and altered country rock (Heap et al., 2015; Siratovich et al., 2016). However, in both a dynamic and a static stress scenario, the permeability depends on the orientation of the stress field and crack and pores (Bonali et al., 2012) and hence permeability changes may be highly directional. Many volcanoes may already be subject to differential static stresses which may readjust following dynamic stresses, resulting in changes in gas permeability and hence degassing.

The contrasting responses of volcanoes outlined by Avouris et al. provides an exciting platform for future research. In particular, the interactions between viscous and brittle behavior in magmas due to the strain rate and magnitude dependence of the brittle-ductile transition (Dingwell, 1996). Both brittle and ductile behavior in magma can now be reproduced in the laboratory at magmatic temperatures and pressures (Martel et al. 2000). The data presented by Avouris et al. and the potential for more remotely sensed data therefore invites experimental and numerical constraints of earthquake triggered viscous and elastic processes, highlighting a tantalizing area of future research.

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