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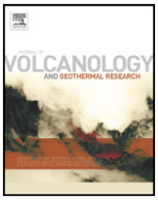

Review

A multi-decadal view of seismic methods for detecting precursors of magma movement and eruption

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ABSTRACT

With the emergence of portable broadband seismic instrumentation, availability of digital networks with wide dynamic range, and development of new powerful analysis techniques made possible by greatly increased computer capacity, volcano seismology has now reached a mature stage where insights are rapidly being gained on the role played by magmatic and hydrothermal fluids in the generation of seismic waves. Volcanoes produce a wide variety of signals originating in the transport of magma and related hydrothermal fluids and their interaction with solid rock. Typical signals include (1) brittle failure earthquakes that reflect the response of the rock to stress changes induced by magma movement; (2) pressure oscillations accompanying the dynamics of liquids and gases in conduits and cracks; and (3) magma fracturing and fragmentation. Oscillatory behaviors within magmatic and hydrothermal systems are the norm and are the expressions of the complex rheologies of these fluids and nonlinear characteristics of associated processes underlying the release of thermo-chemical and gravitational energy from volcanic fluids along their ascent path. The interpretation of these signals and quantification of their source mechanisms form the core of modern volcano seismology. The accuracy to which the forces operating at the source can be resolved depends on the degree of resolution achieved for the volcanic structure. High-resolution tomography based on iterative inversions of seismic travel-time data can image three-dimensional structures at a scale of a few hundred meters provided adequate local short-period earthquake data are available. Hence, forces in a volcano are potentially resolvable for periods longer than ~1 s. In concert with techniques aimed at the interpretation of processes occurring in the fluid, novel seismic methods have emerged that are allowing the detection of stress changes in volcanic structures induced by magma movement. These methods include (1) ambient noise interferometry, in which the ambient seismic noise is used to probe temporal changes in volcanic structures; (2) the measurement of seismic anisotropy, where changes in the alignment of fluid-filled microcracks and pore space are monitored to assess the response of the crust to pressurization of a magmatic system; and (3) the detection of systematic changes in fault plane solutions of volcano-tectonic earthquakes caused by local stress perturbations during conduit pressurization. As new seismic methods refine our understanding of seismic sources and behavior of volcanic structures, we face new challenges in elucidating the physico-chemical processes that cause volcanic unrest and its seismic and gas-discharge manifestations. Future important goals toward meeting those challenges must include a better understanding of the key types of magma movement, degassing and boiling events that produce characteristic seismic phenomena, along with a quantitative understanding of multiphase fluid behavior under dynamic volcanic conditions. Realizing these goals will be essential for the development of an integrated model of volcanic behavior and will require multidisciplinary research involving detailed field measurements, laboratory experiments, and numerical modeling.

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1. Introduction

Magma transport is fundamentally episodic in character as a result of the inherent instability of magmatic systems at all time scales. This episodicity is reflected in seismic activity, which originates in dynamic interactions between gas, liquid and solid along geometrically complex magma transport paths. The geometrical complexity plays a central role in controlling flow disturbances and also providing specific sites where pressure and momentum changes in the fluid are effectively coupled to the Earth. In concert with this activity originating in the fluid are processes occurring in the solid rock, which manifest themselves mainly in the form of earthquakes associated with shear failures in the volcanic edifice. Whereas events originating in the fluid represent volumetric modes of deformation involving a localized conduit response to flow processes, the shear failures act as gauges that map stress concentrations distributed over a large volume surrounding magma conduits and reservoirs. These are called Volcano-Tectonic (VT) earthquakes to differentiate them from pure tectonic earthquakes, although they are indistinguishable from the latter in their broadband spectral characteristics and failure mechanisms.

Seismic signals originating in the dynamics of magmatic and hydrothermal fluids typically include Long-Period (LP) events and tremor (Chouet, 1996a). This terminology stems from the appearance of these signals on the short-period seismometers that have traditionally been used in volcano monitoring. LP events resemble small tectonic earthquakes in duration but differ in their characteristic frequency range and harmonic signature (see Section 4). Tremor is characterized by a signal of sustained amplitude lasting from minutes to days, and sometimes for months or even longer. In many instances, LP events and tremor are found to have essentially the same temporal and spectral components (Latter, 1979; Fehler, 1983), suggesting that a common source process, differing only in duration, underlies the two types of events. Accordingly, LP events and tremor are often grouped under the common appellation LP seismicity. The periods at which LP seismicity is observed typically range from 0.2 to 2 s (Chouet, 1996a), and the characteristic oscillations of LP signals are commonly viewed as a result of acoustic resonance in a fluid-filled cavity or crack (see Section 4).

It is fairly straightforward to understand why resonance is such a pervasive phenomenon in volcanoes. Degassing is the main driving force behind most volcanic phenomena. The separation of vapor and melt phases leads to the formation of bubbles, whose presence decreases magma density, enhances magma buoyancy and propels magma ascent (Wilson and Head, 1981). The presence of bubbles in magma and hydrothermal fluids lowers the sound speed of these fluids, inducing a sharp contrast in velocity between the fluid and encasing solid, which favors the entrapment of acoustic energy in the fluid volume source region. For short-lived excitation, energy losses due to elastic radiation and dissipation processes at the source are the main factors affecting the duration of resonance, hence longer-duration signals are naturally enhanced in low-viscosity bubbly liquids. Other types of gaseous fluid mixtures may be even more efficient at sustaining source resonance. For example, gases laden with solid particles, or gases mixed with liquid droplets, may produce velocity contrasts that are similar to, or stronger than, those associated with bubbly liquids. In particular, dusty gases made of micron-sized particles, or misty gases made of micron-sized droplets, can sustain resonance at the source over durations that far exceed those achieved with bubbly fluids (Kumagai and Chouet, 2000).

In hydrothermal systems, a common LP excitation mechanism involves surges in the heat transfer from an underlying magma body (Kumagai et al., 2002a; Nakano et al., 2003; Kumagai et al., 2005; Waite et al., 2008; Matoza et al., 2009a). Heating by magmatic activity increases pressure in a steam-filled fracture to a critical threshold, at which point an abrupt opening of a pathway allows gas to escape suddenly, initiating a rapid pressure loss, collapse of the fracture, and