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Volcano monitoring

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INTRODUCTION TO VOLCANO RESOURCES

Volcanoes are not randomly distributed over the Earth's surface. Most are concentrated on the edges of continents, along island chains, or beneath the sea where they form long mountain ranges. More than half of the world's active volcanoes above sea level encircle the Pacific Ocean (see Fig. 1). The concept of **plate tectonics** explains the locations of volcanoes and their relationship to other large-scale geologic features. The Earth's surface is made up of a patchwork of about a dozen large plates and a number of smaller ones that move relative to one another at <1 cm to ~10 cm/yr (about the speed at which fingernails grow). These rigid plates, with average thickness of ~80 km, are separating, sliding past each other, or colliding on top of the Earth's hot, viscous interior. Volcanoes tend to form where plates collide or spread apart (Fig. 2) but can also grow in the middle of a plate, like the Hawaiian volcanoes (Fig. 3).

Of the more than 1,500 volcanoes worldwide believed to have been active in the past 10,000 years, 169 are in the United States and its territories (Ewert et al., 2005) (see Fig. 4). As of spring 2007, two of these volcanoes, Kīlauea and Mount St. Helens, are erupting, while several others, including Mauna Loa, Fourpeaked, Korovin, Veniaminof, and Anatahan, exhibit one or more signs of restlessness, such as anomalous earthquakes, deformation of the volcano's surface, or changes in volume and composition of volcanic gas emissions, that could foretell the onset of another eruption.

Volcanoes, by virtue of their geology and typography, display evocative landscapes and are home to diverse ecosystems, many of which are delicate and unique. Volcanic eruptions can obliterate landscapes and threaten lives, ecosystems and property. For example, the 1980 eruption of Mount St. Helens, although relatively modest on the scale of potential volcanic events in the United States, released energy equivalent to a 24-megaton explosion, devastating forests and obliterating wildlife, including almost 7,000 large game animals, over 600 km^2, killing 57 people, and inflicting more than $1 billion in damages to local economy, agriculture, businesses, and structures. Thus, the very processes that produce the esthetic and ecological resources that we associate with volcanoes are also capable of destroying those resources in minutes.

Most volcanoes are capable of eruptions that pose significant threats to natural landscapes, lives, ecosystems, and property, but fortunately, eruptions are typically preceded by weeks to months of increasing restlessness, allowing eruptions to be forecast if volcanoes are properly instrumented and data are interpreted by teams of experts in the fields of geology, seismology, geodesy, and geochemistry of volcanoes.

In the United States, the Robert T. Stafford Disaster Relief and Emergency Assistance Act mandates that the U.S. Geological Survey (USGS) issue timely warnings of potential geologic disasters to the affected populace and civil authorities. Through this act's mandate, the USGS has the primary responsibility to monitor volcanic activity in the United States. The USGS maintains

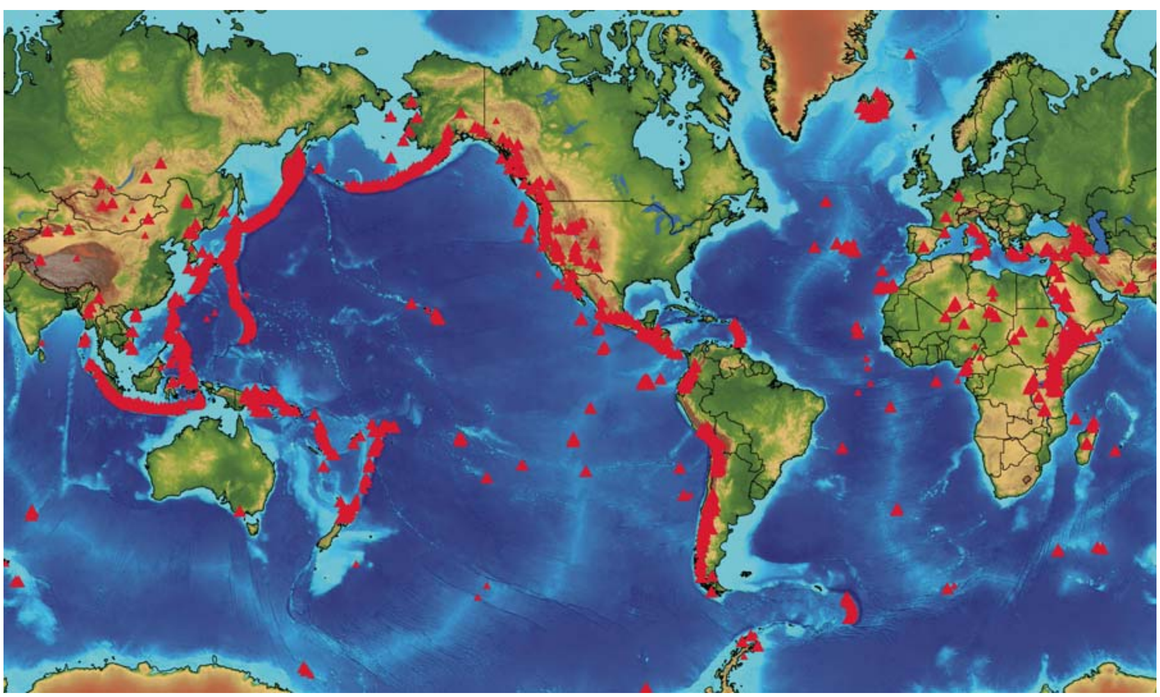

Figure 1. Map of the world showing locations of volcanoes, many surrounding the Pacific Rim and along boundaries of other tectonic plates. Image courtesy of the Smithsonian Institution's Global Volcanism Program (http://www.volcano.si.edu/world/find_regions.cfm). For a more detailed map of volcanoes, earthquakes, impact craters and tectonic plates, see Simkin et al. (2006). Image prepared by Paul Kimberly, Smithsonian Institution Global Volcanism Program.

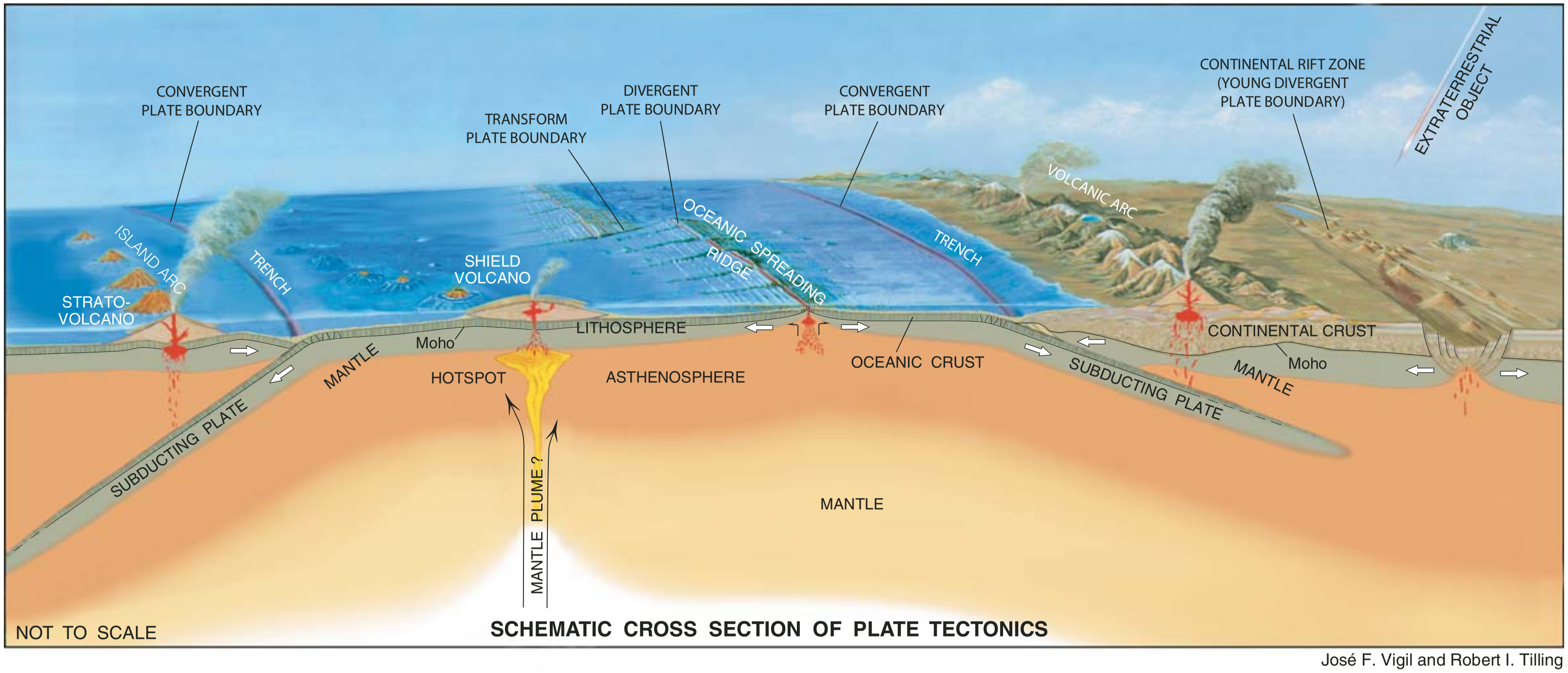

Figure 2. Schematic cross-section of plate tectonics from Simkin et al. (2006) showing different types of plate boundaries. Image prepared by José F. Vigil and Robert I. Tilling.

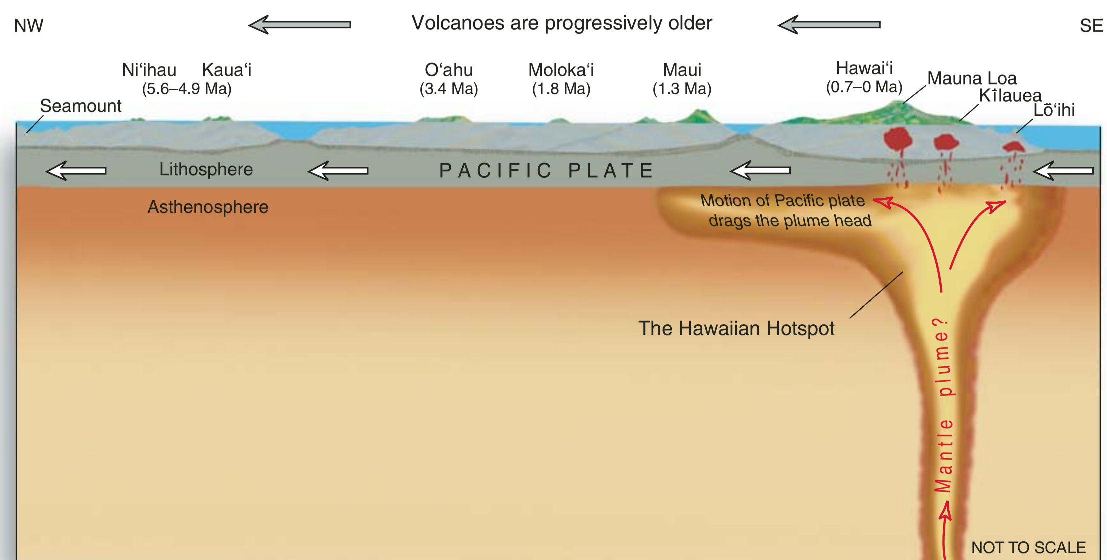

Figure 3. Schematic cutaway view along the Hawaiian Island chain from Simkin et al. (2006) showing the inferred mantle plume that has sustained the Hawaiian hotspot on the overriding Pacific Plate. The geologic ages of the oldest volcano on each island are progressively older to the northwest, consistent with the hotspot model for the origin of the Hawaiian Ridge–Emperor Seamount chain. Prepared by Joel E. Robinson.

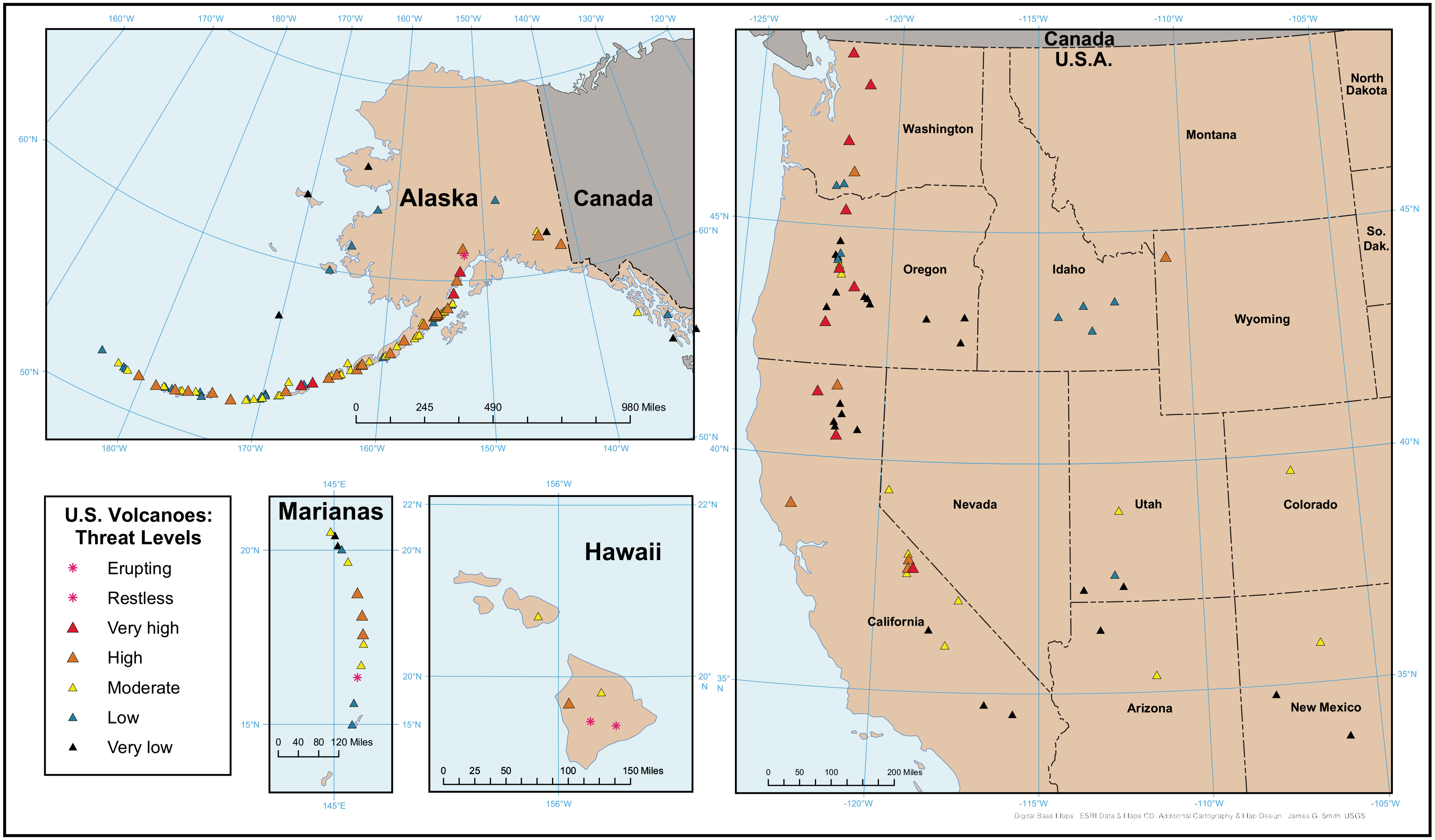

Figure 4. Map showing locations of volcanoes in the United States, classified by threat level as determined by the U.S. Geological Survey National Volcano Early Warning System.

monitoring networks consisting of large numbers and wide varieties of monitoring instruments in order to collect the data needed to forecast volcanic behavior and issue warnings and information to reduce the loss of life, property, and economic impact of hazards related to volcanoes. While the data obtained from these monitoring networks contribute to basic research and advance scientific understanding of volcanoes, the primary justification for instrument deployment is public safety and disaster reduction.

In this chapter, we will discuss the principal vital signs associated with volcanic eruptions, explain the methods for monitoring them, and give a case study. The vital signs described include earthquake activity, ground deformation, gas emission, gas plumes, hydrologic activity, and slope instability. Monitoring methods range from well-established ones to the latest innovations that should become routine in the next few years.

Eruption Style and Frequency

Individual volcanoes erupt different combinations of lava flows, pyroclastic flows, and **tephras** (ash and coarser fragmental ejecta). At some volcanoes, landslides, debris flows, and floods are as hazardous, or more hazardous, than the volcanic eruptions themselves. **Debris flows** are mixtures of mud, rocks, boulders, and water that travel at speeds of tens to as much as 100 km/h. Highly mobile debris flows originating on a volcano are also called **lahars**. Evaluating likely eruptive and hazardous events (event style, size, and frequency) at individual volcanoes is accomplished by constructing geologic maps and conducting hazard assessments.

Factors that influence eruption styles are: the diverse temperatures and chemical compositions of magmas that feed a volcano; the rates at which magma reaches the surface; and local factors, such as the presence of faults or fractures that can serve as easy pathways for magma to reach the surface, or that allow volcanic gases to escape from magma non-explosively. These controlling factors are generally unknown or not sufficiently understood ahead of time to aid in developing detailed hazard assessments or eruption forecasts. Instead, geologic mapping and associated investigations are used to examine, document, and quantify a volcano's past activity. In these investigations, key characteristics are identified that distinguish particular deposits from one another, and overlapping relations between deposits reveal the sequences of events. Tracing individual deposits across the landscape allows geologists to determine the sizes of past events and thus estimate the regions likely to be affected by similar events in the future. Geologists collect samples suitable for age dating by various laboratory techniques. Together, the information on the types of events (eruptions, landslides, debris flows), their magnitudes, and their frequencies are combined to give a history for a volcano. Unexpected features are usually encountered while determining this volcanic history, and detailed studies of these features advance the understanding of general volcanic processes, enabling better-designed monitoring strategies and more accurate forecasts of future behavior.

Volcanic events are **probabilistic**, that is, the time between eruptions, flank collapses, debris flows, or floods can be shorter or longer than the average, and the time intervals can be described by probability distributions (Nathenson, 2001). The simplest approach is to divide the number of known events by the total time encompassed to arrive at an average recurrence interval, but this approach has significant drawbacks. Some volcanoes are known to undergo episodic behavior, where multiple events occur closely spaced in time, and then no events occur for a time interval much longer than the average. Clustering of events is probably typical of all volcanoes to some degree, and underlies the intuition that it is more dangerous to approach a volcano that erupted recently, than it is to approach a volcano which has not erupted for a long time. Furthermore, the likelihood of an event is coupled in some way with the magnitude of the event, with smaller eruptions, debris flows, landslides, or floods taking place more frequently than larger ones. Global data illustrate that long periods of quiet commonly precede the more explosive and dangerous eruptions. For example, of the 16 largest explosive eruptions of the nineteenth and twentieth centuries, 12 were from volcanoes with no previously known historical eruptions (Simkin and Siebert, 1994). Geologic mapping and related field investigations, coupled with age dating, provide the information necessary for probability estimates that link event style, magnitude, and frequency.

Volcano Hazards

Risks from a volcano's hazards commonly extend well beyond a volcano's summit. For example, valley bottoms as far as 80 km beyond Mount Rainier's summit are at risk of inundation by mudflows generated far up on its flanks inside Mount Rainier National Park. More than 150,000 people live in these inundation hazard areas and major transportation lifelines cross them (Driedger and Scott, 2002). Lava flows from the presently restless Mauna Loa volcano in Hawai‘i can reach the highly developed Kona Coast in as little as two hours. The potential harm these hazards can cause, in terms of loss of life and disruption to society and the economy on which it depends, are serious considerations for downslope communities.

Airborne ash clouds are a serious hazard to aircraft. Jet aircraft engines have failed after flying through drifting clouds of even thinly dispersed ash half a continent away from the volcanoes that created them. Large clouds of fine particles of volcanic ash are transported by winds for hundreds to thousands of km beyond their volcanic source (Fig. 5). Volcanic ash particles are angular, abrasive fragments of rocks, minerals, and volcanic glass the size of sand and silt; they have the hardness of a pocketknife blade (Kenedi et al., 2000; Neal et al., 1997). These particles abrade the turbine blades and leading surfaces of aircraft, cause failure of electronics, and melt and coalesce in engines, causing catastrophic and complete loss of power.

Volcanic ash is extremely abrasive. Prolonged breathing of ash causes nasal, throat, and eye irritation and infection in

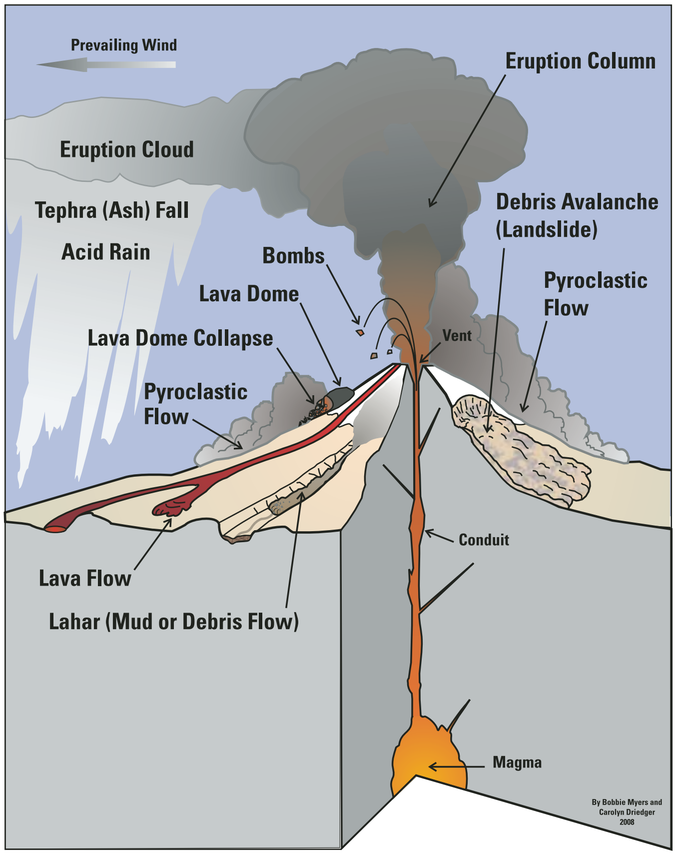

Figure 5. Image of types of volcano hazards. From Myers and Brantley (1995).

both humans and animals. Shortness of breath, sore throats, and bronchitis can occur (from http://volcanoes.usgs.gov/ash/ citing Blong, 1984). Layers of ash just a few millimeters thick will retard growth of plants and if ingested can sicken or kill animals, especially cattle and other domestic and wild ruminants. Thicker ash falls can smother people, plants, and animals. Ash falls can also ruin internal-combustion engines, cause roofs to collapse and communication networks to fail, and break electric power lines. Stones large enough to seriously injure or kill people, plants, and animals can be ejected as far as a few kilometers from an explosive volcano. Winds or even passing vehicles can stir ash back up into the air (Kenedi et al., 2000).

Periods of volcanic unrest, even those that do not lead to eruptions, will likely trigger emergency responses that can lead to area closures and community evacuations. Restless volcanoes challenge public officials because unrest creates uncertainty about how long restlessness will last, when it will end, its severity, who will be affected by it, and even if an eruption will occur at all. All these uncertainties cause major psychological and economic impact in areas around a volcano. Uncertainty brings with it an intense demand for accurate and authoritative information. Civil authorities need information to insure public safety, business owners use information to make business decisions, and news media seek all the information they can get all the time. Satisfying all these demands for accurate and up-to-the-minute information is not easy.

Volcano Threat Levels and Volcano Monitoring

Volcanic threat is a combination of destructive natural phenomena that a volcano is capable of producing (**volcano hazard**) and the people, property, and infrastructure at risk from these phenomena (**exposure**). Matching a volcano's required monitoring level to its threat level provides the most safety for the most people and infrastructure at risk, and it most efficiently distributes funds and scientists' time. Matching required monitoring to threat level became possible in 2005 when the USGS quantified volcano hazard, risk exposure, and threat levels for all 169 geologically active volcanoes in the United States and its territories (Ewert et al., 2005).

Based on its numerical threat score, each volcano was placed in one of five threat categories: very high, high, moderate, low, and very low. Fifty-five of the nation's volcanoes are defined as very high or high threat: this is nearly one-third of all potentially active U.S. volcanoes. Because many volcanoes are either unstudied or incompletely studied, threat scores will likely rise as future studies discover previously unknown past eruptive activity or unrest, and as population and infrastructure at risk increase.

In order to provide adequate warning, volcanoes with high or very high threat levels require intense real-time round-the-clock detailed monitoring. Signals from their monitoring instruments must be transmitted in real-time to a regional volcanic observatory so that volcanologists can quickly diagnose the meanings of the subtlest changes. As a rule of thumb, volcanoes in these two threat categories will require at least 12–20 permanent seismic stations within 20 km of the main volcanic vent, including several stations very close to the vent; routine deformation surveys and continuously recording permanent Global Positioning System (GPS) stations; frequent airborne and ground station measurements of volcanic gases; and instruments along river valleys, sensitive to the unique sounds of passing mudflows, which trigger alarms to warn people downstream. Moderate-threat volcanoes will require real-time monitoring to detect weak pre-eruptive signals as they occur. Typical coverage will require six seismic stations within 20 km of a volcano, including three to four high on its flank, at least six continuously recording, permanent GPS stations in the vicinity, infrequent gas measurements as appropriate for each volcano, and mudflow detectors along river valleys (Ewert et al., 2005).

Of course, if unrest were to start or escalate, or if monitoring data suggested that a given volcano might be moving toward an eruption, monitoring would have to be augmented as quickly as possible for accurate current data to be obtained. In response to increased concern, a wider variety of volcanic phenomena would have to be monitored. New types of instruments would have to be installed, existing networks of instruments would have to be augmented by reconfiguring existing instruments and adding new ones, and data transmission networks would have to be fortified—all to enable volcanologists to interpret volcanic unrest and forecast likely consequences around the clock.

Low-threat and very low-threat volcanoes, on the other hand, require a lower level of monitoring. For these volcanoes, as for all volcanoes, baseline seismic, deformation, gas, and hydrologic baseline data need to be established, after which low-threat volcanoes require only enough monitoring to detect anomalous activity in near-real time. Very low-threat volcanoes would require even less monitoring.

Because resources were insufficient to instrument and monitor all potentially active volcanoes at an adequate level until quite recently, volcano monitoring by the USGS was done reactively; that is, adequate monitoring was not put in place until some form of unrest was observed at the Earth's surface. Therefore, precursory signals went undetected, and the interval between the first observed signs of unrest and a volcanic crisis was often short. Thus, civil authorities, citizens, businesses, and scientists were forced into playing a dangerous game of "catch up" with volcanoes. Authorities worked overtime to put civil-defense measures in place before unrest escalated to dangerous levels, while volcanologists scrambled to augment instrumentation and install upgraded communication networks, often at great expense and danger to themselves.

Quantitative determination of the specific threat level for each U.S. volcano would allow the USGS to apportion resources so that the most threatening volcanoes could be monitored round-the-clock well before they show any signs of unrest. This proactive approach to monitoring, were it to be implemented, would make it possible for volcanologists to send at-risk communities reliable information from the onset of restlessness, thus giving them the maximum amount of time to activate response and mitigation plans. Proactive monitoring by the USGS gives volcanologists the maximum amount of time to augment monitoring should that be necessary. Even though not every restless volcano erupts, proactive monitoring is still necessary to minimize either overreacting, which costs money, or underreacting, which can cost lives. However, the major obstacle to implementing proactive monitoring in the United States and throughout the world is finding the resources to pay for the necessary equipment and scientists.

Proactive monitoring offers many practical advantages over reactive monitoring. Monitoring:

- Minimizes risk of surprise eruptions.
- Increases time to implement civil defense measures before unrest escalates and a volcanic crisis worsens.
- Enables safe installation of instruments and communication networks at preplanned sites in an orderly fashion. Most very high-threat and high-threat volcanoes in the United States are towering snow- and glacier-clad peaks that are inaccessible except during a short summer season, whereas onset of volcanic restlessness can occur in any season. Summertime installation and equipment maintenance maximizes the probability that preferred sites are snow free, ensures maximum safety for volcanologists and support personnel, and gives adequate time to test instruments and communication networks.
- Increases safety to the more than 80,000 airline passengers per day who fly the busy air routes along the Cascade and Aleutian volcanic arcs. When fully implemented, proactive monitoring of these arc volcanoes will enable volcanologists to notify the Federal Aviation Administration (FAA) within five minutes after a major explosive eruption, allowing planes to change course quickly to avoid ash clouds.
- Improves accuracy and timeliness of future warnings. During the past 25 years, understanding of basic volcanic processes has improved tremendously, based in part on data gained from long-term volcano monitoring. Monitoring data help volcanologists formulate and test models of how volcanoes work. Better models, in turn, improve how volcanoes are monitored, identify the most effective monitoring methods, and suggest new monitoring techniques.
- Adds scientific credibility to land managers' designations of safe areas that can remain open to visitors—in some cases even while a volcano continues to erupt. After 18 years of relative quiescence, Mount St. Helens reawakened in late 2004 when swarms of small earthquakes were detected by the USGS, alerting volcanologists to the presence of magma beneath the volcano. The U.S. Forest Service closed all access to the mountain. Over the next year or so, a series of lava domes episodically extruded within the volcano crater, accompanied by explosions and rockfalls (Schilling et al., 2006). However, by mid-2006, USGS monitoring indicated slowing dome growth, falling rates of volcanic gas emission, and an end to explosive blasts whose effects extend beyond the crater. Although the present dome continued to grow at the rate of about a dump-truck load per minute, which rendered the crater off limits for a time, USGS volcanologists were able to provide guidance to U.S. Forest Service officials, allowing them to reopen trails to the summit in mid-2006. A Web-enabled system for obtaining climbing permits helps ensure visitor safety and allows quick notification should volcanic activity change (U.S. Forest Service, [2007–]).

Restless and Erupting Volcanoes Create Management Challenges

Restless and erupting volcanoes create short- and long-term problems for land managers and civil authorities. Deciding how best to protect human safety while maintaining access and continuing daily life, even while restlessness continues, causes the most short-term challenges. Deciding where to rebuild damaged and destroyed facilities and how to manage destroyed and damaged natural resources creates longer-term challenges. A few real examples of problems and responses to volcanic unrest illustrate the challenges land managers and civil authorities potentially face. (For more examples and greater detail, see the day-by-day account of events and responses preceding the cataclysmic eruption of Mount St. Helens volcano on 18 May 1980 in Klimasauskas, 2001.)

Restless and erupting volcanoes:

- *Attract spectators who are naively unaware of volcanoes' dangers, but who are nonetheless eager to see the activity for themselves up close.* On 1 April 1980, six weeks before a restless Mount St. Helens erupted cataclysmically, two counties near the volcano asked their state's National Guard for assistance. The counties had maintained six roadblocks around the clock for just four days before they realized they were unable to keep people from entering officially designated danger zones. An FAA spokesman estimated that as many as 100 planes were in the controlled flight zone around the volcano on the same day. Many planes intentionally maintained radio silence presumably to escape detection (Klimasauskas, 2001). A study of wilderness hikers in Hawai'i Volcanoes National Park who ignored prominent National Park Service (NPS) warning signs and attempted to reach active lava flows found that 77% suffered from dehydration, more than half returned with scrapes and abrasions, and 6% suffered from broken bones. "Many hikers were inexperienced tourists willing to disregard warning signs and enter high-risk areas" (Heggie and Heggie, 2004). Several hikers have even died (Johnson et al., 2000). Takahashi et al. (2003, photos 44, 45, and 55) show the spectacular meeting of molten lava with the ocean that draws park visitors to ignore warnings.
- *Require designating areas of restricted access and complete exclusion which in turn requires posting signs, disseminating restrictions to the public, and increasing law enforcement staff to ensure the public are kept out of harm's way.* Boundaries of closed areas have to be adjusted as volcanic unrest waxes and wanes, sometimes for reasons other than public safety. On 8 April 1980, at Mount St. Helens, "Officials moved the roadblock on State Route 503 from Jack's Store back to the Swift Canal east of Cougar after local merchants threatened to sue them over loss of business" (Klimasauskas, 2001). This action moved the restricted area's boundary closer to the volcano. On 10 April 1980, the reported cost of maintaining roadblocks in the vicinity of Mount St. Helens was $9,000 per day. To save money, the U.S. Forest Service closed its press center and grounded its two observation planes. On 15 April 1980, one county shut down some of its roadblocks citing "expense, public harassment, and the stable pattern of explosions at the volcano" (Klimasauskas, 2001). Mount St. Helens' cataclysmic eruption occurred 34 days later. These kinds of problems can be mitigated. For example, close collaboration between the USGS scientists who monitor Hawaiian volcanoes and Hawai'i Volcanoes National Park staff enables the NPS to post regularly updated information on safe and unsafe areas on the park's Web site (http://www.nps.gov/havo/closed_areas.htm).
- *Affect plants, animals (even insects), and humans. In extreme cases, volcanic ash increases morbidity and mortality of plants and animals in the short term.* Lava, ash, and other eruptive materials are sterile when first deposited. Only after weathering do they become the rich, productive volcanic soils typically associated with volcanoes. In the short term, volcanic ash has a deleterious effect on plants and animals. For example, pine trees growing on recently deposited volcanic ash grow more slowly and are shorter than the same species growing on nearby unaffected soils (Ishii et al., 2003). Ash also can clog streams and raise their acidity to levels lethal to fish and aquatic plants. On 2 April 1980, "Operators of a fish hatchery some 5 miles from Mount St. Helens reported a decrease in pH from 6.8 to 5.8 caused by stream leaching of upstream volcanic ash. At a pH of 5.0 the fish would die, so hatchery managers decided to release the salmon when the pH fell to 5.5" (Klimasauskas, 2001). Ruminants are vulnerable to chemical poisoning when they graze in areas where volcanic ash has fallen and to starvation in areas covered by extensive ash deposits (Blong, 1984). Even insects are affected by ash falls; numbers of some species are significantly reduced while others, freed of insect predators, become pests (Fuentes, 1975). See also Brosnan (2000) for a volcano's effect on plant life.
- *Create stress on land management and law enforcement agencies and their staffs to answer public requests for information.* Requested information is not necessarily relevant to the emergency situation, and contacts by irate citizens are common. On 31 March 1980, local newspapers reported that calls to the U.S. Forest Service offices about restless Mount St. Helens included calls from "frustrated citizens who could not access their cabins within closed areas while members of the press had been allowed in…" to "gamblers requesting the number of explosions in the previous 24 hours, to those blaming the volcano's restlessness on the desecration of Indian graves in the area" (Klimasauskas, 2001).
- *Require decisions under pressure on when to relocate or close facilities and businesses, move valuable portable equipment, and relocate people working and living in newly restricted areas.* Relocations and closures, or just the uncertain possibility of them, can result in significant changes in how businesses and government agencies function. These changes commonly affect local economic activity, which generates pressure to avoid economic loss by delaying decisions or rescinding decisions already made.

Conclusions

A variety of precursory signals are generated by the many processes that occur as molten rock (magma) forces its way up through miles of the Earth's crust before eruption at the surface. Many of these signals are extremely subtle and complex, and consequently require expensive arrays of sensitive instruments to detect and scientists with years of experience to interpret. The sections in the rest of this chapter outline the different major techniques used by the USGS to detect, quantify, and interpret each type of signal. In one way or another, each technique tracks types, magnitudes, and locations of earthquakes; uplift and subsidence of the ground surface; or changes in heat, water, and gasses emitted by volcanoes. Because the techniques measure different processes that occur during magma ascent, effective monitoring requires applying many techniques simultaneously to assess near-real-time developments at a volcano.

Just as doctors monitor patients' potential future health risks by studying their medical histories and interpreting results of lab tests over time, so, too, do volcanologists learn about the possibility and size of future volcanic activity by studying a volcano's historic activity and measuring and evaluating the signals it generates over many years. Doctors and volcanologists both know that routine monitoring over time is the best way to detect potential future problems early, when they are most easily dealt with. While patients can go to laboratories for tests, volcanologists can only assess the state of volcanoes in the field by placing monitoring instruments on and near them. Ideally, complete networks of monitoring instruments are put in place while potentially active volcanoes are still quiet. By missing the earliest signals of restlessness, volcanologists risk losing critical early data needed to establish "baseline" trends and accurately estimate the size of a possible eruption. For example, when Mount St. Helens reawakened in 2004, additional monitoring instruments could not be installed rapidly enough to catch the volcano's initial signals. This prevented confident determination of the volume of magma intruded beneath the volcano (Ewert et al., 2005), which in turn added significant error to estimates of the size of potential eruptions.

For updates on activity of U.S. volcanoes in the past seven days, see http://volcanoes.usgs.gov/vhpfeed.php.

STRESSORS/POSSIBLE CHANGE

Volcano monitoring methods are designed to detect and measure signals caused by magma movement beneath a volcano. Rising magma typically will (1) trigger swarms of earthquakes and other types of seismic events; (2) cause deformation (swelling or subsidence) of a volcano's summit or flanks; and (3) lead to release of volcanic gases from the ground and vents. By monitoring changes in the state of a volcano, scientists are sometimes able to anticipate an eruption days to weeks in advance and to detect remotely the occurrence of certain related events like explosive eruptions and lahars (Guffanti et al., 2001). (See Table 1 for a summary of volcano vital signs and monitoring methods.)

VITAL SIGN MONITORING DESCRIPTIONS

Vital Sign 1. Earthquake Activity

Introduction

Movement of magma and associated fluids within volcanoes often occurs with concurrent, measurable earthquake activity (**seismicity**). At restless volcanoes, evolving seismic activity commonly, but not always, precedes eruptions. The most common seismic disturbances are earthquakes in response to stress changes caused by magma movement beneath a volcano.

When magma rapidly intrudes into surrounding rock, the rock breaks abruptly, causing an earthquake whose signal is similar to that of an earthquake along a tectonic fault (Fig. 6A). This type of earthquake is called a **volcano-tectonic (VT)** earthquake. VT earthquake signatures are characterized by clear and often impulsive, or abrupt, wave onsets and contain energy across a broad range of seismic frequencies.

A second type of earthquake associated with volcanic areas is the direct result of magma or other fluids flowing through conduits in volcanic or active hydrothermal areas (Fig. 6B). Pressure variations in flowing magma or hydrothermal fluids force the cracks through which these fluids move to vibrate. Compared to VT earthquakes, these earthquakes appear with a dominant and lower frequency of oscillation and are called **long-period (LP)** earthquakes (e.g., Lahr et al., 1994; Harlow et al., 1996).

In addition to volcanic earthquakes, continuous or sustained ground oscillation is often observed at restless volcanoes. This is referred to as **volcanic tremor** and is closely linked to LP earthquakes. Tremor can be thought of as sustained crack vibration driven by the moving magma (Fig. 6B and parts of 6C).

Explosions at a volcano's vent or at shallow depths beneath the vent create the fourth type of common volcanic earthquakes. Naturally enough, these are called **explosion earthquakes**. Figure 6D shows a recording of a small explosive event at Mount Pinatubo that lasted for only a few minutes. However, sequences of explosion earthquakes can go on for hours as they did at the cataclysmic eruption of Mount St. Helens in 1980. Explosion earthquakes are generally accompanied by forceful ejection of steam, volcanic gases, ash, and fragments of lava in various proportions.

For additional information on seismic monitoring methods, see Braile (this volume).

Level 3, Method 1: Seismic Monitoring

Volcanic eruptions are almost always preceded by increasing seismicity, and the most reliable indicators of impending eruption are shallow earthquakes and tremor (e.g., Chouet, 1996). Typically, volcanic unrest begins deep beneath a volcano and progresses to shallower depths as time to eruption approaches.

TABLE 1. SUMMARY OF VOLCANO VITAL SIGNS AND MONITORING METHODS

Vital signs and methods	Expertise	Special equipment	Cost*	Personnel	Labor intensity†
Earthquake activity					
Seismic activity	Scientist	Yes	$$$	Group	High
Ground deformation					
Electronic distance measuring (EDM)	Scientist	Yes	$$$	Group	High
Triangulation	Scientist	Yes	$$$	Group	High
Leveling	Scientist	Yes	$$$	Group	High
Tilt	Scientist	Yes	$$$	Group	High
Global Positioning System (GPS)	Scientist	Yes	$$$	Group	High
Aerial photography/light detection and ranging (LIDAR)	Scientist	Yes	$$$	Group	High
Interferometric synthetic aperture radar (InSAR)	Scientist	Yes	$$$	Group	High
Emission at ground level					
Direct fumarole sampling of gases and isotopes	Scientist	Yes	$$$	Group	High
On-site instrumental measurements (open-path Fourier transform infrared spectrometer, differential optical absorption spectrometer, gas chromatograph)	Scientist	Yes	$$$	Group	High
Soil efflux measurements	Scientist	Yes	$$$	Group	High
Emission of gas plume and ash clouds					
Correlation spectrometer (COSPEC) and Mini-UV spectrometer (Flyspec)	Scientist	Yes	$$$	Group	High
LI-COR (infrared spectrometer)	Scientist	Yes	$$$	Group	High
Doppler radar	Scientist	Yes	$–$$$	Group	High
Hydrologic activity					
Hydrologic activity	Scientist	Yes	$$$	Group	Medium-high
Slope instability					
(see Hillslope chapter for determining types of landslides and triggers and causes of landslides)					
Lahar hazard delineation (LAHARZ + GIS)	Scientist	Yes	$$	Group	High
Real-time monitoring of lahars—acoustic flow monitor (AFM)	Scientist	Yes	$$$	Group	High
Techniques that can be used to monitor various vital signs					
Remote sensing via satellite	Scientist	Yes	$$$	Group	High
Unmanned aerial vehicles (UAV)	Scientist	Yes	$$$	Group	High
Interferometric synthetic aperture radar (InSAR)	Scientist	Yes	$$$	Group	High
Infrasound	Scientist	Yes	$$$	Group	High

*Cost (in US$): $ = <$1,000; $$ = $1,000–$10,000; $$$ = >$10,000.
†Labor intensity: medium = <full day; high = >full day.

The object of seismic monitoring at volcanoes is to record and monitor the earthquakes and tremor that accompany volcanic unrest. Seismographic networks record the signals radiated from volcanic seismic sources, then specialists analyze and interpret these signals and their patterns.

Seismologists use seismic data from a network of seismometers to locate an earthquake's **hypocenter** (the point directly beneath the Earth's surface where the rupture on a fault begins) and its **epicenter** (the point on the Earth's surface directly above the hypocenter). Seismicity can be detected at greater distances and from deeper sources than other signs of volcanic unrest. Therefore, seismic monitoring typically provides the earliest signals of volcanic unrest. Evolving patterns of hypocenters and epicenters help scientists to infer whether magma is moving either vertically or laterally. Cataloging events as either VT or LP helps distinguish between tectonic faulting and moving magma earthquake origins.

Seismographic Networks

Effective volcano monitoring networks extend from the volcanic center or active vent outward to distances of 20 km. To determine especially shallow source depths precisely, several seismic monitoring stations in the network must lie within a few kilometers of the vent. To locate epicenters and hypocenters precisely, stations should be distributed evenly around a volcano at varying distances from the vent. Best practice requires 10–20 seismographic stations around each potentially hazardous volcano in the United States.

Each monitoring station in a network is equipped with a seismometer, electronics to amplify and convert the signals for

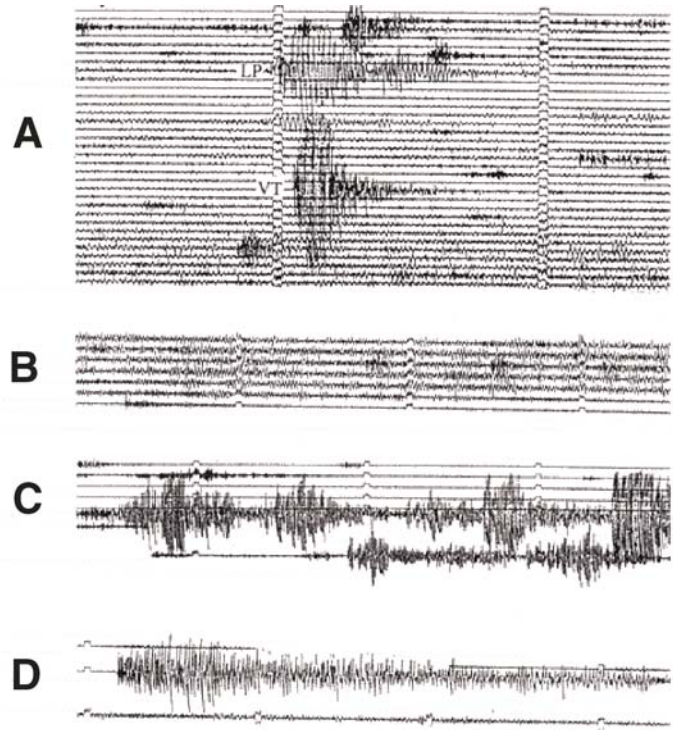

Figure 6. Examples of seismic event signatures observed at Mount Pinatubo in the Philippines, as interpreted and reproduced from Figure 3 of Harlow et al. (1996). (A) Long-period earthquake (LP) and volcano-tectonic earthquake (VT). (B) Tremor consisting of closely spaced LP earthquakes. (C) Tremor consisting of closely spaced deep LP earthquakes. (D) Explosive eruption signal. Time sequence on each seismographic recording is from upper left to lower right; evenly spaced tick marks along each trace mark one-minute intervals.

transmission, telemetry components, and batteries and solar panels to power the station. The seismometer is buried 1–2 m beneath the ground's surface. The station's electronics and power components are installed in small, above-ground housings. The transmission antenna and the solar panel, if not installed atop the station housing, are installed on a short mast. Stations are designed to minimize the impact of the station installation and operation in remote or wilderness areas.

The seismometer registers ground motions, and converts the motions to electrical signals. The converted signals are telemetered in either analog or digital form to a nearby volcano observatory. In general, analog stations cost less to buy and install, use less power, and transmit their signals over longer distances than digital stations. Digital stations provide higher quality data and therefore more accurate recordings of seismic shaking. Once installed, they are simpler to maintain than analog stations. Many seismographic networks use combinations of analog and digital stations. An analog station costs \$7,000 to \$10,000, while a digital station costs \$15,000 to \$20,000 (all amounts herein are in US\$). In the future, it is likely that the performance advantages of digital stations will become more important than the cost differences. Therefore, the proportion of digital seismic stations in volcano monitoring networks will likely increase.

Seismic Data Processing

Data telemetered from field stations to a volcano observatory are collected onto customized computer systems that make possible real-time and near-real-time analysis of seismic data streams and near-real-time posting of seismic analysis products. Important analysis products include locations of epicenters and hypocenters, earthquake magnitudes and continuous seismic amplitude and spectral displays. Real-time data analysis and display greatly facilitates short-term eruption forecasting and evolving hazard assessment. Observatory staff members interactively review the analysis products to verify the output and enter additional information that more completely describes the events. A computer system with these capabilities consists of a number of workstation computers and costs several tens of thousands of dollars. The computers also store and archive the data. Software packages for seismic data acquisition and analysis are commercially available. Alternatively, similar software packages have been developed, are maintained, and made available by the U.S. Geological Survey.

Discussion

While increased seismicity commonly precedes volcanic eruptions, the time from the earliest earthquakes to an eruption varies widely. Increasing numbers of volcano-tectonic earthquakes may occur months or even years before an eruption. However, not every increasingly restless volcano erupts; seismic activity may wax and wane without an eruption for long periods of time.

Volcanic processes are complex and variable, and therefore produce multiple types, patterns, and numbers of earthquakes (e.g., Chouet, 2003). Missing a volcano's crucial early seismic signals impedes scientists' ability to accurately forecast events. Protection of people and property requires installation of seismic monitoring networks at potentially dangerous volcanoes to measure baseline seismicity and monitor for suggestive increases in seismicity, well before unrest begins or obvious signs of significant unrest are noticed at the Earth's surface.

Baseline seismic monitoring of seismic signals from earthquakes near a volcano as well as from the other side of the globe as they travel through a volcano enables scientists to catch the beginnings of unrest and to determine locations of faults and possible accumulations of magma. Volcano scientists use this knowledge to improve their assessment of a volcano's eruption probability, volume of erupted magma, and location of hazardous areas.

Vital Sign 2. Ground Deformation

Introduction

As magma moves beneath a volcano, it creates space for itself by displacing the Earth's surface. Quantifying the characteristics of this deformation over space and time can give important information about the depth, volume change, and geometry of magma reservoirs below the ground. For example, when magma accumulates beneath a volcano, perhaps as a prelude to an eruption, the overlying surface will inflate like a balloon. Similarly, after magma has been erupted, or when magma drains to deeper levels or moves laterally below ground to other locations, the surface deflates in response to this removal of the volume. A more detailed explanation is available at http://hvo.wr.usgs.gov/howwork/subsidence/inflate_deflate.html. Displacements of the Earth's surface can be measured by a variety of methods, including both terrestrial and space-based technologies. Each method has advantages and disadvantages; therefore, deformation monitoring should not rely on a single technique, but should instead incorporate as many methods as possible. Concurrently utilizing several different methods offers the best chance of recognizing surface displacements at a volcano and providing information on the probability and timing of an eruption.

Trailing-Edge Technologies

Though several classic volcano deformation monitoring methods have been replaced by newer methods due to technological advancements, these older monitoring methods may still be useful at some volcanoes. These classic methods include electronic distance measurement (EDM) and triangulation. Both methods require precisely located ground points as references for the measurements. Called **benchmarks**, these points are common, especially at the tops of hills and mountain peaks. Benchmarks are usually brass or aluminum disks (Fig. 7A) with centering marks (often a cross or dimple), but can also be less obvious pins (Fig. 7B) or shapes chiseled into rock. It is important that these marks are not disturbed, because they are used for repeat surveys over time. If the marks are destroyed or moved, they cannot be reoccupied and volcano deformation monitoring capabilities are diminished.

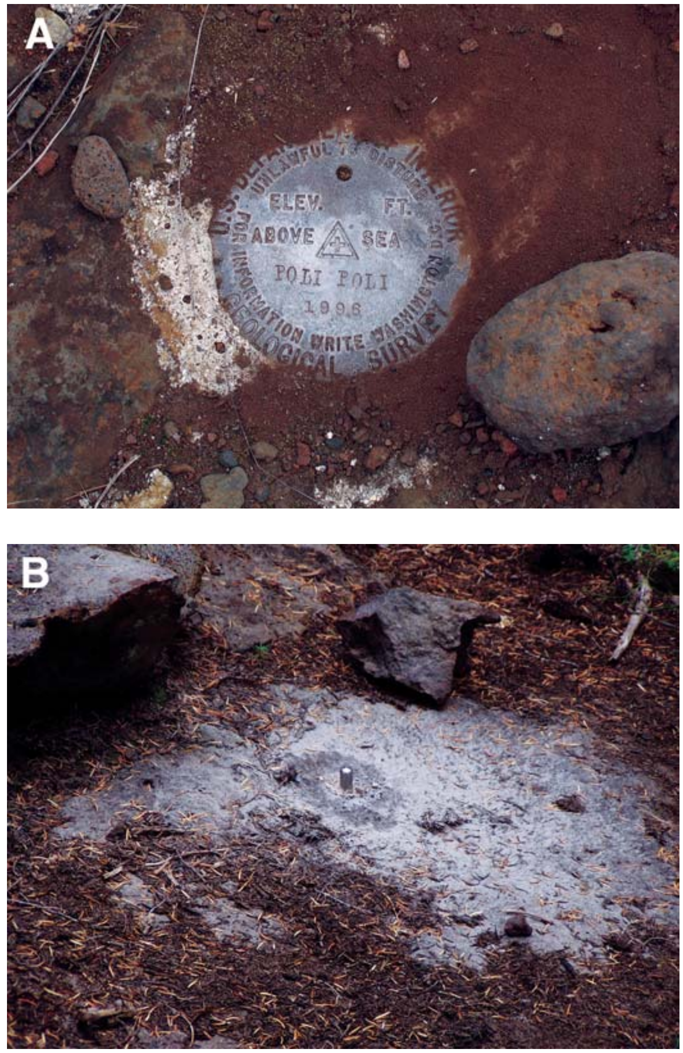

Figure 7. Benchmarks are cemented into the ground and provide known points that can be surveyed year after year. (A) Typical brass disk benchmark, ~10 cm in diameter. The cross at the center of the triangle is the center point of the mark, and is used as the reference point for deformation studies. (B) Occasionally, less conspicuous pins, only ~2 cm in diameter and with center punch at the top, are used as benchmarks. These are harder to see and less likely to be stolen.

Level 3, Method 1: Electronic Distance Measuring (EDM)

EDM measures the distance between two points by placing a laser over a benchmark at one point, pointing it at a reflector array over a benchmark at a second point (perhaps as far away as tens of kilometers), measuring the travel time of a laser pulse between the two benchmarks, and then converting the time to distance. Measured distances are accurate to within a few centimeters. EDM requires at least two people, one at the laser and one at the reflector site. Because variations in atmospheric conditions are the primary source of error in EDM, temperature and atmospheric pressure measurements at both endpoints and along the track of the laser via aircraft are recommended. Repeat measurements between a pair of sites show how the distance changes over time. The Web site http://volcanoes.usgs.gov/activity/methods/deformation/index.php provides a more detailed explanation under the EDM tab.

Networks of EDM line-length measurements were state-of-the-art for determining volcano deformation in the 1960s–1980s. Because EDM is now outdated, EDM equipment is difficult to purchase. Instruments can cost $20,000 to $30,000, depending on the model. Reflectors are over $100 each.

Level 3, Method 2: Triangulation

Triangulation uses precise surveying instruments to measure the horizontal angles of a triangle whose vertices are benchmarks that may be tens of kilometers distant from one another. Changes in the angles over time are used to determine horizontal deformation of the Earth's surface. Vertical angle measurements, for example, from the base of a hill or mountain to its top, may also be taken to determine changes in elevation over time. Triangulation requires a significant investment of time for relatively little data (repeated measurements from each of the vertices in the triangle are required). The instrument used to collect angle measurements is a theodolite, which can cost as much as $20,000.

Though EDM and triangulation were once important deformation monitoring methods, the Global Positioning System (GPS) has largely replaced them. GPS provides better data than most of the classic deformation monitoring methods while requiring less time and personnel (though more specialized training and advanced computing routines are required). Still, many volcano monitoring networks in the United States were originally established using EDM. By comparing past EDM surveys with recent measurements using GPS, it is possible to determine line-length or angle changes since the time of the previous measurement, which can be quite useful for determining long-term deformation of a given volcano. This practice also continues the time series of deformation data, allowing for easier recognition of anomalous signals. For example, an EDM network was established at Lassen Peak in Lassen Volcanic National Park in 1981. InSAR results analyzed in 2004 suggested that the volcano is subsiding ~1.5 cm per year. To obtain independent ground measurements, the EDM network was reoccupied with GPS that same year. Results confirmed the subsidence and suggested that the deformation has been occurring since at least the 1980s.

Both EDM and triangulation measurements require clear lines of sight between the instrument station and target locations. Thus, EDM and triangulation benchmarks tend to be on the tops of hills or mountains, which are often difficult and costly to access. In these cases, it is wise to abandon these sites and establish new GPS stations at more accessible locations. This will reduce the need for helicopter access, decreasing both the expense and intrusiveness of deformation monitoring.

Level 3, Method 3: Leveling

Another classic surveying technique is **leveling**, a method which measures vertical elevations of benchmarks. Unlike EDM and triangulation, however, leveling is still regularly used today. Repeated leveling surveys along a series of benchmarks can determine elevation changes over time to sub-millimeter accuracy. No other method, with the possible exception of continuous GPS, is as sensitive to vertical deformation.

Leveling is accomplished using a pair of precisely graduated rods made of invar (a metal with a low coefficient of thermal expansion), usually 2–3 m tall, and a leveling "gun" (a sight designed to take readings from the rods). The gun is positioned between the two rods and precisely balanced, and the graduations on each rod are read by looking through the gun sight (Fig. 8). Differencing the rod readings determines the difference in elevation between the two rods. After the reading is completed and recorded, one rod leapfrogs the other, the gun is repositioned, and the measurement is repeated. By continuing these measurements along a transect between benchmarks, it is possible to determine the relative elevations of a network of benchmarks. Over time, repeated leveling surveys show how benchmark elevations change, perhaps as a result of magmatic activity beneath the surface.

Figure 8. Leveling crew working in Hawai'i Volcanoes National Park.

Leveling surveys require four to six people: one person to operate the leveling gun, two people to hold the rods, and one to three people to support the survey by finding benchmarks, collecting temperature readings, recording measurements, and directing traffic (most leveling lines are located along roads). An experienced leveling crew can typically survey 5–7 km per day, depending on topography and desired accuracy. Leveling equipment may require reading and recording by the gun operator and an assistant, or may be digitally recorded. In the latter case, the leveling rods have barcodes on them instead of numerical graduations. The gun reads the barcode and determines the elevation difference between rod locations, recording the measurement on a memory card.

A leveling gun costs about $3,000; leveling rods are about $1,000 each for either a digital (barcode) or an optical (graduated) model. Ancillary equipment, including temperature probes, tripods, and traffic signs could cost as much as $1,000. Because the rod scale must be as accurate as possible, recalibration is recommended every 2–4 years (depending on the desired accuracy and frequency of use). Calibration of the rods can only be done by a university laboratory in Quebec and costs about $1,000.

Leveling is still used at numerous volcanoes worldwide. For example, in Hawai'i Volcanoes National Park, annual leveling surveys are an important and informative monitoring method because their great accuracy has shown changes in the magnitude and direction of vertical deformation of Kīlauea volcano. Since the start of the Pu'u 'Ō'ō eruption in 1983 through 2003, the summit of the volcano subsided by as much as 1.5 m. However, the displacement pattern changed to uplift in late 2003, perhaps indicating increasing magma supply to the volcano that may be a precursor to future changes in eruptive activity. In fact, uplift continued through 2007, when new eruptive vents broke out on the east rift zone, leading to a major change in the eruptive style of Kīlauea Volcano. Leveling surveys have also helped characterize volcanic unrest at Yellowstone National Park, where similar changes from uplift to subsidence, thought to be related to the subsurface circulation of hydrothermal fluids, have been observed over short (1–2 year) time spans.

The most useful applications of leveling are on relatively flat volcanoes that are well covered by roads. Because of the large commitment of time and personnel required by the method, leveling over extreme topography or rough terrain, which requires an inordinate amount of time, generally does not justify the cost. For this reason, leveling is an excellent tool for monitoring volcanoes like Yellowstone caldera, but not optimal for use at **stratovolcanoes** (steep, conical volcanoes built by the eruption of viscous lava flows, tephra, and pyroclastic flows) such as Mount Rainier.

Level 3, Method 4: Tilt

Ground **tilt** has been used to monitor volcano deformation for almost 100 years. Thomas A. Jaggar, founder of the Hawaiian Volcano Observatory, first used tilt to monitor volcanic activity at Kīlauea, Hawai‘i, in 1912. Since that time, instrumentation and techniques for measuring tilt have evolved through several iterations. The most cost-effective and modern method uses tiltmeters that are installed in shallow boreholes.

A borehole tiltmeter is analogous to a carpenter's level. The instrument is a cylinder, 0.6–1 m in length (Fig. 9) and filled with an electrolytic fluid that contains a bubble. Electrodes sense the movement of the bubble as the instrument tilts. By placing the tiltmeter in a sand-filled borehole in bedrock, ~2 m deep (which effectively couples the instrument to the Earth), the tilt of the ground surface can be measured. Using a network of tiltmeters, sources of inflation or deflation at active volcanoes can be identified. More information and examples are available at http://volcanoes.usgs.gov/activity/methods/deformation/index.php at the tilt tab.

Figure 9. Borehole tiltmeter installation in Hawai‘i Volcanoes National Park. The instrument is being lowered by its cable into a cased hole. The solar panels, telemetry mast, and electronics box have been installed at the right.

Tilt data can be stored at the instrument site in a data logger and periodically downloaded, but it is far more practical to telemeter the data, ideally in real time, to a volcano observatory. The processing and interpretation of tilt data is trivial, since voltages output by the instrument translate directly to magnitude and direction of ground tilt via a simple calibration factor. The simplicity of the data and processing makes tiltmeters attractive as monitoring instruments, but note that tiltmeters do not record displacements, only tilt. Also, the instruments are quite sensitive to environmental changes, including temperature fluctuations between day and night, atmospheric pressure changes, and rainfall. Thus, tiltmeter sites should be equipped with rain gages, thermometers, and barometers so that raw tilt data can be interpreted with respect to environmental factors.

A tiltmeter costs about $8,000, but much additional equipment is needed to operate a telemetered tiltmeter station. A data logger and radios (which can telemeter both the tilt and environmental data) for the site and a receiving station cost an additional $6,000, and a portable drill (hundreds to a few thousand dollars) is needed to make the borehole. Batteries and solar panels, at a cost of $1,000, are necessary to keep the instrument operational, and environmental sensors (thermometer, barometer, and rain gage) can cost a few hundred dollars.

The best example of tilt as a volcano monitoring method is provided by the Hawaiian Volcano Observatory. In Hawai‘i Volcanoes National Park, almost 20 borehole tiltmeters monitor Kīlauea and Mauna Loa volcanoes. Each instrument takes a reading once a minute, which is immediately telemetered to the Hawaiian Volcano Observatory. These near-real time tilt measurements routinely provide short-term warnings of changes in volcanic activity, like the new magmatic intrusions in 1997 and 1999, and the 2008 episodic deflation/inflation episodes at Kīlauea's summit that lasted hours to two days. No other technique that is currently in use can detect such activity as it occurs.

Level 3, Method 5: Global Positioning System (GPS)

In the late 1980s, the Global Positioning System (GPS) became a viable method for measuring deformation of the Earth's surface, gradually replacing EDM and triangulation. The primary advantage of GPS over all other deformation monitoring methods is the ability to simultaneously measure horizontal and vertical displacements within accuracies of a few millimeters.

GPS is utilized in one of two modes: continuous and survey. Continuous GPS uses a permanently installed GPS receiver and antenna (Fig. 10A) at one location to track the motion of that station over time. The advantage of continuous GPS is that changes in the magnitude and direction of displacement are well resolved. However, the station cannot be moved; thus, any variations in spatial deformation patterns cannot be identified. In survey mode, a GPS antenna on a tripod (Fig. 10B) is set over a benchmark for

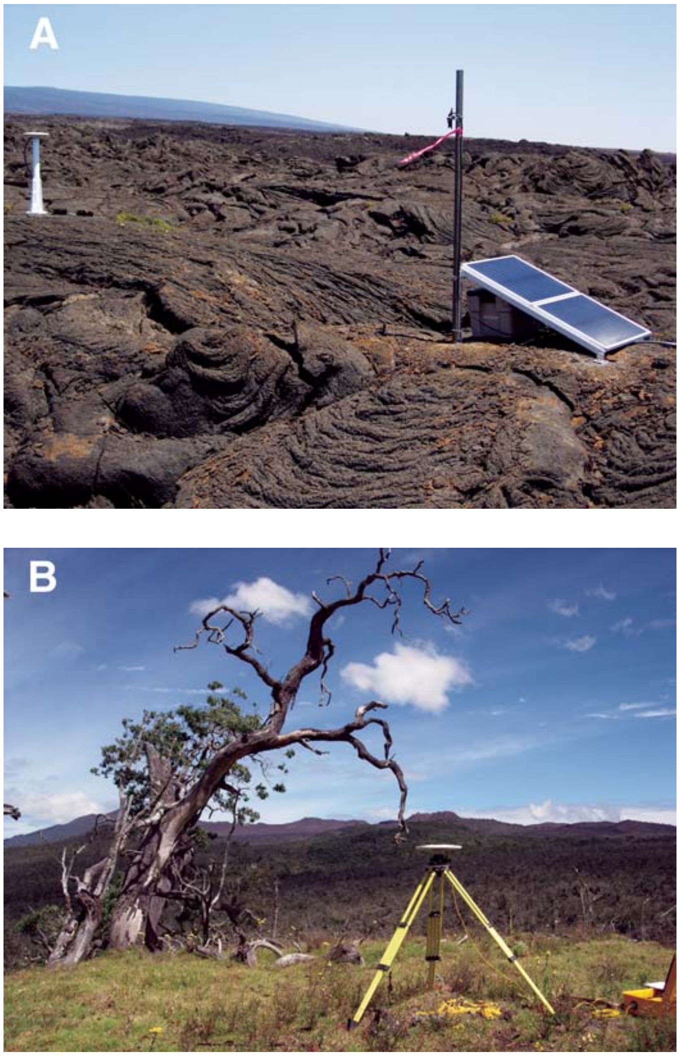

Figure 10. Methods of Global Positioning System (GPS) monitoring. (A) This continuous GPS installation in Hawai‘i Volcanoes National Park consists of an antenna (white disk on the pedestal at the left), solar panels, electronics box (beneath the solar panels), and telemetry mast. (B) A survey GPS site, with a GPS antenna and tripod set up over a benchmark. The box at the lower right contains the GPS receiver and battery.

a short time period (e.g., two days) while the station's position is continuously recorded. The GPS installation is then moved to other sites as needed. Repeat occupation of the same benchmarks provides information about how the surveyed points in a region have moved, but time resolution will be poor.

Both methods of GPS monitoring require a clear view of the sky. Obstructions such as buildings and vegetation obscure the satellite signals and result in poor measurement quality. In addition, short-term GPS measurements tend to be contaminated by multipath (satellite signals that do not travel direct lines between the satellite and the receiving antenna). It is important to collect as much data as possible to average out such effects. Survey sites should record data for at least six to eight hours per day. This is not an issue for continuous installations, which record data 24 hours a day.

GPS positions are calculated using processing software that is generally provided free of charge by research institutions such as the National Aeronautics and Space Administration (NASA) and the Massachusetts Institute of Technology. The software is highly specialized and requires substantial experience and training to use correctly. A GPS receiver and antenna cost about $4,000. Continuous GPS sites require batteries, solar panels, and radio telemetry, at a cost of about $3,000 per site. For equipment that is operated in survey mode, only tripods and batteries are necessary (about $500), in addition to the receiver and antenna.

GPS is the ultimate tool for measuring three-dimensional displacements; therefore, it is no surprise that GPS is presently the dominant method for deformation monitoring at volcanoes. In Hawai‘i Volcanoes National Park, over 50 continuous GPS stations are supplemented by over 100 sites that are occupied for a few days each during annual or event-driven GPS campaigns. This combination of methods provides the best possible temporal and spatial resolution of deformation patterns associated with active volcanism. GPS surveys of ~40 sites, in the vicinity of Mauna Loa supplemented by three continuous stations, first detected inflation of Mauna Loa volcano, Hawai‘i, in 2002. In response to this activity, the continuous GPS network was expanded by ~20 more sites in the following three years. The new continuous stations provide better resolution of surface displacements over time, which will result in more reliable forecasts of future activity of Mauna Loa.

Level 3, Method 6: Aerial Photography/Light Detection and Ranging (LIDAR)

Light detection and ranging (**LIDAR**) surveys and aerial photography are used at restless volcanoes to quantify areas experiencing large surface deformation. Both techniques are also used at erupting volcanoes to quantify the volume of extruded material such as lava flows, volcanic domes, etc. LIDAR surveys and aerial photography are used to construct digital elevation models (**DEMs**) of the ground surface. Volcanologists use DEMs from successive surveys to calculate volume change between surveys. For example, during the 2004–2008 eruption of Mount St. Helens, a time series of DEMs provided the only reliable measure of lava volume as well as its extrusion rate. Tracking volume and extrusion rate helps volcanologists forecast how long an eruption might last and the total volume of lava that might be produced.

Aerial photography is the most basic and cheapest method used to construct DEMs; this is a mature technology in use for decades. A pair of slightly overlapping vertical photos is taken from an aircraft. A stereoscope or specialized computer software is then used to create a topographic map of the ground surface, from which a DEM is generated. During the run-up to the 18 May 1980 eruption of Mount St. Helens, DEMs corroborated the rapidly increasing rate of inflation on the volcano's north flank, leading to the recognition that the north side of the volcano was unstable before the collapse occurred on 18 May 1980.

LIDAR is similar to radar, but uses much higher frequencies of light (usually ultraviolet, visible, or infrared) to survey the elevation of the ground surface. Light, emitted by a laser mounted on an airplane, is reflected from the ground surface, and the travel time is measured by an optical telescope mounted in the same airplane. The light's travel time is converted to distance (analogous to EDM), from which a DEM accurate to within a few centimeters is constructed. LIDAR surveys require precise location of the aircraft, so a reference GPS station on the ground must be available within the survey area. Highly specialized software and extensive operator training are required to process LIDAR results, therefore most LIDAR surveys are completed by private companies.

Generally, the lower cost of aerial photography makes it the method of choice for monitoring volcanoes. A flight to collect aerial photography may cost $1,000 to $5,000, whereas LIDAR flights cost tens of thousands of dollars. LIDAR data also requires several weeks to process, whereas, depending on the desired level of accuracy, aerial photography can be converted into a DEM within days. However, the greater accuracy of LIDAR makes it ideal for locating subtle low-relief features on the ground's surface, such as faults with minor surface offset. In the first weeks following the onset of renewed eruptive activity at Mount St. Helens in late 2004, both LIDAR and aerial photography were used to construct DEMs, which provided important data on the growth of the lava dome in the volcano's crater. However, the great cost of LIDAR caused DEM studies to be done entirely by aerial photography within two months of the start of the eruption.

Level 3, Method 7: InSAR

The use of interferometric synthetic aperture radar (**InSAR**) is described in detail in the Emerging Volcano Monitoring Techniques section below. Although InSAR is rapidly evolving, limiting factors include satellite availability, distortions from atmospheric effects, and the need for relatively long intervals between measurements so that deformation is evident above detection limits. However, InSAR is effective for measuring large-scale, long-term deformation over large areas where other methods would be prohibitively expensive, and it is a good technique for prospecting for deformation where it has not previously been identified, and as a long-term precursor for potential volcanic activity, as illustrated at South Sister volcano (see Emerging Volcano Monitoring Techniques section). With a few exceptions, InSAR is not yet an operational tool for most volcanoes that are showing significant unrest, threatening to erupt, or actually erupting because repeat InSAR images of a given volcano can only be captured at roughly monthly intervals when the satellite is overhead, preventing monitoring of short-term changes.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor surface deformation. Unmanned aerial vehicles (UAVs), also described in the emerging techniques section, are appropriate in areas that are difficult or dangerous to access to monitor changes in active lava domes, lava flows, and vents, such as the growth and collapse of a new lava dome.

Summary

Combinations of monitoring methods allow comprehensive monitoring of spatial and temporal evolution of a volcano's deformation; only a combination of methods can compensate for the weaknesses of any single method. Clearly, various methods and instruments used to monitor deformation at active volcanoes have advantages and disadvantages. For this reason, effective monitoring strategies employ a mix of continuous and survey methods. For example, in Hawai'i Volcanoes National Park, the U.S. Geological Survey's Hawaiian Volcano Observatory uses 20 borehole tiltmeters, more than 50 continuous GPS receivers, more than 100 survey GPS sites, and InSAR data from several different satellites to monitor deformation at Kīlauea and Mauna Loa volcanoes. The same combination of methods is used at Mount St. Helens, where aerial photography is also employed to create DEMs and track the volume and rate of erupted lava over time.

Vital Sign 3. Gas Emission at Ground Level

Introduction

Volcanic gas is naturally released from both active and many inactive volcanoes. Water vapor is typically the most abundant volcanic gas, followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2). Other common volcanic gases are hydrogen sulfide (H_2S), hydrogen chloride (HCl), hydrogen fluoride (HF), carbon monoxide (CO), and hydrogen (H_2), along with many other trace gases and isotopes as well as volatile metals. Concentrations of these gases can vary considerably from one volcano to the next. The majority of potentially active volcanic areas are characterized by one or more low-temperature fumaroles and a fairly well developed hydrothermal system. Large volcanic systems, such as Yellowstone, have numerous vents and fumaroles discharging volcanic gases to the air over a wide geographic area. Some active volcanic systems, such as Kīlauea in Hawai'i, have a variety of gas vents and fumaroles that can range in temperature up to several hundred degrees.

Volcanic gases can be harmful to humans, animals, plants, and property. Usually, the hazards, which can range from minor to life threatening, are restricted to the areas immediately surrounding volcanic vents and fumaroles. However, heavier-than-air gases such as CO_2 can collect in topographic depressions on the flanks of volcanoes and pose a hazard to human health and safety. Acid gases, such as SO_2, when present in abundance, can combine with water in the atmosphere to produce localized acid rain downwind from volcanic vents.

Molten rock, or magma, beneath volcanoes contains abundant gases that are the driving force of eruptions. Volcanoes become restless when magma begins to move from depth toward the Earth's surface. As magma moves into shallower areas under the volcano, it encounters lower pressure conditions that allow more gases to escape into fractures and cracks. Some of these gases are eventually discharged at the surface through hot fumaroles, active vents, or porous ground surfaces where they, if measured, can provide valuable information about the ongoing processes below. Rising magma also heats up the rock mass beneath the volcano and eventually causes water in shallow hydrothermal systems beneath the volcano to boil, releasing additional gases. Land management personnel can contribute significantly to identifying the early signs of volcanic unrest by noting and reporting the appearance of new fumaroles, the sudden appearance of a "rotten egg" smell, an increase in fumarole temperatures or the appearance of new hot ground, unexplained animal deaths, and the onset of anomalous vegetation and tree mortality.

A variety of ground-based methods for measuring volcanic gases includes: direct sampling of gases from fumaroles followed by laboratory analysis, measuring one or more gases at a fumarole with portable instruments, establishing long-term gas monitoring stations at volcanic vents, and conducting soil-gas efflux surveys. Each method is discussed below. All are well-suited for long-term evaluation of volcanic conditions. A strategy involving on-site instrument measurements coupled with laboratory analysis of fumarole gas samples can be particularly effective for geochemical volcano surveillance.

Level 3, Method 1: Direct Fumarole Sampling of Gases and Isotopes

Direct gas sampling is ideally suited for long-term surveillance of volcanic systems because it produces a detailed chemical analysis of specific fumaroles and vents. Volcanic gas samples are typically collected by inserting a chemically inert and durable tube into a hot fumarole. After allowing the tube to heat until condensation in the tube reaches equilibrium with the escaping gases, either a specially-designed evacuated-sample bottle or a flow-through sample bottle is attached to the collection tubing. After the sample is taken, it is sent to an analytical laboratory for analysis by ion and gas chromatography and traditional wet-chemical methods. More information can be found at: http://volcanoes.usgs.gov/activity/methods/gas/sample.php. Field gas sample kits cost less than $1,000, while laboratory analytical instruments for performing this type of gas analysis cost about $30,000 each.

Typically, the full suite of major volcanic gases in the sample can be determined, including water, CO_2, SO_2, H_2S, HCl, HF, CO, and H_2, other gases such as nitrogen (N_2), oxygen (O_2), helium (He), and neon (Ne), if present, plus other trace gases. Fumarole temperature plays a large role in determining the quality and utility of direct samples. The higher the temperature, the better the sample will reflect the conditions of the magma supplying the gas.

Direct gas sampling of fumaroles is not well suited for monitoring rapidly changing conditions because laboratory analyses often take days or weeks to complete. However, detailed gas composition analyses often provide critical information for evaluating volcanic hazards and constructing models that provide insight into the condition of the magma at the depth from which the gases originated.

Isotopes uniquely distinguish sources of volcanic gas. Although sample collection vessels can be slightly different, the procedure and cost is generally similar for collecting gas samples from fumaroles for isotope analysis. Isotopes of light elements, such as hydrogen, carbon, nitrogen, and oxygen, as well as those of noble gases, such as helium, can provide insight into the origin of the volcanic gas and the degree of dilution by atmospheric gases. In particular, higher ratios of the helium isotopes ($^3He/^4He$) imply gases derived from deeper sources. Isotopes are analyzed with mass spectrometers, sophisticated laboratory instruments that can cost up to $300,000.

Level 3, Method 2: On-Site Instrumental Measurements

A portable instrument, such as a gas chromatograph (an analytical instrument that separates mixtures of gas or liquid into measurable components) or a spectrometer (an optical instrument designed for measuring gases at specific wavelengths of light) can measure one or more gases directly from the vent or fumarole. A sample tube is coupled directly into the gas source and the gas is directed into the instrument's sample port, eliminating the need to collect a sample and transport it to a laboratory. Portable instruments can be configured to make measurements over several hours and have the advantage of producing results right away, but they often only measure a few of the volcanic gases of interest. The cost of field portable chromatographs and spectrometers ranges from $5,000 to $25,000.

An important new technique for measuring volcanic gases is open-path Fourier transform infrared spectroscopy (OP-FTS). A Fourier transform infrared spectrometer (FTIR), a special type of infrared spectrometer with a moving mirror assembly and an optical telescope, is mounted on a tripod and aimed across a plume of gas emerging from a fumarole or volcanic vent. A large lamp may be positioned on the opposite side of the gas plume to provide an infrared energy source for the instrument. In other instances, hot rocks or even the sun can be used as the light source. FTIR can rapidly analyze for several gases simultaneously and has the advantage, like the instruments described above, of producing results right away. The cost of a field FTIR system is approximately $100,000.

Some gas emission events are relatively brief and would be missed by occasional sampling of fumaroles or short-term deployment of on-site instrumentation. Thus, continuous gas monitoring stations are often deployed to identify short-lived degassing events as well as long-term changes. These typically consist of one or more chemical or optical gas sensors that measure gas concentrations at or near a fumarole. Similar to seismic or GPS monitoring stations, gas monitoring stations consist of a station housing and batteries to power the sensors and data collection equipment, and cost $3,000 to $10,000 each. Their data are typically telemetered by radio or satellite to an off-site facility, or they can be recorded on-site by a data logger.

During volcanic unrest when rising magma begins to heat the volcano's subsurface, measuring SO_2 is particularly important, as increasing amounts of SO_2 gas are often diagnostic of accelerating unrest. Thus, establishing an array of telemetered Flyspec monitoring stations for continuous gas measurements should always be considered once volcanic unrest is identified. Flyspec, sometimes called mini-DOAS (differential optical absorption spectrometer) is a small ultraviolet spectrometer that measures SO_2 in the air. When used as part of a fixed gas monitoring station, the Flyspec can be configured to scan across the air mass downwind of a volcanic vent or fumarole field. Coupled with wind data from a meteorological station, the Flyspec can produce a reliable measure of the SO_2 emission rate or flux. Flyspec data can be telemetered by radio or satellite links. Telemetered Flyspec monitoring stations cost between \$10,000 and \$15,000 each, depending on the type of telemetry and whether repeater links are required.

Level 3, Method 3: Soil Efflux Measurements

Soil efflux measurement surveys are usually made in areas where volcanic gases, typically CO_2, rise from depth through faults and fractures and discharge into the soil layer just beneath the ground surface. Since CO_2 is heavier than air, it can collect in low spots or in confined spaces or flow downslope as a density current, presenting a significant hazard to all those who enter such areas. In 1990, a U.S. Forest Service ranger in the Inyo National Forest entered a snow-covered cabin in such an area and experienced near-asphyxia. Subsequent investigations revealed potentially lethal concentrations of CO_2 in the vicinity requiring closure of a nearby campground. Fatal encounters with volcanic CO_2 include gas that flowed down a steep slope and across a road, killing about 150 people who were fleeing an eruption at Dieng (Indonesia) in 1979, and sudden releases of CO_2-rich gas from Cameroon's Lakes Monoun and Nyos that killed about 40 and 1,700 people, respectively, in 1984 and 1986.

Zones of soil gas discharge can be either hot or cold and are often characterized by vegetation and tree mortality. Because the gases can escape from the ground over a broad area, a small soil accumulation chamber coupled with an infrared spectrometer and portable computer is typically used to collect and measure the gas at dozens to hundreds of separate sites. These measurements are used to construct a map of the soil CO_2 anomaly to determine a total gas flux. For more details, see http://volcanoes.usgs.gov/activity/methods/gas/soil.php. The cost of field soil efflux instrumentation ranges from \$5,000 to \$20,000. Field surveys are typically conducted by a team of scientists over several days and repeated once to several times per year over several years to evaluate the dynamics of gas discharge from depth.

Soil efflux measurements are also useful to search for faults or other zones where volcanic gas is leaking to the surface. It may sometimes be appropriate to install automated soil efflux monitoring stations in zones of soil gas discharge to monitor short-term (hourly) variations in degassing. Automated monitoring stations cost about \$20,000 each.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor thermal emissions, and volcanic ash and gas clouds.

Vital Sign 4. Emission of Gas Plumes and Ash Clouds

Introduction

Gas and ash emissions are monitored by three techniques described in this section, and also by satellite remote sensing, as described in the section below (Monitoring Techniques used for Numerous Vital Signs). Methods 1 and 2 are used to monitor sulfur dioxide and carbon dioxide, respectively, in volcanic plumes. Both gases are important indicators of magmatic activity. Method 3 describes how volcanic ash clouds can be monitored and tracked, generally in combination with satellite remote sensing. Because of the importance of preventing aircraft from entering volcanic clouds, a coordinated international multiagency process has been developed to track ash clouds in real time and communicate key information to aviation interests.

The rate at which a volcano releases gases into the atmosphere is related to the volume of magma within its magma-reservoir system. By measuring changes in the emission rate, usually in metric tons per day (10^3 kg/d), of key gases such as sulfur dioxide (SO_2) and carbon dioxide (CO_2), it is possible to infer changes that may be occurring in a volcano's magma reservoir and whether magma might be moving toward the surface. Although it is sometimes possible to measure SO_2 discharge from the ground, it is most precisely and safely measured from an airborne platform. Accurate CO_2 emission-rate measurements require an airborne platform. See http://volcanoes.usgs.gov/About/What/Monitor/Gas/plumes.html for more information and illustrations on the methods described in this vital sign.

A typical gas plume, whether exhaled from a small source such as a fumarole or forcefully discharged from a large source such as an erupting volcanic vent, rises to the height where its density reaches equilibrium with the atmosphere. The top part of the cloud may be sheared off and carried away by the wind. The gas emission rate can be determined by measuring the amount of a specific gas in the downwind plume and the wind speed.

Sulfur dioxide emission from inactive volcanoes normally ranges from below instrument detection limits to a few hundred metric tons per day. Because SO_2 can react with water and be lost as a gas phase, it is sometimes not present at quiescent volcanoes until unrest begins. In either case, it is important to measure SO_2 and CO_2 during inactive periods to establish baselines for comparison with future measurements if unrest occurs.

Level 3, Method 1: Correlation Spectrometer (COSPEC) and Mini-UV Spectrometer (Flyspec) Measurements

The importance of looking for SO_2 in volcanic plumes cannot be overestimated. When SO_2 appears in the plume during volcanic unrest, it is the definitive indicator for a shallow magma source, demonstrating sufficient heating of the volcanic edifice to establish dry passageways from depth to the surface in which SO_2 is no longer being removed by reactions with groundwater or a hydrothermal system. Very high and sustained SO_2 emission rates imply that magma has intruded to a high level beneath the volcano and indicate the distinct possibility of an eruption.

The COSPEC (or correlation spectrometer) has been used for more than three decades for measuring SO_2 emission rates from various volcanoes throughout the world. Originally designed for measuring industrial pollutants, the COSPEC measures the amount of ultraviolet light absorbed by SO_2 molecules within a volcanic plume using scattered sunlight as its light source. The instrument is calibrated by comparing all measurements to one or more known SO_2 standards mounted in the instrument. The COSPEC is an optical instrument with an upward-looking telescope, so it is typically mounted in an aircraft with the telescope protruding out a window. Typically, 3–6 traverses are flown underneath the plume at right angles to its direction of travel, to determine the average SO_2 concentration along a vertical cross section of the plume. Wind speed is determined during flight by GPS. From these measurements, a very accurate emission rate can be computed. A COSPEC costs about $80,000 for the instrument and a few hundred dollars for a custom-made mounting plate that is unique to each type of aircraft.

The Flyspec, sometimes called a mini-DOAS (differential optical absorption spectrometer), also measures SO_2 in the ultraviolet light range. However, the Flyspec instrument is considerably smaller and lighter than the COSPEC and can be operated through the USB port of a standard laptop computer. It can be installed in either a helicopter or fixed-wing aircraft and flown underneath the plume using the same measurement strategy as the COSPEC. Depending upon configuration and whether it is a commercial model or not, a Flyspec will cost $5,000 to $12,000.

Flight costs for a typical airborne gas measurement are usually $1,000 to 3,000, but single flights at volcanic systems with widely distributed gas sources, such as Yellowstone, will cost $5,000 or more. Intervals between baseline gas measurement flights at an inactive volcano might be one to three years. At volcanoes experiencing unrest, the flights might be done every one to three months, and when unrest is intense might be needed as often as daily to weekly.

Level 3, Method 2: LI-COR

Carbon dioxide is one of the most important gas species for forecasting eruptive activity because it can provide the earliest geochemical indication of the onset of restlessness within a volcanic system. Because of its low solubility, CO_2 is released from magma very early during its ascent to the surface. Thus a transition of CO_2 from baseline amounts to markedly higher levels indicates that magma is likely involved and on the move from depth. A further increase of CO_2 to even higher emission rates signals that magma is intruding to a high level beneath the volcano. There is no reliable alternative to aircraft for measuring accurate CO_2 emission rates. Aircraft access to restless volcanoes is absolutely essential to adequately and safely monitor gas emissions.

The LI-COR is a small infrared spectrometer that has recently become the standard for determining CO_2 emission rates in volcanic plumes. The LI-COR samples air and volcanic gases through a tube connected to the outside sampling port of a helicopter or twin-engine fixed-wing aircraft; it can analyze CO_2 in the sample air stream at one measurement per second. Unlike the COSPEC and Flyspec which are flown underneath the plume, the LI-COR must be flown through the plume in traverses at different elevations perpendicular to the direction of drift, until an entire vertical cross-section of the plume is analyzed. From these data and a wind speed determined by GPS, an emission rate of CO_2 can be determined.

Because the LI-COR will typically be flown with a COSPEC or Flyspec, the aircraft flight costs and the frequency of measurements will be the same as described above for COSPEC and Flyspec.

Level 3, Method 3: Doppler Radar

Doppler radar monitors the appearance of volcanic clouds and tracks their movements, in contrast to the methods described above, which monitor different chemical components within a volcanic cloud. Thus, Doppler radar is used to help decide when hazardous areas should be closed to people on the ground or to aircraft.

Eruption detection is an easy task when a volcano erupts in good weather, during daylight hours, and/or within plain sight of observers, but it is difficult for eruptions at night, in bad weather, and/or in remote areas. For explosive eruptions, such as might occur at Lassen Peak, Crater Lake, Mount Rainier, and Alaskan volcanoes, these handicaps can be overcome with Doppler radar systems designed to monitor weather. Weather radar detects airborne ash in the same fashion that it detects rain or snow, though it cannot distinguish between ash and weather clouds.

Doppler radar systems produce maps that show anything, including rain, snow, and volcanic ash, that moves and reflects the radar beam. Images are produced at regular intervals and saved as computer files that can be viewed as a time-lapse sequence when other monitoring data indicate possible volcanic activity. For example, unusual seismicity at a volcano indicates that something has happened—perhaps an eruption. If the radar image sequence indicates that a cloud suddenly appeared over the volcano simultaneously with the seismicity, then the cloud was almost certainly produced by an explosive eruption. Thus eruptions can be detected day and night, in both fair and foul weather.

The cost of acquiring radar data ranges from very low to extremely high. The National Weather Service (NWS) provides Doppler radar data for most of the United States at no cost on the internet. However, coverage is limited or nonexistent in some remote areas. NWS radars produce images at intervals of 4, 5, 6, or 10 minutes, depending on weather conditions. Approximately another minute elapses before images become available. Commercial vendors that process and resell NWS radar data will further increase the time between acquisition and delivery to end-users. If images are obtained from NWS radars, telecommunication problems are apt to be an impediment, whether the images are obtained from the internet, directly from NWS data servers, or from a commercial vendor. Furthermore, users have no control over the NWS data stream, and must make do with what data suppliers offer. Consequently, users must work with image intervals that are substantially longer than is desirable, increasing the time required for eruption detection.

If a volcano is not covered by NWS radars, a standalone radar system would need to be acquired and operated. A large dish antenna is placed on a pedestal with an unobstructed view of (at least) the volcano's summit—typically a few tens to 50 km from the volcano. The antenna is typically mounted on top of a building or tower so that nearby objects do not block the radar beam. Cables from the antenna are connected to an electronic "black box" inside the building that controls the antenna and acquires the raw data. A personal computer processes the raw data and displays it on a monitor in various graphic formats that trained operators can easily interpret.

Radar equipment tends to be expensive. The least expensive (and least capable) systems cost about $50,000. More capable systems cost five to ten times as much. Private radar systems require maintenance and repair, and require staff to operate and maintain them. However, radar systems can operate with little attention for extended periods of time.

Remote sensing via satellite, described in the emerging techniques section of this chapter, can also be used to monitor volcanic ash and gas clouds.

Vital Sign 5. Hydrologic Activity

Introduction

Most volcanoes are tall physiographic features with considerable accumulated snow and appreciable groundwater resources. Surface waters can intercept and absorb both the heat and chemical constituents released from the magma. By monitoring the discharge of water, its composition, and its temperature, workers can detect changes to the volcanic system that accompany renewed magmatic activity. The monitoring can include gauging stations on rivers and streams, downhole monitoring of groundwater wells or simple temperature probes (thermistors) placed in streams or lakes. Sometimes observed changes can precede the geophysical signals that are the dominant signs of an awakening volcano.

Level 3, Method 1: Stream and Well Instrumentation

A stream requires some method to measure its depth and volume of flow. Typically, a small concrete structure that is hydraulically connected to the stream is built. This setup permits reproducible measurements that are unaffected by storms. Real-time data transmission requires a telemetry system, generally a satellite transmitter and a source of power (solar cells, batteries or electrical utility lines if available). Additional instrumentation may include a weather station or water-quality instrumentation to measure rainfall, conductivity, or turbidity.

A stream gage measures a river's stage, or its depth relative to some measured datum. Discharge (the volume of water moving past a given point per unit of time) is also commonly monitored. By carefully measuring a river's cross section and water velocity, one can calculate a rating curve that relates the stage to units of flow, typically in cubic feet (ft^3) per second. Ratings curves are remeasured several times per year by water-resources experts. Additional sensors can be placed near the gauging station to measure air and water temperature, water chemistry, or precipitation, and these parameters can be compared with the discharge through the gauging station. Instruments such as thermistors, pressure sensors, and chemical sensors can be placed down wells, providing information about conditions in an aquifer or groundwater system. The data can be collected on a data logger that is routinely downloaded or telemetered to scientists through radio or satellite systems. Information from either wells or rivers can be viewed as time series relative to other monitoring parameters such as seismicity, deformation or satellite observations to see if changes in flow or water chemistry correlate with changes in other measured phenomena. Information from stream gages is also regularly used for flood warnings, wildlife management (especially fisheries) and for water resource management.

Typically, hydrologic monitoring is undertaken with a stream gage, which can cost $30,000 to 40,000 to construct, plus annual operating expenses of approximately $15,000. The price includes full real-time data transmission (usually by satellite) and periodic tests to provide rating curves for each gage, which can change with time. Downhole monitoring systems for wells cost less to maintain because they do not require updated rating curves. Initial costs are around $5,000 for instrumentation to measure temperature and water depths on an existing well. Drilling several new wells costs hundreds of thousands to millions of dollars and is only rarely undertaken at volcanoes for monitoring purposes alone. Simple thermometers with dedicated data loggers can be placed in the ground or in streams for as little as a few hundred dollars. They are only rarely telemetered, and instead collect data continuously for a number of weeks to months prior to data retrieval.

Water data are reviewed routinely in conjunction with other monitoring data. Data are collected every 15 minutes on typical stream gages. Other parameters may be collected more frequently. Alarm systems can be built so that anomalous chemical concentrations, flow rates or pressure changes are immediately forwarded to monitoring personnel.

Stream gages can become unreliable after large storms because storms may change the shape of the river channel and make the rating curve inaccurate. A new rating curve must be determined by field crews. Storms, snow and other environmental conditions can occasionally interfere with data transmission, so that the monitoring record can be periodically interrupted. Downhole sensors can be degraded by high-temperature and high-pressure conditions and may fail and need replacement periodically. Thermistors for soil and surface water monitoring may be vandalized by humans or animals and can degrade with time due to harsh conditions.

Large changes in temperature, chemistry or flow that are apparently unrelated to climatic parameters may be due to changes in the volcanic system. Further studies and evaluation are then undertaken.

Stream gages are common throughout the developed world, but less so in the rest of the world. However, not all stream gages are useful for monitoring volcanoes unless they are placed with that objective in mind. One gauging station used expressly for volcano monitoring is located at the Norris Geyser Basin in Yellowstone National Park (http://waterdata.usgs.gov/mt/nwis/uv?site_no=06036940). Real-time data from the Chance water well, monitored by the Long Valley Observatory are located at http://lvo.wr.usgs.gov/cw3_main.htm.

Vital Sign 6. Slope Instability

Introduction

Volcanoes are subject to various types of slope instability, some linked to eruptive processes, others to the steep terrain and unstable slopes that characterize many volcanic edifices. This section addresses **debris flows**, which are rapidly flowing mixtures of rock fragments, mud, and water that originate on steep slopes. Known as lahars when they originate on volcanoes, they are among the most destructive and persistent of volcanic hazards. Lahars threaten lives and property not only on volcanoes but far downstream in valleys that drain volcanoes, where they arrive suddenly and inundate entire valley bottoms. Debris flows can destroy vegetation and structures in their path, including bridges and buildings. Their deposits can cover roads, recreation areas and railways, and fill or divert stream channels, thereby reducing their flood-carrying capacity and navigability.

Lahars may occur as primary or secondary lahars. **Primary lahars** begin during volcanic eruptions, as a result of hot eruptive materials that melt snow and ice or breach lakes or other impounded waters. **Secondary lahars** can develop at any time after eruptions, as the result of heavy rains or glacial outburst floods that mobilize ash, erodible soils or glacial till. Outburst floods have been recorded from four glaciers in Mount Rainier National Park during periods of unusually hot or rainy weather in summer or early autumn, and have inundated downstream roads and recreation areas (Walder and Driedger, 1994a). Unlike some other volcano hazards that are not necessarily constrained by topography, such as ash falls and pyroclastic flows, debris flows are usually contained in valley bottoms and follow predictable paths along stream channels, thus making hazard mitigation practical through delineation of possible inundation zones and real-time monitoring of debris flow channels.

Susceptibility and potential triggers for debris flows can be determined for a volcano and the potential triggering activity monitored. The presence of a crater lake, significant amounts of snow or ice, or structurally unsound rock, such as material that has been physically and chemically altered by volcanic gases and fluids, can be assessed through geologic field work and mapping. Field studies can also reveal debris flow deposits from previous eruptions, providing perspective on the potential local and regional hazards. Debris flow deposits can sometimes extend for tens of miles from a volcano.

For additional information on slope instability, see the chapter on monitoring slope movements.

Selected Methods for Monitoring Slope Movement

The elements or vital signs of monitoring slope movement relevant to volcano monitoring include (1) determination of types of landslides, (2) monitoring of landslide triggers and causes, (3) lahar hazard delineation, and (4) real-time lahar monitoring. The first two vital signs are covered in the chapter on slopes. Two methods are described below to monitor lahar hazards and movements.

Level 3, Method 1: Lahar Hazard Delineation

LAHARZ is a rapid, objective, and reproducible method utilizing a geographic information system (GIS) with digital elevation models (DEMs) to delineate lahar inundation zones (Iverson et al., 1998). The U.S. Geological Survey developed the method for volcanoes where data, time, funding, or personnel are inadequate to apply traditional geologic mapping methods. Both LAHARZ and traditional mapping methods are based on the same principles: (1) inundation by past lahars provides a basis for predicting inundation by future lahars; (2) distal lahar hazards are confined to valleys that head on volcano flanks; (3) lahar volume largely controls the extent of inundation downstream; (4) voluminous lahars occur less often than small lahars; and (5) no one can foretell the size of the next lahar to descend a given drainage.

The LAHARZ GIS program is an automated method that combines statistical analyses of lahar-inundation data from nine volcanoes to develop quantitative equations that predict the valley cross-sectional area and planimetric area that would be inundated by lahars with various volumes. The GIS method simultaneously delineates inundation areas for a variety of lahar volumes, thereby depicting gradations of the inundation hazard. Inundation hazard is greatest in valley bottoms close to a volcano and diminishes as elevations above valley floors and distances from the volcano increase. Automated portrayal of gradations in hazard is one of the chief advantages of this GIS methodology. The method requires a DEM of sufficient accuracy and resolution combined with a working knowledge of GIS programs. The LAHARZ program is available from the U.S. Geological Survey Cascades Volcano Observatory.

Level 3, Method 2: Real-time Monitoring of Lahars

Real-time detection of lahars close to their sources can provide timely warnings to people in delineated inundation zones, if adequate communication systems and evacuation plans exist. Continuous, automated debris flow monitoring can also provide information useful in identifying specific weather conditions that increase the likelihood of rainfall-triggered lahars or meltwater-triggered glacial outburst floods. Scientists at the U.S. Geological Survey have developed an inexpensive, durable, portable, and quick-to-install system to detect and continuously monitor the arrival and passage of debris flows and floods in valleys draining volcanoes (LaHusen, 1996). This automated system, the **Acoustic Flow Monitor (AFM)**, senses and analyzes ground vibrations with a compact, solar-powered unit that is installed near specific channels where lahars may travel. It uses a rugged sensor and an on-site microprocessor to continuously analyze vibration signals and detect debris flows and floods based on frequency, composition, amplitude, and duration of the vibration signal. A two-way radio system communicates between each sensing unit and a base station through a radio network. An AFM system is in place to detect large-scale lahars that might occur at Mount Rainier; see http://ic.ucsc.edu/~syschwar/eart3/exercises/Rainier_warning_sys.html.

Each AFM station measures the amplitude of the ground vibration signal every second and sends data by radio to the base station at regular intervals—typically 15 minutes. If the instrument senses vibrations that exceed a certain threshold value (adjustable for each individual site) for longer than 40 seconds, the AFM transmits immediate alert messages. It continues to send alert data at 1-minute intervals for as long as the signal remains above the threshold level. When the signal drops below the threshold level, the AFM resumes normal operation, transmitting at less-frequent intervals. The AFM system has distinct advantages over other detection systems: (1) the sensor and microprocessor are set to analyze specifically the peak vibrations typically produced by debris flows and floods, and screen out other noise or tremor that would affect normal seismographs; (2) flows are monitored as they approach, and recede from, individual monitored sites; and (3) the equipment is ready to detect subsequent flows immediately without any additional maintenance.

Typically two or three AFM stations are positioned in each selected drainage so that lahar velocity can be determined from arrival times between stations; this provides a robust, redundant system. One or more hilltop radio repeaters may be needed to relay the signals downstream to a base station where appropriate actions can be initiated. The cost for installing a basic AFM monitoring system is about $50,000 per drainage covered.

MONITORING TECHNIQUES USED FOR NUMEROUS VITAL SIGNS

Method 1. Remote Sensing via Satellite

Description

Satellite remote sensing is useful to monitor and measure a variety of volcanic phenomena, including thermal emissions, volcanic ash and gas clouds, and surface deformation. Typically, satellites using infrared sensors are used to detect and track volcanic activity, and ultraviolet and radar sensors are used to measure gases and ground surfaces. Many volcanic processes emit heat. Processes that emit heat as part of an eruption are termed **active sources**. Examples include pyroclastic flows, lava flows, lava domes, and lava fountains. Processes that emit heat for long periods of time but that do not normally indicate an impending eruption are termed **passive sources**. Examples include hot springs, geysers, fumaroles, fractures, and crater lakes.

For less explosive volcanic phenomena, such as lava flows and lava fountains, satellite remote sensing can aid in the interpretation of seismic data, especially for remote or difficult to access volcanoes. Remote sensing may determine whether a type of seismic signal typically observed during an eruption (volcanic tremor) is related to a relatively slow process such as magma rising in a conduit, or a more hazardous explosive eruption. In other cases (e.g., Kīlauea, Mount Etna), remote sensing has been used to detect changes in lava flow character, from the type fed from a subsurface tube system to a surface flow (Harris et al., 1997a), as well as lava effusion rates (Harris et al., 2000). Although this change in flow character may not be apparent in seismic data, it can signal a transition in the type and location of lava flow hazard.

Thermal remote sensing of active processes has in some instances successfully identified precursors to hazardous volcanic activity and aided in the short-term forecasting (days to weeks) of hazardous explosive volcanic activity (Schneider et al., 2000; Dehn et al., 2002; Dean et al., 2004). For example, as magma intrudes into a lava-dome, its flanks can become oversteepened, leading to collapse. This generates hot block and ash flows (pyroclastic flows) which can be detected in satellite imagery. A large dome collapse can trigger a larger-volume explosive eruption as underlying, gas-rich magma is rapidly depressurized, leading to eruption columns and ash clouds traveling thousands of kilometers.

Explosive volcanic eruptions can inject large volumes of volcanic ash and gas into the atmosphere, where they are dispersed by winds. Volcanic ash is an unconsolidated mixture of sand- to dust-sized fragments of rock, crystals and glass, which pose a severe hazard to aircraft and machinery. From 1973 through 2003, nearly 100 encounters of aircraft with airborne volcanic ash have been documented, several of which nearly resulted in loss of the aircraft. Typical costs per encounter range from several tens of thousands of dollars to as much as $80,000,000 (Marianne Guffanti, U.S. Geological Survey, 2005, personal commun.). Drifting ash clouds (those that have detached from the vent) are undetectable by an aircraft's onboard radar, and are difficult to see in low light and at night. Satellite detection and tracking of drifting ash clouds, cloud dispersion forecast modeling, and prompt communication of analyses are used to mitigate the volcanic ash hazard. In addition to the airborne hazard, ash fall can occur as a result of an eruption cloud. This can range from a light dusting to thick deposits of ash, even at great distances from the volcano (Houghton et al., 2000). Satellite tracking and modeling of ash plumes also helps to predict ash fall. Forecasts and modeling of typical ash-fall patterns can help managers mitigate the effects of ash load on human and animal health, machinery, and structures.

Volcanic gases are also emitted during an explosive eruption, with water, carbon dioxide and sulfur dioxide being the most abundant. Although these gases do not pose an acute hazard to aircraft, in large quantities they can be a chronic hazard to health, infrastructure and the environment. Once sulfur dioxide is emitted into the atmosphere, it combines with water to produce a sulfuric acid (sulfate) aerosol. In large quantities, these acid droplets can affect global climate by reflecting incoming solar radiation. Sulfuric acid droplets are very small, so they can remain airborne for months to years. Structures or aircraft in areas that contain sulfate aerosol could sustain chronic damage, such as crazing of acrylic windows, corrosion of the supports and rubber seals, and accumulation of deposits within air-handlers or engines. These affects are difficult to document because they can occur slowly over a period of years. Satellite remote sensing offers the capability to detect and quantify the amounts of sulfur dioxide released during an eruption, as well as the resulting sulfate aerosol. This includes non-explosive degassing of sulfur dioxide, which has been successfully monitored at Kīlauea for years. Although ground-based gas measurements are the most useful for routine monitoring, satellite analysis provides a synoptic overview of the extent of the gas plume, and aids in visualizing and measuring the volcanic fog (“vog”) cloud produced from the vent, or by the entrance of lava from Kīlauea into the ocean (See Sutton et al., 1997).

Routine thermal monitoring of passive sources using satellite technology has, in a few instances, identified eruption precursors during volcanic unrest, when measurable increase in thermal emissions provided evidence for magma intrusion and the subsequent release of hot gases (Sparks, 2003). However, in practice, passive sources are difficult to monitor by satellite because their temperatures are low and their features are generally too small to be resolved by available thermal sensors, which typically have a spatial resolution of 60 m.

Monitoring Methods

Satellite remote sensing can monitor volcanic activity frequently and at low to moderate cost (Harris et al., 1997b). Much of the satellite data are available in near real-time online, so in many cases the expenses do not include receiving stations to downlink data. Satellite remote sensing and seismic monitoring can be symbiotically combined to determine the type and potential hazard of an erupted ash. The satellite imagery also provides information on phenomena that cannot be observed in any other way, such as thermal anomalies, large-volume gas emission, and hazardous volcanic ash clouds. A variety of complementary satellite data (Table 2) are available to make these observations. These data can be generally classified as (1) frequent, near real-time, low spatial resolution, such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and Geostationary Operational Environmental Satellite (GOES) sensors; or (2) infrequent, non-real-time, high spatial resolution images, such as land remote sensing satellite (Landsat) and Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) sensors. The combined use of both types of satellite data provides a robust method for detecting volcanic activity and mapping volcanic landforms and eruption deposits.

Some satellite sensors measure light at wavelengths not visible by the human eye. The most useful for monitoring volcanoes are infrared wavelengths, just longer than those humans can see. Most infrared wavelengths are absorbed by the Earth’s atmosphere, except for a few “atmospheric windows” where absorption of infrared rays is minimal.

One useful atmospheric window is the short-wave infrared (SWIR) with wavelengths between 3 and 5 microns. SWIR is used to monitor high-temperature thermal features such as lava or pyroclastic flows. The hotter an object is, the more energy it will emit, and at shorter wavelengths. For example, an object with a temperature of 25 °C, such as the Earth’s surface, has a peak emission at a wavelength of ~10 microns. However, a volcanic feature with a temperature of 800 °C has a peak emission at ~3 microns. Many volcanic features are sub-pixel in size, meaning they cover an area smaller than 1 km on a side for AVHRR or MODIS. The temperature recorded by the satellite is a complex mixture of the temperatures of a hot and cold component, and their respective areas. If multiple channels of data are available at different wavelengths, it is possible to take advantage of these relationships to estimate both temperature and area of a hot volcanic component (Rothery et al., 1988).

Another useful atmospheric window is the thermal infrared (TIR) with wavelengths between 8 and 14 microns. Data at these wavelengths are used to detect volcanic ash and sulfur dioxide clouds. The most common method of discriminating volcanic ash clouds from meteorological clouds is the “split-window” method. Here the brightness temperature difference (BTD) is compared between 2 satellite channels at 11 and 12 micron wavelengths. Semitransparent volcanic clouds generally have negative BTDs while meteorological clouds generally have positive BTDs (Prata, 1989). Though many factors affect the magnitude of the BTD signal, including (but not limited to) cloud opacity; the amounts, size and distribution of ash and water in the cloud; and the temperature contrast between the cloud and background surface; the amount of volcanic ash can be estimated from satellite data using a complex radiative transfer model (Wen and Rose, 1994). A similar method is utilized to detect and measure sulfur dioxide clouds from either passive degassing (using ASTER), or from explosive eruptions (using MODIS) by using wavelengths at 7.3 or 8.6 microns, where there is absorption due to sulfur dioxide (Watson et al., 2004).

Real-time satellite data analysis and monitoring requires rapid and reliable access to large amounts of satellite data. Useful data sets include AVHRR and GOES sensors on meteorological satellites operated by NOAA, and MODIS on research satellites operated by NASA. Direct reception of satellite signals is the most reliable, but also the most expensive method of data acquisition. A satellite receiving station costs between $50,000 and $150,000. A separate receiving dish and associated computer hardware is needed for each data stream, which increases the costs by $25,000 to $50,000 per dish. Installation costs vary depending upon the infrastructure needs and assets of a particular site and could range from $5,000 to $15,000. A dedicated station

TABLE 2. SUMMARY OF SENSOR CHARACTERISTICS FOR INSTRUMENTS TYPICALLY UTILIZED IN REMOTE SENSING OF VOLCANIC PHENOMENA

Satellite sensor	Volcanic phenomena detected	Channels (microns)	Spatial resolution	Temporal resolution
Polar orbiting sensors, low spatial resolution				
AVHRR (Advanced Very High Resolution Radiometer) NOAA satellites	Thermal anomalies Volcanic ash	5 Channels b1-2 Visible b3 SWIR b4-b5 TIR	1100 m (all bands)	6–12 images/day
MODIS (Moderate Resolution Imaging Spectroradiometer) NASA satellites	Thermal anomalies Volcanic ash Sulfur dioxide	36 Channels b1, b3-4 Visible b8-14 Visible b2, b5, b26 NIR b15-19 NIR b6-7, 20-25 SWIR b27-28 SWIR b29-36 TIR	250–500 m Visible 1000 m IR	2–6 images/day
Geostationary satellites				
GOES (Geostationary Operational Environmental Satellite) NOAA satellites	Thermal anomalies Volcanic ash	5 Channels b1 Visible b2-3 SWIR b4-b5 TIR	1000 m Visible 4000 m IR	48–96 images/day
High-resolution polar orbiting sensors				
ETM + (Enhanced Thematic Mapper Plus) NASA Landsat satellite	Thermal anomalies	7 Channels b1-3 Visible b4 NIR b5-6 SWIR b7 TIR	15 m Visible 30 m VNIR 60 m TIR	Every 8–16 days
ASTER (Advanced Spaceborne Thermal Emission Reflection Radiometer) NASA satellites	Thermal anomalies Volcanic ash Sulfur dioxide	14 Channels b1-2 Visible b3 NIR b4-9 SWIR b10-14 TIR	15 m VNIR 30 m SWIR 90 m TIR	Every 8–16 days

Note: NOAA—National Oceanic and Atmospheric Administration; NASA—National Aeronautics and Space Administration; IR—infrared; NIR—near infrared; SWIR—short-wave infrared; TIR—thermal infrared; VNIR—visible and near infrared.

manager operates the systems and archives the data. Salaries of remote sensing scientists and data analysts are further costs.

Satellite data can also be acquired online from government agencies and universities at a cost of around $10,000 to $20,000 per year. Approximately $10,000 is also needed for specialized computer software, plus costs of computer workstations and large storage devices to store data received at a rate of many gigabytes per day. A robust, reliable computer network capable of handling this volume of data is also needed.

Non-real-time data from satellites such as Landsat and ASTER are still lower cost alternatives. Data from Landsat and ASTER can reveal smaller features (15–90 m) than satellites that provide near real-time data (1 km). Therefore, Landsat and ASTER data are used primarily to improve interpretation of real-time data described above. This approach has advantages over near real-time data, such as lower cost ($50 to $300 per scene covering ~34,000 km^2), higher spatial resolution, and the ability to detect smaller regions of elevated surface temperature and measure non-eruptive emissions of sulfur dioxide gas. Furthermore, all data processing is done with desktop computers using specialized, but relatively inexpensive software ($500 to $2,000).

The disadvantages are limited data availability and cloud cover. Presently, Landsat and ASTER data are available only every 8–16 days. Cloud cover, however, is the main disadvantage. In cloud covered areas, volcanic ash and gas clouds produced by explosive eruptions can only be observed once they rise above the weather clouds. Any thermal activity at the surface is partially or completely obscured by the presence of clouds.

In summary, to create an effective near-real time volcano monitoring system via satellite, the primary goal is repeat observations at adequate temporal resolution to match the volcanic process being observed. Long term precursors (e.g., deformation, gradual heating) permit us to use the higher resolution data sets. Lava flows and explosions where changes occur on the scale of minutes require the coarse spatial resolution of polar-orbiting or geostationary satellites providing imagery every hour.

EMERGING VOLCANO MONITORING TECHNIQUES

Introduction

Volcano monitoring techniques are rapidly evolving as a consequence of technological innovation and our expanding understanding of the processes that cause eruptions. This section describes three examples of new remote-monitoring methods that are being used to monitor active volcanoes. The first uses unmanned aerial vehicles (UAVs) to access hazardous areas, the second uses repeat measurements of the distance between a satellite and the ground (InSAR), and the third senses low-frequency sound waves (infrasound) to detect explosions.

All of the more traditional monitoring methods are also changing. For example, the rapid expansion of small-footprint satellite communications and internet technology is driving a revolution in the way that volcanoes are monitored. Currently, seismic, gas, deformation, and even visual imagery is monitored at remote volcanoes, some located thousands of kilometers from base stations, using satellite and internet communications. In addition, new low-cost solid-state accelerometers, GPS, and wireless local-area radio systems allow rapid helicopter deployment of small sensors with real-time data communication, even within the craters of active volcanoes

Volcanic gas monitoring is also rapidly changing, and new instruments, such as the Fourier transform infrared spectrometers (FTIR) are now available, which can remotely measure gas species, such as chlorine, that have previously only been possible to detect using more dangerous direct sampling from vent areas; these instruments provide a better understanding of the gas contents and potential explosivity of volcanoes.

Level 3, Method 1: Unmanned Aerial Vehicles (UAVs)

The development of autonomous UAVs has allowed scientists to explore uncharted anomalies in places that are difficult to reach or hazardous to access. Volcano monitoring promises to benefit from the development UAVs. In late September 2004, Mount St. Helens began its first sustained eruption since 1986, and for the first time UAVs were sent into the crater of an erupting volcano (McGarry, 2005; Patterson et al., 2005). This experiment demonstrated that small (2.45 m wingspan) and relatively inexpensive unmanned aircraft can be precisely navigated to less than a kilometer above an active volcanic vent and held on station for extended periods using pre-programmed routes and computer-stabilized flight. The UAVs delivered real-time optical and infrared imagery data to a mobile base station 10 km from the crater (Figs. 11 and 12). These data were used to monitor visible and thermal changes in the active lava dome and vent, such as growth and collapse of the new lava dome, and the extent and growth of hot areas. UAVs also offer potential advantages for use in sensitive and hazardous areas. Noise levels are typically lower than manned aircraft; at altitudes of more than a thousand feet, the small UAVs used at Mount St. Helens typically cannot be heard over background and wind noise. Since no pilot is needed and little fuel is used (there are many fuel options—alcohol, gasoline, or heavy fuels), the lower risks, costs, and environmental impacts offer significant advantages over other monitoring methods.

Figure 11. Unmanned aerial vehicle mounted on the pneumatic launching catapult in the parking lot at the Johnson Ridge Observatory at Mount St. Helens, where it was launched and recovered.

UAVs with varying payload and aeronautical capabilities are now becoming available or are under development for civilian and government use. These include both fixed-wing and rotorcraft configurations, and a range of power plant types and sizes, payloads, and flight range/duration capabilities. Because of the low cost, current availability, and ability to launch from small and remote locations, the smaller fixed-wing and rotorcraft types of UAVs offer considerable potential for unobtrusive volcano monitoring.

The 2.45 m, man-portable class of fixed-wing UAV used at Mount St. Helens cost approximately $25,000 per plane with an autopilot, onboard radio telemetry, and flight tracking/data relay computer. These aircraft are capable of carrying a payload of up to 4 kg, but larger models can accommodate payloads up to 10 kg. The maximum smaller model payload volume is ~10 cm diameter × 20 cm cross-sectional area, whereas the larger models have a payload dimension of ~45 × 28 × 12 cm. As in any aircraft, there are trade-offs between velocity, payload and duration. However, durations of 10–20 hours at 30–60 knots at day or night, and ranges of up to 1000 km with preprogrammed routes and autonomous GPS tracking are possible, although real-time data relay is typically limited to 30 km line-of-sight distance without radio repeaters. Because these aircraft are unmanned, in certain high-risk/high-benefit conditions they are considered expendable. A complete mobile base station with radio telemetry, flight controller, data acquisition/processing, and portable (30 kg) launch catapult costs about $85,000. Flight support services such as those outlined above are commercially available.

The use of UAVs for volcano monitoring is currently limited by the availability of small lightweight sensors. Only optical and

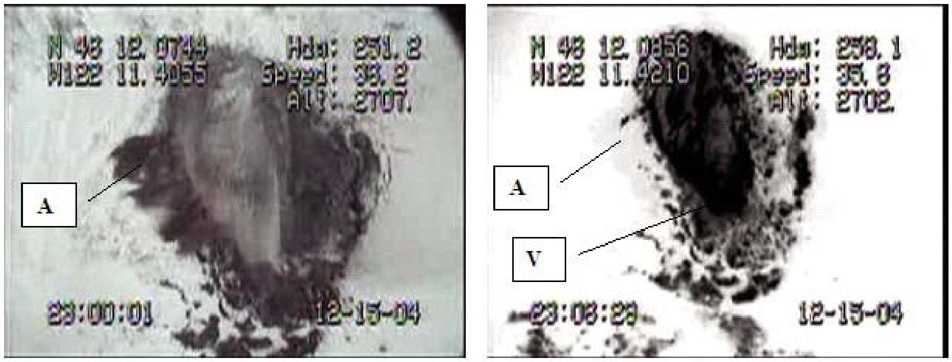

Figure 12. Still images taken from video captured from an unmanned aerial vehicle of the new lava dome ~300 m long. The left image shows an enhanced image, which accentuates the topography, thereby giving volcanologists a sense of the steepness of the lava dome. (The steepness determines the likelihood of a collapse, which could generate hazardous pyroclastic flows.) The right image is an inverted-grayscale infrared image, in which the deeper shades of gray and black represent hotter material. This image shows the hot (black) U-shaped area where new lava is being extruded (indicated by V). It also shows that the recent ash deposits (A), so prominent in the left-center of the image on the left, are relatively cold.

uncalibrated infrared cameras were tested at Mount St. Helens, although several new miniature sensors are being developed or modified for UAV use. For example, the latest generations of light-weight sulfur dioxide (SO_2) spectrometers are readily adaptable to UAV use, and will provide an alternative method for volcanic gas monitoring. Another off-the-shelf application is the use of high-resolution digital still photography and stereo imaging to document, monitor, and measure changes, such as characteristics of hazardous vent areas, and extents of lava flows and other eruptive products. One of the promises offered by UAV-based volcano monitoring is in providing observations during poor weather; however, this is also one of the greatest challenges. Currently, available GPS tracking and autonomous flight allow operation of UAV aircraft in cloudy weather, although operation in icing conditions could be problematic. A greater technical challenge is in developing sensors that can see through clouds. Researchers are currently testing a lightweight UAV-based radar system, which offers promise for observations in poor weather conditions.

To date, most UAV development and testing have taken place in military airspace, where civilian flight is prohibited or closely monitored. A principal concern about UAV operation in civilian airspace is providing separation between the UAV and commercial and private aircraft that are operating in the same area. UAV operations at Mount St. Helens were permitted under a certificate of authorization granted by the FAA to the UAV operator for flight in temporary flight restriction zone surrounding the volcano.

Level 3, Method 2: Interferometric Synthetic Aperture Radar (InSAR)

Interferometric synthetic aperture radar (**InSAR**), developed in the mid-1990s, is the most recent advancement in detecting deformation of the Earth's surface. InSAR uses two satellite radar images of the same area on the ground acquired from an identical point in space at different times. Radar range measurements, which contain information about the distance between the satellite and ground, from the later image are subtracted from the earlier to form an interferogram, which shows how much surface deformation occurred in the interval between the acquisition of the two images (Helz, 2005). Surface displacements as small as one cm can be identified in a single interferogram. When multiple interferograms are combined, displacements as small as a few mm may be recognized. A more comprehensive explanation is available from http://volcanoes.usgs.gov/insar/.

InSAR has two primary advantages over other monitoring methods. First, InSAR provides high spatial resolution along swaths that are 100 km wide and as long as thousands of kilometers. Second, the method needs no equipment on the ground. Thus, remote or isolated volcanoes may be monitored using InSAR without visiting the field area. These two characteristics combine to make InSAR particularly useful for detecting deformation at poorly monitored volcanoes. For example, until recently, South Sister volcano in Oregon was not well monitored because it showed no obvious signs of unrest, such as seismic activity or gas emissions. However, InSAR studies of the volcano in 2001 indicated that an area immediately west of the volcano was inflating ~3 cm per year, probably because magma was accumulating below the surface. As a result, the U.S. Geological Survey began annual GPS and leveling surveys at South Sister and installed continuous GPS and seismic instruments. Now any signs of an impending eruption should be recognized well in advance.

InSAR, however, has some significant drawbacks. In its present state of development, InSAR is not an operational tool for monitoring most volcanoes showing significant unrest, threatening to erupt, or actually erupting. Present limitations in satellite availability and tasking priorities create long intervals between repeat image acquisitions, which constrain InSAR's present role to supporting long-term characterization of deformation, similar to survey-mode measurements like leveling or survey GPS. An InSAR image can be taken only when a satellite is overhead, typically on an average of a few times per month.

Atmospheric effects, including storms or cells with high concentrations of water vapor, can also introduce error to InSAR measurements. Such conditions do not lead to incoherence, but rather introduce biased signals to the data that may be incorrectly interpreted as deformation. Thus, it is important to confirm the results of any single interferogram with other data, including terrestrial deformation measurements or other temporally independent interferograms.

InSAR only images surface displacements that occur in the same direction as the radar's line-of-sight, which is usually inclined 15°–45° from vertical. Thus, an interferogram contains a combination of horizontal and vertical deformation components. Converting InSAR measurements into separate horizontal and vertical displacements, similar to those provided by GPS, requires at least two interferograms that cover the same time period and image the ground from different points in space. Such conditions are difficult to satisfy; thus, it is best to use InSAR in combination with other methods that unambiguously monitor horizontal, vertical, or both components of surface deformation.

While InSAR may be cheaper than other monitoring methods for remote volcanoes, data acquisition and analysis can still be quite expensive. Data processing requires specialized software that can include free software, which comes without technical support and therefore requires an expert already trained in its use, or technically supported software, which may cost as much as $30,000 and still requires an operator with a good background in working with radar data. Radar scenes generally cost about $100 per 100 km^2 frame, depending on how they are acquired. As of 2008, only the Canadian, European, and Japanese Space Agencies operate satellites with InSAR capabilities, so all data must be purchased from those organizations.

Variations in surface characteristics between satellite passes caused by ice, snow, and vegetation cause the radar signal to break down in some areas, preventing recovery of a deformation measurement. This "incoherence" is a significant problem on ice- and snow-covered or vegetated volcanoes, such as Mount Rainier, so InSAR is not presently a reliable monitoring tool at such sites. Future satellite missions and new signal processing techniques may reduce this problem in the coming decade.

Level 3, Method 3: Monitoring Volcanic Explosions with Infrasound

Many natural phenomena and human activities create sound waves in the atmosphere at sub-audible frequencies, generally between 1–25 Hz. Termed **infrasound**, it is generated by sources such as wind, ocean waves, heavy industry, rockfalls, aircraft, meteors, and explosions. Infrasonic waves can travel long distances through the atmosphere and, because the atmosphere has a relatively simple structure compared to the heterogeneous Earth, infrasonic waves are far less distorted by their trip through the atmosphere than are seismic waves by their trip through the Earth. Thus, infrasonic signals created by a volcanic source such as an explosion can be much simpler, and therefore easier to interpret, when received at an infrasonic sensor (such as a microphone or microbarograph) than seismic waves generated by the same explosion when received at a seismograph. Explosions in particular produce very characteristic infrasonic signals, and infrasonic sensors installed around active volcanoes have proven useful in distinguishing between explosions and other seismic sources such as rockfalls, avalanches, and wind gusts (Johnson et al., 2003).

Explosions are often recorded on seismic stations as well. For example, two explosions that occurred at Mount St. Helens in 2005 were detected first by seismic stations. However, seismographs can be so swamped by seismic waves from local earthquakes that any ground-shaking produced by explosions can be completely obscured. During the first two weeks of the 2004–2005 eruption of Mount St. Helens, earthquake activity was so intense that explosions could only be detected visually. Thus another key benefit of infrasonic monitoring at volcanoes is that explosions will still show up on infrasonic sensors when intense earthquake activity has made seismic stations all but useless for explosion detection.

What Can Be Learned

The most important question that infrasonic monitoring can answer at a volcano is, "Are explosions presently occurring?" Therefore, data from infrasonic sensors must be transmitted to observatories in real time. Having two or more infrasonic sensors at the same site greatly improves the ability to assess whether a given signal is infrasonic (traveling at the speed of sound) or subsonic (such as wind gusts, which travel at a fraction of the speed of sound).

Secondary questions include, "Where is the explosion source located?" and possibly, "What is the explosion's size?" (Although, in some instances, no direct correlation between the size of an infrasonic signal from an explosion and the size of an explosion has been found [Johnson et al., 2005].) To answer these secondary questions, two or more sets of arrays, each consisting of at least four infrasonic sensors, are needed.

Infrasonic Monitoring—Mechanics

Infrasonic sensors detect minute pressure changes in the atmosphere over a time scale ranging from milliseconds to minutes or longer and at sub-audible frequencies—generally less than 25 Hz. Infrasonic stations can consist of single sensors (commonly co-located with a seismometer; see Fig. 13) or arrays of sensors which, through array analysis techniques, can provide information on source location. Signals from these stations are typically telemetered to a volcano observatory where they are recorded, digitized, stored, and analyzed. For volcano monitoring, three to four infrasonic sites are generally sufficient to adequately monitor all sectors of a volcano, but the actual

Figure 13. Typical single-microphone station at Mount St. Helens in 2004. This site is ~2 km north-northeast of the vent, but did not record any explosion-related infrasonic signals from the two explosions that occurred after its installation. The microphone is located inside the metal box. Soaker hose extending from the box helps reduce (but not eliminate) wind noise. Photo by Seth Moran (U.S. Geological Survey).

number will vary depending upon size and characteristics of the individual volcano. Infrasonic sensors can be placed at distances of 20 km or greater from a volcano, so it is feasible to install such equipment near a restless volcano without exposing field personnel to hazardous conditions.

Individual microphones cost between $1,000 and $10,000, depending upon the amount of noise reduction and sensitivity desired. Additional equipment, such as radios or satellite dishes for transmitting data, and batteries and solar panels for powering the site, cost an additional $4,000 to $10,000. Total installation costs range from $5,000 for a single telemetered microphone to more than $50,000 for a four-microphone array with associated solar panels, batteries, infrastructure, and satellite telemetry.

For a low-power, telemetered site with a single low-sensitivity microphone, a typical installation includes: an analog radio, an equipment enclosure (typically a ~0.3 m × 0.3 m × 1 m metal box) with a single 100 A–hour lead-acid battery and an electronics box, an antenna mast, antenna, solar panel, microphone (packaged in PVC pipe), and ~7–10 m of soaker hose (to reduce wind noise). For a site with an array of four high-quality microphones, a typical installation would include a radio or satellite modem to transmit data, an equipment enclosure somewhat larger than the single-microphone site, with as many as ten 100 A–hour batteries, and sufficient infrastructure to mount several solar panels and a radio antenna.

An observatory to which telemetered data are sent needs its own receiver and equipment to process and store the signals. Equipment costs are about the same as for an infrasonic sensor site, minus the cost of the sensor. If the infrasonic sensor site and the observatory are not line-of-site, then additional repeater stations will be needed.

The principal goal is explosion detection in real time. Trained analysts can examine incoming signals, or computers can send automated alarm messages to on-call staff when an explosion is detected. However, infrasonic signals from single microphones can be confused with wind noise or other non-volcanic sources. Wind noise (if it does not saturate individual sensors) can be easily distinguished from true infrasonic signals by looking at the difference in arrival times of a given signal at two or more infrasonic sensors in an array. Because wind gusts move at the speed of air, the time differences will be much greater for wind gusts than for infrasonic signals (which move at the speed of sound). Data from arrays of four or more sensors in an array can be processed in near real time to identify coherent phases sweeping across the array from a given azimuth undetectable to the naked eye. To locate explosions, at least two array sites are required. Because volcanoes are generally windy environments, multiple infrasonic sites at different points around the volcano improve the chances that one site will record an explosion free of wind noise.

Infrasonic monitoring is not needed at inactive volcanoes. However, a cache of sensors and equipment for infrasonic stations should be maintained to facilitate rapid deployment when a volcano awakens. Typical field installations require one to three people, while periodic maintenance of field stations requires one or two persons. Monitoring is best done at an observatory where data from infrasonic sensors can be viewed simultaneously with data from seismographs, remote cameras, GPS instruments, and other monitoring equipment. The best locations for most infrasonic monitoring sites are off road, so helicopter access is needed a minimum of every few years to replace heavy batteries. More frequent maintenance visits are often required for high-altitude sites.

Infrasound does have a few drawbacks. Wind noise can completely obscure infrasonic signals from explosions, so site selection is critical in mitigating wind noise. For as-yet unexplained reasons, not all explosions produce infrasound (Johnson et al., 2005). Finally, because infrasound is produced by explosions, it is only useful as an explosion detector. The method cannot therefore assist in forecasting future explosions or other volcanic events.

STUDY DESIGN

The U.S. Geological Survey has the primary responsibility for monitoring volcanoes in the United States, as mandated by the Stafford Act. That mandate, and extensive experience in volcano monitoring, makes the USGS the lead agency for development of study designs. Effective volcano monitoring requires specialized scientific expertise and instrumentation, and appropriately timed data collection and analysis. A volcano's threat level determines the degree of monitoring needed to protect lives, property, and infrastructure from volcanic activity.

Land managers and civil authorities responsible for public safety should work with the USGS to target volcano monitoring, provide necessary access to volcanoes and their surroundings, and facilitate emplacement of monitoring equipment. Monitoring, combined with studies of a volcano's hazards and eruptive history, can reduce risk by warning of impending activity and its potential nature and scope. Land managers should plan appropriate responses to future volcanic activity, so that they then can take timely actions to protect life and property when activity is imminent.

CASE STUDY

Mount Rainier, Washington

Geologic studies at Mount Rainier, Washington, illustrate many volcano monitoring methods. The volcano is built almost entirely of andesite and dacite lava flows, with subsidiary pyroclastic flow deposits, very sparse tephras, and only one known lava dome (Sisson et al., 2001). Its lava flows extend as far as 20 km from the summit and have individual volumes up to 9 km^3. Most of its lava flows are much smaller, extending 5–10 km from the summit, with individual volumes of a few hundredths to a few tenths of a km^3. Though these lava flows were too small to reach now heavily populated areas, they lie within a region of extensive glacial ice. Similar future eruptions of mobile lavas will lead to glacial melting, with consequent downstream flooding and debris flows capable of reaching densely populated areas.

When hot pyroclastic flows erupted from the volcano, these flows commonly traversed glaciers, where they scoured, entrained, and melted ice, transforming the pyroclastic flows directly into mobile lahars. This process is fast, and little warning can be given for debris flows created by suddenly erupted pyroclastic flows, although hazards assessments can indicate likely inundation areas. The hazards potentially associated with this eruption type are illustrated by the 1985 eruption of Nevado del Ruíz (Colombia), in which a relatively small eruption melted ice and snow in the summit area, generating lahars that flowed tens of kilometers down flank valleys, killing more than 22,000 people—history's fourth largest single-eruption death toll. In addition, portions of upper Mount Rainier have been transformed to relatively weak, clay-rich rocks through the action of circulating hot acidic waters (a process known as hydrothermal alteration) (Fiske, et al., 1963; Crowley and Zimbelman, 1997; Finn et al., 2001). In the past, large areas of altered rocks have collapsed, producing voluminous, highly mobile lahars. One such collapse 5600 years ago removed the volcano's summit, core, and northeast slope, creating the Osceola Mudflow that now underlies much of the southern Puget Sound lowlands south of Seattle and east of Tacoma (Crandell and Waldron, 1956; Vallance and Scott, 1997). Another collapse of altered rock 500 years ago, called the Electron Mudflow, suddenly buried the area now occupied by the town of Orting, Washington, (population 4,000) with mud, boulders, and downed timber from several meters to several tens of meters thick (Crandell, 1971; Scott et al., 1995). No conventional building can withstand such a lahar. During the past 10,000 years, Mount Rainier has produced at least 60 lahars of various sizes, including the aforementioned large events with deposits extending into the Puget Sound lowland. Currently, ~150,000 people live in areas that were swept by lahars from Mount Rainier or by associated flooding induced by laharic sediments (Sisson et al., 2001).

Evaluating hazards from Mount Rainier is a priority because of the potential for large loss of life and property from future eruptions and debris flows. Geologic mapping and age measurements show that the modern volcano began to grow ~500,000 years ago atop the deeply eroded remains of an earlier one (Sisson et al., 2001). The volcano's construction occurred during four or perhaps five alternating stages of fast and modest growth. Well-defined fast growth stages extended from 500,000 to 420,000 years ago and from 280,000 to 180,000 years ago. These episodes of fast growth saw the assembly of a high edifice and the eruption of nearly all of the far-traveled, large-volume lava flows. Fast growth stages were also episodes of widespread hydrothermal alteration. During modest growth stages, the high edifice was eroded extensively and may have been reduced in elevation. Volcanic output has been mostly modest since 180,000 years ago, but the eruption rate increased notably 40,000 years ago, constructing much of the present upper Mount Rainier. This increase in eruption rate could mark the beginning of a fifth stage of fast growth, or it could be a fluctuation within the range typical of the modest growth stages.

Mount Rainier's Holocene tephra deposits preserve additional readily quantified evidence of episodic eruptions. Eleven eruptions in the past 10,000 years cast ash, pumice, scoria, and denser rocks high enough into the air to deposit distinctive tephra layers that can be recognized across a wide area (Mullineaux, 1974). Besides these, there are an additional 15–25 thin, fine-grained ash layers restricted to close to the volcano. These fine-grained ashes are products of weakly explosive eruptions, such as small explosions during the release of lava flows, or fine-grained ash billowing up from small pyroclastic flows. The exact number of these thin ashes is hard to determine because they are similar to each other in appearance and because they erode readily, therefore, various layers are missing in one locality or another. The eruptions that created these fine-grained ashes were clustered in time. For example, there are five recognizable subgroups of thin ashes deposited during the period ~2700–2200 yr B.P., followed closely by a sizeable pumice eruption 2200 yr B.P. (J. Vallance and T. Sisson, unpublished results). Each subgroup consists of from one to perhaps as many as five ash layers similar in chemical composition. Each subgroup probably represents the deposits of an eruptive phase consisting of multiple explosive events. Multiple lahars, one known pyroclastic flow, and two groups of lava flows correlate with the fine-grained ash deposits. During this 500-year period, significant eruptive phases took place every 100 years, on average, and each phase consisted of multiple explosive events. This highly active period was preceded by a nearly 2000-year span with no known eruptive deposits. Before this apparent dormant span, the volcano was in another period of frequent eruptions that commenced shortly before the major edifice collapse 5600 years ago that created the Osceola Mudflow.

That eruptive period has not been studied in detail, but included the eruption of pumice and ash concurrent with the Osceola edifice collapse event, as well as at ~4700 and 4500 years ago (Mullineaux, 1974). Another period of frequent eruptions was between roughly 7600–6600 years ago, preceded by a period of dormancy, or only small eruptions of close to 2000-year duration (Sisson et al., 2001).

The eruptive periods 5600–4500 and 2700–2200 years ago were dominated by effusions of lava that almost completely filled the crater left by the Osceola collapse event. Subsequent eruptions took place 1600 and 1100 years ago, although the last was very small. The eruption 1600 years ago is inferred mainly from lahar deposits, and the eruption 1100 years ago was probably of a pyroclastic flow that transformed to a lahar (Hoblitt et al., 1998), although no primary pyroclastic flow deposit is preserved. The major flank collapse 500 years ago that produced the Electron Mudflow has no known associated eruptions.

Based on the historic record, at least three dozen glacial outburst floods have occurred in the twentieth century at Mount Rainier. Glacial outburst floods are unrelated to volcanic activity at Mount Rainier. Glacial outburst floods result from the sudden release of water from glaciers and mainly form during hot weather or heavy rainfall in late summer or early fall, when snowpack has been reduced by summer melting (Walder and Driedger, 1994b). In the absence of snow cover, meltwater or rainfall move over and through the glaciers rapidly. The water bursts or surges from the glacial terminus, entraining loose sediments from channel walls and banks and thereby can transform to a lahar as the surge moves downstream. These outburst floods pose a serious hazard to facilities along stream valleys close to the volcano. Bridges, roads, and visitor facilities have been destroyed or damaged on ~10 occasions since 1926.

The time necessary to perform geologic mapping to understand the past eruptive behavior of a volcano or volcanic system depends on the detail needed to understand the system, and the size and logistical issues of a particular area. In a relatively flat area with many roads traversing it, the mapping of 150 km^2 might be done in a few weeks. Office time to compile the map in a geographic information system (GIS), prepare rocks for chemical analysis, and perform age dating would require another few weeks. These actual work times are spread out over a couple to a few years, because the process of geologic mapping is iterative between field, office, and lab work, and mapping is frequently done on many quadrangles making up the area of interest. The nominal time for geologic mapping can be extended by many times as the complexity of the geology increases, or as access becomes difficult because of fewer roads, steep terrain, or wilderness constraints. Mount Rainier, for example, requires technical mountaineering skills for safe working. In some areas, helicopter use can mitigate access issues, but this is not always possible in all protected areas. Geologic mapping requires that rock samples be collected for chemical analysis and petrographic study. During eruptions, mapping of lava flows and dome extrusion can be done by aerial photography and/or LIDAR imagery with results put in a GIS, but results can take a few weeks. Short active lava flows can be mapped by walking the contact with a GPS unit and coordinates put in a GIS. Longer active lava flows can be mapped with a GPS unit in a helicopter, and both methods have proven very effective for the ongoing eruption in Hawai'i Volcanoes National Park.

REFERENCES CITED

Blong, R.J., 1984, Volcanic hazards: a sourcebook on the effects of eruptions: Sidney, Australia, Academic Press, 424 p.

Braile, L.W., 2009, this volume, Seismic monitoring, *in* Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, doi: 10.1130/2009.monitoring(10).

Brosnan, D.M., 2000, Ecological impacts of the Montserrat volcano: a pictorial account of its effects on land and sea life: Sustainable Ecosystems Institute, Portland, Oregon (available only on the Web at http://www.sei.org/impacts.html; accessed 4 February 2009).

Chouet, B.A., 1996, New methods and future trends in seismological volcano monitoring, *in* Scarpa, R., and Tilling, R.I., eds., Monitoring and Mitigation of Volcanic Hazards: Berlin, Springer-Verlag, p. 23–88.

Chouet, B.A., 2003, Volcano seismology: Pure and Applied Geophysics, v. 160, p. 739–788, doi: 10.1007/PL00012556.

Crandell, D.R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: U.S. Geological Survey Professional Paper 677, 75 p.

Crandell, D.R., and Waldron, H.H., 1956, A recent volcanic mudflow of exceptional dimensions from Mount Rainier, Washington: American Journal of Science, v. 254, p. 349–362.

Crowley, J.K., and Zimbelman, D.R., 1997, Mapping hydrothermally altered rocks on Mount Rainier, Washington, with airborne visible/infrared imaging spectrometer (AVIRIS) data: Geology, v. 25, p. 559–562, doi: 10.1130/0091-7613(1997)025<0559:MHAROM>2.3.CO;2.

Dean, K.G., Dehn, J., Papp, K.R., Smith, S., Izbekov, P., Peterson, R., Kearney, C., and Steffke, A., 2004, Integrated satellite observations of the 2001 eruption of Mt. Cleveland, Alaska: Journal of Volcanology and Geothermal Research, v. 135, p. 51–74, doi: 10.1016/j.jvolgeores.2003.12.013.

Dehn, J., Dean, K.G., Engle, K., and Izbekov, P., 2002, Thermal precursors in satellite images of the 1999 eruption of Shishaldin Volcano: Bulletin of Volcanology, v. 64, p. 525–534, doi: 10.1007/s00445-002-0227-0.

Driedger, C.L., and Scott, K.M., 2002, Mount Rainier—Learning to live with volcanic risk: U.S. Geological Survey Fact Sheet 034-02, 4 p. (available only on the Web at http://www.fs.fed.us/gpnf/mshnvm/education/teachers-corner/library/documents/fs065-97-mt-rainier.pdf#search=%22%22volcano%20hazards%22%20%22Mount%20Rainier%22%22; accessed 4 February 2009).

Ewert, J.W., Guffanti, M., and Murray, T.L., 2005, An assessment of volcanic threat and monitoring capabilities in the United States: Framework for a National Volcano Early Warning System: U.S. Geological Survey Open-File Report 2005-1164, 62 p. (http://pubs.usgs.gov/of/2005/1164/; accessed 6 February 2009).

Finn, C.A., Sisson, T.W., and Deszcz-Pan, M., 2001, Aerogeophysical measurements of collapse-prone hydrothermally altered zones at Mount Rainier volcano: Nature, v. 409, p. 600–603, doi: 10.1038/35054533.

Fiske, R.S., Hopson, C.A., and Waters, A.C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geological Survey Professional Paper 444, 93 p.

Fuentes, W.A., 1975, Effectos de cenizas del volcán Irazu [Costa Rica] en varios insectos: Revista Biología Tropicál, v. 2, p. 165–175. (English abstract available on the Web at http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=pubmed&dopt=Abstract&list_uids=1224020&query_hl=5&itool=pubmed_DocSum. Accessed 4 February 2009.)

Guffanti, M.G., Brantley, S.R., and McClelland, L., eds., 2001, Volcanism in National Parks: Summary of the Workshop Convened by the U.S. Geological Survey and National Park Service, 26–29 September 2000, Redding, California: U.S. Geological Survey Open-File Report 01–435. (Available only on the Web at http://geopubs.wr.usgs.gov/open-file/of01-435/ofr01-435_report.html; accessed 5 February 2009.)

Harlow, D.H., Power, J.A., Laguerta, E.P., Ambubuyog, G., White, R.A., and Hoblitt, R.P., 1996, Precursory seismicity and forecasting of the June 15, 1991, eruption of Mount Pinatubo, *in* Newhall, C.G., and Punongbayan, R.S., eds., Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines, p. 285–305, http://pubs.usgs.gov/pinatubo/harlow/index.html (accessed 4 February 2009).

Harris, A.J.L., Keszthelyi, L., Flynn, L.P., Mouginis-Mark, P.J., Thornber, C., Kauahikaua, J., Sherrod, D., Trusdell, F., Sawyer, M.W., and Flament, P., 1997a, Chronology of the episode 54 eruption at Kilauea Volcano, Hawai‘i, from GOES-9 satellite data: Geophysical Research Letters, v. 24, p. 3281–3284, doi: 10.1029/97GL03165.

Harris, A.J.L., Butterworth, A.L., Carlton, R.W., Downey, I., Miller, P., Navarro, P., and Rothery, D.A., 1997b, Low-cost volcano surveillance from space: case studies from Etna, Krafla, Cerro Negro, Fogo, Lascar and Erebus: Bulletin of Volcanology, v. 59, p. 49–64, doi: 10.1007/s004450050174.

Harris, A.J.L., Murray, J.B., Aries, S.E., Davies, M.A., Flynn, L.P., Wooster, M.J., Wright, R., and Rothery, D.A., 2000, Effusion rate trends at Etna and Krafla and their implications for eruptive mechanisms: Journal of Volcanology and Geothermal Research, v. 102, p. 237–270, doi: 10.1016/S0377-0273(00)00190-6.

Heggie, T.W., and Heggie, T.M., 2004, Viewing lava safely: an epidemiology of hiker injury and illness in Hawai‘i Volcanoes National Park: Wilderness & Environmental Medicine, v. 15, p. 77–81, http://www.wemjournal.org/pdfserv/i1080-6032-015-02-0077.pdf (accessed 4 February 2009).

Helz, R.L., 2005, Monitoring ground deformation from space: U.S. Geological Survey Fact Sheet 2005–3025, 4 p., http://pubs.usgs.gov/fs/2005/3025/2005-3025.pdf (accessed 4 February 2009).

Hoblitt, R.P., Walder, J.S., Driedger, C.L., Scott, K.M., Pringle, P.T., and Vallance, J.W., 1998, Volcano hazards from Mount Rainier, Washington, Revised 1998: U.S. Geological Survey Open-File Report 98-428, 11 p., 2 plates, scale 1:100,000, 1:400,000.

Houghton, B.F., Wilson, C.J.N., and Pyle, D.M., 2000, Pyroclastic fall deposits, *in* Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H., and Stix, J., eds., Encyclopedia of Volcanoes, New York, Academic Press, p. 555–570.

Ishii, H., Ooishi, M., Maruyama, Y., and Koike, T., 2003, Acclimation of shoot and needle morphology and photosynthesis of two Picea species to differences in soil nutrient availability: Tree Physiology, v. 7, p. 453–461.

Iverson, R.M., Schilling, S.S., and Vallance, J. W., 1998, Objective delineation of lahar-inundation hazard zones: Geological Society of America Bulletin, v. 110, p. 972–984, doi: 10.1130/0016-7606(1998)110<0972:ODOLIH>2.3.CO;2.

Johnson, J., Steven, R., Brantley, S.R., Swanson, D.A., Stauffer, P.H., and Hendley, J.W., II, 2000,Viewing Hawai‘i’s lava safely—Common sense is not enough: U.S. Geological Survey Fact Sheet 152-00, version 1.1, 1 p., http://pubs.usgs.gov/fs/2000/fs152-00/fs152-00.pdf (accessed 4 February 2009).

Johnson, J.B., Aster, R.C., Ruiz, M.C., Malone, S.D., McChesney, P.J., Lees, J.M., and Kyle, P.R., 2003, Interpretation and utility of infrasonic records from erupting volcanoes: Journal of Volcanology and Geothermal Research, v. 121, no. 1–2, p. 15–63, doi: 10.1016/S0377-0273(02)00409-2.

Johnson, J.B., Ruiz, M.C., Lees, J.M., and Ramon, P., 2005, Poor scaling between elastic energy release and eruption intensity at Tungurahua Volcano, Ecuador: Geophysical Research Letters, v. 32, p. L15304, doi: 10.1029/2005GL022847.

Kenedi, C.A., Brantley, S.R., Hendley, P.W., II, and Stauffer, P.H., 2000, Volcanic ash fall—a “hard rain” of abrasive particles: U.S. Geological Survey Fact Sheet 027–00, 1 sheet, http://pubs.usgs.gov/fs/fs027-00/fs027-00.pdf (accessed 4 February 2009).

Klimasauskas, E., 2001, Mount St. Helens precursory activity (A day by day chronicle of events and actions leading up to the cataclysmic eruption of Mount St. Helens volcano on 18 May 2000.) (Available only on the Web at http://vulcan.wr.usgs.gov/Volcanoes/MSH/May18/MSHThisWeek/intro.htm; accessed 4 February 2009)

Lahr, J.C., Chouet, B.A., Stephens, C.D., Power, J.A., and Page, R.A., 1994, Earthquake classification, location, and error analysis in a volcanic environment: Implications for the magmatic system of the 1989–1990 eruptions of Redoubt Volcano, Alaska: Journal of Volcanology and Geothermal Research, v. 62, p. 137–152, doi: 10.1016/0377-0273(94)90031-0.

LaHusen, R.G., 1996, Detecting debris flows using ground vibrations: U.S. Geological Survey Fact Sheet 236-96, http://vulcan.wr.usgs.gov/Projects/AFM/Publications/FS236-96/framework.html; accessed 4 February 2009).

McGarry, T.W., 2005, Boldly going where no UAV has gone before: Association for Unmanned Vehicle Systems International, v. 23, no. 1, p. 38–39.

Mullineaux, D.L., 1974, Pumice and other pyroclastic deposits in Mount Rainier National Park, Washington: U.S. Geological Survey Bulletin 1326, 83 p.

Myers, B., and Brantley, S.R., 1995, Volcano hazards fact sheet: Hazardous phenomena at volcanoes: U.S. Geological Survey Open File Report 95-231, http://vulcan.wr.usgs.gov/Hazards/Publications/OFR95-231/OFR95-231.html (accessed 4 February 2009).

Nathenson, M., 2001, Probabilities of volcanic eruptions and application to the recent history of Medicine Lake Volcano, *in* Vecchia, A.V., Compiler: a unified approach to probabilistic risk assessments for earthquakes, floods, landslides, and volcanoes, November 16–17, 1999, Golden, Colorado: U.S. Geological Survey Open-File Report 01-324, p. 71–74.

Neal, C.A., Casadevall, T.J., Miller, T.P., Hendley, J.W., II, and Stauffer, P.H., 1997, Volcanic ash—danger to aircraft in the North Pacific: U.S. Geological Survey Fact Sheet 030-97, 2 p., http://pubs.usgs.gov/fs/fs030-97/fs030-97.pdf (accessed 4 February 2009).

Patterson, M.C.L., Wardell, L., Mulligan, A., Douglas, J., Robinson, J., and Pallister, J.S., 2005, Volcano surveillance by ACR Silver Fox, 1st AIAA, Advancing Contemporary Aerospace Technologies and Their Integration, Crystal City 26–29 September 2005: American Institute of Aeronautics and Astronautics, v. 2005, p. 6954–6960.

Prata, A.J., 1989, Infrared radiative transfer calculations for volcanic ash clouds: Geophysical Research Letters, v. 16, p. 1293–1296, doi: 10.1029/GL016i011p01293.

Rothery, D.A., Francis, P.W., and Wood, C.A., 1988, Volcano monitoring using short wavelength infrared data from satellites: Journal of Geophysical Research, v. 93, p. 7993–8008, doi: 10.1029/JB093iB07p07993.

Schilling, S.P., Ramsey, D.W., Messerich, J.A., and Thompson, R.A., 2006, Rebuilding Mount St. Helens: U.S. Geological Survey Scientific Investigations Map 2928, http://pubs.usgs.gov/sim/2006/2928/ (accessed 4 February 2009).

Schneider, D.J., Dean, K.G., Dehn, J., Miller, T.P., and Kirianov, V.Yu., 2000, Monitoring and analysis of volcanic activity using remote sensing data at the Alaska Volcano Observatory, Case study for Kamchatka, Russia, December 1997, *in* Mouginis-Mark, P.J., Crisp, J.A., and Fink, J.H., eds., Remote Sensing of Active Volcanism: American Geophysical Union Geophysical Monograph 116, p. 65–85.

Scott, K.M., Vallance, J.W., and Pringle, P.T., 1995, Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington: U.S. Geological Survey Professional Paper 1547, 56 p.

Simkin, T., and Siebert, L., 1994, Volcanoes of the World, second edition: Tucson, Arizona, Geoscience Press, published in association with the Smithsonian Institution, Global Volcanism Program, Washington, D.C., 349 pp.

Simkin, T., Tilling, R.I., Vogt, P.R., Kirby, S.H., Kimberley, P., and Stewart, D.B., 2006, This Dynamic Planet—World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics: U.S. Geological Survey Geologic Investigations Series Map I-2800, scale: 1:30,000,0001 two sheets.

Sisson, T.W., Vallance, J.W., and Pringle, P.T., 2001, Progress made in understanding Mount Rainier’s hazards: Eos (Transactions, American Geophysical Union), v. 82, p. 113, 117–120, doi: 10.1029/01EO00057.

Sparks, R.S.J., 2003, Forecasting volcanic eruptions: Earth and Planetary Science Letters, v. 210, p. 1–15, doi: 10.1016/S0012-821X(03)00124-9.

Sutton, J., Elias, T., Hendley, J.W., II, and Stauffer, P.H., 1997, Volcanic air pollution—a hazard in Hawai‘i: U.S. Geological Survey Fact Sheet 169-97, 1 sheet, http://pubs.usgs.gov/fs/fs169-97/ (accessed 4 February 2009).

Takahashi, T.J., Heliker, C., and Diggles, M.F., 2003, Selected images of the Pu‘u ‘O‘o–Kupaianaha [Hawai‘i] Eruption, 1983–1997: U.S. Geological Survey Digital Data Series DDS-80, available on the Web at http://pubs.usgs.gov/dds/dds-80/#introduction. (Accessed February 4, 2009).

U.S. Forest Service Mount St. Helens National Volcanic Monument, [2007–], Climbing Mount St. Helens: U.S. Forest Service, http://www.fs.fed.us/gpnf/recreation/mount-st-helens/ (accessed 4 February 2009).

Vallance, J.W., and Scott, K.M., 1997, The Osceola Mudflow from Mount Rainier: Sedimentology and hazard implications of a huge clay-rich debris flow: Geological Society of America Bulletin, v. 109, p. 143–163, doi: 10.1130/0016-7606(1997)109<0143:TOMFMR>2.3.CO;2.

Walder, J.S., and Driedger, C.L., 1994a, Geomorphic change caused by outburst floods and debris flows at Mount Rainier, Washington, with emphasis on Tahoma Creek valley: U.S. Geological Survey Water Resources Investigations Report 93-4093, 93 p.

Walder, J.S., and Driedger, C.L., 1994b, Rapid geomorphic change caused by glacial outburst floods and debris flows along Tahoma Creek, Mount Rainier, Washington, USA: Arctic and Alpine Research, v. 26, p. 319–327, doi: 10.2307/1551792.

Watson, I.M., Realmuto, V.J., Rose, W.I., Prata, A.J., Bluth, G.J.S., Gua, Y., Badera, C.E., and Yua, T., 2004, Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer: Journal of Volcanology and Geothermal Research, v. 135, p. 75–89, doi: 10.1016/j.jvolgeores.2003.12.017.

Wen, S., and Rose, W.I., 1994, Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5: Journal of Geophysical Research, v. 99, p. 5421–5431, doi: 10.1029/93JD03340.

SUGGESTED FURTHER READING—INTRODUCTION

Camp, V., 2009, How volcanoes work: San Diego State University, Department of Geological Sciences, on line teaching module (http://www.geology.sdsu.edu/how_volcanoes_work/; accessed 4 February 2009). *This site, and the links on it, contain short and easy to understand descriptions and illustrations of major volcanic hazards, volcano processes, how volcanoes evolve, etc. An excellent site to learn more about volcanoes.*

Guffanti, M.G, Brantley, S.R., and McClelland, L., eds., 2000, Volcanism in National Parks: Summary of the Workshop Convened by the U.S. Geological Survey and National Park Service, 26–29 September 2000, Redding, California: U.S. Geological Survey Open-File Report 01-435, http://geopubs.wr.usgs.gov/open-file/of01-435/ofr01-435_report.html; accessed 5 February 2009). *"In recognition of the importance of volcanism to diverse park issues, the Geologic Resources Division of the National Park Service and the Volcano Hazards Program of the USGS convened a workshop in September 2000 to bring together USGS and NPS scientists, managers, and interpreters. The purpose of the gathering was to lay the groundwork for improving scientific input to park management (operations, resource management, interpretation, and planning) and for facilitating volcano research and hazard monitoring in parks. This report summarizes key aspects of the workshop."*

U.S. Geological Survey, 2009, Types of Volcano Hazards: U.S. Geological Survey Volcano Hazards Program, http://volcanoes.usgs.gov/hazards/index.php; accessed 6 February 2009). *Diagrams and short text explanations of the six major volcano hazards (gas, lahars (volcanic mudflows), landslides, lava flows, pyroclastic flows, and tephra). Short case studies of historic eruptive activity including activity at Mount Rainier, Washington, Kilauea and Mauna Loa, Hawai'i, and Long Valley Caldera, California.*

U.S. Geological Survey, 1996, Perilous Beauty, The Hidden Dangers of Mount Rainier: VHS video, 29 min. *Volcanic activity, enormous landslides, and glacial erosion have continuously re-shaped Mount Rainier's magnificent cone. These natural processes have also sent large and dangerous lahars (volcanic mudflows) rushing down all river valleys leading away from the volcano. Understanding the nature of these past events is key to reducing our risk from Mount Rainier's future activity. This 29-minute video uses computer animation, eruption footage, interviews with scientists, and vivid aerial and ground shots of the mountain to show how mudflows from Mount Rainier can affect communities in Western Washington.*

Siebert L., and Simkin T., [2002–], Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, a continually updated version of this publication is available at http://www.volcano.si.edu/world/ (accessed 6 February 2009). *The Web site for this publication is the worldwide volcanological community's virtual archive for information about the world's 1,300–1,500 volcanoes known to have erupted in the past 12,000 years. Includes photographs of volcanoes, types of volcanic deposits, volcanic processes, maps, detailed eruptive histories, and volcanic activity reports—all linked by a searchable database. A downloadable Google Earth Placemark layer makes it possible to zoom in to volcanic features around the world.*

Simkin, T., Tilling, R.I., Vogt, P.R., Kirby, S.H., Kimberly, P., and Stewart, D.B., 2006, This dynamic planet: world map of volcanoes, earthquakes, impact craters, and plate tectonics: U.S. Geological Survey Investigations Series Map I-2800, 1 sheet, http://www.minerals.si.edu/tdpmap/index.htm (accessed 6 February 2009). *"An interactive map designed to show Earth's most prominent features when viewed from a distance, and more detailed features upon closer inspection. Highlights examples of fundamental processes, while providing text, timelines, references, and other resources to enhance understanding of this dynamic planet. The main and polar maps, are interactive, inviting you to make your own regional map, using whichever 'layers' you choose. Data for any volcano, earthquake, or impact symbol can be found via the 'Identify' tool." (Authors)*

Takahashi, T.J, Heliker, C, and, Diggles, M.F., 2003, Selected images of the Pu'u 'O'o–Kupaianaha [Hawai'i] Eruption, 1983–1997: U.S. Geological Survey Digital Data Series DDS-80, http://pubs.usgs.gov/dds/dds-80/#introduction (accessed 4 February 2009). *The spectacular digital photos on this CD and its Web version document the activity of Kilauea volcano during one phase of its eruption and illustrate some hazards that shield volcanoes present. For example, photos 50, 52, 53, and 54 show the Waha'ula Visitor Center in Hawai'i Volcanoes National Park before, during, and after its destruction by advancing lava flows. All photos are in the public domain and may be freely distributed.*

U.S. Geological Survey, 2009, Types of Volcano Hazards: U.S. Geological Survey Volcano Hazards Program, http://volcanoes.usgs.gov/hazards/index.php (accessed 6 February 2009). *Diagrams and short text explanations of the six major volcano hazards (gas, lahars (volcanic mudflows), landslides, lava flows, pyroclastic flows, and tephra). Short case studies of historic eruptive activity including activity at Mount Rainier, Washington, Kilauea and Mauna Loa, Hawai'i, and Long Valley Caldera, California.*

U.S. Geological Survey, 2009, Volcanic ash: What it can do and how to prevent damage: U.S. Geological Survey, http://volcanoes.usgs.gov/ash/ (accessed 4 February 2009). *This site has details on calculating the weight of ash on roofs (ash is about ten times as heavy as snow); how to keep electric transmission lines and communications equipment from failing during ash falls; and harmful effects on water supply and sewerage systems (as little as 1 cm) has caused sewage treatment plants to fail.*

SUGGESTED FURTHER READING—GAS EMISSION AT GROUND LEVEL

General information about the nature of volcanic gases and the hazards they pose is at http://volcanoes.usgs.gov/hazards/gas/index.php.

Farrar, C.D., Sorey, M.L., Evans, W.C., Howle, J.F., Kerr, B.D., Kennedy, B.M., King, C.-Y., and Southon, J.R., 1995, Forest-killing diffuse CO_2 emission at Mammoth Mountain as a sign of magmatic unrest: Nature, v. 376, p. 675–678.

McGee, K.A., Elias, T., Sutton, A.J., Doukas, M.P., Zemek, P.G., and Gerlach, T.M., 2005, Reconnaissance gas measurements on the East Rift Zone of Kilauea volcano, Hawai'i by Fourier transform infrared spectroscopy: U.S. Geological Survey Open File Report 2005-1062, 28 p., http://pubs.usgs.gov/of/2005/1062/.

McGee, K.A. and Gerlach, T.M., 1995, Volcanic gas: U.S. Geological Survey Volcano Hazards Fact Sheet, U.S. Geological Survey Open-File Report No. 95-85, 2 p., http://vulcan.wr.usgs.gov/Glossary/Emissions/OFR95-85/framework.html (accessed 4 February 2009).

McGee, K.A., Elias, T., Sutton, A.J., Doukas, M.P., Zemek, P.G., and Gerlach, T.M., 2005, Reconnaissance gas measurements on the East Rift Zone of Kilauea volcano, Hawai'i by Fourier transform infrared spectroscopy: U.S. Geological Survey Open File Report 2005-1062, 28 p., http://pubs.usgs.gov/of/2005/1062/ (accessed 4 February 2009).

Sorey, M.L., Farrar, C.D., Gerlach, T.M., McGee, K.M, Evans, W.C., Colvard, E.M., Hill, D.P., Bailey, R.A., Rogie, J.D., Hendley, J.W., II, and Stauffer, P.H., 1996, Invisible CO_2 Gas Killing Trees at Mammoth Mountain, California: U.S. Geological Survey Fact Sheet 172-96, Online Version 2.0 (revised June 2000), 1 p., http://pubs.usgs.gov/fs/fs172-96/fs172-96.pdf (accessed 4 February 2009).

Sutton, A.J., McGee, K.A., Casadevall, T.J., and Stokes, J.B., 1992, Fundamental volcanic-gas-study techniques: an integrated approach to monitoring, *in* Ewert, J.W., and Swanson, D.A., eds., Monitoring volcanoes: techniques and strategies used by the staff of the Cascades Volcano Observatory, 1980–1990: U.S. Geological Survey Bulletin 1966, p. 181–188.

SUGGESTED FURTHER READING—GAS PLUME AND ASH CLOUD EMISSION

General information about monitoring gases in volcanic plumes can be found at: http://volcanoes.usgs.gov/About/What/Monitor/Gas/plumes.html (accessed 4 February 2009).

Gerlach, T.M., Delgado, H., McGee, K.A., Doukas, M.P., Venegas, J.J., and Cárdenas, L., 1997, Application of the LI–COR CO2 analyzer to volcanic plumes: A case study, Volcán Popocatéptl, Mexico, June 7 and 10, 1995: Journal of Geophysical Research, v. 102, no. B4, p. 8005–8019.

McGee, K.A., Doukas, M.P., and Gerlach, T.M., 2001, Quiescent hydrogen sulfide and carbon dioxide degassing from Mount Baker, Washington: Geophysical Research Letters, v. 28, n. 23, p. 4479–4483.

Sutton, A.J., McGee, K.A., Casadevall, T.J., and Stokes, J.B., 1992, Fundamental volcanic-gas-study techniques: an integrated approach to monitoring, *in* Ewert, J.W., and Swanson, D.A., eds., Monitoring volcanoes: techniques and strategies used by the staff of the Cascades Volcano Observatory, 1980–90: U.S. Geological Survey Bulletin 1966, p. 181–188.

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