EXTENSION MODULE 4.2

Mitigating and Forecasting Volcanic Hazards

This module describes the hazards of different volcanic eruption phenomena and how geologists provide information to decrease the risks of volcanic eruptions and to forecast impending eruptions.

A. Introduction

How can humans at least partly diminish the negative impacts of natural processes on human life and settlement? Reducing the risk to people and property (mitigation) and estimating when an event might happen (forecasting) are two actions that can help. **Figure EM4.2-1** illustrates the hazardous impacts of the 1991 eruption of Unzen volcano in Japan. Over a period of many months the volcano erupted lava domes and pyroclastic flows, and rainfall eroded the pyroclastic debris to produce damaging lahars (rapid flow of water and loose debris from volcanoes).

Volcanic eruptions are natural processes, but they become hazardous simply because people live near volcanoes. Approximately 270,000 people lost their lives as a result of volcanic eruptions between 1600 and 2000. Disease and starvation following widespread devastation of crops by major eruptions account for approximately 40 percent of those fatalities. Many volcanic regions are densely populated and are commonly the sites of extensive agriculture because they have fertile soil produced by weathering of volcanic ash. Keeping these areas off limits for habitation or evacuating them prematurely or without sufficient evidence of a threat can cause severe economic and human hardship. Volcanologists must, therefore, use the best possible judgment in identifying the threat of a volcanic eruption and providing information to government officials. The goal is to minimize risk to people and property without jeopardizing them or the local economy. Plans to mitigate the consequences, however, can be complicated, as some eruptions may affect localities many tens to more than 100 kilometers from the volcano.

B. Mitigating Hazards from Volcanic Eruptions

A key aspect of mitigating volcanic hazards is to recognize what areas are at risk to different types of destructive volcanic phenomena. Risk areas can be mapped in advance of destructive eruptions, and decision makers can use the maps to (1) design land-use plans that limit development in areas of greatest risk, or (2) plan evacuations when an eruption seems imminent or is beginning. In many cases, these risk maps make use of the known distribution of different types of deposits produced by past eruptions of the volcano, with the assumption that future activity will most likely be within the same range. Mitigating the risk of eruptions requires a full understanding of the processes.

▲ **Figure EM4.2-1 Eruption of Mount Unzen.** The 1991 eruption of Unzen volcano in Japan was very destructive. Lava-flow domes formed at the steaming summit of the volcano and collapsed to form pyroclastic flows that destroyed residential areas at the base of the mountain. Heavy rain eroded the loose pyroclastic debris, forming lahars that caused further devastation along valleys to the coastline. (*Source*: Michael S. Yamashita)

Lava Flows

How Are Lava Flows Hazardous?

Lava flows bury arable lands and burn buildings. Thick lava flows effectively “bulldoze” buildings to the ground and crush them.

About 90 percent of historically erupted lava flows are of basalt or transitional basalt-to-andesite composition. Eruption temperatures are on the order of 900–1150°C, incredibly hot compared to the ignition temperatures of cloth, paper, and wood, which are all below 250°C. Most lava flows advance at rates between a few meters per hour to 4 kilometers per hour, although there have been rare occurrences of lava flows moving faster than 30 kilometers per hour (comparable to an Olympic sprinter).

What Is the Potential Risk of Loss of Life?

Lava flows pose little risk to human life because most flows move slowly enough to evacuate people out of danger. Fewer than 1000 fatalities, or less than one-half of 1 percent of all volcano-related deaths since 1600, were directly caused by lava flows.

Most loss of life results from unusually rapidly moving lava flows that cut off escape routes and isolate people in places where they could not escape. As many as 700 people perished when rapidly moving lava flows surrounded and then buried villages on the flank of Vesuvius, in Italy, in 1631. A more recent disaster occurred in 1977 on the flank of Nyiragongo, Zaire. Lava initially descended the slope of the shield volcano at rates in excess of 100 km/hr. Although the flows slowed to 30 km/hr, they still advanced through nearby villages before residents could be evacuated and faster than people could flee on foot. The death toll was nearly 100 people.

What Is the Potential Risk of Loss of Property?

Lava flows completely destroy all buildings and most engineered structures (bridges, for example) in their path and bury productive farmland and forests under many meters of uneven rock and rubble. This buried land typically remains unusable for agriculture for centuries or millennia. Although some prehistoric lava flows covered more than 100,000 square kilometers (slightly larger than the area of Indiana), most historic lava flows have covered less than 100 square kilometers and have traveled no more than 25 kilometers. Therefore, risk of loss to lava flows is greatest in areas close to volcanoes. Lava flows, like water, move toward the low elevations in the landscape. If the volcanic area has deep valleys, then the lava flows in the valleys and leaves the intervening ridges unaffected.

How Are Lava-Flow Hazards Mitigated?

Very little can be done to prevent losses from lava flows except to get people out of the way. In areas with deep river valleys, efforts are made to locate facilities away from valley bottoms, despite the greater ease of building structures and raising crops in the valleys. The most active volcanoes erupt so much lava that there are few if any deep valleys, so the lava flows in sheets that bury nearly all of the nearby landscape.

If a study of the volcano's older deposits reveals a limited range in composition, then the risk of lava-flow destruction can be roughly assessed before an eruption. The risk of widespread damage by lava flows is greatest near volcanoes that most commonly erupt basaltic magma. Viscosity typically increases with increasing silica content, so the area covered by lava flows usually diminishes as the silica content increases.

There are many historical accounts of attempts to stop or divert moving lava flows. The construction of walls in front of lava flows is rarely effective because a moving lava flow is very strong. At best, construction of walls buys time for evacuation and removal of building contents, but eventually the walls are almost always broken down or overtopped. In some cases, digging trenches diverts lava flows away from habitations. If the lava flow is very voluminous, then trenches only have a temporary effect and may cause further problems downslope if careful thought is not given beforehand of where the diverted lava might flow. Diversion of lava flows on Mount Etna on the island of Sicily in Italy destroyed one village while another was saved several times throughout history, so a law was adopted in the seventeenth century that forbade such efforts.

Spraying water on the lava is one technique that has shown some success at slowing, or even stopping, lava flows. Water quickly cools the lava below its solidification temperature. The citizens of Heimaey, an island off the south coast of Iceland, in 1973, enacted the best-known case of such an effort, shown in **Figure EM4.2-2**. Basalt lava flows erupted on land but flowed into the ocean and threatened to close off the entrance to the harbor that was home to Iceland's largest fishing fleet and fish-processing facilities. Although the lower part of the lava chilled as it entered the sea, the flow was much thicker than the water was deep and advanced relentlessly like a bulldozer tread. Fireboats were dispatched to the front of lava flow and hoses sprayed the land near where lava flowed into the town. As much as 32,400 tons of seawater were pumped each hour onto the lava surface for four months. This effort is credited with saving the harbor and much of the town.

▲ **Figure EM4.2-2** **Stopping a lava flow by hosing it with water.** Hoses spray water on lava flows from Helgafell volcano, Heimaey, Iceland, to halt their advance into the town of Vestmannaeyjar and its harbor during an eruption in 1973. (*Source*: Solarfilma)

Pyroclastic Fall

How Are Pyroclastic Falls Hazardous?

The most damaging effects of falling pyroclastic fragments result from the impact of large projectiles and the fires that ravage buildings hit by super-hot pyroclasts. These dramatic circumstances only occur within a few kilometers of the erupting volcano, because at greater distances the falling fragments are smaller, cooler, and less likely to cause damage.

At greater distances, significant damage occurs by the accumulated thickness of ash rather than by the size or high temperature of the fragments. **Figure EM4.2-3** illustrates the hazard and nuisance of falling pyroclasts. Ash accumulating on roofs can cause building collapse and ash accumulating on leaves defoliates plants.

Ash plumes drifting downwind at high altitudes are a serious hazard for jet aircraft. As a plane flies at high speed through airborne ash, the fine particles abrade windows to opaque and damage mechanical parts controlling steering. Even more of a serious problem occurs when unfiltered jet engines ingest ash, which melts at the high operating temperature of the engine. The newly formed "lava" coats the engine turbines, which causes high operating stress and eventual engine failure. The risk of flying through ash clouds was dramatically illustrated in June 1982, when a British Airways Boeing 747 encountered a drifting ash cloud from Galunggung volcano, in Indonesia, while 150 kilometers downwind of the volcano at an altitude of 11,300 meters. The cockpit windshield quickly abraded so that the crew could not see out of the airplane; simultaneously the paint was removed from wing surfaces. More critically, all four engines stalled and the plane fell 7500 meters in 16 minutes until three engines restarted and the aircraft limped to an emergency landing.

What Is the Potential Risk of Loss of Life?

Falling pyroclastic fragments caused perhaps as many as 11,000 deaths since 1600, or about 5 percent of all volcano-related fatalities. Many of these deaths resulted from the impact of large bombs that caused severe head trauma or completely crushed people who remained too close to erupting volcanoes. In some cases, volcanologists making measurements close to craters have fallen victim to falling projectiles, as happened when nine scientists (and some accompanying tourists) perished at Galeras volcano, Colombia, in 1993. Many deaths related to pyroclastic fall occur at greater distances from volcanoes where roofs collapse under the weight of accumulating lapilli and ash.

What Is the Potential Risk of Loss of Property?

Property losses due to pyroclastic fall include building collapse and destruction of crops. Flat roofs are most susceptible to collapse because the ash does not slide off and steadily accumulates. Roofs in snowy areas are commonly constructed to withstand load pressures on the order of 100 kilograms per cubic meter (kg/m^3). By contrast, consider that 20 centimenters of ash with a bulk density of $1.0\ g/cm^3$ comprise a load of $200\ kg/m^3$. A thickness of 20 centimeters of ash can accumulate at a distance of 10 kilometers during very minor eruptions and as far away as 100 kilometers during more explosive ones. Therefore, the risk to buildings can be widespread. The weight of ash increases if it is wet from rainfall. Building collapse during the 1991 eruption of Pinatubo, which caused more than 300 deaths, was caused by the simultaneous occurrence of typhoon rains and a powerful eruption that dispersed a huge volume of ash to great distances.

▲ **Figure EM4.2-3** **Rain-soaked volcanic ash.** Children run to school along a street covered in rain-soaked volcanic ash falling from nearby Sakurajima volcano, Japan, in February 1992. They wear hard hats for protection from falling volcanic bombs. (*Source*: Roger Ressmeyer)

How Are Pyroclastic-Fall Hazards Mitigated?

The most important fact to consider when assessing the hazards of pyroclastic falls is that the fragments are bigger and hotter, and the deposits are thicker, closer to the volcano. Therefore, the risk of injury or damage is greatest in close proximity to the volcano. Days or weeks of minor premonitory activity precede most very explosive eruptions, which should permit sufficient time to evacuate people to a safe distance if the appropriate precautions are taken. Construction of sloping roofs with strong support beams decreases the risk of building collapse, and, economics permitting, buildings closer to the volcano can be built or rebuilt to better withstand the hazard. Work during an actual eruption is important too, and removal of ash on rooftops before it accumulates to the point of building collapse should be done when possible.

The risk of damage from pyroclastic fall can be assessed in advance not only by considering proximity to the volcano and the possible thickness of deposits resulting from eruptions of different scales but also by considering prevailing wind directions. Although wind may blow from any direction, most regions experience a prevailing direction at most times of the year. The thickest deposits are forecasted downwind from the volcano. If possible, essential emergency services and even airports, through which evacuation of people and receipt of emergency supplies can occur, should be located upwind of active volcanoes.

Routing planes to avoid far-flung ash clouds diminishes risks to flying aircraft. This is not as easily accomplished as you might think. If eruptions occur at night or when clouds hang low around the volcano, ground observers may not even know that an eruption occurred. This problem has become acute in the northwest Pacific, where dozens of explosive volcanoes dot the Aleutian Islands of Alaska and the Kamchatka Peninsula of far eastern Siberia. Although sparsely populated, this region is along busy transpolar aircraft routes between Europe and Asia. Several potential catastrophes have been barely averted as jumbo jets have encountered ash clouds. Increased surveillance of volcanoes in this region and close scrutiny of satellite and radar imagery commonly reveal ash clouds not visible from the ground, and pilots can be warned to adjust their routes. If aircraft encounter an ash cloud, then pilots decrease engine thrust, which decreases the operating temperature of the engine, and turn completely around and fly in the opposite direction.

Pyroclastic Flows

How Are Pyroclastic Flows Hazardous?

Pyroclastic flows are hazardous because they move at velocities of 10 to >100 m/s and with temperatures of 300°C to more than 1000°C. The main mass of pyroclastic flows follows the low paths through the topography, but they are accompanied by roiling clouds of ash that are nearly as hot and equally fast moving. These ash clouds sweep up over ridges and cover vastly larger area than the flows themselves. This cloud dominates the view in **Figure EM4.2-4** and conceals the pyroclastic flow moving along the ground surface. Pyroclastic flows typically devastate everything in their path—stripping vegetation from the landscape, leveling or burying buildings, and burning all combustible objects.

Although prehistoric pyroclastic-flow deposits reveal devastation over areas as great as 50,000 square kilometers, historic flows have rarely extended more than 25 kilometers from the volcano and typically affect less than 250 square kilometers. Nonetheless, the great extent of prehistoric deposits reminds volcanologists that horrendous catastrophes are likely in the future. Pyroclastic flows are the greatest hazard of any volcanic eruption because they move much more quickly than lava flows and their devastation is less influenced by topography.

What Is the Potential Risk of Loss of Life?

More than 50,000 people died between 1600 and 2000 as a consequence of pyroclastic flows. More than half of that loss occurred during the 1902 eruption of Montagne Pelée, which destroyed the city of St. Pierre, Martinique, French West Indies. Pyroclastic flows are unforgiving destroyers leaving few survivors. To remain close to an explosively erupting felsic volcano means almost certain death.

▲ **Figure EM4.2-4** **Pyroclastic flow rushes toward destruction.** Billowing clouds of ash rise above a fast-moving pyroclastic flow descending the slopes of the Soufriere Hills volcano toward villages on the West Indies Island of Montserrat in August 1997. (*Source*: Kevin West)

The ash clouds accompanying pyroclastic flows are just as deadly as the valley-hugging flows themselves. St. Pierre may have succumbed to such a cloud, although the nature of the catastrophe remains controversial in light of the near absence of eyewitness accounts. In June 1991, the ash cloud associated with a pyroclastic flow erupted from Unzen, Japan, killed 40 journalists and three experienced volcanologists who mistakenly thought they were at a safe distance above the valley floor where smaller pyroclastic flows had traveled in previous days. This disaster left a deposit of ash merely a few centimeters thick but killed everyone present, leveled nearby homes and trees, and tossed automobiles about like toys.

Although some victims of pyroclastic flows are horribly burned or crushed, autopsies indicate asphyxiation as the most common cause of death. Lungs and sinus passages typically pack full of ash.

What Is the Potential Risk of Loss of Property?

Property loss in the path of pyroclastic flows is always complete. If buildings and other structures are not leveled to the ground completely, they are buried in hot deposits that may be many tens of meters deep. Agricultural lands and forests are decimated, although regrowth may be possible within a decade or less, depending on how quickly the deposits cool.

How Are Pyroclastic-Flow Hazards Mitigated?

Pyroclastic-flow deposits range in composition from basalt to rhyolite but are much more common at volcanoes that commonly erupt dacitic and more felsic magma. Geologists can assess the potential pyroclastic-flow-producing eruptions in the future, then, by examining the composition of older eruption products.

Days or weeks of premonitory earthquakes and minor eruptions typically precede catastrophic explosive eruptions with pyroclastic flows. This timeframe should allow enough time to evacuate people to a safe distance by taking the appropriate precautions. The 1902 catastrophe at St. Pierre was a true human tragedy—it resulted in part because of a lack of understanding of pyroclastic-flow hazards at that time but mostly because authorities prohibited evacuation of the city so as not to disrupt an important upcoming political election. By contrast, when pyroclastic flows from Soufriere Hills (Figure EM4.2-4) destroyed the city of Plymouth in 1998, authorities heeded volcanologists' warnings that the city was at risk and there was little loss of life.

Pyroclastic flows move extremely rapidly and the associated ash clouds rise to heights of many hundreds of meters, so there is no practical way of blocking or diverting the flows. The best way to avoid losses to pyroclastic flows is to avoid development in areas where pyroclastic-flow deposits are left from past eruptions and to evacuate areas that are likely at risk once eruptions appear imminent.

Mudflows and Floods (Lahars)

How Are Lahars Hazardous?

Lahar is an Indonesian word that translates most directly as "lava flow." Agrarian Indonesians have used the word for centuries to refer to any phenomenon occurring on a volcano from which you would run—lava flows, pyroclastic flows, mudflows, and floods. Volcanologists adopted the term to refer to any mixture of water and debris that descends the slopes of a volcano. Lahars are a grave volcanic hazard and nearly as destructive as pyroclastic flows.

Lahars form in many ways, but most result either from snowmelt produced by volcanic eruptions or from rainfall on thick deposits of recently erupted, loose, easily eroded pyroclastic material. Snowmelt-generated lahars are chronic problems on high, midlatitude volcanoes with perennial snow; these include volcanoes in Alaska, the Cascade Range, and much of the South American Andes Mountains. Rainfall-generated lahars are most common on volcanoes in tropical countries, where rainfall can be very intense; these include volcanoes in Indonesia, the Philippines, Central America, and the Caribbean.

Lahars produce destruction similar to common river floods but can be more devastating because the density of floodwater, carrying large volumes of pyroclastic fragments and other sediment, exerts a great deal of force on buildings and other structures, shoving them from foundations or crushing them. In the extreme, these floods contain more sediment than water, and the result is debris flows that extensively damage structures and bury communities and agricultural fields with gooey deposits many meters thick. Entire cities disappeared beneath lahar deposits in the valleys surrounding Pinatubo, Philippines, during the rainy seasons following its 1991 eruption, as illustrated in **Figure EM4.2-5**.

▲ **Figure EM4.2-5** **City destroyed by lahar.**
This view of a village street in the Philippines shows the buildings buried almost to the top of the first story by lahar-deposited ash and pumice eroded from Pinatubo volcano. (*Source*: Thomas Pierson [USGS])

Lahar hazards may exist for a decade or longer after eruptions, especially in regions receiving heavy rainfall. Explosive eruptions typically destroy or bury most vegetation on steep hillslopes near the volcano, leaving the land more susceptible to erosion and runoff during heavy rain. Depending on how long it takes for vegetation to become reestablished to reduce erosion of sediment and runoff of water, these hazards can persist for years. Lahars deposit thick accumulations of sediment, sometimes completely filling river channels and causing them to relocate. River channels filled with sediment can also dam tributaries to form lakes that inundate communities and farmland.

What Is the Potential Risk of Loss of Life?

Of volcanic hazards, lahars are second to pyroclastic flows as direct killers, having claimed approximately 40,000 lives since 1600. A very minor eruption of Nevada del Ruiz, Colombia, in 1985 accounts for more than 25,000 of those fatalities. Pyroclastic flows melted snow at the summit of the 5389-meters-high volcano, unleashing a huge flood that transformed into a debris flow as it eroded debris along the river channel. Two and a half hours later, the lahar struck the sleeping city of Armero, 70 kilometers from the volcano summit, as a 40-meters-high wave of water and debris. The resulting devastation is shown in Figure 4.27 of your text.

Lahars kill by drowning people, burying them alive in sediment or crushing them under collapsing structures. Lahars move at velocities between 10 and 150 km/hr in river channels but slow down considerably where they spread out onto floodplains, so even though there can be serious property losses, people can survive when lahars inundate inhabited areas if they receive warning to evacuate.

What Is the Potential Risk of Loss of Property?
Lahars are capable of considerable destruction to buildings and other structures because they exert strong forces against objects. The high velocity at which lahars move and their high density (compared to clear water) due to abundant sediment in the flow are responsible for their great force. Single lahar events deposit as much as 10 meters of sediment over a period of several hours, effectively burying buildings not destroyed by the force of the flow. Some lahars are also very erosive, causing considerable widening of river channels and collapse of buildings into the flow as riverbanks erode. Once lahars spread out beyond stream banks, they not only inundate communities but also bury farmland. The resulting deposits commonly include large boulders, and it can be difficult to make the land suitable for cultivation.

How Are Lahar Hazards Mitigated?
Human habitations along rivers draining the slopes of volcanoes face the most risk from the hazards of lahars, so we can predict that these areas are most likely to be affected by lahars. Historic eruptions produced lahars that traveled more than 100 kilometers from the source volcano. While other volcanic hazards are more dangerous closer to the volcano, this phenomenon is the most destructive volcanic process at great distances from a volcano. In most cases, lahars are spotted close to a volcano in time to alert downstream communities, and hasty evacuations can diminish loss of life even if they cannot save property. Riverside communities close to volcanoes are best evacuated at the onset of eruptions and left vacant until long after the threat has passed. Development on river floodplains downstream from volcanoes should take into consideration the risk of lahar inundation. Building in high-risk areas should be avoided if possible, and road systems should be designed to permit rapid, efficient evacuation, if necessary.

Traditional flood-control structures, such as dikes and levees, can be effective in protecting lives and property in instances where lahar volume is relatively small. When lahars are deliberately confined to some extent within river channels, rather than permitted to spread out on floodplains, they do tend to travel farther downstream where adequate precautions may not have been taken. Lahars may deposit enough sediment to fill channels and overtop dikes and levees. In Indonesia, Japan, and the Philippines, dams are constructed across streams draining volcanoes, but streams are allowed to flow underneath, instead of forming a reservoir, except when lahars arrive and are impounded behind the dam. Lahars fill in behind and may overtop the dam, but this construction still diminishes lahar hazards downstream. In between eruptions, the lahar-deposited sediment is dredged out so that the dam is once again effective. A very large sediment-retention dam was built on the largest river draining the Mount St. Helens, Washington, area in the late 1980s. This structure was constructed too late to provide protection from the destruction by lahars that traveled more than 100 kilometers in May 1980. It does, however, protect communities and deep shipping lanes from the high volumes of sediment that still erode from the area devastated near the volcano in 1980.

C. Forecasting Volcanic Eruptions

Although you may think of the words "forecast" and "prediction" as synonyms, scientists regard a forecast as being less reliable than a prediction. Natural phenomena result from a large number of variables, so that precise predictions are challenging to make and rarely accomplished. Keep this in mind the next time you are critical of weather conditions that were not forecasted on your favorite television station; this was only a forecast, not a prediction.

Nonetheless, can volcanologists offer forecasts of volcanic eruptions and their particular hazards in much the same way meteorologists forecast weather and its potential dangers? The answer is yes—and no. Some volcanoes erupt frequently and exhibit a narrow range of phenomena that makes eruption forecasts nearly as dependable as weather forecasts. Other volcanoes are far from predictable.

Volcanic eruptions are forecast by detecting events that commonly precede volcanic activity. The key to forecasting threats from volcanic eruptions is careful monitoring of active and potentially active volcanoes. Special observatories in some regions and on some volcanoes house geologists who specifically monitor geologic attributes that permit warnings of impending eruptions. In other cases, instruments are brought in and quickly set up to monitor a volcano once it stirs to life. Some monitoring techniques require frequent visits to specific sites or instrument locations in order to have ongoing measurements. In the last decade, however, most monitoring techniques have been instrumented in such a way that measurements are made automatically and the results relayed by radio- or satellite-telemetry to an observatory located at a safe distance from a volcano. This permits continual monitoring of the volcano when weather or dangerous volcanic activity might preclude human visits.

Earthquakes

How Are Earthquakes Related to Volcanic Activity?
Cracks form in rock as magma forces its way upward toward Earth's surface. The formation of these cracks causes earthquakes. Most earthquakes produced by rising magma are very small and unfelt by humans, but on occasion larger ones are noticed, although they seldom cause damage. While their causes have become known only in the last 100 or so years, pre-eruption earthquakes have been noted for many centuries.

How Are Earthquakes Measured?

Instruments called **seismometers** record earthquakes, as shown in **Figure EM4.2-6**. A part of the instrument is solidly anchored in the ground. Even the slightest disturbance produces an electronic signal that is amplified and recorded both digitally and on paper (a seismogram) as a series of up-and-down movements that represent waves of energy produced by the earthquake. Various measurements of the earthquake waves recorded by many seismographs can be used to determine the size of the earthquake and where it occurred.

How Are Earthquakes Used to Forecast Eruptions?

Seismometers record earthquakes that are too small humans to feel but that herald the movement of magma toward the surface. Many active or recently active volcanoes experience small earthquakes. When a large volume of magma starts moving toward the surface the amount of activity increases dramatically, sometimes to as many as 500 measured earthquakes each day. Seismologists inform local authorities when they detect a large increase in the number of earthquakes below a volcano. If the measurements indicate that the earthquakes are being produced at depths of 10 kilometers or more, then the threat may not be seen as very great. Intrusion at that depth produces earthquakes but may not lead to magma reaching the surface. An eruption forecast may be issued if the earthquakes take place at shallow depths or occur at progressively shallower levels over time. The preciseness of a forecast depends on measurements of other phenomena as well whether there is a history for the volcano in displaying this type of earthquake activity in the past. For large volcanoes with many craters, the location of earthquakes can also indicate where on the volcano the eruption is likely to take place. Earthquakes usually precede eruptions by several days to several weeks, so they can provide reliable early warning for emergency-services preparations and development of evacuation plans.

Ground Deformation

How Is Ground Deformation Related to Volcanic Activity?

When magma intrudes close to the surface below a volcano, the ground bows upward. If the magma withdraws to the deeper magma chamber, the ground sinks. Measurement of ground deformation can, therefore, track shallow movement of magma. Usually the deformation is very localized, analogous to pushing your fist up through a sheet of clay or dough. Therefore, not only is there local uplift as the magma rises, but the ground surface tilts away in all directions from the uplift.

How Is Ground Deformation Measured?

Sometimes volcano ground deformation is so great it can be observed. When Usu, Japan, erupted in 1944, the ground locally rose upward by 50 meters as magma intruded and then finally erupted to the surface as a lava dome. Most ground deformation associated with shallow intrusion of magma is, however, much more subtle and requires careful measurement.

▲ **Figure EM4.2-6** **Seismometer recording.**
Squiggly lines on paper sheets on these rotating seismometer drums record earthquakes. (*Source*: Russell D. Curtis)

Geologists use a variety of measurements to determine ground deformation. In some cases, sophisticated levels, similar in concept to a carpenter's level, are placed below the ground and detect the tilting associated with uplift and subsidence caused by magma movement. In other cases, the elevations and distances between selected points are surveyed with great precision and marked with permanent monuments, such as shown in **Figure EM4.2-7**. Deformation associated with magma movement can be precisely detected through repeated surveying that records changes in elevation and distance between points. These surveys can be conducted with laser instruments or by use of global positioning system receivers, which use signals from satellites to determine elevation and position with high precision.

▲ **Figure EM4.2-7** **Surveying for ground deformation.**
Volcanologists survey the slopes of steaming White Island volcano, off the northern coast of New Zealand. (*Source*: Kim Westerskov)

How Is Ground Deformation Used to Forecast Eruptions?

Precise measurements of the amount of uplift, the amount of tilting of the ground surface, and the extent of the uplifted area are used to calculate depth and estimate volume of moving magma. Rapid changes in ground deformation rates, usually accompanied by increased earthquake activity, provide a good basis for issuing an eruption forecast. On large volcanoes with many craters, the location of most intense ground deformation can also allow for a forecast of where the eruption will take place.

Gas Release

How Is Gas Release Related to Volcanic Activity?

Hot springs and gas-emitting steam vents are present on or near many active volcanoes. Most of the gas emitted is water vapor resulting from heating of ground water in proximity to hot rocks below the volcano. Carbon dioxide, chlorine, hydrogen sulfide, and sulfur dioxide are other less abundant volcanic gases. These gases commonly release from magma intrusions that cool and crystallize below the volcano. When new, gas-rich magma rises below the volcano, the abundance of gaseous compounds also changes, along with, commonly, the ratios of the compounds emitted at hot springs and other thermal features on the surface.

How Is Gas Release Measured?

To obtain the most accurate and complete measurements of volcanic gases, a volcanologist must visit the thermal features, collect hot-spring water or steam-vent gas, and return it to the laboratory for a time-consuming analysis. **Figure EM4.2-8**a shows a volcanologist taking gas samples for such an analysis.

Complete picture of erupted gases or not, it may not be safe to visit thermal features in the crater once an eruption has started. Therefore, volcanologists have developed instruments that allow them to measure remotely some gases, as shown in Figure EM4.2-8b. One such instrument can be used from a distance of several kilometers, or even from within an aircraft on sunny days with few clouds. This instrument measures the absorption of ultraviolet radiation from the sun by sulfur dioxide gas, one of the most abundant gases in magma, and it is able to do so nearly continuously and from a safe distance. New methods that use data collected from orbiting satellites also estimate the amount and type of gases emitted from volcanoes.

How Is Gas Release Used to Forecast Eruptions?

The simple presence of magmatic gases does not necessarily reveal the threat of a volcanic eruption, because the gases can rise from a solidifying intrusion related to volcanic activity that took place tens of thousands of years ago. The key is to detect changes in the overall abundance of gas and the ratio of gases. Increases in sulfurous compounds are particularly sensitive indicators of new, gas-rich magma rising into a volcano's plumbing system. Not only does the measurement of gas content permit warnings of the reawakening of a volcano, it can help track changes in the intensity of activity during a prolonged eruption. Some volcanoes experience periods of heightened activity that persist for several years. On most days, for example, a volcano may be quiet. A day or two of violent explosions that carry ash high into the sky then breaks the peace. Changes in gas content, however, commonly precede such outbursts and can be measured remotely without risking a close approach to the volcano. Information about these changes can be used to alert people to expect an eruption and to stay away from the volcano.

▲ **Figure EM4.2-8** **Measuring volcanic gases.** (a) A volcanologist samples gas emitted from a steam vent on a volcano in Japan. The rocks are encrusted with yellow sulfur that condenses from the caustic gases. (b) Volcanologists point instruments at a plume of ash and gas erupted from Popocatapetl, Mexico. The instruments measure the amount of gas in the plume by measuring the intensity of ultraviolet radiation passing through the plume. This method works because some gaseous compounds, such as sulfur dioxide, absorb ultraviolet radiation from the sun. (*Source*: Fraser Goff)

Putting It Together

- Pyroclastic flows and lahars pose the greatest volcanic hazards because they move quickly and devastate areas far from volcanoes. Lava flows are destructive but cause little loss of life because they move slowly. Pyroclastic falls are primarily hazardous close to volcanic craters, where falling pyroclastic fragments are large enough and hot enough to cause damage and fatalities. Far-traveled ash clouds can, however, immobilize aircraft, and so as a hazard pyroclastic falls have the most impact the greatest distance from a volcano.
- Volcanic hazards can be mitigated primarily by human avoidance. Community development should be discouraged close to active volcanoes and in valleys where lava flows, pyroclastic flows, and lahars typically travel.
- Volcanic eruptions are forecast by detecting premonitory events that commonly precede volcanic activity. These include earthquakes, ground deformation, and changes in volcanic-gas emissions from hot springs and gas vents; all of these events result from magma moving upward in the volcano plumbing system.