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When fluid in a shallow aquifer near a volcano becomes heated and pressurized, the resulting pressure can lead to a phreatic eruption—an explosion of steam, water, ash, and rock. The 2014 phreatic eruption of Japan's Mount Ontake claimed the lives of 63 individuals who, unaware of the impending disaster, were buried in ash or asphyxiated by hydrogen sulfide gas as they hiked near the summit. The eruptions are extremely hazardous and difficult to predict. Unlike geysers such as Yellowstone's Old Faithful, which are limited to plumes of steam and water, a phreatic eruption also expels rock and mud. During the past century in Japan, nine eruptions have each killed at least 10 people, and the 1979 phreatic eruption in Indonesia killed more than 100.

The buildup of pressure in an aquifer generally deforms Earth's crust near the future vent, or outlet from which material erupts, before a phreatic eruption occurs. Until recently, however, monitoring systems have been unable to detect the small-amplitude deformation of deadly eruptions.

That challenge has now been met. Tomokazu Kobayashi, Yu Morishita, and Hiroshi Munekane at the Geospatial Information Authority of Japan have detected the telltale crustal deformation in satellite ground deformation data.[1] They developed an algorithm that tracks temporal changes in high-spatial-resolution ground position data that were obtained from interferometric synthetic aperture radar (InSAR) data taken by Japan's *Advanced Land Observing Satellite-2* (*ALOS-2*; see PHYSICS TODAY, August 2015, page 76).

The researchers applied their tool to Japan's Mount Hakone, a volcano located west of Tokyo in the geothermally active Owakudani valley, shown in figure 1. In their analysis of archival data, they identified previously undetected ground deformation in the six months before a small phreatic eruption on 29–30 June 2015. Moreover, those observations allowed the team to model what might happen beneath the surface before an eruption occurs.

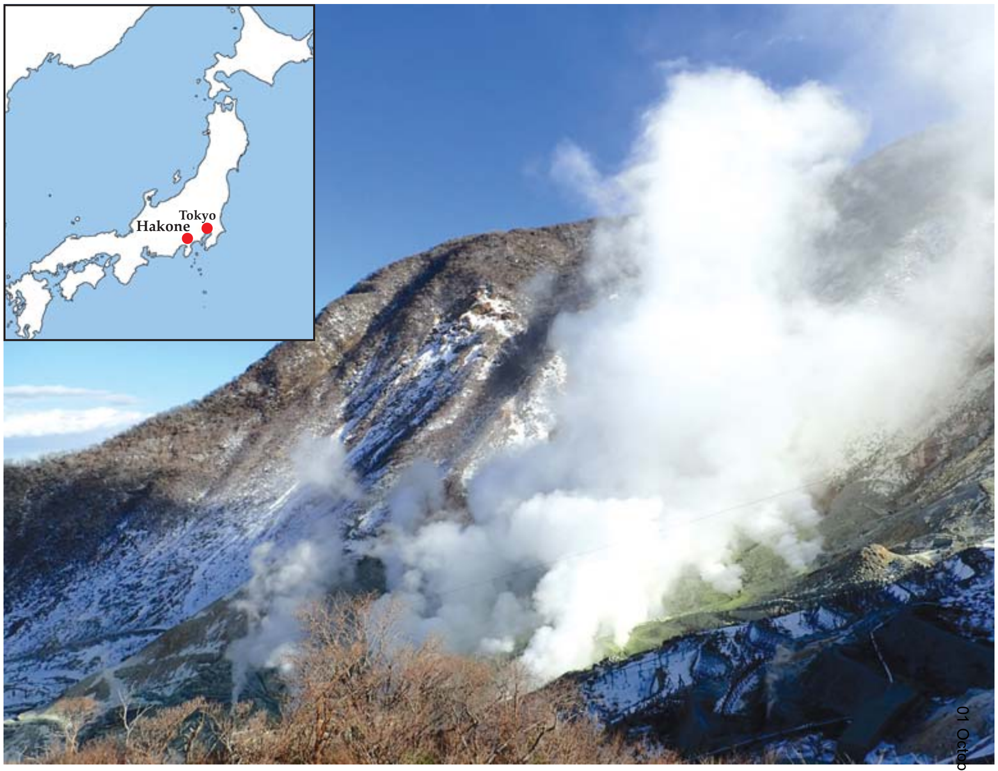

FIGURE 1. ACTIVE VENTS after the eruption of Japan's Mount Hakone, taken in July 2015, after peak activity at the Owakudani geothermal area. Owakudani means "great boiling valley." (Photo by Aitaro Kato.)

Subtle signals

Hakone, a popular resort destination because of the nearby active sulfur vents and hot springs, had last experienced phreatic activity 800 years ago. In late April 2015, scientists at the Japan Meteorological Agency (JMA) noticed several anomalies at ground-based GPS stations in the Owakudani area. Geodetic observation networks showed that distances between ground stations were increasing, which indicated pressure changes in the crust. Seismometers detected multiple swarms of hundreds of earthquakes, possibly indicators of subsurface volcanic or geothermal activity.

In response to the increase in seismicity and volcano inflation, the JMA in early May issued a level 2 warning (on a 5-level scale) for people not to approach the crater. After that, Kobayashi and colleagues requested an emergency observation from *ALOS-2* and found that local deformation had begun. On 29–30 June, a small phreatic eruption at Hakone formed several vents, with diameters of 20 m, from which a hundred tons of ash erupted in plumes. After the eruption had begun, the JMA increased the warning level to 3 and restricted entry to a 1 km radius of the Owakudani volcanic vents. The satellite observations helped the JMA to determine the exact position and spatial extent of the inflation.

GPS signals alone do not suffice to directly measure ground deformation above the subsurface aquifer. In contrast, InSAR can provide topographically sensitive maps of ground deformation, which in turn can provide information on local subsurface conditions.

To make those maps, Kobayashi and his colleagues used their observations from *ALOS-2*. "The *ALOS-2* satellite has the best ability and performance for mountainous areas due to its high spatial resolution," Kobayashi says. The team also used imagery from the Canadian Space Agency's *RADARSAT-2* satellite to extend the observational base. That combination of satellite data gave the group

10 images each month for 12 months between 2014 and 2015.

Standard InSAR time-series analysis uses spatial and temporal differences in the phase of the waves reflecting off Earth's surface and returning to the satellite to generate maps of surface elevation and deformations.[2] Achieving highly accurate displacement measurements typically requires 10 or more images with pixels that have strong reflection intensity. "Such pixels often correspond to highly reflective manmade infrastructure, such as concrete buildings and bridges," says Kobayashi. "But there are few such highly-reflective pixels in a mountainous area." He and his colleagues developed a statistical analysis method that uses all the pixels within an image to estimate the deformation.

The team found that beginning about six months before the eruption, the surface within a 200 m radius of the main vent that opened during the eruption rose at 5 mm/month. The rate of ground inflation accelerated more than 20-fold two months before the eruption, as shown in figure 2. The ground eventually rose 30 cm at the position of the eruption, as shown in the figure 2 inset.

Beneath the surface

The synchronization between seismicity—a characteristic signal of deep magma movement—and ground deformation indicates that heat from magma deep within Earth drove the shallow hydrothermal activity.[3] That connection led Kobayashi and company to propose that an expanding magma chamber, which feeds nearby Mount Komagatake,[4] caused the surface extension at Hakone that was observed in the GPS data taken in the final months before the eruption (see figure 3). Their goal is to improve understanding of changes in the hydrothermal system, which could contribute to future assessments of where phreatic eruption is likely.

Hydrothermal systems commonly develop within a volcano's shallow sediments (with depths of roughly 100 m). Mineral-rich water settles there horizontally and fills a lens-shaped aquifer. As liquid water is heated and pools in the aquifer, the aquifer bulges and inflates, which lifts up the surface above.

One unresolved question is what caused the inflation rate to speed up two months before the eruption. Kobayashi and colleagues propose that deep magma movement triggered an influx

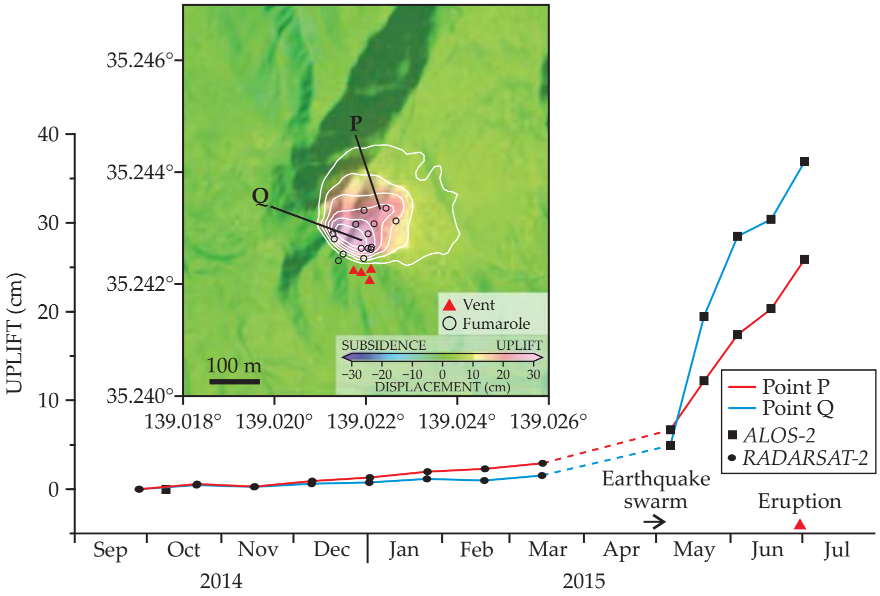

FIGURE 2. GROUND DEFORMATION AND SEISMIC OBSERVATIONS leading to the 2015 phreatic eruption at Mount Hakone. The red and blue lines show time series line-of-sight (LOS) displacements for the central (point P) and southern (point Q) parts of the deformed area at Hakone in the months preceding the phreatic eruption in late June. Earthquake swarms accompanied the increased deformation that began in early May. The inset shows cumulative vertical displacements derived from satellite data in May and June 2015 that reached a maximum value of 30 cm. Red triangles and open circles represent main vents that opened during the eruption and narrow, steam-emitting fumaroles, respectively. (Adapted from ref. 1.)

of mineral-rich fluid and heat to the area's sediments in the geothermal area through a conduit that had been established over previous decades by thermal stress. The minerals crystallized and sealed the conduit. But an influx of fluid from below continued, so pressure built locally and eventually broke the seal. Fluid then continued to feed the aquifer, and the increasing bulk pressure ultimately triggered an eruption.

Kobayashi's team created a model of a disk-shaped, fluid-filled crack that develops 150 m deep in Earth's crust in response to a pressure increase. To agree with GPS observations, the model includes inflation of a spherical heat source, 4.8 km below the crust, a typical depth for a magma chamber. Figure 3 shows a schematic of the Hakone hydrothermal subsurface.

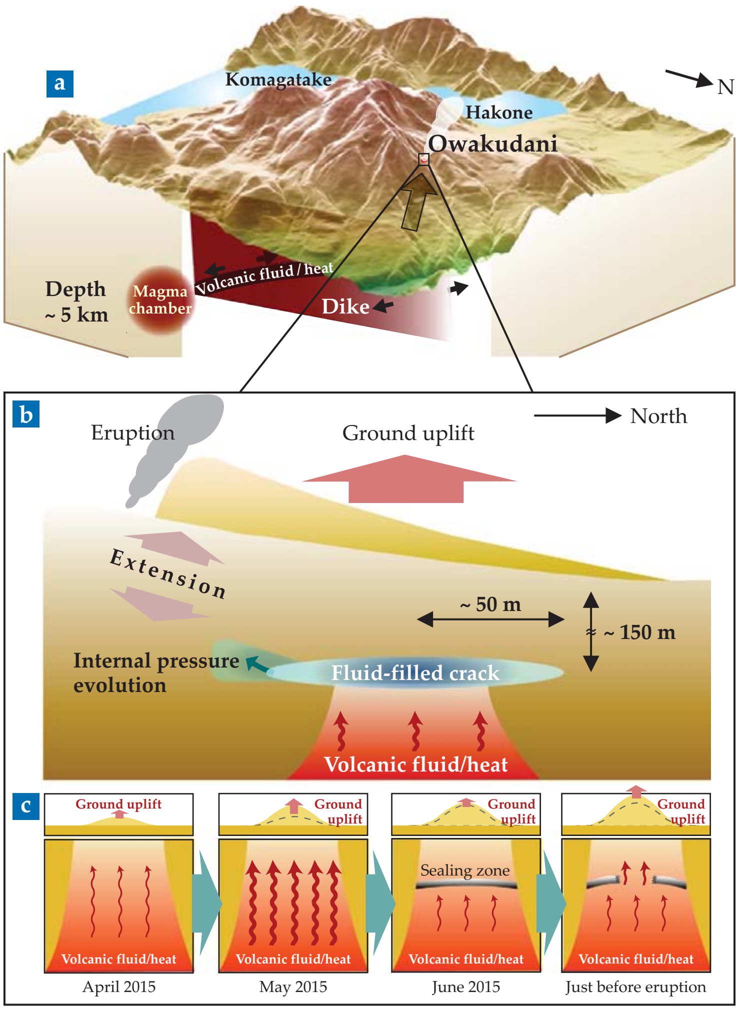

FIGURE 3. SCHEMATIC OF THE PHREATIC ERUPTION PROCESS in the months before Mount Hakone's 2015 eruption. **(a)** A deep magma chamber beneath nearby Mount Komagatake provides a heat source for the Owakudani geothermal area via a dike that trends north–south. **(b)** Ground uplift occurs in response to pressure changes in the fluid-filled crack. **(c)** In the final months before the eruption, heat and fluid influx increases and a crystallized seal allows pressure to build in the fluid-filled crack. Just before eruption, the seal breaks. (Adapted from ref. 1.)

Forecasting in the future

Although the Hakone phreatic eruption did not kill or even injure any people, others have been much worse. In 1926 a phreatic eruption at Mount Tokachi in Hokkaidō killed 144 people. Only 10 minutes before Mount Ontake's deadly 2014 blast, seismometers and tiltmeters between Nagoya and Tokyo detected immediate precursor signals, but it was too late for local authorities to issue an effective warning.[5,6]

"The [Hakone] observations and model might also be relevant to both Ontake and Tokachi," says seismologist Steve Ingebritsen of the US Geological Survey.

Data had not been readily available in the years preceding the Ontake catastrophe: *ALOS-2* was launched in May 2014, and the European Space Agency's *Sentinel-1A* was not yet ready for InSAR observation. Data from commercial satellites like *RADARSAT-2* were "prohibitively expensive," says Kobayashi, acknowledging that he was fortunate to have obtained them. He says that ground deformation similar to that at Hakone would almost certainly have occurred before Ontake's eplosion. But at that time, he recalls, "I couldn't imagine that InSAR had the potential to detect local ground inflation prior to the eruption."

Other geophysicists are quick to note that a better local geodetic network of InSAR data could have facilitated near-real-time interpretation of seismic and geodetic changes at Ontake and in similar hydrothermal systems. While magma eruptions are often preceded by characteristic seismic tremors and by ground deformation measurable by GPS, phreatic eruptions occur without magma movement and hence lack the similar precursor signals.

"InSAR image analysis will be a revolutionary tool of monitoring for small-sized phreatic eruptions," says Kato Aitaro of the University of Tokyo.

Still, a reliable forecasting system will require scientists to have access to a more constant stream of satellite images than is currently available. "We need better temporal resolution. There simply isn't enough available data," says Kobayashi. To apply InSAR methods, the satellite position and beam direction need to be nearly identical in consecutive observations, which can be several weeks apart. For *ALOS-2*, the revisit time is two weeks.

Next up for Kobayashi and colleagues: applying their analysis technique to InSAR satellite data from areas where historical phreatic eruptions have already taken place.

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