Spatio-temporal evolution of volcano seismicity: laboratory simulations

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The measurement and analysis of seismicity in active volcanic areas is the main tool used in volcanic hazard mitigation. However, seismic monitoring technologies have met with only mixed success in forecasting eruptive episodes. This arises because, although our understanding of the spatio-temporal processes generating the observed seismic signals has increased substantially with the wide scale adoption of new and improving technologies, such as modern broadband seismology and GPS, there is still no universally accepted quantitative physical model for determining whether or not a sequence of precursory phenomena will end in an eruption, or for forecasting the time or the type of eruption. Hence, most forecasting strategies rely on long-term observation and monitoring of the edifice, rather than directly assessing the fundamental micromechanics of the rock/fluid interaction processes involved.

It is therefore our view that, in order to move forward, we need to study these coupled rock-fluid-mechanical processes in detail under the controlled conditions available in laboratory-scale simulations. Specifically, we aim to investigate the micromechanical original of the three key types of reported volcano seismicity: (1) high frequency volcano tectonic (VT) earthquakes, generated by fracture and faulting; (2) low frequency (LF) earthquakes, hypothesised to be generated by rapid fluid flow though fracture-damage zones; and (3) seismicity that exhibits features of both VT seismicity and LF tremor, known as hybrid (HY) events.

Here, we report results from a suite of laboratory experiments in which dry and water-saturated samples of basalt from Mount Etna volcano (50 mm in diameter by 125 mm in length, with a centrally pre-drilled 3mm diameter conduit) were deformed and fractured under an effective confining pressure representative of conditions at depth under a volcanic edifice (40 MPa). Particular attention was paid to the formation of a fracture and damage zone that would allow us to stimulate the types of coupled fluid-mechanical interactions thought to be responsible for generating the different seismic signals recorded from deforming volcanic edifices preceding eruption events. Experiments were conducted in two phases. In phase 1, samples were deformed at a constant strain rate of 4×10^{-6} s^{-1} until brittle failure occurred. This resulted in the creation of a localized shear fault and an associated crack damage zone. In phase 2, the fluid stored in the sample (including both pre-existing microcracks and the new fault damage zone) was rapidly decompressed from the top of the sample, stimulating rapid fluid flow out of the sample via the damage zone and the pre-drilled conduit. The output of microseismicity (acoustic emission) was recorded continuously throughout both phases using an array of up to 16 transducers. In addition to recording waveforms, the array was used to locate individual acoustic emission (AE) events using a downhill simplex routine and a triaxial velocity model. We also computed source characteristics of the located events via relative amplitude moment tensor analysis.

Following an initially low rate of AE as pre-existing cracks were closed in phase 1, we observed an exponentially increasing rate as differential stress was increased and new, dilatant cracks nucleated and propagated. Of the located events, the majority were located within the damage zone of the shear fault, or its conjugate (Fig. 1A). They exhibited dominantly double-couple (DC) source characteristics, similar to VT events, and entirely as expected for the faulting phase of the experiment. We verified that the presence of the central conduit did not significantly affect the mechanics of deformation and failure by conducting identical experiments without a conduit, and obtaining essentially identical results.

In phase 2, we rapidly decompressed the pressurized pore fluid by means of a valve at the top of the apparatus. The decompression was accompanied by a swarm of AE events that were again located primarily within or near the fault damage zone generated during stage 1 (Fig. 1B). However, In contrast to those from phase 1 of the experiment, the source characteristics of the decompression-related events exhibited low components of shear, but a high volumetric component (Fig. 1B). We therefore postulate that the rapid flow of the pore fluid through the tortuous fracture damage zone created conditions conducive to the generation of a swarm of AE events analogous to LF events recorded at active volcanoes. Source mechanisms involving high levels of volumetric change have been widely reported in volcanic regions, and in areas of tectonic subduction and fault overpressure; all of which have been linked to fluid movement.

In order to investigate the microstructural origin of located AE events, we analyzed backscattered scanning electron microscopy images of the deformed and decompressed sample. These showed a complex damage zone formed in the lower half of the sample, dominated by two major, conjugate faults (as seen in Fig. 1). During decompression, events were located within this damage zone. The detailed locations of AE clusters imply that the fluids producing these events were following highly tortuous pathways, with many pinch-outs and undulating features. Such geometries have long been postulated to be responsible for tremor-type events. SEM observations showed that many of the cracks were filled with broken and comminuted rock, as also reported from field observations of fractured magma. Taken together, these observations suggest that LF events in volcanic areas are generated when hydrothermal fluids (water,

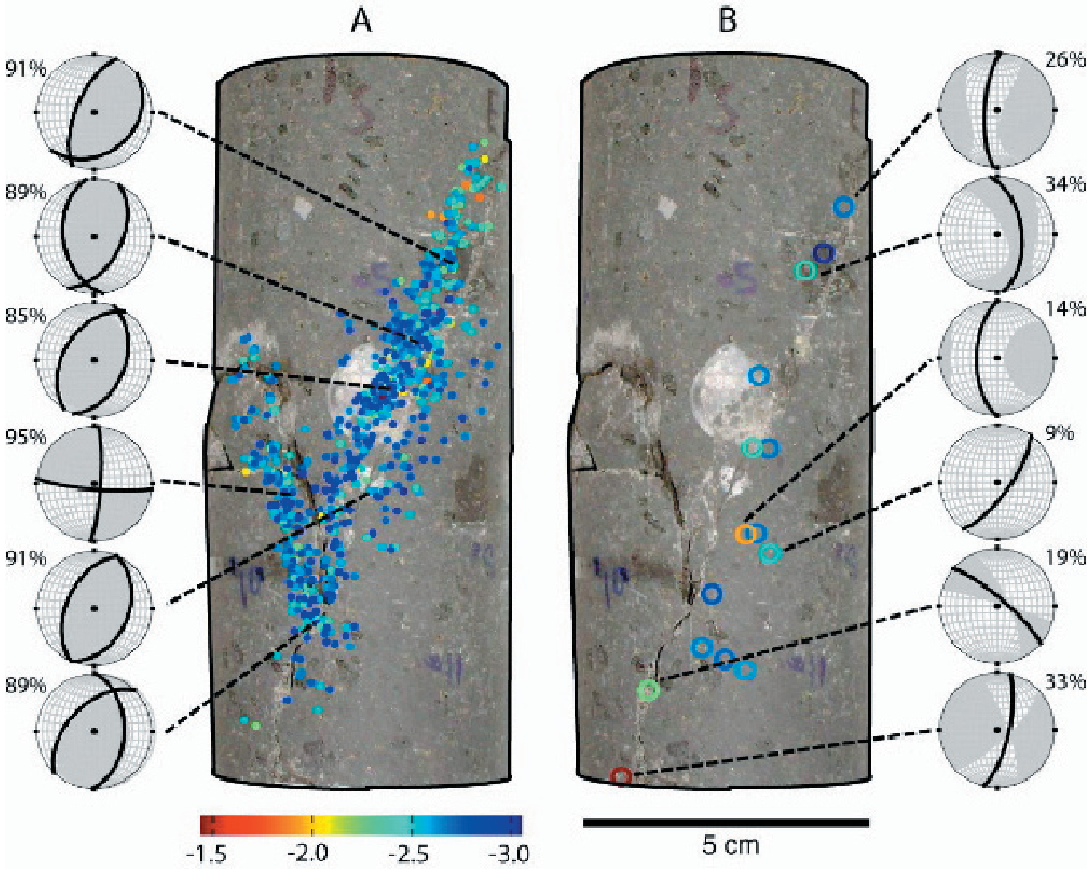

Figure 1: Post-test sample of Etna basalt showing a single through-going fault and its conjugate. AE locations resulting from the deformation phase of the experiment (A, solid dots), and from the rapid decompression of the pore fluid (B, open circles), are superimposed. The colour-bar indicates dimensionless event pseudo-magnitudes. All AE events are located on the fault or within the fracture damage zone. Source characteristics (mechanisms) associated with deformation (A) exhibit high percentage components of double couple (shear); whereas those relating to pore fluid decompression (B) show much lower double couple components.

steam, dusty gasses and/or magma itself) move through pre-existing crack networks comprising both large faults and their associated fracture damage zones.

Finally, using a simple size-frequency scaling relationship, we show that LF events with laboratory length (d_L) and frequency (f_L) scales (50 mm and 18-50 kHz, respectively) can be scaled appropriately to data from source dimensions (d_V) and seismic frequencies (f_V) typical of natural volcanic events (200 m – 1 km and 1-2 Hz, respectively). Since AE obeys power law relationships, just as field scale seismicity, we can employ similar statistics. Following the treatment of (Burlini et al., 2007), we can write $d_L \times f_L = d_V \times f_V$, if the two processes show the same scaling characteristics. With the measurements quoted above this yields $d_V/d_L = 4\text{-}20 \times 10^3$ and $f_L/f_V = 9\text{-}50 \times 10^3$, in excellent agreement. Although somewhat simplistic, this first order treatment confirms that our laboratory data scales to natural volcanic data. Likewise, other parameters relevant to volcano physics, such as viscosity (V), can also be scaled in this simple way. Using $V_L = 10^{-2}$ poise for laboratory pore water and $V_V = 10^3$ poise for basaltic lava, respectively, and length scales of d_L = 50 mm and d_V = 10 km (common for effusive eruptions), we find that $d_V/d_L = 2 \times 10^5$ and $V_V/V_L = 1 \times 10^5$; again providing excellent agreement.