U.S. Department of the Interior/Geological Survey

Monitoring Active Volcanoes

Lava fountains, approximately 100 meters high, play at the vent during the September 1977 eruption of Kilauea Volcano. New lava flows and downed trees in foreground *(photo by Boone Morrison).*

Cover photograph: Scientist measures 350-meter-high fountain during March 1983 eruption at Kilauea Volcano, Hawaii.

Monitoring Active Volcanoes

by Robert I. Tilling

Protected against radiant heat by foil-lined clothing and headgear, scientist collects sample from front of advancing lava flow.

One of the most spectacular, awesomely beautiful, and at times destructive displays of natural energy is an erupting volcano, belching fume and ash thousands of meters into the atmosphere and pouring out red-hot molten lava in fountains and streams.

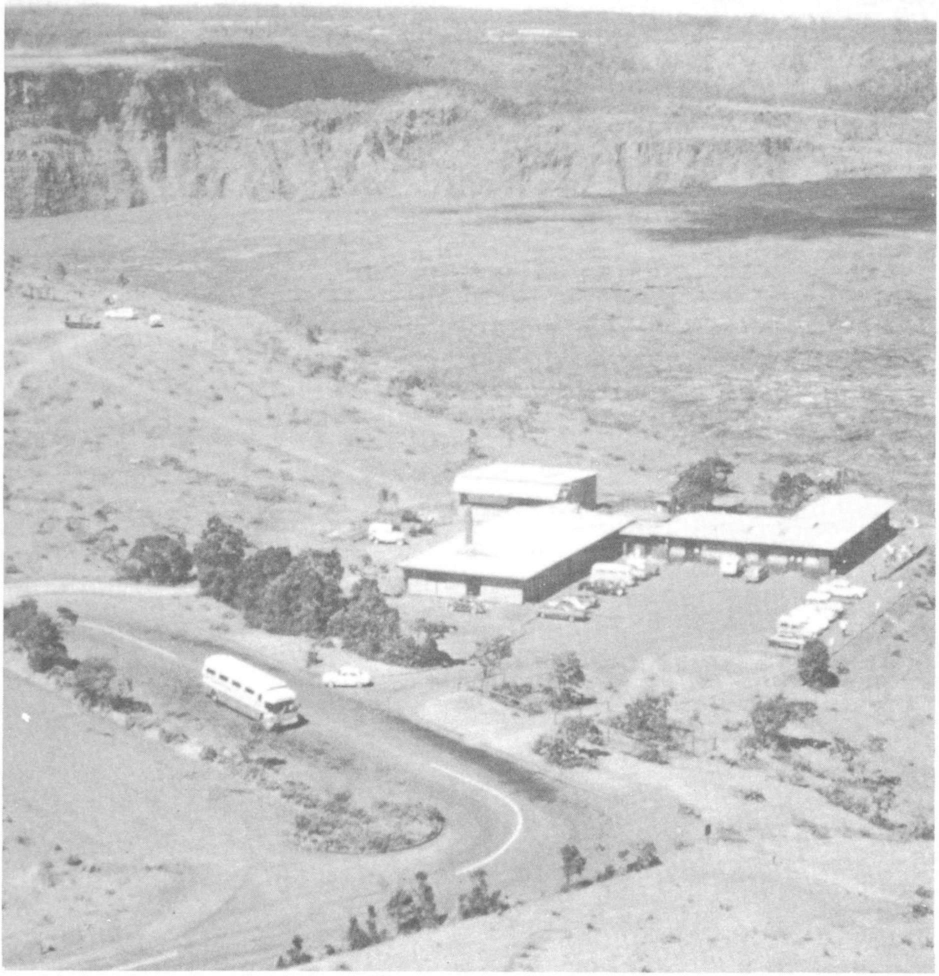
Countless eruptions in the geologic past have produced volcanic rocks that form much of the Earth's present surface. The gradual disintegration and weathering of these rocks have yielded some of the richest farmlands in the world, and these fertile soils play a significant role in sustaining our large and growing population. Were it not for volcanic activity, the Hawaiian Islands—with their sugar cane and pineapple fields and magnificent landscapes and seascapes—would not exist to support their residents and to charm their visitors. Yet, the actual eruptive processes are catastrophic and can claim life and property.

Eruptions of the volcanoes that dot the margins of the moving rigid plates of the Earth's crust characteristically are violently explosive. For example, in 1902 a single explosive eruption of Mount Pelée, Island of Martinique in the Lesser Antilles, virtually destroyed the entire city of St. Pierre, killing some 30,000 persons. On the other hand, eruptions of the Hawaiian basaltic shield volcanoes generally are nonexplosive and more benign, posing a threat to property, but rarely to life. For example, lava flows of the 1960 eruption of Kilauea Volcano burned and buried the small village of Kapoho on the eastern tip of the island of Hawaii. Not a single person was injured or killed, however, because warning signals of impending eruptive activity were detected in time to permit safe evacuation of Kapoho residents.

About 500 active volcanoes are known on the Earth, not counting those that lie beneath the sea. Scientists have estimated that at least 200,000 persons have lost their lives as a result of volcanic eruptions during the last 500 years. Little wonder that people living in the shadow of active or dormant volcanoes have feared eruptive outbreaks in times past and present.

Centuries ago, the Romans attributed volcanic and related phenomena (including earthquakes) mainly to the movement of wind imprisoned inside the Earth rushing violently to the surface. The Polynesians believed volcanic activity to be caused by the beautiful but wrathful Pele, Goddess of Volcanoes, whenever she was angered by actions of other deities or mortals. Today, scientists know that volcanic eruptions occur when buoyant magma (molten rock) that formed deep in the Earth ascends to the surface and ultimately is ejected upon release of gas pressure. More importantly, with precise instruments and refined data analysis, it is now possible to track the subsurface movements of magma by monitoring the earthquakes and measuring the ground changes that accompany such movements.

Although the present state of knowledge does not permit the prediction of the exact time and place of eruptions, we can detect departures from usual behavior that augur impending activity. Systematic monitoring studies are conducted only on a few active volcanoes—those in Hawaii, and some in Italy,



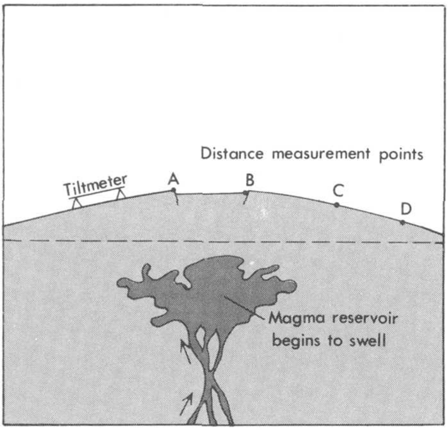
Aerial view shows Hawaiian Volcano Observatory on the rim of Kilauea's crater.

Japan, New Zealand, and Kamchatka (U.S.S.R.). Most of the active volcanoes are not monitored, little understood, and hence, extremely hazardous if located in populated regions.

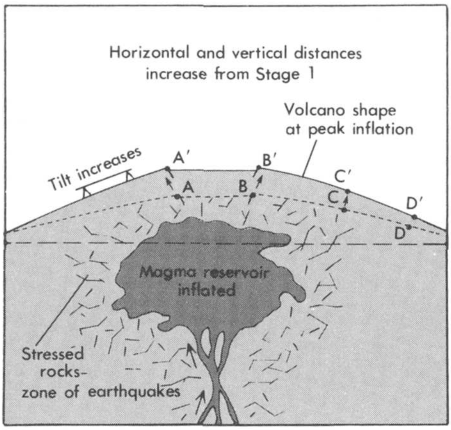
Monitoring Techniques

Volcano monitoring involves the recording and analysis of measurable phenomena such as ground movements, earthquakes, variations in gas compositions, and deviations in local electrical and magnetic fields that reflect pressure and stresses induced by the subterranean magma movements. To date, monitoring of earthquakes and ground deformations before, during, and following eruptions has provided the most reliable criteria in predicting volcanic activity, although other geochemical and geophysical techniques hold great promise.

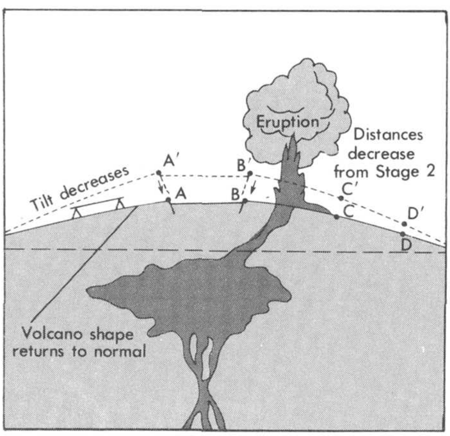
Most of the commonly used monitoring methods were largely pioneered and developed by the



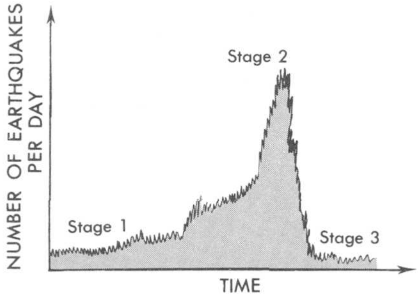
STAGE 1
INFLATION BEGINS

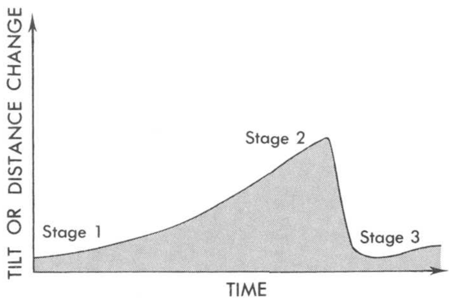


STAGE 2
INFLATION AT PEAK



STAGE 3
ERUPTION-DEFLATION





Schematic diagrams show three commonly observed stages in the course of a typical Hawaiian eruption. The lower part of the figure shows idealized graphs of earthquake frequency, tilt, and distance changes as a function of time during the three stages. See text for additional discussion. *(Modified from illustration by John D. Unger in Earthquake Information Bulletin, 1974, v. 6, p. 7).*

Hawaiian Volcano Observatory (HVO), established in 1912 by Thomas Jaggar, Massachusetts Institute of Technology, and operated continuously by the U.S. Geological Survey since 1948. The many years of continuous observations of Kilauea and Mauna Loa, two of the world's most active volcanoes, have fostered fundamental developments in instrumentation and measurement techniques, which are increasingly used in the study of other active volcanoes the world over. Moreover, early major advances in seismic research at HVO contributed significantly to subsequent systematic investigations of earthquake and related crustal processes, now conducted as part of the Geological Survey's *Earthquake Hazards Program.*

The volcanic plumbing and reservoir system beneath Kilauea can be pictured schematically as a balloon buried under thin layers of sand and plaster. When magma is fed into the reservoir (analogous to air filling a balloon), the internal pressure increases, and the sand-plaster surface layers are pushed upward and outward in order to accommodate the swelling or inflation. The net effects of such inflation include: the steepening of slope of the volcano's surface; increases in horizontal and vertical distances between points on the surface; and, in places, the fracturing of sand-plaster layers stretched beyond the breaking point. Such rupturing of materials adjusting to magma-movement pressures results in earthquakes. A shrinking or rapidly draining reservoir to feed surface eruptions (analogous to deflating or popping the balloon) would produce the opposite effects: flattening of slopes, reduction in distances between surface points, and decrease in earthquake frequency.

Changes in slope in a real volcano can be measured precisely by various electronic-mechanical "tiltmeters" or field tilt surveying techniques, which, for example, can detect the change in slope of a kilometer-long board if raised by the thickness of a dime placed under one end. Similarly, minute changes in horizontal distances can be measured by an instrument that uses a laser beam; tiny changes in vertical distances can be measured by making a series of precise levelling surveys. Such changes can be easily detected to a precision of only a few parts per million. The notion of one part per million can be dramatized in terms of a very dry martini—1 drop of vermouth per 16 gallons of gin. The frequency, location, and magnitude of earthquakes generated by magma movement can be easily and accurately determined by data

HVO scientist makes horizontal distance measurement with a "geodimeter," an electronic-laser beam instrument.

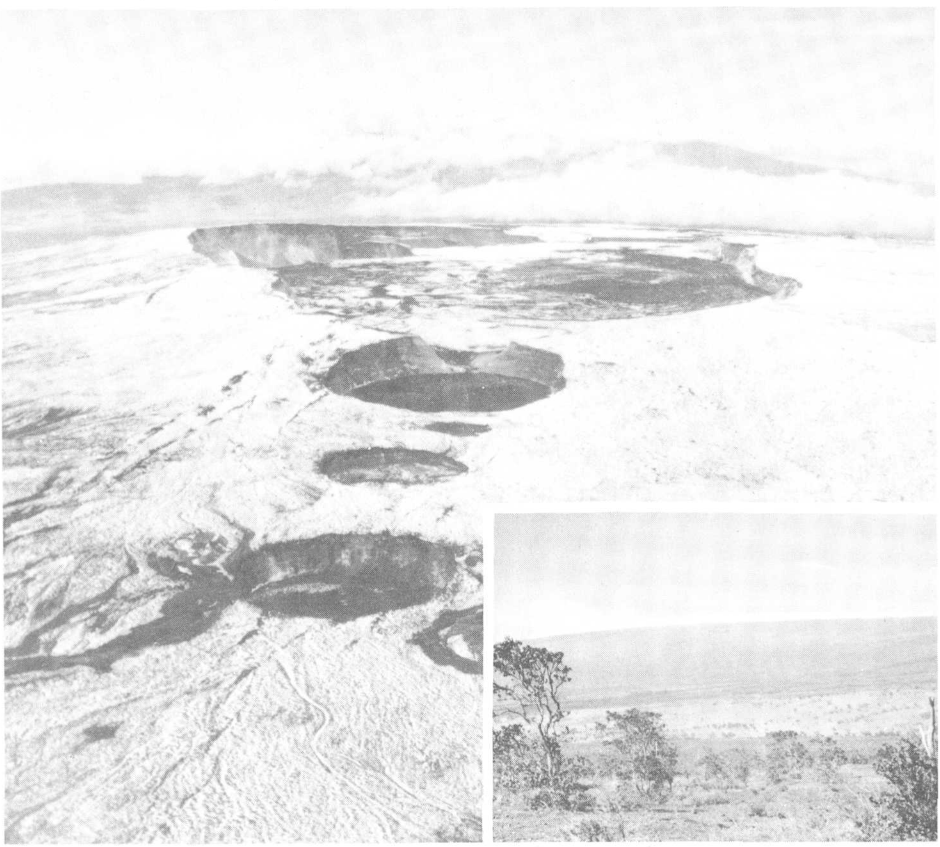
obtained from a properly designed seismic network. The Hawaiian Volcano Observatory has recently expanded its seismic networks to 45 stations to record the earthquake activity of Kilauea and Mauna Loa on a round-the-clock basis.

The continuous monitoring of earthquakes and changes in volcano shape alone is not sufficient for predicting eruptions, however. The proper analysis of present-day data requires a basic understanding of the prehistoric eruptive record and behavior of a volcano that can only be reconstructed from regional geophysical, geochemical, and geologic studies using modern age-dating methods. Such glimpses into a volcano's prehistoric past are critically important because historic records extend over too short a time to permit the making of reliable predictions of future behavior.

Some Case Studies

Investigations carried out as part of the USGS Volcano Hazards Program provide case studies of monitoring two of the world's most active and best understood volcanoes, Mauna Loa and Kilauea on the "Big Island" of Hawaii.

Mauna Loa Volcano last erupted July 5–6, 1975. At that time it had been inactive for a quarter of a century since the June 1950 eruption along its southwest rift zone. The first hint of change leading up to the 1975 eruption was a marked increase



Summit caldera and pit craters on Mauna Loa, Hawaii. The inset shows Mauna Loa as it appears from the Hawaiian Volcano Observatory, 50 kilometers away.

in the number of earthquakes beginning in April 1974, more than a year before the eruption. Inflation or swelling of the summit of Mauna Loa was detected 4 months later during the annual "laser beam" remeasurement of horizontal distances across the summit crater. The 1974 set of measurements showed the first significant increases in the horizontal distances of the lines across the summit crater since the inception of the precise distance monitoring program in 1967. The Hawaiian Volcano Observatory immediately alerted Hawaiian officials and the general public to the possible reawakening of Mauna Loa from its long slumber.

During the next 12 months, both the ground-deformation and seismic networks on Mauna Loa were expanded. Records showed that the numbers of earthquakes and the rate of summit inflation increased steadily, reaching a crescendo during the summit eruption that began on July 5 of 1975. The exact timing of the eruption could not be predicted, even though all premonitory indicators pointed toward an eruption any day. Although the earthquake frequency tapered off sharply in the weeks following the July eruption, swelling of the summit resumed, indicating that magma was continuing to accumulate in Mauna Loa's summit reservoir. Measurements made on six separate occasions over a period of a year and a half following the eruption all confirmed continued swelling. From analysis of the written records of the past historic eruptive behavior and the fact that both the earthquakes and swelling had extended out along the northeast rift, Observatory scientists suggested that a flank eruption on the northeast rift was likely sometime before the summer of 1978, *if Mauna Loa were to behave as it had for the past 200 years.* This conclusion was conveyed to members of the Hawaiian Congressional delegation and Hawaii Civil Defense officials, announced to the media, and published in a scientific journal.

Newly observed changes in the geodimeter lines in July of 1977, however, suggest that Mauna Loa may be departing from previous behavior, and the timetable for the predicted eruption may have to be revised. Inflation of Mauna Loa Volcano has slowed. The northeast rift zone has contracted slightly, and there has been little seismicity of significance in recent months. According to Survey scientists, the volcano is neither shrinking nor deflating. The magma that accumulated in the summit region over a period of more than 3 years (since April 1974) has not drained away. Thus the potential for an eruption is still very much present. The new data do suggest, however, that the predicted eruption may be farther away in time than before the summer of 1978. A new forecast of the probable time of eruption is not possible until Mauna Loa's swelling and earthquakes resume and analysis can be made of its changing pattern of eruptive behavior.

These recent developments show that the relatively limited time span of intensive monitoring (3 years) and the short historic record (about 200 years) are simply inadequate to establish statistically reliable probabilities for the exact time and place of the next eruption, even though Mauna Loa is still "primed" for action.

Kilauea has been closely monitored for a longer period of time than Mauna Loa, but the necessary state of knowledge for prediction of eruptive activity has not been achieved. There have been some notable successes, however. For example, in the late 1960's and early 1970's, several eruptions were predicted with sufficient certainty 4 to 8 hours in advance, so that HVO scientists could advise officials of Hawaii Volcanoes National Park to evacuate certain sections. The park rangers were able to clear park visitors safely from the actual outbreak areas in ample time. But there also have been false alarms—when all of the premonitory indicators signaled movement of magma from the summit reservoir, only to have the magma injected into the rift zones below ground without breaking through to the surface.

HVO scientist measures height of lava fountain during 1977 eruption of Kilauea Volcano.

In the fall of 1976, increased steaming and dying of the forest near Heiheiahulu of Kilauea's lower east-rift zone to the north of Kalapana caused HVO staff members to increase the monitoring of this area. Although significant changes were observed, they were ascribed largely to continued southward shifting of Kilauea's south flank following the effects of the devastating 7.2 magnitude (Richter Scale) earthquake of November 29, 1975. Since the summer of 1977, however, changes in the Heiheiahulu area have taken place at an increased rate. Swelling of the general area around the Heiheiahulu cone began. The area underwent uplift, accompanied by additional southward horizontal movement, suggesting the accumulation of magma in this area, but without the occurrence of increased seismicity, which at Kilauea typically accompanies such magma movement. Additional monitoring instruments were installed, even though HVO records dating back to 1958 show that similar swelling has occurred here before without the advent of eruption.

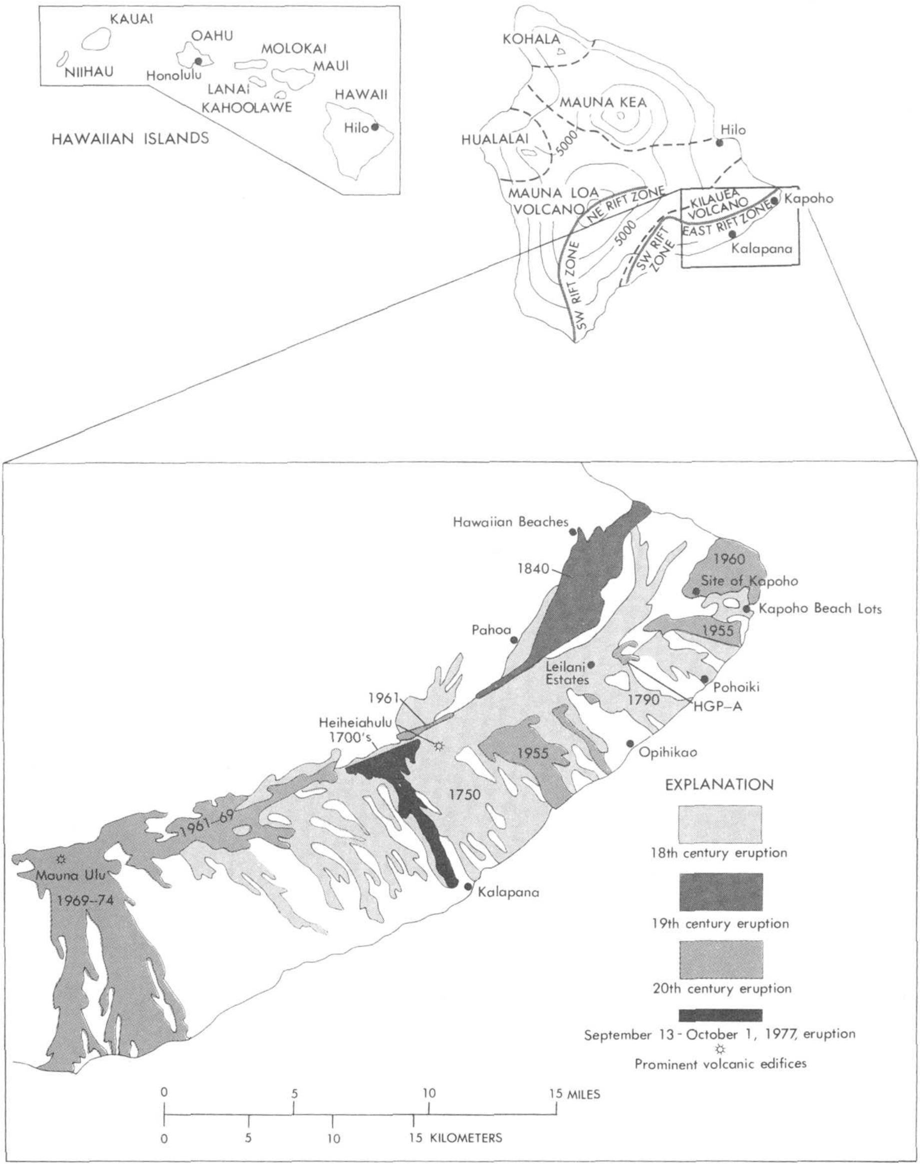
Because the east rift zone of Kilauea has long been the locale of recurring lava flows, eruptive activity could pose a threat to downslope cultivated and populated areas. Hawaii County Civil Defense officials were advised of the unstable conditions. Hawaii residents were informed by a news statement issued on July 29, 1977. At 7:30 p.m. (Hawaiian Standard Time), September 13, lava fountains 25-30 meters high spurted along a 5-kilometer-long fissure only a few kilometers uprift (WSW) of the swollen Heiheiahulu area, following an intense earthquake flurry and abrupt deflation that began about 24 hours before. The eruption continued intermittently for the next 18 days along a restricted part of the fissure. Episodes of vigorous fountaining alternated with interludes of relative inactivity or feeble spattering of lava. The final and most voluminous phase of the activity produced a rapidly moving lava flow, which posed a potential threat to the village of Kalapana downslope. Unlike the nearby village of Kapoho, which was destroyed during the 1960 eruption, Kalapana was spared. The lava fountains stopped on October 1, and the 15-meter-high flow front slowly ground to a halt—only about 400 meters from the nearest dwellings.

Conclusions

Tremendous strides have been made in recent years in intensifying the monitoring of Mauna Loa and Kilauea as part of the Volcano Hazards Program, and an understanding of the typically non-explosive, Hawaiian-type of volcanism has increased markedly. But reliable and specific prediction capability for eruptions in Hawaii still eludes the scientists. The predictive capability is much poorer for explosive volcanoes, such as those in the Cascade Range of the northwestern United States (Mount Rainier, Mount Hood, Mount Lassen), Alaska and elsewhere around the Circum-Pacific "Ring of Fire."

Scientist, wearing asbestos gloves and gas mask, samples volcanic gases from active vent.

The explosive Cascade volcanoes, which have erupted only rarely within recorded historic times, are potentially much more destructive and deadly than Hawaiian volcanoes. Should they erupt violently, large population centers in the northwest, such as Seattle and Portland, could be seriously threatened if wind directions are unfavorable. Clearly, present intensive monitoring of Hawaiian volcanoes should be maintained, and fundamental studies and systematic

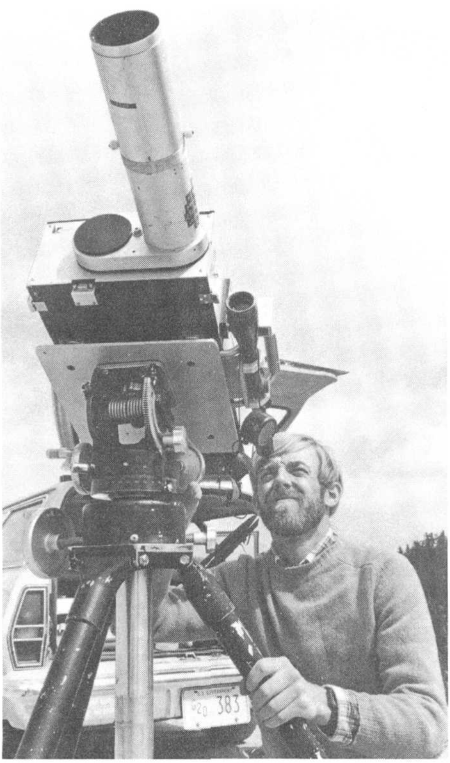


Sketch map shows historic lava flows erupted from Kilauea Volcano's east rift zone, including those of the Sept. 13-Oct. 1, 1977 eruption. Note the locations of villages and subdivisions relative to these lavas. HGP-A marks the site of a 1,969 meter-deep test hole of the Hawaii Geothermal Project of the University of Hawaii.

monitoring of the Cascade volcanoes should be expanded and accelerated.

Update—April 1983

Since the original publication of this article in the USGS Yearbook, Fiscal Year 1977, several events have dramatically increased the public's awareness of volcanic activity and have underscored the importance of volcano monitoring. In March 1980, Mount St. Helens, one of the explosive volcanoes of the Cascade Range, roared back to life after being dormant for 123 years. Mount St. Helens' activity climaxed with the catastrophic eruption of May 18, 1980, which caused the worst volcanic disaster in the recorded history of the United States. Mount St. Helens continues to be intermittently active—the most recent eruption occurred in February 1983—and may remain active for years or even decades. In 1981, the Geological Survey established the David A. Johnston Cascades Volcano Observatory in memory of the USGS volcanologist killed during the May 1980 eruption. This facility is a sister facility to the Hawaiian Volcano Observatory and serves as the headquarters for the continued monitoring of Mount St. Helens as well as for monitoring studies of other potentially active Cascade volcanoes.



USGS volcanologist uses a correlation spectrometer (COSPEC) to measure the sulfur dioxide content of gases ejected during the Mount St. Helens eruption.

The Geological Survey has published two fully illustrated volumes on the 1980 eruptions of Mount St. Helens:

Lipman, P. W., and Mullineaux, D. R., 1981, editors, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p. (The most comprehensive collection of scientific articles available to date, containing 62 reports on diverse aspects of the 1980 eruptions.)

Foxworthy, B. L., and Hill, Mary, 1982, Volcanic eruptions of 1980 at Mount St. Helens: The first 100 days: U.S. Geological Survey Professional Paper 1249, 125 p. (A description of the events during the first 100 days of the eruptive activity in nontechnical language that serves as a backdrop for the more technical articles in Professional Paper 1250.)

In March and April of 1982, El Chichón—an obscure and largely forgotten volcano in southeastern Mexico—erupted violently. During three major explosive bursts

(March 28, April 3, and April 4), El Chichón spewed about the same volume of air-fall ash as Mount St. Helens did during May 18, 1980, and generated high-velocity, incandescent, ground hugging ash flows that leveled villages within about 8 kilometers of the volcano. El Chichón's eruptions were the most destructive in Mexico's history; the number of deaths attributed to the eruptions is unknown, but may exceed 500. In addition, the El Chichón eruptions were much more gas-rich than was the May 1980 eruption of Mount St. Helens and injected a very large volume of aerosols (mainly sulfuric acid particles) into the stratosphere. Atmospheric scientists are predicting that El Chichón's stratospheric cloud may affect global climate. Unfortunately, no systematic monitoring studies were carried out at El Chichón after its "discovery" in 1928. Thus the 1982 eruptions came as a tragic surprise.

In May 1980 the Mammoth Lakes resort area in California, on the eastern slope of the Sierra Nevada mountain range, was racked by a historically unprecedented series of earthquakes. Since then, accelerated seismic and ground-deformation monitoring studies have shown measurable uplift of the ground—as much as 25 cm locally. The Mammoth Lakes area lies in the southwestern part of the Long Valley Caldera, a large volcanic crater formed by collapse during violent eruptions about 700,000 years ago. Scientists are interpreting the current heightened seismicity and measured ground bulging to be related to subsurface movement of magma known to lie a few kilometers below the caldera. Intensive monitoring of the region is being conducted to detect the earliest precursors of possible renewed volcanic activity.

In the first major activity since September-October 1977, Kilauea Volcano began to erupt along its east rift zone on January 3, 1983, and, with only intermittent lulls, the eruption continues as of this writing. The area of the 1983 outbreak is about 8 kilometers to the west ("up rift," see sketch map, p. 10) of the 1977 eruption site. Unlike the 1977 activity, however, the present eruption has already destroyed two dwellings and many building lots in the Royal Garden subdivision, marking the first destruction of housing by an eruption in Hawaii since 1960. Scientists of the Hawaiian Volcano Observatory are monitoring the continuing eruptions on a round-the-clock basis.

Since 1977, significant advances have been made in the measurement of gas emissions to monitor active volcanoes. The underlying principle in gas monitoring is that changes in the composition of the emissions are related to major subsurface movement of magma. In general, as the magma rises closer to the surface, the magmatic component of the gas mixture, collected and analyzed at the surface, increases at the expense of nonmagmatic gases derived mainly from the atmosphere and meteoric waters. Currently at Kilauea more than 10 different species of gas are monitored at 25 sites, sampled at least twice a week, to try to detect departures from "normal" or background amounts. The data from this systematic gas monitoring

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show that the changes in composition of the emissions can be related to the inflation (swelling) and deflation (shrinking) of the magma reservoir.

Measurements of sulfur dioxide gas, using the correlation spectrometer (see photograph) have proved useful at Mount St. Helens, Kilauea, and other volcanoes. The *continuous monitoring* of hydrogen emission at Mount St. Helens, Kilauea, Mauna Loa, and Mammoth Lakes is currently being done remotely by using sophisticated electrochemical sensors and satellite transmission of collected data. Data obtained to date suggest that the monitoring of hydrogen emission promises to be an effective technique, especially at places too inaccessible and/or dangerous for *frequent direct gas sampling* by conventional means.

Mount St. Helens about noon on May 18, 1980, some 3 hours after the beginning of the catastrophic eruption that devastated the area north of the volcano and showered ash over wide parts of eastern Washington.

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