Monitoring Volcanoes

R. S. J. Sparks, *et al.*

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time, the ethanol preference disappeared. Thus, rejection or deprivation of sex leaves male flies in a state that increases the preferential consumption of ethanol. Copulation overrides the deprived state and ethanol preference is reduced.

In mammals (e.g., rats and mice), neuropeptide Y (NPY) influences ethanol-related behaviors (*4*). For example, elimination of NPY expression in the mouse increases ethanol consumption. The homolog of NPY in *Drosophila* is neuropeptide F (NPF) (*5*, *6*). In no animal model has the NPF/NPY neural system connected sexual experience to ethanol-related behaviors. Shohat-Ophir *et al*. discovered that courtship rejection reduced the amount of NPF produced in the male fly brain. They also found that reduced signaling by the NPF receptor (by decreasing NPF receptor expression with RNA interference) resulted in males that preferred ethanol-spiked food even after mating (these flies did not have the NPF signaling effect of sex). Extrinsic activation of NPF-expressing neurons (by triggering the opening of TRPA1 cation channels) in virgin males decreased their preference for ethanol intake—ethanol intake was similar to that of males that had previously copulated.

Could the NPF neural circuit in the fly brain be part of a reward system? Pairing of ethanol exposure (at inebriating concentrations) with an odor leads to a long-term memory and preference for that odor in *Drosophila*, suggesting that ethanol experience is rewarding (*7*). Shohat-Ophir *et al*. observed that pairing of male flies with virgin female flies in the presence of an odor (there is presumably some copulation taking place) led to a later preference of those males for the odor. These results suggest that sex is rewarding. Extrinsic activation of the NPF-expressing neurons in the presence of an odor, the same technique that decreases ethanol consumption, increases flies' preference for that odor. The data of Shohat-Ophir *et al*. suggest that the NPF neural circuit is part of a reward system that adjusts reward-seeking behavior (ethanol intake) appropriately.

Although it is titillating to think about the relationship between spurned advances and ethanol consumption (anthropomorphizing the results from flies is difficult to suppress, but the relevance to human behavior is obviously not yet established), the study of Shohat-Ophir *et al*. study should not be taken lightly. The authors provide new insights into a neural circuit that links a rewarding social interaction with a lasting change in behavior preferences. Identifying the NPF system as critical in this linkage offers exciting prospects for determining the molecular and genetic mechanisms of reward and could potentially influence our understanding of the mechanisms of drugs of abuse.

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GEOPHYSICS

Monitoring Volcanoes

Despite technological advances, volcano monitoring around the world is woefully incomplete.

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The ascent of magma in volcanoes is typically accompanied by numerous small earthquakes, the release of magmatic gases, and surface deformation (*1*). Systematic volcano monitoring to detect these phenomena began in 1845 with the completion of the Osservatorio Vesuviano. Other volcano observatories soon followed, such as the Hawaiian Volcano Observatory, which celebrates its 100th anniversary this year. Today, the World Organization of Volcano Observatories has 80 members. The range and sophistication of the detection systems has increased dramatically, and advanced models of volcanic processes are helping to interpret monitoring data. Yet, key problems remain both with distinguishing volcanoes that will erupt from those that will not and with global data coverage.

Seismic signals remain a key aspect of volcano monitoring. As magma moves toward the Earth's surface, stress changes in the volcanic edifice, as well as magma rupture and stick-slip motion of the magma body, lead to highly regular seismic patterns, often referred to as volcanic tremor (*2*). The signals are typically very weak and may be missed by regional networks, requiring a dedicated network of seismometers near the volcanic edifice. Seismic monitoring is therefore at the heart of every volcano observatory.

Early attempts to interpret seismic signals on volcanoes used methods adopted from earthquake seismology. Simple event counts or amplitude estimates were used as crude indicators for the level of volcanic activity. In the past 20 years, broadband seismic sensors have enabled detection of seismic signals from volcanic earthquakes in a wide frequency range, allowing volcano seismologists to distinguish between different types of volcanic events and to attribute different signals to different volcanic processes (*3*). Conceptual models help to detect and quantify magma or fluid movements, or to identify stress changes in the volcanic edifice. Hence, short-term forecasting can be achieved by interpreting systematic changes in seismic energy release as changes in magma ascent rates and changes in seismic patterns and spectral characteristics as indicators of critical changes in magma properties.

Compared with global seismology, where data exchange is routine, volcano observatories are more independent and less willing to share data. Particularly during a crisis, raw seismic data are often confidential, such that only the local observatory can give advice. Some observatories have established links to research institutions. However, it is crucial that advice to authorities is channeled through the observatories or official scientific advisory committees; maverick interpretations from outside groups can be a problem.

Most volcanic eruptions are preceded and accompanied by ground deformation. Methods to measure surface movements include high-precision leveling, electronic distance measurement with lasers, ground tiltmeters, and—in the past 20 years—the Global Positioning System (*4*). These methods are typically used in combination. Strain meters in boreholes (*5*), one of the world's most sensitive geophysical instruments, are used at very few volcanoes. Deformation data were long interpreted with a simple point source model, the Mogi model (*6*), but today's numeri-

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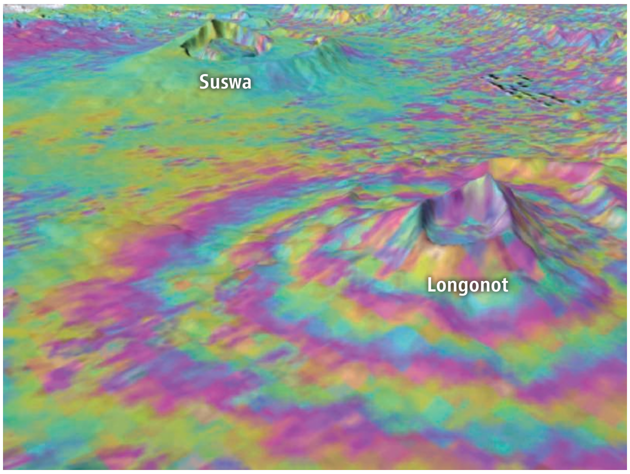
cal models incorporate representations of crustal rheology and of differently shaped pressure sources (*7*). With these new models, the shape and depth of the magma chamber can be determined more precisely.

Satellite-based methods provide a route to detecting unrest on currently unmonitored volcanoes (*8*). Interferometric synthetic aperture radar (InSAR) uses the phase component of radar images to determine the position of the Earth's surface. Simultaneously recorded images from different radars produce digital elevation models, vital for predicting the path and run-out of pyroclastic flows and lahars, and time-separated images measure deformation. The radar beam can pass through clouds. This is particularly useful in the tropics, where cloud cover frequently obscures visual observations.



Not dormant. This InSAR image shows a pulse of uplift during 2004 to 2006 at Mount Longonot, Kenya, a volcano previously believed to be dormant. The image, from the ESA satellite Envisat, is draped over a digital elevation model from the Shuttle Radar Topography Mission. Each complete color cycle (fringe) represents 2.8 cm of displacement toward the satellite (*14*). The distance between craters is ~35 km.

The satellite view provides a global perspective, mapping tectonic strain across continents and allowing the exploration of volcanoes in remote, underfunded, or inaccessible environments. As a result, the list of volcanoes previously thought to be dormant but now known to be showing signs of unrest (see the figure) is growing rapidly. These observations enable targeting of resources for more detailed, ground-based monitoring.

Despite its enormous potential, InSAR is still a young endeavor. Technical issues, such as repeat times and mission longevity, are in the hands of the space agencies. In a promising development, the European Space Agency's (ESA) Sentinel satellites, due for launch in 2013, are expected to acquire data over all land masses every 6 days for the next 20 years. Attaching radar systems to unmanned aerial vehicles (UAVs) promises greater flexibility and bespoke acquisition plans, although flight paths are more complex than those of satellites, complicating the data interpretation. The challenges will be, first, to distinguish between magmatic, hydrothermal, and even atmospheric errors, and second, to determine which processes will culminate in eruption.

Measurements of volcanic gas composition and fluxes, as well as temperature, have long been stalwarts of monitoring. Until recently, these measurements were made on fumaroles and hot springs, sometimes placing scientists at high risk. In situ data remain very valuable, but there has been prodigious progress in remote measurements from ground-based instruments and satellites. Analytical petrological estimates, notably from melt inclusion studies, have advanced understanding of gas inventories (*9*). Networks of ultraviolet spectrometers and imaging cameras provide detailed sulfur dioxide (SO_2) time series that can be combined with seismic and deformation data to give a much more complete and informative picture of volcano behavior (*10*). Likewise, SO_2 and thermal data are now measured from satellites (*11*), although it is proving hard to get agreement between the ground-based and satellite measurements (*12*). Furthermore, SO_2 data are often difficult to interpret: A decrease in SO_2 may mean that the threat of eruption is diminishing because of decreased magma supply or that the gas is being trapped at depth and the threat is increasing.

Other novel monitoring techniques include infrasound and portable ground radar, which are already being deployed to document explosive eruptions and ash clouds. Muon tomography holds promise for imaging the interior of lavas, and UAVs may provide new monitoring capability, but both methods will need considerable development to become widely used.

Despite these technological advances and the increasing integration of different data types, early warning of eruptions still faces major challenges. The most important issue is how to tell whether a period of volcanic unrest will lead to eruption. There are more cases of unrest that do not lead to eruption than those that do. False alarms are one of the most problematic issues for observatories. Evacuations that are called but then nothing happens can undermine public trust, whereas evacuations that are called too late or not at all can lead to tragedy. Volcanic systems are likely to fail suddenly. Sometimes, very minor differences in system properties determine whether failure and eruption occur or not. The exact timing of eruptions may be difficult to predict, and it is even likely that some volcanic systems are inherently unpredictable. Monitoring can provide insights into patterns and consequences of activity that can help draw evacuation plans.

Furthermore, most volcanoes around the world are not monitored effectively or at all. A study of 441 active volcanoes in 16 developing countries (*13*) reveals that 384 have rudimentary or no monitoring, including 65 volcanoes identified as posing a high risk to large populations. Satellite systems such as InSAR can provide regional, or even global, data but are rarely applied in real time. This unsatisfactory situation is to some extent ameliorated by rapid response teams at the request of countries during volcanic emergencies, notably the Volcanic Disaster Assistance Program of the U.S. Geological Survey. But even well-funded observatories suffer from a wide gap between research developments and their implementation as forecasting tools on an operational level. Developing capacity and closing these gaps is a priority for the volcanological community.

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