sity may be the product of the greater extent of warm areas in the past (*10*). On the other hand, extreme warming may have caused tropical extinctions or vegetation die-offs (*11*). Hence, the heat sensitivity of tropical lowland species is an open question.

Furthermore, Colwell *et al.* assume that temperature alone sets range limits. Although temperature is clearly a limiting factor for some tropical species at high altitudes, most studies on the distributions of lowland species focus on precipitation as limiting, because moisture has such an obvious impact (see the figure) (*12*, *13*). As an example of moisture precedence, 30% of Panama's tree species limited to above 600 m above sea level on the dry Pacific slope occur near sea level on the wet Caribbean slope (*14*). Even where temperature is an important limiting factor, it is unlikely to be operating alone (*15*): The idiosyncratic range dynamics of small-mammal species at Yosemite (*1*) warn against the assumption that ranges simply reflect temperature tolerances. Finally, range limits estimated from small samples gathered at one location can only be underestimates (*16*); predictions of extinction risk will be overestimated if ranges are underestimated.

Colwell *et al.* provide an important illustration of the potential risk posed by global warming to tropical diversity. In fact, even bleaker predictions have been made. One general circulation model predicts loss of Amazonian forest by the middle of this century due to drought stress (*17*). But forecasts of the impact of global warming on tropical diversity are hampered by uncertainties about what causes range limits. Even in temperate communities, little direct evidence of such factors goes into models; most models are based on correlations between current range and climate.

A key research focus should thus be to find direct evidence of how species respond to relevant environmental variables. The framework outlined by Colwell *et al.* can then be used more accurately, and will also be relevant outside the tropics. Even lowland attrition may occur here, because climatic shifts are likely to exceed species' migration capacities (*18*, *19*).

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GEOPHYSICS

Volcanic Symphony in the Lab

Analysis of acoustic signals from lab samples links rapid pressure drops of pore fluids with low-frequency volcanic earthquakes.

Luigi Burlini[1] and Giulio Di Toro[2]

Like philharmonic orchestras that perform symphonies with different musical instruments, active volcanoes produce a mix of seismic signals (earthquakes) that vary in their periodicity. Because each type of signal is associated to different physical processes, seismic monitoring can be a powerful tool for eruption forecasting, especially when combined with geochemical data (such as composition of escaping gases) and ground-deformation monitoring (*1*). The key issue is how to associate volcanic processes—which include fracture and dike propagation, magma feeding, and degassing—with each type of earthquake (*2*, *3*). One approach is to recreate volcanic conditions with small laboratory samples, and then extrapolate the experimental signals (sonic to ultrasonic waves) to the scale of volcanic features. On page 249 of this issue, Benson *et al.* (*4*) measured acoustic emissions (AEs) in a basalt sample from Mount Etna during loading and fracturing, and then on a rapid decompression of fluid. The AE signals recorded during the pore fluid decompression are similar to those detected during low-frequency earthquakes associated with volcanoes, which suggests that some natural quakes also originate from the rapid release of pressure in fluids (melts, gas, and supercritical fluids) flowing in fractures.

The seismic signals from volcanoes include high-frequency waves similar to those detected during tectonic earthquakes as well as low-frequency or long-period earthquakes and very-long-period earthquakes; tremors (continuous low-frequency ground vibration) and hybrid events that can mix these signals are also observed (*2*). Several theories have been proposed that connect volcanic with different seismic signals (*3*), but lab experiments potentially can allow observation of each physical mechanism separately—just as a clarinet passage is easier to recognize in a symphony performance if you have first heard the clarinet playing alone. Benson *et al.*, using the tools typical of passive seismology (which looks at seismic signals and includes three-dimensional earthquake location, waveform analysis, and computation of focal mechanisms), interpreted volcanic seismicity on the basis of experiments that reproduce variation of the physical conditions (such as pressure drop in a conduit) occurring in volcanic environments.

In rock deformation experiments, AEs are elastic waves produced by local strain events such as microfracturing, interaction of fluids with the crack walls, etc. (*5*, *6*), although only rarely are emissions transmitted at audible frequencies (20 to 20,000 Hz). Following the pioneering work of Obert and Duvall (*7*), who used geophones to measure these signals, the use of arrays of piezoelectric transducers has enabled researchers to pinpoint the source of the AE and follow the evolution of sample damage (*6*, *8*, *9*).

To what extent can we link these lab studies and data from volcanoes? Experimental and natural waveforms can be similar in shape but can differ by orders of magnitude in frequency and amplitude (see the figure). Earthquakes are detected by seismometers and accelerometers that record ground motion and acceleration, whereas AEs are detected by

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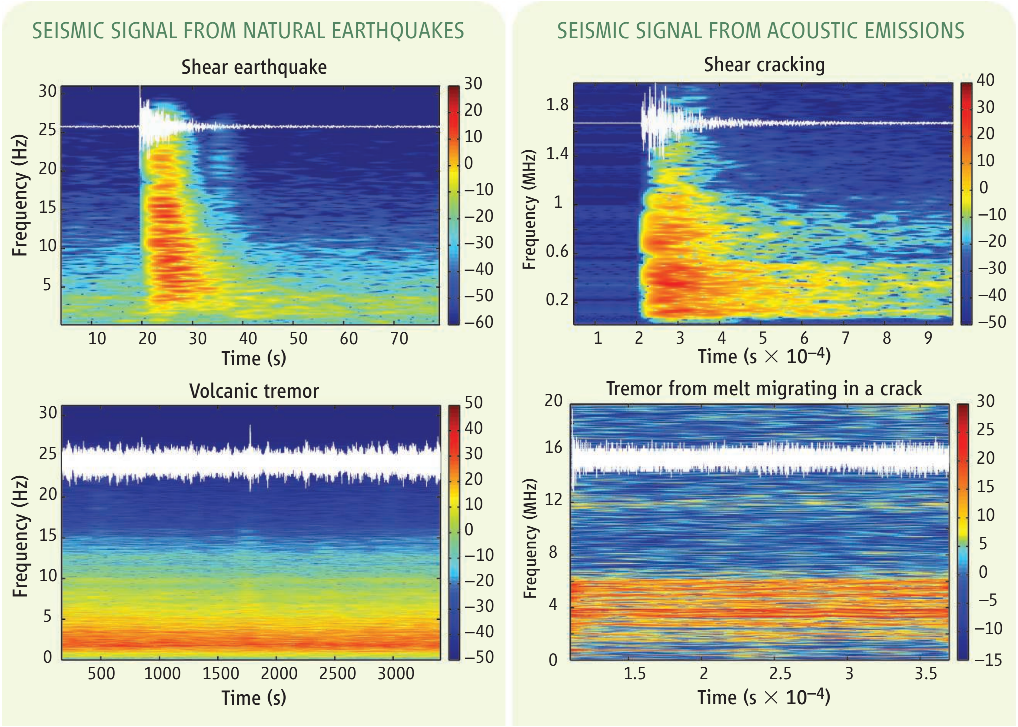

Scaling the volcanic symphony. Seismic signal (white line) and spectrogram from Mount Etna earthquakes (**left column**) and acoustic emissions (AEs) (**right column**). Note the similarities of natural shear earthquake with shear-cracking and of volcanic tremor with the signal from melt migration in a small sample. (**Top left**) Shear earthquake, 11 April 2002, 10:22. (**Bottom left**) Long-lasting tremor, 12 November 2002, 23:00. (**Top right**) AE of a shear crack produced during loading and fracturing a basalt from Mount Etna. (**Bottom right**) AE emitted from a basaltic melt intruding an ~0.1-mm-long fracture in an olivine aggregate. Color bars are arbitrary units from normalized amplitudes.

piezoelectric transducers, which record stress variation (and therefore deformation of the transducer and its acceleration). There are several reasons for believing that the lab studies are good models for earthquakes:

1) The ratio between the energy content of the AEs and their occurrence follows the Gutenberg-Richter earthquake statistic law (*6*, *10*), which states that the cumulative number of events is inversely proportional to their energy.

2) There are strong similarities between the small quakes that follow a main earthquake (the so-called aftershock sequence) and the AE activity that follows sample fracturing (*6*).

3) AEs range from 10^5 to 10^7 Hz, whereas seismic waves have frequencies around 1 Hz. This difference can be related to the length of the fractures generated (at most 1 cm in the lab versus kilometers in the field). Benson *et al.* confirmed that the length of the microfractures observed after the experiments scaled with the dominant frequency of the AEs (*11*), similar to what is predicted for natural earthquakes (*12*).

4) The fluid viscosity of the fluid producing a tremorlike signal can be scaled from laboratory to nature, as Benson *et al.* have documented.

5) The spectrograms of natural and laboratory seismicity, once allowance is made for the different frequencies, are similar. We infer that the evolution of the seismic signal with time is similar, which suggests that the underlying physical process is the same.

This final point is well illustrated in Benson *et al.*; the introduction of waveform analysis of the AEs allowed the synthesis of spectrograms that describe the frequency and amplitude content of each AE (*11*) that are remarkably similar to those of natural seismic waves (see the figure).

Experimentally reproducing sections of the volcanic symphony in the laboratory has several advantages but some limitations. Application of pressures and temperatures typical of volcanic areas at depths of 5 km (about 130 MPa and 300° to 600°C) requires small sample size (centimeter scale), and the AEs have small amplitudes because they originate from micrometer-scale displacements. Because the seismic signal decays rapidly with distance, the piezoelectric transducers must be placed as close as possible to the sample. Unfortunately, the transducer performance drops above 250°C, so working at higher temperatures requires that ceramic buffer rods are placed between the sample and the transducers to keep the latter cool.

Because Benson *et al.* were mainly looking at the effects of fluid–conduit wall interactions, they could work at room temperature and place the transducers directly on the specimen. Their experimental configuration reproduces schematically a volcanic conduit, and their array of piezoelectric transducers simulates a volcanic seismic network. The waveforms Benson *et al.* recorded (often referred as microseismicity) were in fact similar to earthquakes registered during natural volcanic activity, despite working at room temperature. The microstructural analysis of the specimens after the experiments allowed them to identify a damage zone where the microseismicity was localized. From the geometry of the newly created fractures within the damage zone, they built a model explaining the nature of the microseismicity. Just as the turbulence of the air at the tip of a clarinet emits the typical sound, the tortuosity of the damage zone produces the turbulence of the fluid flow during the decompression. The fluids in volcanoes can be magma, supercritical fluids, and gases, but Benson *et al.* successfully simulated a volcano using only water.

Scale-invariant numerical modeling could be used to extrapolate these results to the dimensions of volcanoes and make the comparison more robust. This understanding should allow for better predictions of the intensity and timing of volcanic eruptions, so that early warning and alert can save lives.

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