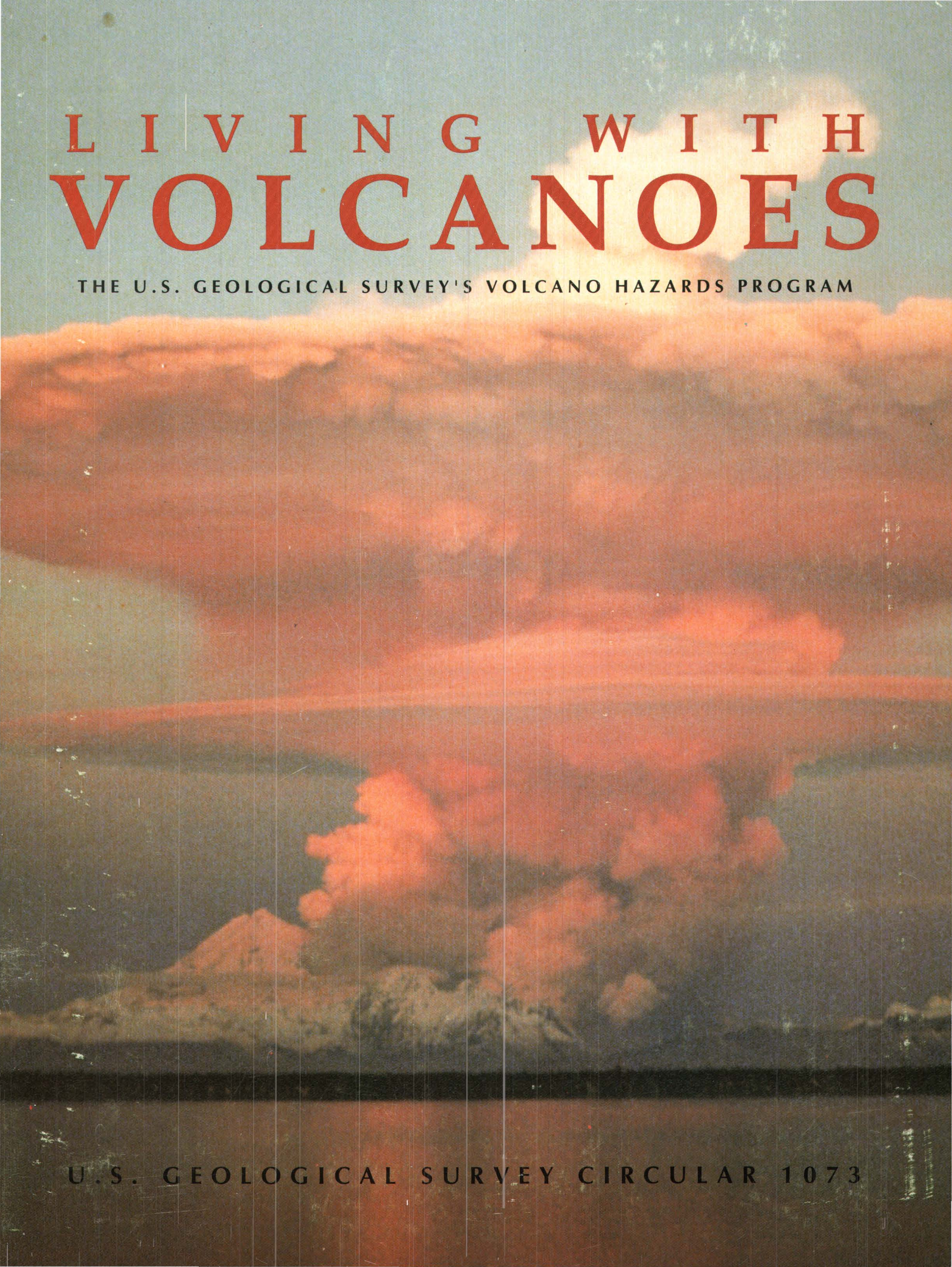
LIVING WITH VOLCANOES

THE U.S. GEOLOGICAL SURVEY'S VOLCANO HAZARDS PROGRAM



U.S. GEOLOGICAL SURVEY CIRCULAR 1073

Front cover: *April 21, 1990, eruption of Redoubt Volcano, Cook Inlet, Alaska, showing layered plume rising into the stratosphere. Copyrighted photograph by Joyce Warren. Used with permission.*

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The U.S. Geological Survey's Volcano Hazards Program

By

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and

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U.S. Geological Survey Circular 1073

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SPECIAL TOPICS

Conversion Factors

For readers who wish to convert measurements from the metric system of units to the inch-pound system, the conversion factors are listed below.

Multiply	By	To obtain
	Length	
centimeter	0.394	inch
meter	3.281	foot
kilometer	0.621	mile
	Area	
square kilometer	0.386	square mile
square hectometer	2.471	acre
	Volume	
cubic meter	1.308	cubic yard

A simple rule of thumb for approximate conversions: 1 inch equals about 2.5 centimeters; 1 yard equals about 1 meter

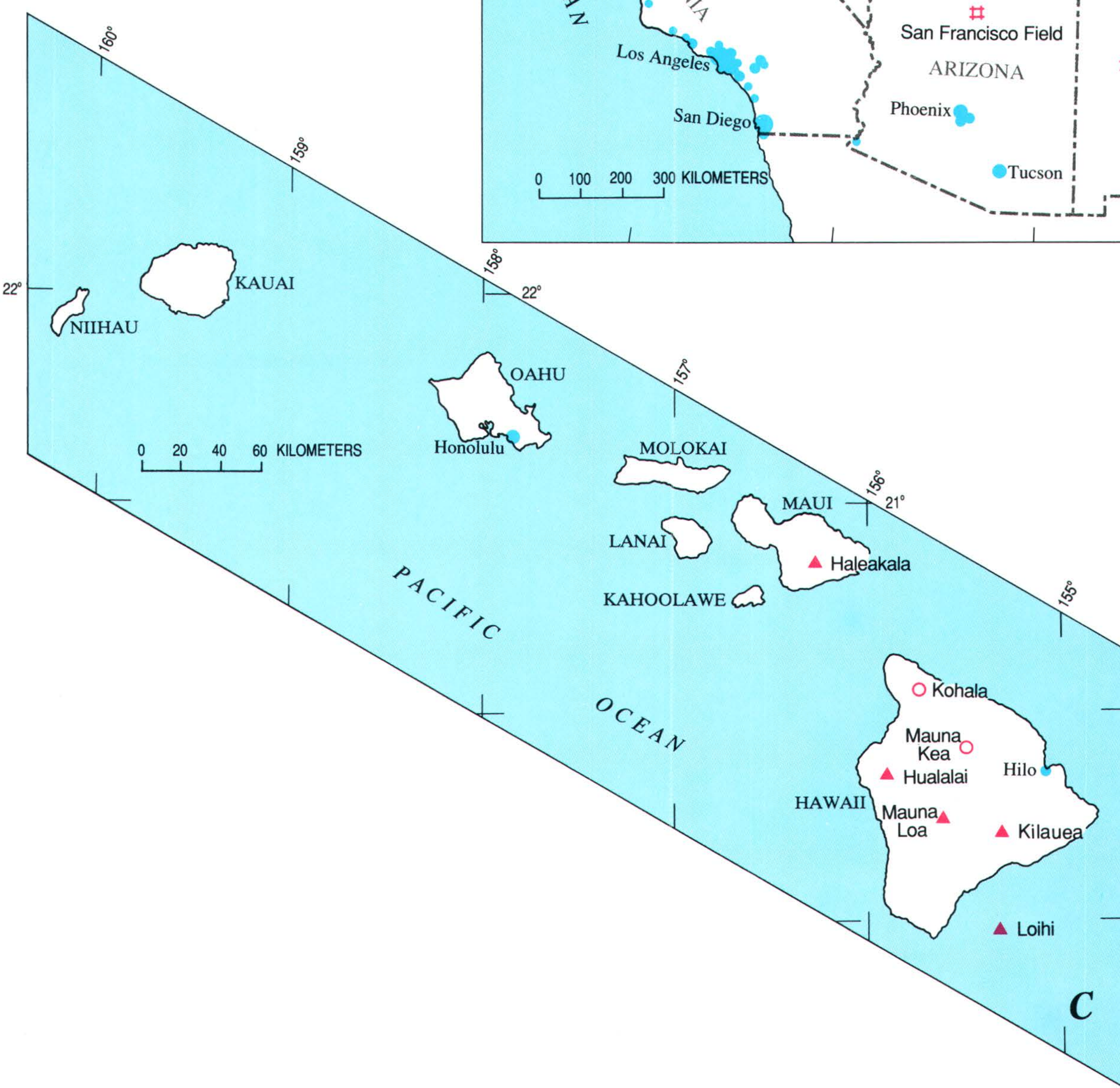
Index maps showing locations of active and potentially active volcanoes and nearby population centers (not all labeled) of the United States. See Appendix 1 for a summary of volcanic activity at all features shown here, and for complete names, as approved by the U.S. Board on Geographic Names. Asterisk denotes informal name. A, Volcanoes of the Alaska Peninsula and Aleutian Islands, Alaska. B, Principal Cascade Range volcanoes, conterminous Western United States. C, Volcanoes of the Hawaiian Islands, including the active Loihi Seamount.

EXPLANATION

- ▲ Volcano active during past 2,000 years
- ○ Potentially active volcano
- ⌗ Area of potential volcanic activity

Population centers

- 40,000 to 100,000
- 100,000 to 350,000
- 350,000 to 1,000,000
- Greater than 1,000,000



EXPLANATION

- ▲ Volcano active during past 2,000 years
- ○ Potentially active volcano

Population centers

- 50,000 to 100,000
- 350,000 to 1,000,000

LIVING WITH VOLCANOES

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INTRODUCTION

The 1980 cataclysmic eruption of Mount St. Helens (Lipman and Mullineaux, 1981) in southwestern Washington ushered in a decade marked by more worldwide volcanic disasters and crises than any other in recorded history. Volcanoes killed more people (over 28,500) in the 1980's than during the 78 years following the 1902 eruption of Mont Pelée (Martinique). Not surprisingly, volcanic phenomena and attendant hazards received attention from government authorities, the news media, and the general public. As part of this enhanced global awareness of volcanic hazards, the U.S. government significantly expanded the Volcano Hazards Program of the U.S. Geological Survey (Bailey and others, 1983) in response to the eruptions or volcanic unrest during the 1980's at Mount St. Helens (Washington), Mauna Loa and Kilauea (Hawaii), Long Valley Caldera (California), and Redoubt Volcano (Alaska). Entering the 1990s, the sustained eruptive activity at Kilauea persists unabated, Mount St. Helens and Redoubt are still erupting intermittently, and the caldera unrest at Long Valley also continues, albeit less energetically than during the early 1980's.

In addition to the areas mentioned above, the U.S. has many other active or potentially active volcanoes—over 65, which is more than all other countries except for Indonesia and Japan (Simkin and others, 1981; Tom Simkin, written commun., 1990). Most of these volcanoes are located in Alaska, and 55 of them, including 8 on the U.S. mainland, have shown activity since the U.S. was founded, just some 200 years ago.

CONTINUOUS ERUPTION AND HAZARDS AT KILAUEA SINCE 1983

Plume of primary SO_2-rich gas (vog) rising from Puu Oo vent (upper right) and a secondary plume of HCl-rich steam (laze) rising from the entry of lava into the ocean (middle left) during the ongoing eruption of Kilauea on Hawaii. Photograph by J.D. Griggs.

Volcanic haze on west coast of the Island of Hawaii carried by tradewinds from Kilauea and trapped by an inversion layer on the lee side of Mauna Loa. The acid-bearing volcanic pollutants affect crops and water catchment systems. Photograph by Dorian Weisel.

As of May 1991, the eruption on Kilauea's east rift zone that began in January 1983 continues uninterrupted. Longest lived of any rift activity in recorded history at any Hawaiian volcano, lava flows produced during this prolonged eruption have destroyed more than 180 homes and obliterated the world-renowned black-sand beach at Kaimu, on the south coast of the Island of Hawaii. Fortunately, no people have been killed or injured, but more than $5 million in property damage and economic loss has been incurred to date. In addition to hazards from ongoing lava flows, the persistent eruption has spewed noxious plumes of acidic volcanic gases that have affected many communities on the island. These plumes originate both at the erupting vent, producing **vog** (volcanic fog) where sulfur dioxide is converted to sulfuric acid a short distance downwind, and at the ocean, where lava entry produces hydrochloric acid-bearing **laze** (lava haze) by boiling of seawater. The plumes, which also contain particulate matter (for example, volcanic glass or trace metals), are then carried by winds far from their source. Both vog and laze obscure scenic views, lower agricultural yields for certain crops, adversely affect people with respiratory or heart conditions, and acidify rainwater catchment tanks thereby producing a secondary hazard of leached lead in local water supplies.

The current eruption shows no signs of stopping, and the continuing hazards pose a serious concern throughout the County and State of Hawaii, for citizens, tourists, and officials alike.

MOUNT ST. HELENS REAWAKENS

The first earthquakes struck on March 20, 1980. Seismologists quickly determined that the quakes were centered beneath a snowy mountain, known to them, but not to the general public, as a potentially dangerous volcano, which had been dormant for more than a century. During the next week, the number of earthquakes increased, and these quakes triggered snow avalanches, which in turn forced closure of winter recreation areas around the mountain. Geologists and geophysicists converged on the scene to monitor the activity and met with local authorities to alert them to the possibility of an eruption. On March 27, steam and ash exploded from the summit of the volcano and marked the beginning of several small eruptions during the next two months.

Public authorities prudently closed the area surrounding the mountain after being informed of the volcano's past violent behavior by those who had conducted careful geological studies during the preceding 20 years. Although closure was a necessary precautionary measure, it created discontent and even anger on the part of some citizens who wanted access to their property and recreation sites. Continued monitoring of the volcano indicated that its north flank, which towered above the most popular recreation area, was becoming increasingly unstable. Warnings were issued for landslides and large-scale snow avalanches. These warnings supported the need for continued closure of the area, although public pressure eventually led to brief, authorized forays into the area by cabin owners to retrieve belongings. One such trip was scheduled for the morning of May 18, but it never took place.

At 8:32 a.m. on May 18, an earthquake triggered a gigantic landslide on the unstable north flank, which in turn unleashed a scorching, explosive blast of hot gas laden with rock fragments; massive floods of mud and rock down most river valleys; flows of hot, gas-rich volcanic rock; and an enormous plume of ash. The water-soaked landslide debris produced a series of dense slurries that raced downstream and nearly severed Interstate Highway 5 and the AMTRAK rail line connecting Portland, Oregon, and Seattle, Washington. These debris flows brought shipping on the Columbia River to a halt and came close to blocking cooling-water intakes at an operating nuclear powerplant. These events transformed a lush landscape of dense, green forest into a dusty volcanic wasteland and killed 57 people who were too close to the mountain. The eastern half of the State, where people were virtually unaware of any volcanic hazard, was blanketed with ash. The death toll, though large, could have been much, much higher without the previous warnings and resultant land closure. Luck also played a role in keeping the number of fatalities down. Had the eruption occurred on Monday rather than Sunday, several hundred loggers, working in an area near the volcano but outside the closed area, would have died. During the next decade, continued enforcement of restricted zones and careful observation and prediction of activity warned the public of impending eruptions, and no additional lives were lost. Research into what had caused the catastrophic eruption led to increased appreciation of the inherent instability of high, snow-covered volcanoes and the hazards they pose.

Eruptions from U.S. volcanoes can generate serious volcanic hazards, any of which can be deadly: glowing rivers of molten rock (lava flows), devastating shock waves and fiery blasts of debris from volcanic explosions (pyroclastic surges), red-hot avalanches of rock fragments racing down mountainsides (pyroclastic flows), and suffocating blankets of volcanic ash falling from the sky (pyroclastic falls). But that is not all. A number of equally deadly processes involve water (Pierson, 1989), and in fact, over 80 percent of the more than 28,500 volcano-related fatalities this past decade were caused by such hydrologic processes. Although many hydrologic hazards at volcanoes are directly associated with eruptions, others are not. It is the latter that are especially dangerous because debris avalanches, debris flows, and floods can strike *without warning*, for example, following periods of heavy rainfall, and they occur with a greater frequency than eruptions. Furthermore, hydrologic hazards typically endanger populations in river valleys at considerable distances from their source volcanoes—

as far as 150 kilometers downstream. Within the last few thousand years, large debris avalanches, debris flows, and (or) floods have occurred at most volcanoes in the Cascades and in Alaska (Heath, 1960; Hyde and Crandell, 1978; Riehle and others, 1981; Beget, 1982; Siebert, 1984; Gallino and Pierson, 1985; Cameron and Pringle, 1986; Osterkamp and others, 1986; Riehle and others, 1987; Siebert and others, 1987; Major and Newhall, 1989; Major and Scott, 1988; Scott, 1988; Siebert and others, 1989; Nye and Turner, 1990; Scott and others, 1990).

Damaging earthquakes and sea waves (tsunami) may also be closely related to volcanoes and volcanic activity. Large earthquakes related to intrusion of magma into Hawaii's active rift zones of Mauna Loa and Kilauea have caused extensive damage on land and also triggered tsunami in 1868 and 1975 that devastated low-lying coastal areas (Tilling and others, 1976). Large landslides from Alaskan volcanoes near the sea have also generated tsunami that destroyed coastal villages (Kienle and others, 1987). Recent research in Hawaii has shown that much larger tsunami have, in the more distant past, washed as much as 366 meters up on some of the islands (Moore and Moore, 1984). These waves appear to have been generated by gigantic submarine landslides that removed large parts of the Hawaiian volcanoes (Moore and others, 1989). These colossal failures have also torn away and submerged subaerial parts of islands.

A short list of notable eruptions and other volcanic activity at U.S volcanoes during the 20th century is given in table 1. A more complete listing of U.S. volcanoes active within the last 2,000 years, as well as older volcanic areas that have active geothermal systems, have shown recent signs of unrest, or which represent a particularly catastrophic event are shown in Appendix 1. Not listed are several dormant volcanic fields on the U.S. mainland that have erupted in the past 10,000-50,000 years and which could erupt again (Smith and Luedke, 1984; Simkin and others, 1981; Miller, 1989). The eruption recurrence intervals for such volcanic fields are large; many of these fields have a deceptively tranquil appearance, show no obvious signs of their violent past, and the land overlying and surrounding these fields is used for agriculture, recreation, or is developed for commercial or residential use. However, the possibility remains that one or more of the currently inactive volcanic fields could erupt again, probably preceded by a period of unrest sufficient to prepare for renewed eruption.

The hazards posed by the U.S. volcanoes provide a fairly complete sampling of hazards shown by volcanoes worldwide. The variety of hazards, in conjunction with the relative abundance of volcanic systems having eruption potential in the U.S., are difficult challenges for the U.S. Geological Survey's Volcano Hazards Program. To address these challenges, we rely on observations and studies made at currently active volcanoes to understand their past histories. The combination of present observations and the reconstructed history of volcanoes, both currently inactive and recently active, allows scientists to estimate the types of hazards and the likelihood of their occurrence for all potentially active or otherwise unstable volcanoes and volcanic areas in the U.S. We recognize, however, that an improved understanding of volcanic processes in itself is insufficient to mitigate volcanic hazards. Effective and timely communication of hazards information to emergency-management authorities *before and during* a volcanic crisis is equally, if not more, important in reducing risk. This publication summarizes the Volcano Hazards Program—its goals, the activities designed to achieve these goals, some key accomplishments of the past two decades, and a plan for work in the 1990's. Additional background information and bibliographic resources on volcanology and volcano hazards are given by Tilling (1989a, b).

ACKNOWLEDGMENTS

This summary of the Volcano Hazards Program, updated from Bailey and others (1983), was conceived at a workshop held in Vancouver, Washington, in November 1989, convened by Bob Christiansen, John Costa, and Chris

Table 1. Notable eruptions of volcanoes in the United States during the 20th century

[A complete listing of volcanoes and their eruptive history is given in Appendix 1]

Volcano	Year	Eruption type	Impact
Novarupta, Alaska (Katmai group).	1912	Explosive; dome	Largest eruption of the 20th century; produced 21 cubic kilometers of volcanic material, which is equivalent to 230 years of eruption at Kilauea. Pyroclastic flow filled Valley of Ten Thousand Smokes, and as much as 0.3 meter of ash fell 161 kilometers away.
Lassen Peak, California	1914–1917	Explosive	Pyroclastic flows, debris flows, and lava flows covered over 16 square kilometers.
Mount St. Helens, Washington.	1980–1986	Explosive; dome	Initial debris avalanche and lateral blast on May 18, 1980, removed the upper 396 meters of the volcano, killed 57 people, and triggered debris flows that temporarily stopped shipping on the Columbia River and disrupted highways and rail lines. The blast devastated 596 square kilometers, and destroyed timber valued at several millions of dollars. Measurable amounts of ash fell as far east as North Dakota. Subsequent to May 1980, the volcano produced pyroclastic flows, debris flows, and lava domes.
Kilauea, Hawaii	Ongoing since 1983	Lava flows	Nearly 78 square kilometers covered by lava and over 180 dwellings destroyed including, in 1990, the entire historic community of Kalapana. 121 square hectometers of new land added to the Island of Hawaii.
Mauna Loa, Hawaii	1984	Lava flows	Hilo, largest city on the Island of Hawaii, threatened.
Augustine Volcano, Alaska.	1986	Explosive; dome	Ash plume disrupted air traffic and deposited ash in Anchorage. A dome built in the crater led to fear of dome collapse triggering a tsunami along the east shore of Cook Inlet, as happened in 1883.
Redoubt Volcano, Alaska.	1989–1990	Explosive; dome	Debris flows caused temporary closing of the Drift River Oil Terminal. A 747 jet aircraft temporarily lost power in all 4 engines when it entered the volcanic ash plume, and it would have crashed had its engines not been started just 1,219 meters above the mountain peaks toward which it was heading.

Newhall. The workshop brought together persons from the Water Resources and Geologic Divisions of the U.S. Geological Survey to discuss all aspects of the Volcano Hazards Program. A list of the workshop participants is given in Appendix 4. Working groups were formed to cover different aspects of the program. Leaders of the working groups prepared a written summary of goals and accomplishments, derived in part from contributions made by individual workshop participants, and the discussions held by the group. Early versions of the present manuscript were substantially improved through reviews by Steve Brantley, John Costa, Dave Hill, Chris Newhall, Don Swanson, and Bob Tilling. Tables were checked for accuracy by Dan Dzurisin, Dan Miller, and Tom Miller. The authors are indebted to the following individuals for contributing illustration material: Darcy Bevens, Steve Brantley, John Dvorak, Chris Janda, Dick Janda, Bob Krimmel, John Langbein, Steve Malone, Susan Mayfield, Dan Miller, Tina Neal, Chris Newhall, Keith Ronnholm, Lyn Topinka, and Joyce Warren. We are indebted to Tom Simkin of the Smithsonian Institution Global Volcanism Project for providing information from the database on Global Volcanism (see

Simkin and others, 1981) on volcanoes active in the past 2,000 and 200 years. The final version of the manuscript was reviewed by Jeff Troll, Carolyn Donlin, Chris Newhall, and Bob Tilling. Tilling in particular deserves our thanks for his efforts to increase the readability of this document by a general audience, and for his assistance in facilitating the editorial process.

PROGRAM GOALS AND ACTIVITIES THROUGHOUT THE 1980'S

The Volcano Hazards Program was formed with the goals of:

- preventing loss of life and property resulting from volcanic eruptions and volcano-related hydrologic events, and
- minimizing economic hardship and social disruption that commonly occur when volcanoes threaten to erupt.

To understand the hazards we extensively monitor currently active volcanoes, and concurrently conduct a vigorous program of research in volcanic processes with the end goal of discovering how volcanoes work. The U.S. Geological Survey (USGS) provides volcano-hazards information at a number of levels: to Federal, State, and local officials, to local citizens, and to other concerned groups. In delivering hazard information that others must act on, the USGS does not dictate or even recommend specific mitigation measures, because such measures must be balanced by social and economic considerations beyond USGS mandate or expertise. Rather, the program provides information about volcanic hazards that will help people to choose and manage the risks associated with living near a volcano.

The Volcano Hazards Program includes the following activities:

- Identifying potentially active volcanoes.
- Directly observing, measuring, and analyzing volcanic unrest.
- Studying and monitoring volcanic and hydrologic processes associated with different kinds of volcanoes and eruptions.
- Reconstructing eruptive and erosional history of volcanoes through study of morphologic and depositional evidence of past events.
- Studying effects of volcanic emissions on the atmosphere, soil, and water supply.
- Preparing geologic and hydrologic volcano hazard maps for individual volcanoes.
- Coordinating with officials responsible for public safety prior to and during eruptive activity.
- Communicating information about potential hazards at a volcano, including the likelihood of their occurrence and potential areas of impact, to public officials, emergency management personnel, and the population at risk.

The activities of the program enable the accumulation of fundamental information on the nature of volcanic processes and associated hazards and, at the same time, provide the means for public officials to respond rapidly and effectively to volcanic crises. Program activities are carried out at many USGS facilities (table 2) and involve the active collaboration of other agencies—Federal, State, and local—and several academic institutions (table 3).

VOLCANO OBSERVATORIES:
TAKING THE PULSE OF ACTIVE VOLCANOES

To study active volcanism, the Volcano Hazards Program depends principally on the research and monitoring conducted at three permanent installations: the Hawaiian, Cascades, and Alaska Volcano Observatories. Each observatory provides continuous and periodic monitoring of the seismicity, other geophysical changes, ground movements, gas chemistry, and hydrologic conditions and activity between and during eruptions. They also provide

Table 2. Facilities and activities of the U.S. Geological Survey Volcano Hazards Program

Facility	Location	Activities
Alaska Volcano Observatory (AVO).	Anchorage, Alaska (headquarters).	Coordination of Volcano Hazard Program activities in Alaska.
AVO	Fairbanks, Alaska	Volcano observation, research, and hazard evaluation for Alaska.
Cascades Volcano Observatory (CVO).	Vancouver, Washington	Volcano observation, hydrologic and geologic monitoring, research, and hazard evaluation for the Cascade Range and western U.S. (monitoring includes Yellowstone and Long Valley Calderas); mapping of Cascades volcanoes.
Hawaiian Volcano Observatory (HVO).	Hawaii Volcanoes National Park, Hawaii.	Volcano observation, monitoring, research, and hazard evaluation for the Hawaiian Islands.
Headquarters	Reston, Virginia	Program coordination; research in volcano processes and products.
Western Regional Center	Menlo Park, California	Program coordination; monitoring Long Valley Caldera (in conjunction with CVO); research in volcanic processes and products; mapping of Cascades volcanoes.
Central Regional Center	Denver, Colorado	Research in volcanic processes and products.
Flagstaff Field Center	Flagstaff, Arizona	Research in volcanic processes and products.

Hawaiian Volcano Observatory, Hawaii Volcanoes National Park, Hawaii. Halemaumau Crater and Kilauea Caldera in the background. Photograph by J.D. Griggs.

a detailed record of eruptions in progress. These observations serve to characterize eruptive behavior, identify the nature of precursory activity leading to eruption, define the processes by which different types of deposits are emplaced, and specify the hazards that could be unleashed by each kind of eruption. From direct observation of precursory signs, it is possible to anticipate eruptions. Underlying all observatory operations is an ongoing program of fundamental research in volcanic processes, supplemented by collaborative studies conducted at other USGS centers (table 3). Such research typically includes direct interpretation of the monitoring and eruption data, and it leads to formulation of conceptual models that can be tested by theoretical or laboratory simulations of volcanic systems.

The Hawaiian Volcano Observatory (HVO) is the U.S. Geological Survey's oldest such facility, founded in 1912 by Thomas A. Jaggar and run continuously by the USGS since 1948 (Heliker and others, 1986). It is located on the summit of Kilauea, one of the most active volcanoes in the world, on the Island of Hawaii. With the frequent eruptions at Kilauea and nearby Mauna Loa, HVO is a training ground for most of the volcanologists at the USGS. Many volcano-monitoring techniques used worldwide were originally developed at HVO, which is a testing ground for new techniques and instruments. The existence of HVO gave the USGS the unique capability of responding to activity at other U.S. volcanoes. When Mount St. Helens reawakened in March 1980, the USGS was well prepared to respond to the crisis. Scientists who had previously deciphered the volcanic history of Mount St. Helens, together with HVO alumni, quickly assembled to monitor the seismic activity and steam explosions. All worked together with the many agencies and public officials who were anxious to know when and if a large eruption was going to occur and what hazards it might create. Guided by USGS information, public officials designated zones of restricted access, and the loss of life from the May 18th eruption was thereby minimized, even though the timing of this event could not be precisely predicted.

After the devastating explosive eruption in 1980, the Cascades Volcano Observatory (CVO), in Vancouver, Washington, was founded and staffed with hydrologists, geologists, geochemists, and geophysicists (Brantley and Topinka, 1984). The observatory quickly broke new ground in its study of the ongoing eruption cycle at Mount St. Helens. In mapping and interpreting the origin of the deposits of the May 18 eruption, scientists had the unique advantage of direct observation of the landslides, eruption, and volcanic debris flows. Monitoring the growth of the lava dome in the crater of Mount St. Helens resulted in accurate predictions, 1 to 3 days in advance, of 16 out of 17 dome-building eruptions—an unprecedented feat in the young science of volcanology.

In 1988, the USGS added a third volcano observatory, the Alaska Volcano Observatory (AVO), in Anchorage and Fairbanks, Alaska, to expand and coordinate existing monitoring of the many active volcanoes along the Alaska Peninsula and in the Aleutian Islands. Many international flightpaths lie directly over Alaska, and the frequent eruptions of these volcanoes pose a serious hazard to aircraft far downwind. Study of Alaskan eruptions also provides more frequent opportunities to study volcanic activity similar to that of the less frequently active Cascade Range volcanoes.

In May 1980, just 1 week after the eruption at Mount St. Helens, a strong earthquake swarm occurred at Long Valley, California, site of a huge eruption of silicic magma about 700,000 years ago. The most recent volcanic activity in the area resulted in the formation of lava domes 550 years ago, accompanied by phreatic explosions that blanketed much of eastern California and western Nevada with volcanic ash (Bailey and others, 1976; Miller, 1985). Following the 1980 earthquakes, the USGS began monitoring Long Valley by setting up an observatory-like project operated from the USGS center in Menlo Park, California. Studies conducted since 1980 have documented almost 2 feet of uplift of the ground within the Long Valley Caldera and have accurately located earthquakes occurring as swarms in and around the caldera, the most recent of which took place in 1990 and 1991. The work at Long Valley is designed to monitor and interpret the current unrest and to make forecasts of any activity that might occur. Thus, the Long Valley project effectively constitutes a fourth volcano observatory in function and responsibilities, if not in name. The largest possible volcanic event at Long Valley, a catastrophic explosive eruption associated with renewed caldera collapse, is also the most difficult to forecast because of the long time interval between such eruptions and the absence of historically documented large caldera-forming eruptions anywhere in the world (see Newhall and Dzurisin, 1988).

Table 3. Collaborative work with the U.S. Geological Survey (USGS) Volcano Hazards Program

USGS facility	Collaborating organization	Nature of work
Alaska Volcano Observatory (AVO).	Geophysical Institute of the University of Alaska.	Volcano monitoring. Maintenance of the Augustine and Iliamna seismic networks.
	State of Alaska, Division of Geological and Geophysical Surveys.	Geologic mapping of Alaskan volcanoes.
Cascades Volcano Observatory (CVO).	University of Washington Geophysics Program.	Operation of the Washington and northern Oregon seismic network.
	University of Utah........................	Operation of seismic network around Yellowstone Caldera.
	Office of Foreign Disaster Assistance Volcano Disaster Assistance Project (OFDA VDAP).	Funding USGS Volcano Crisis Assistance Team (VCAT) for foreign volcano assistance.
Hawaiian Volcano Observatory (HVO).	State of Hawaii, Department of Land and Natural Resources.	Shared funding toward development of Geographic Information Systems (GIS) capability at HVO; sharing of digital geographic and geologic data.
	University of Hawaii at Hilo, Center for Study of Active Volcanism (CSAV).	Summer training program in volcano monitoring for foreign applicants.
	National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory.	Remote sensing of Hawaiian volcanoes.
	Earth Observing System (EOS; multi-agency effort including University of Hawaii at Manoa).	Remote monitoring of Hawaiian volcanoes.
	National Park Service	Assistance in volcano monitoring when there is volcanic activity within Hawaii Volcanoes National Park.
	Commonwealth of the Northern Marianas.	Funding for monitoring active volcanoes in the Marianas Islands.
	U.S. Department of Energy	Funding continuous gravity observations on Kilauea.
USGS Headquarters, Reston, Virginia.	U.S. Agency for International Development (AID).	Coordination and funding of volcano crisis assistance abroad.
	Smithsonian Global Volcanism Project ..	Publish maps (some jointly) of volcanoes and their activity. USGS provides information to the Smithsonian for their monthly bulletin of worldwide volcanic activity.
	National Oceanographic and Atmospheric Administration (NOAA).	Study of undersea volcanism.
	Federal Aviation Administration (FAA)	Developing appropriate levels of alert and response to prevent commercial, as well as private, aircraft from flying into volcanic ash clouds.
	USGS Office of International Geology ...	Coordinating foreign exchange programs (for example, the 1990-1991 exchange of U.S. Geological Survey volcano observatory personnel with personnel from the Institute of Volcanology, Petropavlovsk, Kamchatskii) and facilitating foreign collaborations in volcano monitoring (for example, the recently completed multiyear collaboration with the Volcanological Survey of Indonesia).

Taking a Volcano's Pulse

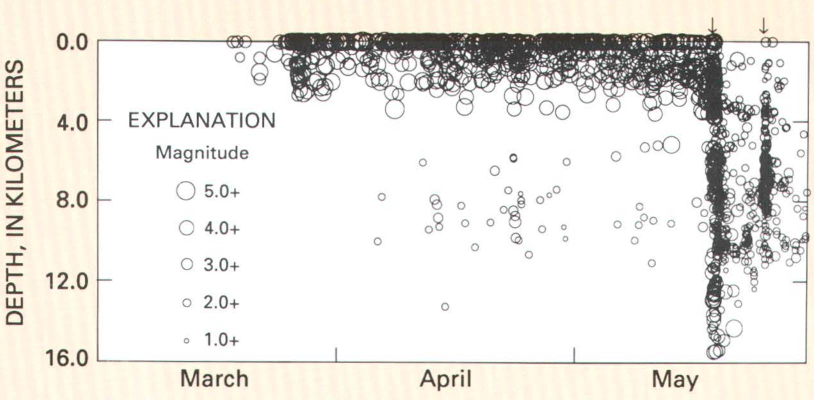
The three USGS volcano observatories and the Long Valley project have the following goals in common:

- Research directed toward understanding volcanic processes and products.
- Evaluation of the ongoing hazards posed by the active volcanoes.
- Delivery of warnings to public officials regarding these hazards.

To realize these goals, it is necessary to conduct visual and instrumental monitoring of volcanic activity. Monitored changes common to each volcano include the following:

Monitoring seismicity at a site in the crater of Mount St. Helens, Washington. Data from several such seismometers are telemetered via radio to Cascades Volcano Observatory, Vancouver, Washington, and to Seattle, Washington, where the location and magnitude of the earthquakes are determined using computer-based techniques. Photograph by Lyn Topinka.

Seismicity. Earthquakes commonly provide the earliest warning of volcanic unrest, and earthquake swarms immediately precede most volcanic eruptions.

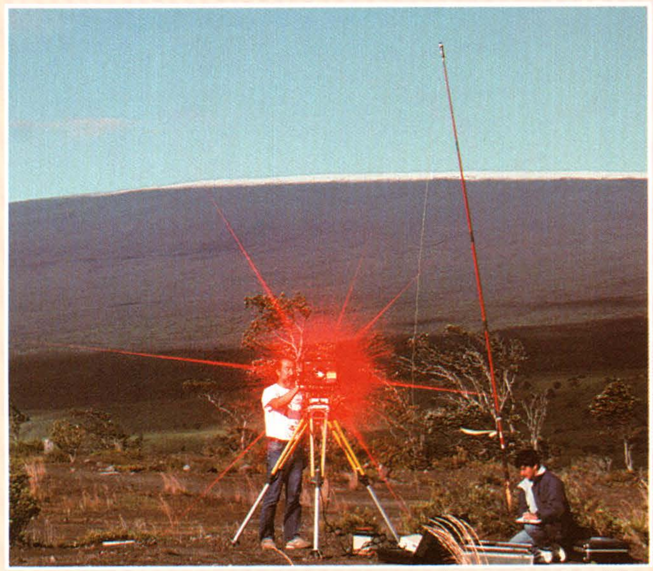


Earthquakes (denoted by circles) beneath Mount St. Helens, March 1 to May 31, 1980. Note the abrupt onset of earthquakes around March 17, building quickly to continuous, shallow seismicity from March 26 (beginning of explosions) to the climactic eruption on May 18. There was no additional increase in seismicity immediately preceding the May 18 event. Coincident with eruptions on May 18 and May 25 (denoted by arrows), earthquake hypocenters trace the movement of magma from depths above and below 5 kilometers, where there may have been a shallow magma storage area. Modified from Malone (1990). Used with permission.

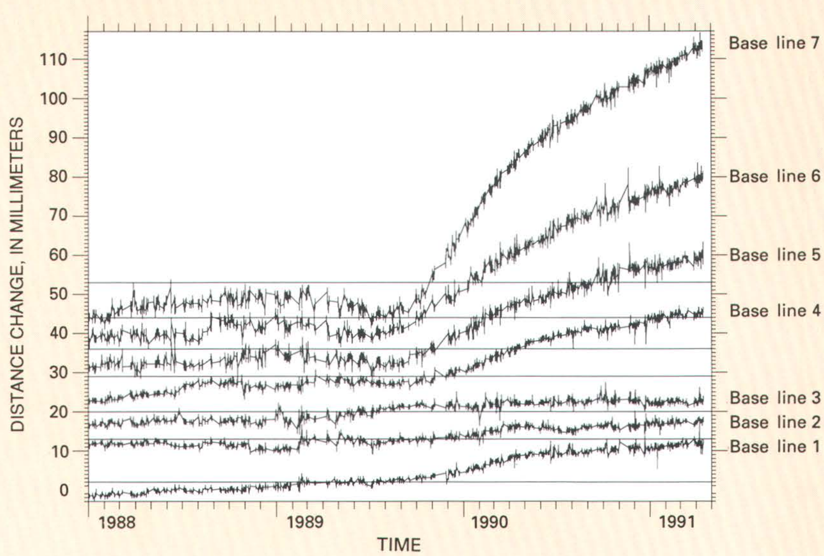
Ground movements. Geodetic networks are set up to measure the changing shape of the volcano surface caused by the pressure of magma moving underground. Techniques commonly used include electronic distance measurement using a laser light source (EDM); measurement of **tilt**, both electronically and by repeated leveling of triangular arrays; and standard **leveling** surveys to obtain elevation changes. Additionally, very simple and inexpensive techniques, such as measuring crack openings using a steel tape, or noting changes in water level around a crater lake, have proven useful in certain situations. Upward and outward movement of the ground above a magma storage area commonly occurs before eruption. Localized ground displacement on steep volcanoes may indicate slope instability precursory to mass failure.

Geophysical properties. Changes in **electrical conductivity**, **magnetic field strength**, and the force of **gravity** also trace magma movement. These measurements may respond to magma movement even when no earthquakes or measurable ground deformation occurs.

Gas geochemistry. Changes in fumarole gas composition, or in the emission rate of SO_2 and other gases, may be related to variation in magma supply rate, change in magma type, or modifications in the pathways of gas escape induced by magma movement.



Monitoring horizontal distance changes at Kilauea, Hawaii, using a conventional electronic distance measuring (EDM) instrument; the red laser beam sends a signal and the round-trip transit time of that signal gives a very accurate distance measurement. Snow-covered Mauna Loa in background. Photograph by J.D. Griggs.



Results of two-color laser ground-deformation measurements of 7 base lines at Long Valley Caldera, California. Note the recent (starting in late 1989) lengthening of lines, particularly for base lines 4 to 7, across the caldera, interpreted to be the result of magma movement to shallower depths beneath the caldera.

Hydrologic regime. Changes in ground water temperature or level, rates of streamflow and transport of stream sediment, lake levels, and snow and ice accumulation are recorded to evaluate (1) the role of ground water in generating eruptions, (2) the potential hazards when hot, energetic volcanic products interact with snow, ice, and surface streams, and (3) the long-term hazard of infilling of river channels leading to increased flood potential.

Reconstructing a Volcano's History

Direct observations of volcanoes before, during, and after eruptions are essential to understanding a volcano's current behavior. The following studies complement information gained from

HOW SCIENTISTS STUDY VOLCANOES

Monitoring ground tilt in Kilauea Caldera, Hawaii, using single set-up leveling (also called dry tilt). Photograph by J.D. Griggs.

monitoring and allow specification of the entire history of activity at a given volcano or volcanic field.

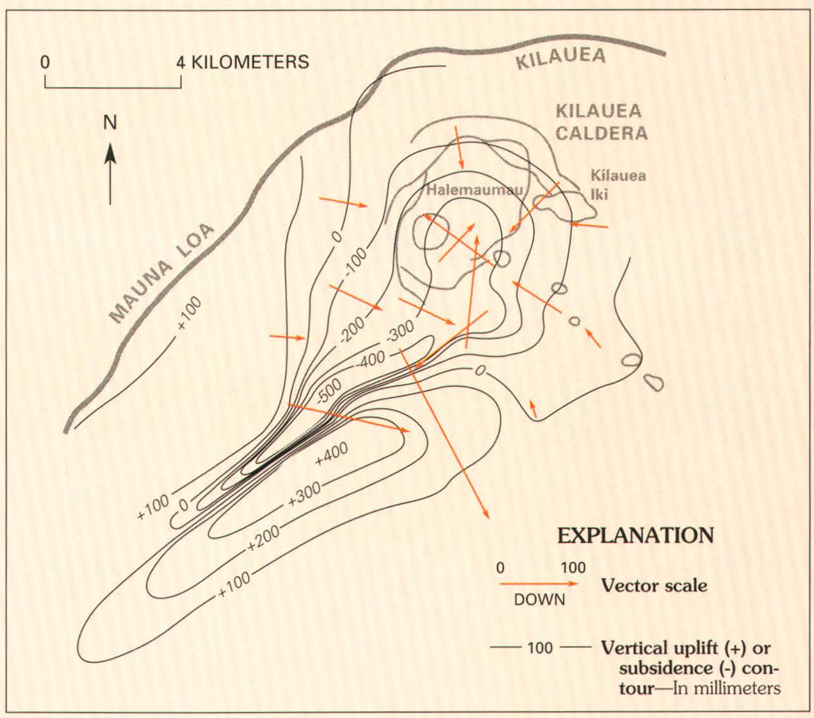
Geologic mapping places layered and more irregular deposits in the proper stratigraphic order and establishes their thickness and areal extent (and thus volume). Field descriptions of stratigraphic units are used to classify deposits and interpret the type of eruption that produced them. Mapping of ash deposits is used to correlate widely separated stratigraphic sections associated with a given volcano. Dating of ash layers is especially valuable to bracket ages of other, less extensive, deposits in individual stratigraphic sections.

Dating of deposits establishes the time intervals in which eruptions or hydrologic events occurred. Techniques commonly used for young deposits are:

Carbon-14. This technique is used where eruptions overlie or incorporate vegetation or organic-rich soil and the carbon-bearing material is preserved.

Tree rings. Traumatic injuries to trees are represented by interruption or distortion of growth rings. In some cases, the season in which the event occurred can be specified based on knowledge of the yearly cycles of tree-ring growth.

Paleomagnetism. In some areas, it has been possible to calibrate yearly changes in the position of the Earth's magnetic pole over the past several hundreds or thousands of years. In such cases the magnetic directions preserved in a series of eruptive deposits may be used to specify their approximate age.



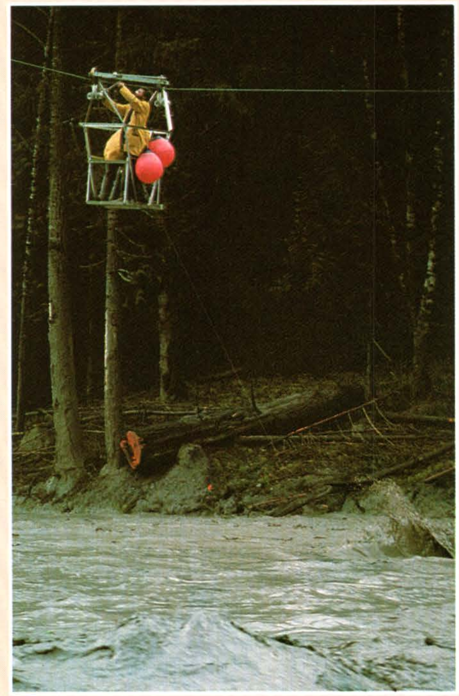
Contoured elevation changes and ground tilt vectors for the period June-August 1981, following underground magma emplacement (intrusion) on southwest rift zone of Kilauea. Vector scale in microradians.

Understanding Volcanic and Hydrologic Processes

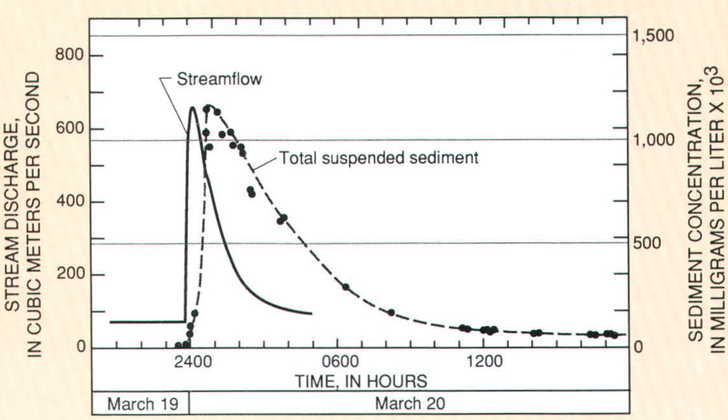
Direct observation of volcanic and hydrologic events gives important but incomplete insights into the nature of volcano hazards. The following topics represent some of the avenues pursued to gain a fuller understanding of volcanic processes that control hazardous events.

Numerical modeling is used to test our understanding of physical processes, and hazard predictions can eventually be made on the basis of modeled events. Volcano-related processes amenable to modeling include (1) the gravity-driven flow of lava, hot pyroclastic debris, landslide debris, water-saturated mixtures of mud and rock, and water floods; (2) the dispersal of volcanic ash plumes and thickness of ash accumulation on the ground; (3) the development of eruption- or landslide-induced waves; (4) the time of occurrence and magnitude of outbreak floods from lakes dammed by volcanic debris; and (5) the flow of ground water and the dynamics of hydrothermal systems.

Experimental research is necessary to model volcanic processes that cannot be studied directly or safely in the field or are too complicated to model numerically. Experiments can be designed to simulate volcanic conditions and infer possible consequences of volcanic activity. For example, a gelatin mold injected with a colored fluid mimics patterns of subsurface magma movement. Specially designed flumes simulate the properties of dense slurries and help scientists to better understand the development and movement of debris flows. Other topics, such as the origin of magmas by melting in the Earth's mantle, and their subsequent crystallization, can be studied by a combination of laboratory experiments, numerical modeling, and interpretation of chemical variation in the erupted lavas.



A scientist from the Cascades Volcano Observatory, Vancouver, Washington, in a cablecar measuring flow discharge and sediment load during a flood in the Toutle River, a watershed heavily impacted by the 1980 eruption of Mount St. Helens. By monitoring such hydrologic changes, scientists are able to determine how much sediment will be carried downstream to clog channels and thereby cause floods. Photograph by Lyn Topinka.



Streamflow rate and excessively high suspended-sediment concentration measured by Cascades Volcano Observatory staff on an eruption-triggered flood wave from Mount St. Helens on March 19, 1982, 73 kilometers downstream from the volcano's crater on the Toutle River.

A VOLCANO'S HISTORY:
KEY TO ASSESSMENT OF HAZARDS

Any volcano is the sum total of past constructive and destructive processes, both volcanic and hydrologic, that have occurred over a period of time, usually thousands of years. When the pattern, magnitude, and frequency of past events can be determined and evaluated in light of information gained by studying modern eruptions, reasonable predictions of future activity can be made. Thus, knowing a volcano's history is crucial to understanding its potential future behavior. The essential link between the reconstruction of volcanic history and study of volcanic eruptions was recognized late in the 19th century. In 1882, three years after the U.S. Geological Survey was founded, Clarence Dutton was asked to head a Division of Volcanic Geology within the USGS. Dutton was sent to Hawaii "with the purpose of studying the features and processes of a volcano in action, and thus obtaining the practical knowledge which is essential to the investigation of extinct volcanoes" (Dutton, 1884, p. xxvi).

The principal means of understanding a volcano's history are geologic mapping and dating of volcanic deposits whose stratigraphic positions are known. Understanding the processes that produced the deposits depends on study of active volcanoes. Eruption style and vigor can be determined for older deposits by matching a deposit produced during an observed volcanic event with a similar deposit in a geologic section. By determining the kinds of eruption represented in a volcano's deposits, its eruption history can be reconstructed. Once all or part of this eruption history is known, geologists can discern the patterns, if any, in its eruptive cycle. Such patterns can help volcanologists to determine when a volcano may erupt again and the type of hazards expected from renewed eruption.

In all of the currently active volcanic areas in the United States, an effective collaboration

Pahoehoe lava issuing from a fissure eruption near Puu Oo vent, Kilauea east rift zone, Hawaii. Photograph at top of facing page shows the resulting deposits of this event. Photograph by J.D. Griggs.

Freshly cooled pahoehoe lava surface, Kilauea. Photograph by Taeko J. Takahashi.

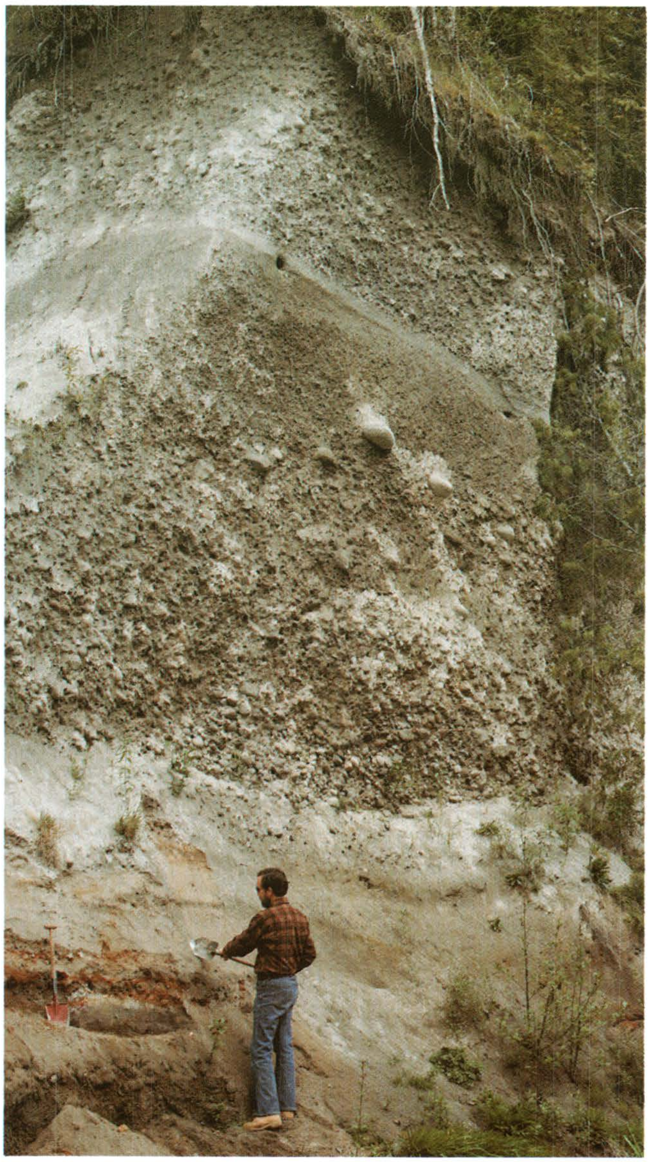
is maintained between those who study active volcanism and those who study the prehistoric eruptions and fill in the eruptive history; many individuals do both. In Hawaii, a new geologic map of the Island of Hawaii and its active volcanoes is being compiled (Wolfe and others, unpub. data) and a USGS general-interest publication on the volcanic and seismic hazards of the island has been published (Heliker, 1990). Geologists mapping and dating deposits from individual volcanoes have produced a series of geologic hazard evaluations for volcanoes in the Cascade Range (for example; Mount Baker—Hyde and Crandell, 1978; Mount Rainier—Crandell, 1973; Mount St. Helens—Crandell and Mullineaux, 1978; Mount Hood—Crandell, 1980; Mount Shasta—Miller, 1980). Teams of geologists and hydrologists at CVO are evalu-

These layers of thin pahoehoe lavas, exposed in a roadcut, were produced during the 1970-74 Mauna Ulu eruption of Kilauea, Hawaii. The pahoehoe flows have smooth tops and central gas cavities. Photograph by Taeko J. Takahashi.

Debris flow after coming to rest in the Toutle River drainage during the eruption of May 18, 1980, at Mount St. Helens, Washington. Photograph by Bob Krimmel.

ating the past occurrence of debris avalanches, debris flows, and floods at a number of volcanoes, as well as carrying out research to better understand how these hydrologic hazards can be triggered and how they behave once triggered (Voight and others, 1983; Crandell and others, 1984; Pierson and Scott, 1985; Meyer and others, 1986; Laenen and Orzal, 1987; Siebert and others, 1987; Scott, 1988; Glicken and others, 1989; Major and Newhall, 1989; Pierson and others, 1990; Scott and others, 1990).

In Alaska, geologic mapping and hazard assessment are just beginning at the most hazardous volcanoes in the Cook Inlet area. Studies also are being conducted at sites in the U.S. where seismic activity and ground deformation suggest the possibility of future eruptions. Long Valley and Yellowstone Calderas in the continental interior are areas where recent geologic mapping has shown the occurrence of prehistoric volcanic activity widely ranging in scale from small basaltic eruptions, through explosive eruptions the size of the 1980 eruption of Mount St. Helens, to catastrophic caldera-forming eruptions of a magnitude never witnessed in recorded history (Bailey and others, 1976). Both areas are seismically active and show episodic uplift of the ground surface; the seismic activity and geodetic changes are being closely monitored by USGS personnel supported under the Volcano Hazards Program (Dzurisin and others, 1990; Hill and others, 1990).



Sequence of older debris-flow deposits in Toutle River valley approximately 60 kilometers downstream from Mount St. Helens, Washington. These massive flows originated 2,500-3,000 years ago as outbreak floods from a lake dammed by volcanic deposits. Photograph by Tom Pierson.

From the mapping and dating of volcanic and volcaniclastic deposits, geologists can determine the eruptive and mass-failure history for a given volcano, from which the nature, size, and frequency of previous hazardous events can be specified. This history can then be used to predict the type and likelihood of future events. The most common means by which a volcano's history and potential for future activity can be presented is a map outlining areas of risk from a particular kind of volcanic or hydrologic hazard. The hazard zones must outline an area likely to be affected by a given kind of event and should also give some idea of the recurrence interval for that event (see Crandell and Mullineaux, 1975). Thus, the criteria used to specify hazard zones must be based on the following: (1) the type of activity (for example, debris flow, lava flow, ash fall); (2) the magnitude of a typical event, expressed as distance traveled or area covered, and (3) the frequency of occurrence, as deduced from the historical and geologic record.

Maps have been prepared for several active volcanoes in the Cascade Range that outline the hazards from lava flows, pyroclastic flows, debris flows, and floods (Crandell and others, 1979). The mapping and hazard assessment completed for Mount St. Helens in the 1970's resulted in publications (Crandell and others, 1975; Crandell and Mullineaux, 1978) that accurately forecast an eruption before the end of the century. The May 1980 eruption impacted areas indicated as being at risk on a hazard map published in 1978 (Crandell and Mullineaux). Another hazard-zone map depicting lava-flow hazards on the Island of Hawaii has recently been published (Heliker, 1990). Hazard-zone maps are perhaps the most easily un-

WATER, ROCK, AND GRAVITY:
A POTENTIALLY DEADLY COMBINATION AT VOLCANOES

Research conducted at Mount St. Helens and elsewhere has shown that even small eruptions of hot volcanic material can almost instantaneously melt large volumes of snow and ice. The resulting floods of meltwater can erode and incorporate several times their original volume in new sediment and water, forming debris flows—dense, powerful, and fast-moving mixtures of mud, rock, and water having the consistency of wet concrete—that can travel far down valleys heading on the volcano. For example, the eruption at Nevado del Ruiz in November 1985 ejected a very small amount of magma—only about 3 percent of that erupted at Mount St. Helens. Yet, this tiny eruption generated high-volume debris flows that killed more than 23,000 people. A more recent example took place on January 2, 1990, during the eruption of Redoubt Volcano in Alaska. The rapid melting of snow and ice by a pyroclastic flow moving across Drift Glacier resulted in a flood and debris flow, larger than the Mississippi River at flood stage, that quickly moved down the Drift River valley. No lives were lost during this event, but a valuable oil storage terminal located at the mouth of the valley was closed temporarily because of the risk of further debris flows. Debris flows can also be generated when a volcano is inactive, typically during or following heavy rainfall, when unconsolidated volcanic debris on steep slopes becomes water saturated.

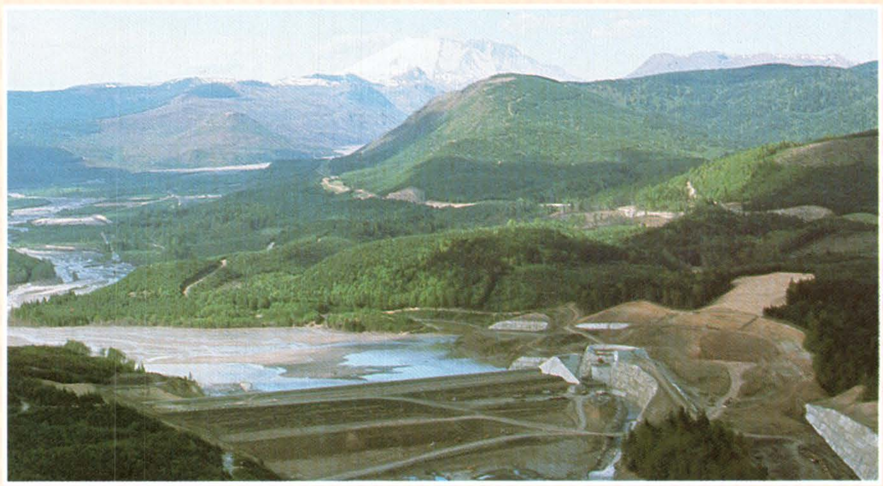
Drift River Oil Terminal (circled) located within the Drift River valley, Alaska; the Drift River headwaters lie in glaciers and snowfields associated with Redoubt Volcano (center). Photograph by Robert McGimsey.

Channel swept by large volcanic debris flow, North Fork Toutle River, Washington, approximately 35 kilometers downstream from Mount St. Helens, May 19, 1980. Photograph by Don Swanson.

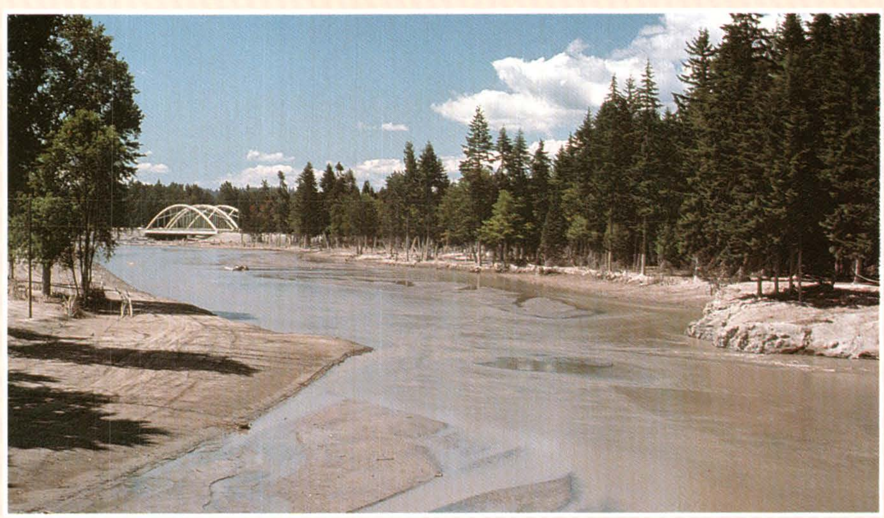
As a direct result of research at Mount St. Helens, combined with experience of the 1985 Ruiz disaster, these extremely hazardous events are now receiving much more scientific attention. The knowledge gained is now being applied in other volcanic terranes to assess the hazards posed by debris flows, which worldwide have caused some of the greatest losses of life. While the hazard posed by individual debris flows is generally understood, the frequency of their occurrence is poorly known. Hazards mapping at Mount Rainier has shown many more such flows in the recent geologic past than had been recognized previously. Parts of Tacoma, Washington, and many other smaller communities between Tacoma and Seattle lie within the reach of large debris flows originating high on the slopes of the mountain.

Recent fieldwork at both oceanic and continental volcanoes around the world is demonstrating that structural failure ("sector collapse") of large parts of volcanic cones is not uncommon. Giant landslides in the Cascades, for example, have produced debris avalanches that have swept over as much as 440 square kilometers, depositing as much as 25 cubic kilometers of debris. The May 18, 1980, debris avalanche and flow at Mount St. Helens, 2.8 cubic kilometers in volume, raced 35 kilometers downvalley at speeds as high as 253 kilometers per hour. Even larger failures of the oceanic volcanoes forming the Hawaiian Islands have occurred in the past. Single landslides can involve more than 1,000 cubic kilometers of material and remove as much as half of the subaerial island and 10 to 20 percent of the entire volcano. Significantly, large sector collapses may not necessarily occur during eruptive periods.

In addition to the direct risk from debris flows and debris avalanches, voluminous deposition of volcanic material in valleys commonly forms unstable natural dams by blocking preexisting drainages. If the size and structural integrity of the blockage is insufficient to hold back the reservoir that will form (or withstand the erosion by overtopping flow), catastrophic failure of the dam will result. Such a hazardous situation may persist for months, years, or decades following an eruption. Another, less-obvious threat comes from the gradual infilling of river channels by sediment transported from highly erodible, volcanically disturbed landscapes following large eruptions. This sediment can aggrade channel beds with excess sand and gravel for tens to hundreds of kilometers downstream. Such aggradation promotes lateral migration of channels and may cause serious flooding during rainstorms, due to loss of channel capacity necessary to convey floodwaters.



Sediment-retention dam constructed on Toutle River in Washington by U.S. Army Corps of Engineers to hold back the large volumes of sediment that would otherwise be carried downstream and clog Toutle and Cowlitz River channels. Photograph by Steve Brantley.

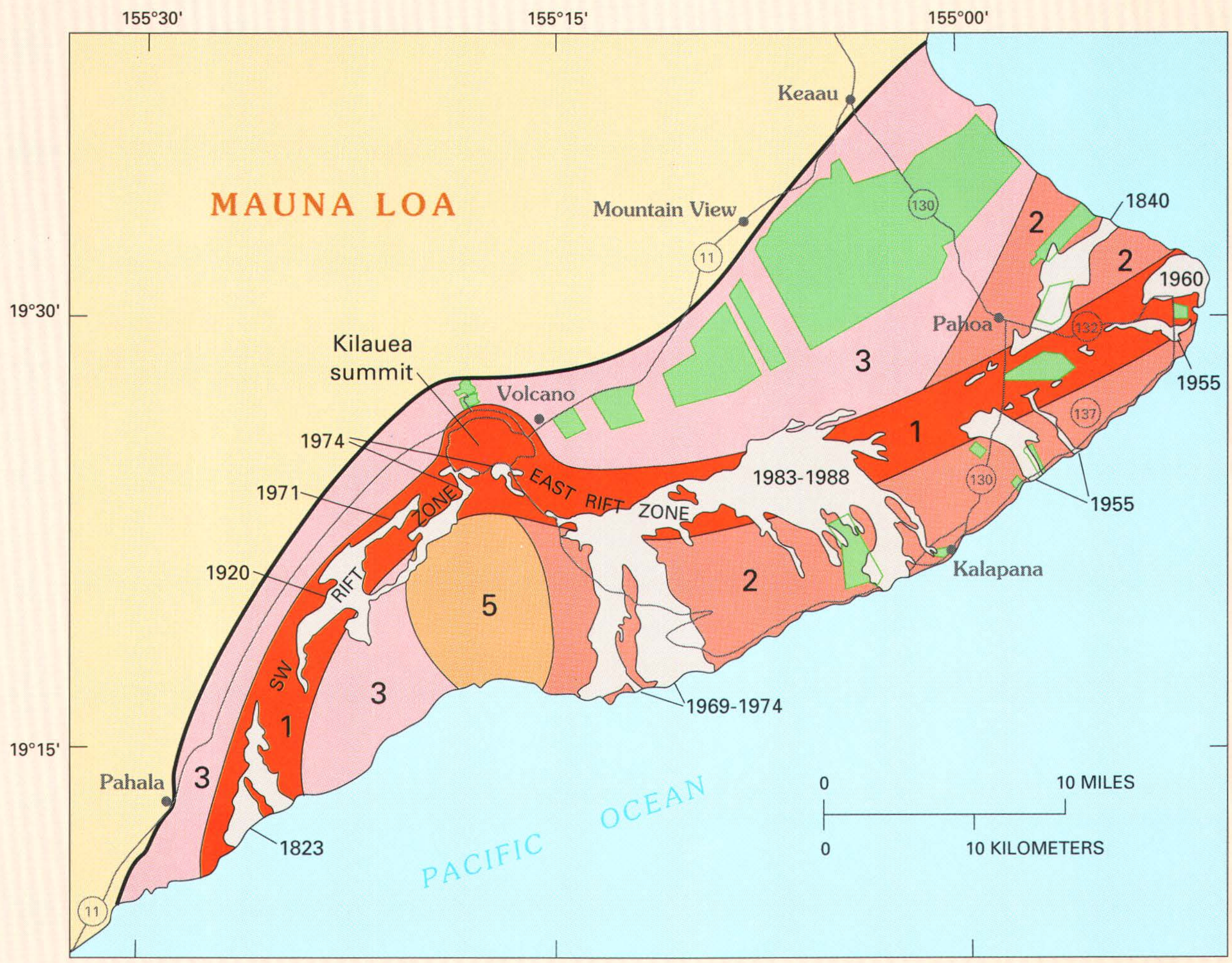


Channel aggradation 1.6 kilometers upstream from mouth of Toutle River in Washington caused by the May 18, 1980, debris flow and avalanche at Mount St. Helens and by subsequent high sedimentation rates resulting from the new vast source of easily erodible sediment upstream. Photograph by Lyn Topinka.

HAZARD-ZONE MAPS AND VOLCANIC RISK

The purpose of hazard-zone maps is to give accurate information on the type and frequency of volcanic eruptions and consequent volcanic and hydrologic processes that could impact a given area—information vital to sound land-use planning. In 1951, two decades before the first comprehensive hazard assessment for volcanoes in Hawaii, a developer could have felt secure in placing a subdivision on Kilauea's lower east rift zone knowing that: (1) Kilauea had not erupted at all for the past 17 years, and (2) Kilauea had not erupted on its lower east rift zone since 1840, more than a century of inactivity. Such time periods are long by human standards and commonly influence judgment in land-use decisions. But he would have made a mistake. Kilauea became active again, at its summit, in 1952 and over the succeeding 38 years there were 13 separate east rift eruptions, two of which persisted longer than 4 years. From the first return of activity at the lower east rift zone in 1955 to the pre-sent, almost 30 percent of the land surface between the rift zone and a 51-kilometer stretch of coastline has been covered by lava.

Geologic mapping and dating of volcanic deposits at Kilauea form the basis for an astonishing statistic—over 90 percent of the land surface of Kilauea has been covered by lava since the time of arrival of the Hawaiians, about 1,500 years ago. Had the developer been made aware of the entire



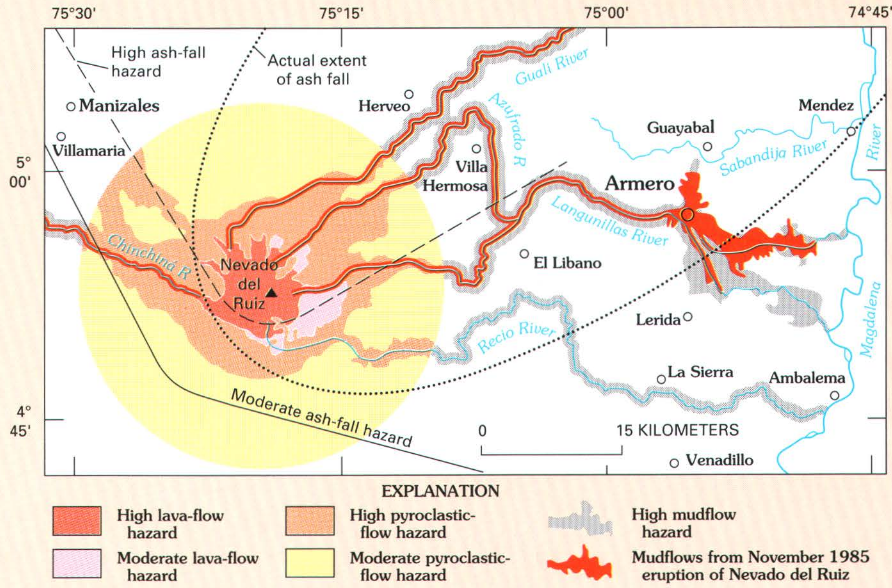
Hazards from lava flows at Kilauea, Hawaii. Relative hazard ranges from 1 (high) to 5 (low). Lava flows erupted since 1823 shown in gray; principal subdivisions shown in green. Over 90 percent of the entire surface of Kilauea has been covered by lava since Hawaiian occupation began about 1,500 years ago. Nearly 30 percent of the land surface in hazard zone 2 south of the east rift zone has been covered since 1955. Since this map was prepared, an additional area from 6 kilometers west to almost 1.6 kilometers east of Kalapana has been covered during 1989-90 activity. Modified from Heliker (1990, p. 24).

HAZARD-ZONE MAPS AND VOLCANIC RISK

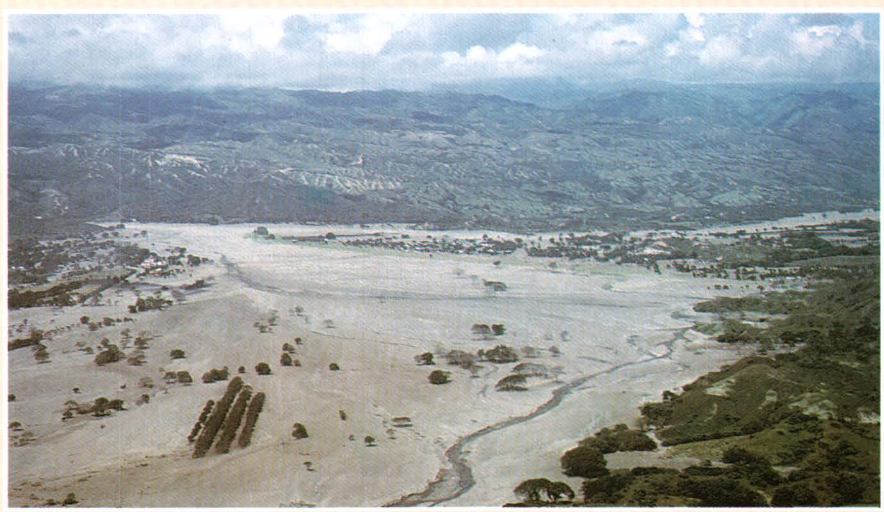
history of Kilauea's activity, the risk of developing the east rift zone would have been understood to be higher than could be inferred from just considering the record of the preceding 111 years.

The 123-year period of inactivity at Mount St. Helens also created a false sense of security regarding future activity. However, in this case, a hazard assessment was made in 1978 which correctly inferred an end to the period of repose and alerted people to the possibility of renewed activity.

The 1985 Ruiz eruption offers another, much more tragic example of the need to understand the entire history of a volcano in assessing hazards. The town of Armero, Colombia—buried by mudflows triggered by the 1985 eruption at Nevado del Ruiz—was located on a debris fan that was overrun by destructive mudflows in the year 1595, shortly after the arrival of the Spanish colonists, and again in 1845, killing hundreds of people in each instance. During the ensuing 140-year period of inactivity, people forgot and the town was rebuilt at the same site and grew in population. Although a preliminary hazard-zone map for Ruiz, completed 1 month before the November 1985 eruption, clearly delineated Armero as being especially vulnerable to mudflows, emergency-response measures taken during the eruption were entirely inadequate to save the more than 23,000 lives lost when the mudflows struck.



Map showing hazards expected from an eruption of Nevado del Ruiz, Colombia. Such a map was prepared by INGEOMINAS (Colombian Institute of Geology and Mines) and circulated 1 month prior to the November 13, 1985, eruption of Nevado del Ruiz. Map shows danger from mudflows in the valley occupied by the town of Armero, Colombia, as well as areas affected by the hazards that resulted from this eruption. Circle denotes 20-kilometer limit.

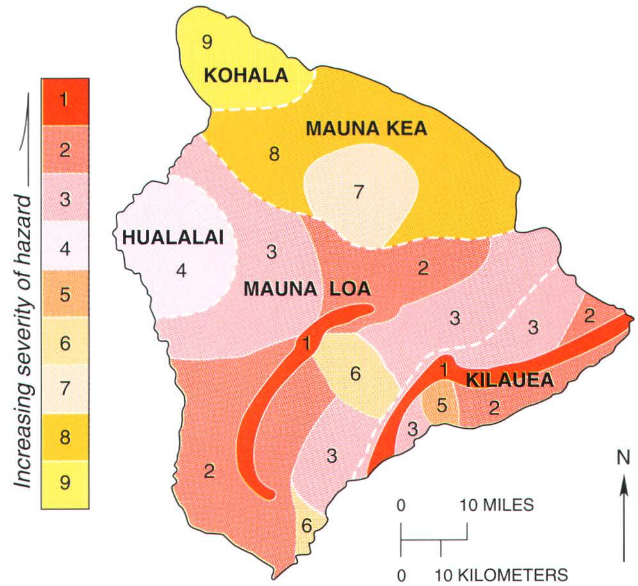


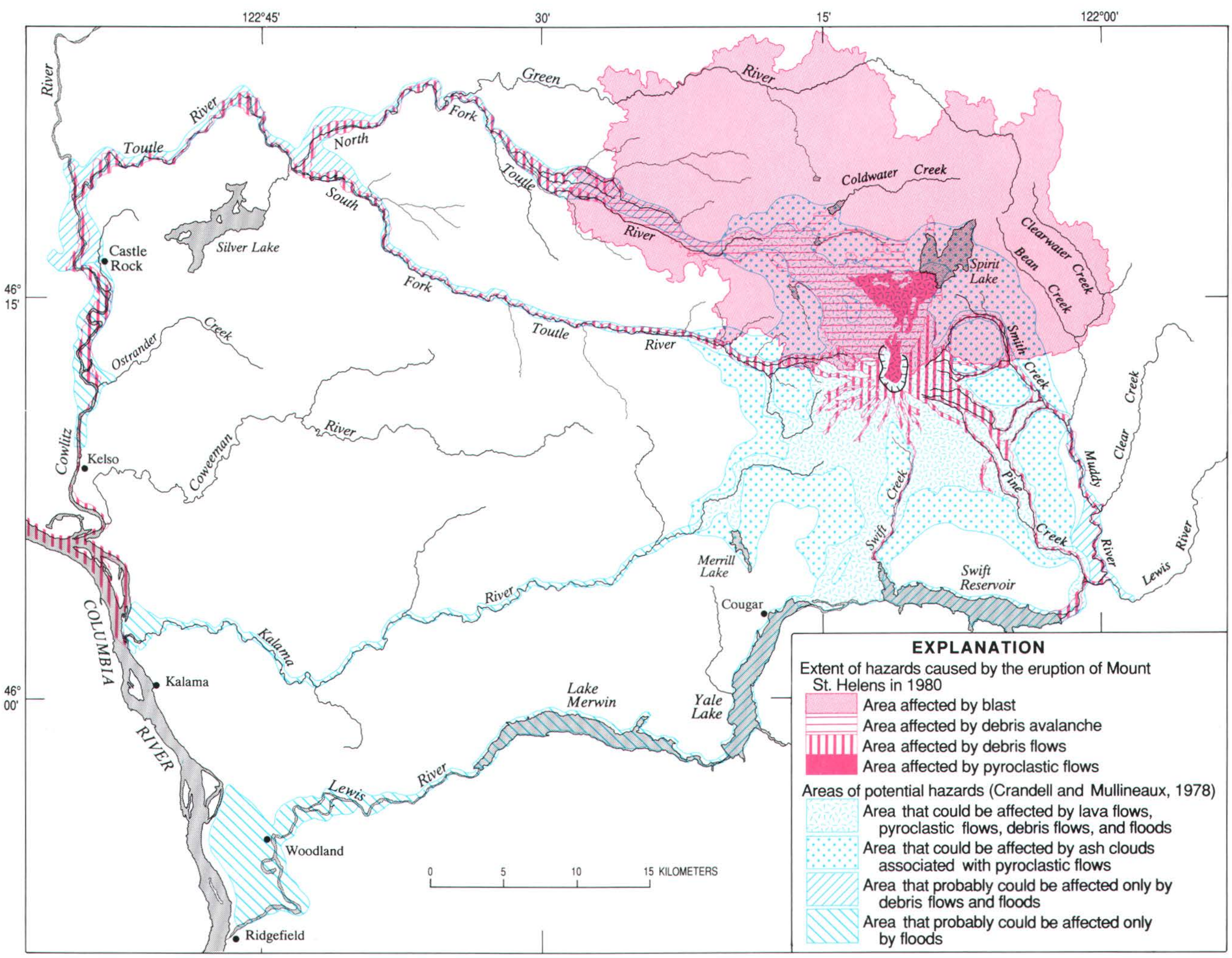
Remains of Armero, Colombia (in left foreground), surrounded by a sea of mud, after having been swept over by a volcanic debris flow roughly 3 meters deep. Photograph by Dick Janda.

derstandable information that public officials and ordinary citizens can use in planning for volcanic emergencies. Maps combining information on land classification with the volcanic history of an area and the associated hazards also form the basis for prudent land-use planning and preparation for the contingency of eruptions far into the future.

Appendix 2 summarizes the status of hazard-related studies for all of the volcanoes listed in Appendix 1. Much work remains to be done. Hazards at all volcanoes near populated areas have been qualitatively assessed, but much of the information must be quantified and many of the published hazard assessments need updating.

Lava flow hazard-zone map for the Island of Hawaii. Hazard zones range from low (9), associated with the dormant Kohala, to high (1 and 2), marking the active summit and rift zones of Mauna Loa and Kilauea and the areas directly downslope from active vents. Volcano boundaries denoted by dashed white lines. Modified from Heliker (1990, p. 22).





The actual extent of damage during the May 18, 1980, eruption of Mount St. Helens, Washington, compared with that anticipated in the hazard-zone map published two years earlier (Crandell and Mullineaux, 1978). Hachured line denotes outline of caldera.

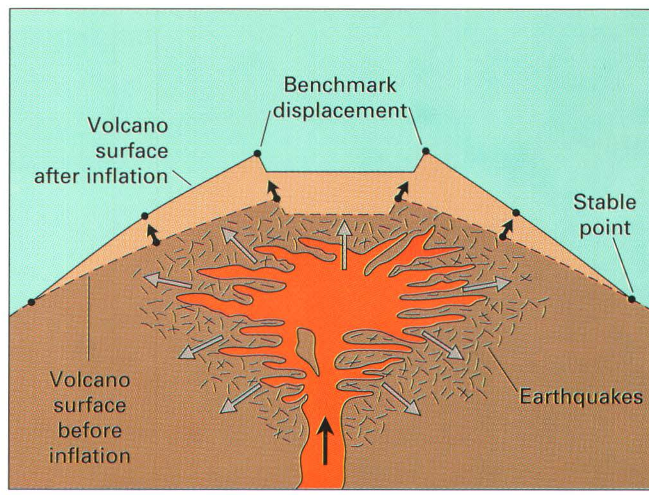
THE CHALLENGE OF PREDICTING ERUPTIONS

A primary goal of the Volcano Hazards Program is forecasting and predicting eruptions. Several increasingly specific and useful steps lead toward prediction (see "How Scientists Study Volcanoes"). Initially, when little is known about the past history and preeruption behavior of a volcano, we may only be able to give **factual information** about current unrest; for example, that swarms of small earthquakes are occurring beneath the volcano, similar to those which have preceded eruptions elsewhere.

When the average repose period and other information regarding a particular volcano's eruptions, for example, when the amount of inflation preceding the previous eruption is matched by current conditions at that volcano, a general **forecast** can be made that the volcano is "ready" to erupt. The start of microearthquakes or other common eruption precursors would lead to an updated forecast—that the volcano may erupt soon.

In the past, forecasts of eruptions were based solely on recurring patterns of unrest before eruptions. The occurrence of one particularly diagnostic type of unrest, for example, volcanic tremor, might be the basis for a **prediction** that the volcano would erupt within a specified number of hours or days. The appearance of other known eruption precursors helped narrow the time window and lent certainty to the prediction.

We now recognize the need to understand why particular patterns and events occur before some eruptions, and this need requires a thorough physical understanding of the volcano's internal plumbing and the processes associated with the generation, transport, storage, and, *ultimately*, eruption of magma. For example, a combination of seismic and geodetic data demonstrates the existence of a complex magma reservoir 2 to 6 kilometers beneath Kilauea's summit from which all eruptions on the volcano ultimately originate. Earthquake foci outline the area of magma storage, whereas horizontal, vertical, and tilt changes above the reservoir define the depth to "centers" of inflation (swelling) or deflation. Understanding of this storage system has greatly improved the ability to determine when Kilauea is fully inflated and ready to erupt. Accurate short-term (within days to weeks) prediction of Hawaiian eruptions remains elusive, as both Kilauea and Mauna Loa may reach a highly inflated state, and wait with no further ground deformation or increase in seismicity until eruption occurs. Some Kilauea rift eruptions are preceded within hours by a strong earthquake swarm whose foci migrate toward the point of outbreak, giving a short but accurate prediction of this type of activity. Volcano monitoring, combined with study of Kilauea's volcanic history, yields the information necessary for long-term eruption forecasts.



Kilauea's summit plumbing system, deduced from seismic and ground-deformation data. Volcano profile prior to inflation (swelling) is shown by dashed line. Volcano surface after inflation is shown as a solid line. Small arrows connect dots depicting position of points on the ground before and after inflation. All measurements are relative to a "stable" point, assumed not to move during inflation. Earthquake hypocenters are shown as short lines surrounding the magma storage area (red). Large arrows denote the direction of magma flow into the storage reservoir, and the direction of strain applied to the surrounding rock from movement of magma into the reservoir. From Tilling and others (1987, p. 17).

As with Hawaiian eruptions, the dome-building eruptions of Mount St. Helens are not predictable many months ahead. Prediction of dome-building eruptions were made, however, within days or weeks, using very simple methods, with relatively little prior knowledge or understanding of the volcano's plumbing system.

PREDICTIONS, FORECASTS, AND FACTUAL STATEMENTS

Successful Eruption Prediction at Mount St. Helens, Washington

As magma moves into the dome in the crater of Mount St. Helens, horizontal fault planes form on the crater floor. The edge of the dome moves on the crater floor in response to magma pushing outward. The amount of movement is measured by the distance between the dome talus and the crater floor using nails and a steel tape. Photograph by Terry Leighley.

The terms **forecast** and **prediction** are often used interchangeably, and both are confused with simple factual statements regarding past occurrence of eruptions. Herein, the following distinctions are made:

A **factual statement** describes current conditions but does not anticipate future events. Mauna Loa erupted 35 times in the past 200 years, and the last large debris flow from Mount Rainier was 500 years ago are two examples of factual statements. The accumulation and analysis of such factual information form the basis for forecasts and predictions.

A **forecast** is a comparatively imprecise statement of the time, place, and, ideally, the nature and size of impending activity. For example, Mauna Loa is likely to erupt at its summit within the

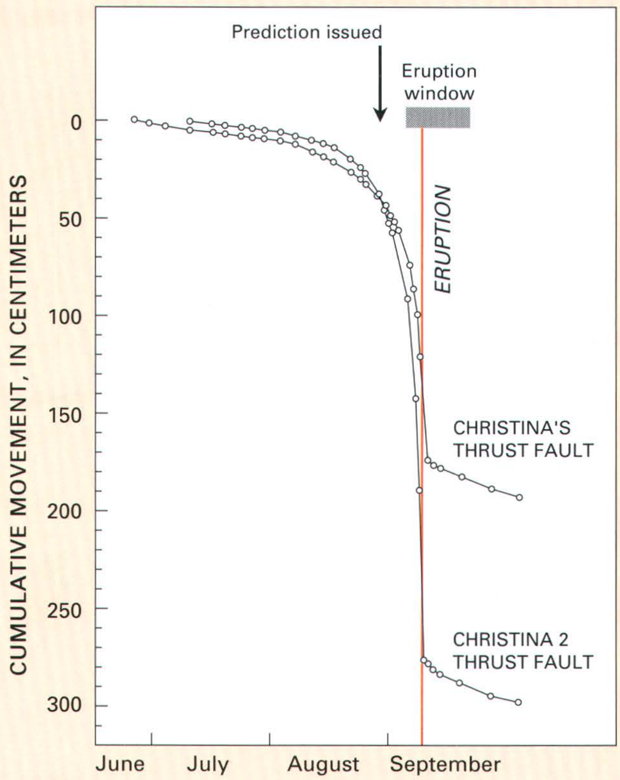
Accurate predictions are still rare in volcanology, and probabilities associated with eruption from a given volcanic system may change after an eruption takes place. Often volcanic systems are in delicate balance and may be considered "ready" to erupt; this determination of readiness allows a medium-range forecast of increased likelihood of eruption. For many currently dormant but potentially active volcanoes, we may only be able to give factual information regarding past activity without specifying what the future holds. For well-studied, historically active volcanoes we can make more specific forecasts of future activity. The most accurate predictions are in the short-term where either rapid ground movements or an earthquake swarm directly precedes eruption at the surface.

COMMUNICATING RESEARCH RESULTS AND HAZARDS INFORMATION

For information derived from the Volcano Hazards Program to be of maximum benefit, it must be communicated in ways that can be easily and directly applied in the reduction of volcanic disasters. Such communication can take place in two ways:

• Working directly with local officials responsible for public safety before, during, and immediately after volcanic eruptions or damaging hydrologic events. Information on anticipated or actual volcanic hazards is used to guide decisions on closing and reopening of

PREDICTIONS, FORECASTS, AND FACTUAL STATEMENTS



When movement on the faults accelerates, an eruption prediction is issued with a prediction window of several days. This window is narrowed as the eruption approaches. Several dome-building eruptions were predicted correctly to within 2 days of the actual eruption.

next five years, as determined from its rate of reinflation and historical eruptive patterns.

A **prediction** is a relatively precise statement giving the time and place of eruption based on interpretations and measurements of ongoing monitoring results and only secondarily on a projection of past history. For example, on the basis of accelerated movement of thrust faults on the crater floor, the next eruption of Mount St. Helens will occur in the summit crater between March 17 and March 20 and will be a dome-building event.

Volcanologists strive to make accurate predictions, although most often a forecast is the most reliable statement that can be made, given the available data and technology. In areas already developed or proposed for development, all three types of information can be used both for land-use planning and as a basis for developing procedures to ensure public safety in anticipation of a volcanic eruption.

Dacitic magma emerges, adding to the dome. Magma extrusion was often accompanied by explosions that partially destroyed the preexisting dome and sent ash over the countryside tens of kilometers from the crater. Photograph by Lyn Topinka.

roads or recreational areas and evacuating people.

• Providing background information on volcanic hazards to local jurisdictions, including planners, developers, public safety officials, and current and potential residents, for the dual purpose of supporting informed decisions regarding land use and encouraging adequate planning for future volcanic crises.

In working directly with public officials, the means of communication is generally face-to-face or by telephone. Discussions in anticipation of volcanic activity may result in adoption of hazard-mitigation strategies such as warning systems or a hierarchy of alert levels. These are activated according to information acquired and delivered by the USGS prior to or during a volcanic emergency.

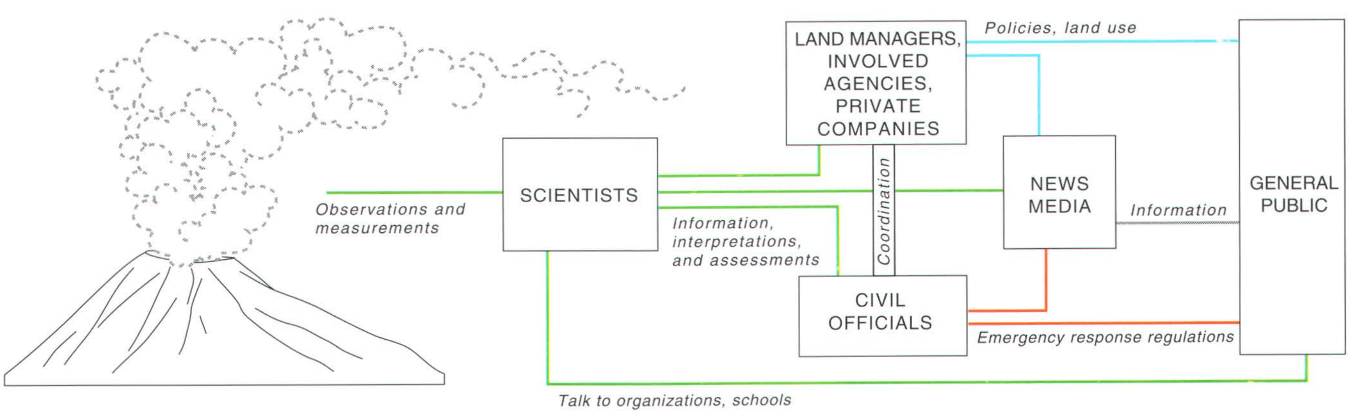
Ongoing communication with public officials is an essential part of the operation of each volcano observatory, and it is a task taken on by the other USGS offices for restless volcanoes away from the observatory sites. The Hawaiian Volcano Observatory has developed an informal and effective communication with the National Park Service and Hawaii County Civil Defense Agency, the two agencies on the Island of Hawaii responsible for public safety.

Hawaiian Volcano Observatory scientist briefing Hawaii State and County officials on volcanic hazards in Hawaii. Photograph by J.D. Griggs.

The Cascades Volcano Observatory delivers warnings of activity at Mount St. Helens in a more complex setting, where information on volcanic hazards is delivered to many agencies at the Federal, State, county, and local levels (see Peterson, 1988). This communication also has been effective and serves as a model for dealing with the many other Cascades volcanoes that have erupted in the not-too-distant past and that could erupt again.

The Alaska Volcano Observatory also has to respond to and communicate with a different mix of agencies, including the Federal Aviation Administration (FAA). In recent years,

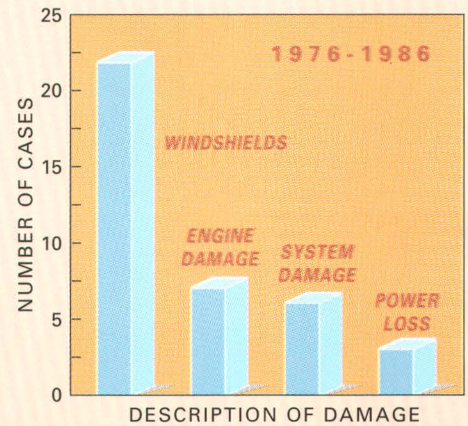
Flow of information about Mount St. Helens, Washington, and its hazards. Scientists must interact with other authorized groups, including State and County leaders, law-enforcement agencies, land managers, and various public agencies and private firms responsible for establishing and enforcing restricted zones and for ordering and supervising evacuation when necessary. The U.S. Forest Service, large timber companies, and other State and Federal agencies and private companies whose operations and decisions are affected by the volcano depend on this information. Other groups, such as the National Weather Service, Federal Aviation Administration, Army Corps of Engineers, fish and wildlife agencies, public utilities, and many others also depend on volcanologists for information and advice. The news media also receive information from scientists, civil officials, and land managers and convey it to the public.



DANGER IN THE STRATOSPHERE: AIRCRAFT AND VOLCANIC PLUMES

During the past 14 years, there have been 23 incidents involving aircraft that have inadvertently encountered eruption plumes. Apart from windshield pitting resulting in loss of visibility, the most common result is engine damage that occurs when volcanic ash enters the jet intakes; the volcanic ash melts and coats turbine blades, often causing the engines to stall. Fortunately, in all past cases, engines have restarted, but only after severe loss of altitude. Most recently a Boeing 747 aircraft lost power in all four of its engines after encountering the plume of the explosive eruption of Redoubt Volcano on December 15, 1989; it glided without power from 8,534 meters (28,000 feet) until engines were restarted at 4,267 meters (14,000 ft), *only* 1,219 meters (4,000 feet) above nearby mountain peaks. The airliner landed safely in Anchorage and no one was hurt, but the damage to the aircraft has been estimated to exceed $80 million (Steenblik, 1990).

Personnel from the Volcano Hazards Program, particularly those at the Alaska Volcano Observatory, are working with officials of the Federal Aviation Administration (FAA) to develop automatic early warning systems for large ash clouds and to streamline communication for eruptions at U.S. volcanoes that might impact aircraft. Other countries have developed or are developing similar procedures, assisted in part by the World Organization of Volcano Observatories and coordinated through the International Civil Aviation Organization.



Number of aircraft (worldwide) that encountered volcanic ash plumes, and the type of damage they incurred, 1976 to 1986.

tragedies have nearly occurred because of temporary engine failures when commercial jetliners flew into ash plumes. The need to issue timely warnings to aircraft has led to development of a system of sensors that detect ash clouds and lightning originating from them, as well as wind speed and direction.

The USGS's ability to effectively communicate information about potential future volcanic activity has been put to its greatest test at Long Valley, where the end result of ongoing unrest is difficult to forecast and where negative economic consequences of that information were anticipated or experienced. Nonetheless, in all of the areas marked by volcanic unrest, the goal of the Volcano Hazards Program remains that of keeping the public apprised as to the likelihood of eruption and the hazards that would be posed.

The USGS publishes hazard assessments, including hazard-zone maps, and general-interest publications on volcanic phenomena. Booklets describing volcano hazards in lay terms, some of which are accompanied by hazard-zone maps, are available for several volcanic areas; the most recent assessments are for Mount Shasta (Crandell and Nichols, 1987, based on Miller, 1980), the Island of Hawaii (Heliker, 1990), and the State of California (Miller, 1989). In addition to volcanic hazard assessments, specific flood and debris-flow hazards have been evaluated at Mount Rainier (Scott and others, 1990), Mount St. Helens (Swift and Kresch, 1982; Meyer and others, 1986; Laenen and Orzal, 1987; Major and Scott, 1988; Glicken and others, 1989), Three Sisters (Laenen and others, 1987), and Mount Shasta (Osterkamp and others, 1986). General-interest publications are available that discuss the volcanic activity of Hawaii (Tilling and others, 1987), Mount St. Helens (Tilling and others, 1990), and Redoubt Volcano (Brantley, 1990). Other activities, conducted in a noncrisis atmosphere, are media briefings on volcanic processes and their associated hazards, local forums to discuss the hazards of a specific area, or meetings with public officials responsible for long-range planning at which USGS scientists are invited to provide hazards information.

Public acceptance of volcano-hazard information as a necessary component of land-use planning and decisionmaking is much more difficult to achieve than is the coordination of response during a volcanic emergency. The USGS is empowered only to communicate information, not to recommend how that information is to be used. Acting on hazard information provided by the USGS requires that public agencies recognize the difference between **hazard** and **risk**. Public officials must make the often difficult assessment of what is an **acceptable risk.** Many, if not most, areas prone to eruption hazards are already developed to the extent that mitigation rather than prevention of volcanic destruction is the most that can be hoped for. Lives can be saved, however, by a combination of a well-informed populace, an ongoing effective interaction between scientists and local officials, and timely warnings of imminent eruption and associated hazards.

The consequences of imperfect communication or ineffective interaction between scientists and public officials can be extremely serious. Severe economic hardship and social disruption can result from either an actual hazard that is not perceived, or from a hazard that is blown out of proportion and made to seem worse than it is. A dependable communication link—between the scientific personnel responsible for making hazards evaluations and the news media—must transmit information in an accurate and timely fashion. For example, the Cascades Volcano Observatory assigned a public information officer to their staff while volcanic activity continued at Mount St. Helens to ensure consistency of information delivered to public officials and the media.

Ultimately, effective coexistence with volcanoes requires difficult and sometimes controversial compromises to be made between the economic pressures to develop land for commercial and residential use, and the need to set aside areas of highest volcanic hazard for wilderness, recreation, or other low-density use. Thoughtful land-use planning serves in the long run to lessen the risks to the local populace in the event of a volcanic eruption.

HAZARD, RISK, AND ACCEPTABLE RISK

The terms **hazard** and **risk**, often used interchangeably, are defined herein as follows:

Hazard: an event or process that is potentially destructive.

Risk: the magnitude of a potential loss—of life, property, or productive capacity—within the area subject to hazard(s).

The threat posed by volcano hazards is a function of those natural processes and can be viewed as constant, whether or not lives and property are in jeopardy. Degree of risk, by contrast, is directly tied to the scale and value of human activity in the path of potential hazards. Options for controlling volcanic hazards are limited: most volcanic events cannot be modified by humans. However, much can be done to minimize volcanic risk—by prudent land use, timely warnings, and community preparedness.

Acceptable risk is that which individuals, businesses, or governments are willing to accept in return for perceived benefits. The level of acceptable risk is usually defined by local governments, taking into account information on volcanic hazards and combining it with economic, social, and political factors specific to the area threatened. In some situations risks will be judged acceptable without special precautions. In other situations local governments can take action to reduce the risk to acceptable levels, such as zoning to control population density, or restricting placement of critical facilities (for example, hospitals) in areas judged to be threatened.

MEETING THE DEMANDS FOR GLOBAL VOLCANO HAZARDS REDUCTION

A volcanologist's laboratory is the world's volcanoes. Although U.S. volcanoes are an important part of that laboratory, none except Kilauea erupts frequently enough for the laboratory to be "open" at all times, and processes at Kilauea differ markedly from those of the more dangerous, but less active, explosive volcanoes of the Cascades and Alaska. Only 2 to 3 volcanoes erupt each year in the U.S., most in remote locations in Alaska, in contrast to 50 to 60 worldwide. Participation in investigations at volcanoes abroad provides a practical way to study more eruptions in the larger laboratory, from which new scientific insights can be applied to U.S. volcanoes. In turn, well-studied U.S. eruptions such as that at Mount St. Helens offer insights that can be applied to similar volcanoes worldwide. Cooperative international programs in volcanology also offer the opportunity of sharing information on volcano-monitoring techniques.

Three examples, one from the U.S., one from South America, and one from the Philippines, illustrate the value of a global view of volcanism:

A massive landslide-debris avalanche and a laterally directed blast from Mount St. Helens in May 1980 thrust those phenomena from obscurity to prominence in volcanology. Direct visual and instrumental observation of the emplacement of that avalanche greatly facilitated identification of similar events at other volcanoes from study of their deposits. Before 1980, only a handful of large volcanic debris avalanches were known; today more than 200 have been recognized and more are being documented each year. Thus the first modern observation of such an event has yielded knowledge that can be applied to saving lives around the world.

The tragedy associated with the November 1985 eruption of Nevado del Ruiz Volcano, Colombia, offered other lessons for the international community. A map, accurately depicting the probable path of a debris flow down the river valley whose canyon mouth was directly upstream of the town of Armero, had been prepared and was available a month *before* the disaster (see "Hazard-Zone Maps and Volcanic Risk"). After steam explosions began, the volcano was monitored by an international group of scientists, and local officials issued an evacuation warning to the populace of Armero less than 2 hours before the debris flow arrived (Voight, 1990). For reasons still not fully known, the warnings were not translated into effective emergency actions, with the result that in that town alone over 21,000 lives were lost. The Ruiz tragedy provided a tragic, costly lesson regarding the need for more effective communication with local citizens and public officials prior to an expected eruption. Mount Rainier (see back cover), in the U.S. Cascade Range, is a similar volcano and, therefore, presents many of the same hazards found at Nevado del Ruiz. Mount Rainier is high and snow-covered, is built of unstable volcanic debris, and has been deeply eroded by glaciers; geologic mapping has revealed that in the past 10,000 years a number of huge debris avalanches and debris flows have run down drainages in which many towns between Tacoma and Seattle are built. The lessons from Colombia, if applied, will help avert a future volcanic disaster that may affect the towns and cities near Mount Rainier.

The June 15, 1991, eruption of Mount Pinatubo in the Philippines (Island of Luzon) provided the most recent opportunity for international cooperation. Geologists from the USGS and PHIVOLCS (Philippine Institute of Volcanology and Seismology) worked together before and during the eruption. Their combined efforts produced a result very different from that at Nevado del Ruiz—successful prediction of a very large eruption combined with an effective response to the volcanic emergency.

ASSISTANCE TO DEVELOPING COUNTRIES

Most of the world's high-risk volcanoes are in developing countries whose growing populations are rapidly encroaching on these volcanoes. This encroachment has greatly increased the vulnerability of communities and economies to devastation from volcanic eruptions and associated hazards. At present, few of these nations have the capability to assess volcanic histories to the degree that would allow them to accurately assess future potential hazards. The USGS, through the Volcano Hazards Program, assumes a professional responsibility to assist foreign colleagues who seek to expand their own volcano-hazards expertise. Technical assistance missions fulfill this responsibility and, in return, afford us the opportunity to study many more active volcanoes than otherwise possible. U.S. scientists can gain valuable experience during overseas volcano crises, and they can join foreign colleagues in working to find simple, low-cost solutions to problems of volcano monitoring and hazard assessment.

The USGS contributes, through its Volcano Crisis Assistance Team (VCAT), to an international Volcano Early Warning and Disaster Assistance Program (VDAP) funded by the U.S. Agency for International Development's Office of Foreign Disaster Assistance (USAID/OFDA) and the USGS. VDAP's nominal mission is global but its main work to date has been in Latin America, mainly in Ecuador, Colombia, and Guatemala. VDAP began as a rapid-response team but has evolved to include a substantial component of work toward pre-eruption preparedness. It has, for example, helped to establish the Observatorio Vulcanologico de Colombia and upgraded capabilities of the Guatemalan Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia, and the Ecuadorian Instituto Geofisico, Escuela Politecnica Nacional.

Another USAID/OFDA project, recently completed, involved assistance to the Volcanological Survey of Indonesia (VSI). That project began as help in upgrading VSI's premier volcano observatory, the Merapi Volcano Observatory; with eruptions at other volcanoes and changes in the funding, the project evolved into one of general institution-building assistance to VSI and encouraged several specific disaster-coordination initiatives. Over the decade of the 1980's, VSI made significant progress toward a modern observational capability, despite a severe domestic funding crisis.

Merapi Volcano Observatory, Indonesia. The USGS has a cooperative program to train Indonesian scientists and technicians in volcano-monitoring techniques. Photograph by John Dvorak.

A third project, just getting underway, is the Center for Study of Active Volcanism (CSAV), located at the University of Hawaii, Hilo Campus. CSAV is funded by the State of Hawaii to train students from developing countries in the techniques of volcano monitoring. It draws additional resources from the main branch of the University of Hawaii in Honolulu and works closely with the USGS Hawaiian Volcano Observatory in both classroom training and assistance in teaching field-monitoring techniques.

Hawaiian Volcano Observatory scientists teaching foreign students enrolled in the University of Hawaii's (Hilo) Center for Study of Active Volcanoes (CSAV) the techniques of recording and locating earthquakes. Photograph by Darcy Bevens.

A VOLCANIC DISASTER AVERTED IN THE PHILIPPINES

On April 2, 1991, people from the village of Patal Pinto, on the Philippine Island of Luzon, saw small explosions followed by steaming and the smell of rotten eggs (H_2S gas) coming from the upper slopes of Mount Pinatubo, a dormant volcano whose last known eruption was 600 years ago. Thus began the unrest that within 10 weeks led to one of the largest 20th century eruptions.

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) immediately installed portable seismometers near the mountain and began recording several hundred earthquakes a day. At the request of PHIVOLCS, made through the USAID office in Manila, U.S. Geological Survey personnel arrived on April 23. Within 2 weeks the team of Philippine and American volcanologists had installed a radiotelemetered seismic network capable of locating the increasing number of earthquakes. They began tape measurements across fractures opened during the early steam explosions, and they later installed tiltmeters to detect new ground movement. With the help of the U.S. Air Force, measurements of the SO_2 content of gas in the steam plumes, now continuously visible at Pinatubo, were begun. Between May 13 and May 28, a 10-fold rise in SO_2 content was measured. All signals indicated that magma was rising within the volcano.

Meanwhile, Philippine and American geologists made a geological reconnaissance of the volcano and established a set of alert levels ranging from 1 (low-level unrest) to 5 (eruption underway). When the alert system was completed on May 13, the level was set at 2 meaning that magma was probably involved in the unrest. The geological reconnaissance showed the dominant lava products were dacite domes near the summit and valley-filling pyroclastic flows extending radially out from the summit to a distance of 10 to15 kilometers. Small villages on the volcano's northwest slope and part of Clark Air Base lay within the potential range of pyroclastic flows. Numerous communities, including the city of Angeles with a population of 300,000 lay within the apron of debris flows extending well beyond the volcano. A hazard map was prepared and distributed to local officials by May 23 showing virtually all of the hazards subsequently encountered when Pinatubo erupted.

Seismic activity escalated in early June, and on June 5 PHIVOLCS raised the alert level to 3—eruption possible within 2 weeks. A small dome extruded on the north flank on June 7 accompanied by thousands of small earthquakes triggering a level 4 alert—explosive eruption possible within 24 hours. Continuous ash emission began, and 2 days later PHIVOLCS raised the alert level to 5 signifying an eruption had begun. Clark Air Base was evacuated on June 10. On June 12, the first of several major explosions took place, sending airborne ash to the west and pyroclastic flows down the northwest slope of the volcano. Areas potentially impacted by the pyroclastic flows had been evacuated in response to the level 3 alert. The city of Angeles was put on evacuation alert. A climactic eruption took place on June 15 during passage of a typhoon, which had already resulted in closure of the International Airport at Manila. The typhoon compounded the effects of the eruption by generating mudflows in addition to ash fall and greatly hampering evacuation efforts. By June 16 when the weather cleared, the top of the volcano was gone, replaced by a

Personnel from the U.S. Geological Survey and Philippine Institute of Volcanology and Seismology installing a seismometer to record earthquakes at Mount Pinatubo. Photograph by John Ewert.

A VOLCANIC DISASTER AVERTED IN THE PHILIPPINES

Timing of events and responses during Mount Pinatubo eruption, Luzon Island, the Philippines

Date (1991)	Volcanic activity	Monitoring	Alert level	Response
4/2	Small steam explosions; earthquakes began.			PHIVOLCS alerted.
4/5		PHIVOLCS installed portable seismometers.		
4/23		USGS joined PHIVOLCS efforts in monitoring and hazard assessment.		Villages within 10 kilometers of the summit were evacuated.
4/30-5/10		PHIVOLCS-USGS radio-telemetered seismic network installed. Earthquakes located on northwest side of summit.		
5/13	Continued earthquakes and steam emission.	Correlation spectrometer (COSPEC) measurements began. SO_2 emission equaled 500 tons/day.	2	Alert system in place.
5/23		Hazard map completed.		
5/28		SO_2 emission equaled 5,000 tons/day.		
6/5	Greatly increased earthquake activity; volcanic tremor identified.	Continued seismic and other monitoring provided basis for eruption forecast and setting of alert levels.	3	Villages on northwest slope were evacuated again.
6/8	Dome extruded; further increase in number of earthquakes and increased volcanic tremor; beginning of continuous ash emission.		4	
6/9			5	
6/10				Near-total evacuation of Clark Air Base.
6/12	First large explosive eruption; pyroclastic flows moved down northwest valleys.			
6/15	Climactic (caldera-forming) eruption. Dome collapse; widespread ashfall; large pyroclastic flows and mudflows.			Buildings collapsed from loading by water-saturated ash combined with felt earthquakes. Manila International Airport closed.
Ongoing from 6/16.	Continuous ash emission punctuated by larger ash eruptions all smaller than June 15 event; continued small pyroclastic flows to northwest and mudflows in all directions.	Continuing PHIVOLCS-USGS monitoring		Continuing PHIVOLCS-USGS hazard evaluation.

2-kilometer-wide caldera, and pyroclastic flow deposits had largely filled preexisting valleys on all sectors of the volcano. Ash had fallen over a vast area beyond the volcano. The weight of the thick blanket of heavy, water-saturated ash combined with continued felt earthquakes resulted in the collapse of many buildings in Philippine cities and villages as well as on Clark Air Base and the more distant Subic Bay Naval Base. The ash reached thicknesses of 30 centimeters as far as 40 kilometers away from the volcano. Following the climactic eruption, continuous ash emission at a lower level continues at this writing (July 1991).

Loss of life in the Pinatubo eruption was remarkably low, given the size of the eruption—350 people died, mostly in buildings that collapsed. The alert system put in place by PHIVOLCS combined with effective communication among the USGS, PHIVOLCS, local civil defense agencies, and the U.S. Military Command prevented a much greater human disaster. The scientific information necessary to guide the alerts was gathered by USGS and Philippine geologists working side by side, each complementing the others' expertise in order to turn potential disaster into a responsibly handled volcanic emergency. As an exercise in both eruption prediction and effective response, the 1991 Pinatubo eruption provides an important model for future situations in which dormant volcanoes come to life.

A LOOK TOWARD THE FUTURE

The 1990's have been designated the International Decade for Natural Disaster Reduction (IDNDR). The USGS, as an active participant in the IDNDR Program, recognizes several challenges to both our understanding of volcanic activity and to our ability to communicate scientific results in a way that can be used by communities facing volcanic hazards. We list below a representative list of challenges that can be met during the 1990's, listed under five important elements of the Volcano Hazards Program. Tasks designed to meet these challenges are given in Appendix 3.

Eruption Prediction

Precursory earthquakes and ground deformation are likely at any volcano about to become active. Establishment and monitoring of base line seismic and geodetic networks at all volcanoes that present a potential risk to populated areas are essential to early detection of volcanic unrest and potential eruption. The technology for monitoring volcanic unrest is rapidly changing. It is possible now to telemeter data from seismometers to a central facility, where earthquake hypocenters can be located automatically within minutes after they occur. It will soon be possible to also telemeter data on ground movements via Global Positioning Satellite (GPS) geodesy. We anticipate that within two decades GPS instrumentation will replace conventional geodetic techniques of volcano monitoring. This will make possible the early detection of volcanic unrest wherever it occurs, allowing time to augment geodetic and seismic monitoring with other techniques, and adequate time to take proper measures to reduce volcanic risk, should the unrest culminate in eruption.

Volcano Hazard Assessment

Hazard assessments at several U.S. volcanoes, using data from many sources, need to be completed or updated. Integration and analysis of the wide variety of data that are used in volcano hazard assessment will be greatly facilitated by the emerging technology of Geographic Information Systems (GIS). Using GIS, the entire spectrum of maps covering different types of hazards in a given volcanic area could be displayed and printed when needed. To be effective, GIS requires both accurate and up-to-date geologic, geochemical, geophysical, and hydrologic data. In turn, fundamental geologic and hydrologic studies in volcanic regions must be expanded and updated. Another developing technology is computer modeling of the paths of lava flows, debris flows, or debris avalanches. For such modeling it is essential to have accurately digitized topographic maps of volcanoes. The results of flow-path modeling will allow precise forecasts of the area and timing of impact for a volcanic event if the source area, for example, volcanic vent or potential landslide scarp, is known. Computer modeling also holds promise for predicting downwind transport rates, altitudes, and dispersion of ash clouds.

Research in Volcano Processes

Of all the various types of eruptive activity, explosive eruptions pose the greatest threat to life and property. Large-scale explosive activity involves interaction of liquid magma or very hot rock with the surrounding ground-water system. At present we have an inadequate understanding of the processes associated with magma-water interactions. It is possible now to address these problems by combining increasingly sophisticated geophysical techniques with measurements from wells and advanced ground-water modeling.

Large-scale debris avalanches (often accompanied by debris flows and floods) have potential to cause the greatest loss of life near many of the world's volcanoes. Modeling of ground water and magma fluid pressures, stress distributions in volcanic cones, and susceptibility to seismic destabilization will allow us to (1) recognize sectors of volcanic cones that are potentially unstable, (2) identify seismic, geodetic, or other precursory signs to catastrophic failures, and (3) predict the timing, ultimate size, or runout distance of an avalanche if failure is anticipated. Our understanding of the flow dynamics of large debris flows and related sediment-charged flood waves is also far from complete. Quantitative characterization of these, on a par with our understanding of normal floods, is necessary for accurate prediction of arrival times and inundation depths in downstream areas. Theoretical and experimental data collection is now being planned as a cooperative research project between the USGS (at CVO) and the U.S. Forest Service.

Another promising area of inquiry is the relation of certain seismic signals, for example, harmonic tremor, to the movement of magma toward the surface—specifically, to the release of dissolved gases during magma transport and to the boiling of ground water. Greater understanding of the behavior of magma underground will contribute to more accurate forecasting of eruptions and to discrimination of geophysical signals that are actual precursors to eruption from those that merely signify temporary volcanic unrest.

Effective Communication

During the 1980's we gained valuable experience in working with public officials and local communities faced with volcanic eruptions in Hawaii (from Mauna Loa and Kilauea), Washington and Oregon (from Mount St. Helens), and Alaska (from Mount Augustine and Redoubt Volcano), and with a threat of volcanic eruption at Long Valley, California. We also learned lessons from various volcanic crises and disasters elsewhere in the world. A major challenge of the 1990's is to develop emergency response plans that can be quickly put in place in any area that shows signs of volcanic unrest. Experience indicates that graduated levels of alert and response are best. The implementation of such plans will require close coordination and cooperation with local officials responsible for public safety and with the affected community.

Two USGS publications released within a month after the October 17, 1989, Loma Prieta earthquake in California summarize the lessons learned and deliver an important message regarding the likelihood of more damaging earthquakes in California within the next 30 years (Plafker and Galloway, 1989; Ward and Page, 1989). The Loma Prieta earthquake also was the catalyst to prepare "The Next Big Earthquake in the Bay Area May Come Sooner than You Think. Are You Prepared?," a magazine supplement in nontechnical English, Spanish, and Chinese that was distributed to over 2.8 million San Francisco Bay Area residents a year later. Just as earthquakes continue to happen in California, so will some of the presently dormant volcanoes in the U.S. reawaken and erupt. The Volcano Hazards Program strives to anticipate these eruptions and to provide a firm basis for community preparedness before a volcanic crisis strikes.

Working in the World Laboratory

At the beginning of the International Decade of Natural Disaster Reduction, a number of volcanoes around the world were nominated for intensified collaborative study. U.S. volcanoes are Mount Rainier, Mauna Loa, and Long Valley Caldera. The first was an obvious selection for the magnitude of the threat to densely populated areas west of the volcano. The second was chosen because it is relatively easy to study, much is already known to guide further study, and like the work done at Kilauea, we expect to be able to develop and test volcano-monitoring techniques on Mauna Loa for use on other volcanoes where access is more difficult. The third is a caldera that is now showing unrest. It is a type of volcano with the potential for widespread destruction, but it is also a type for which very little is known in terms of eruption precursors. We anticipate that international collaboration will yield far greater insights into the nature of volcanic processes and the hazards they pose than would the effort of any single nation.

EPILOG

Even with anticipated technological advances in the 1990's, the work of the Volcano Hazards Program will continue to be people-intensive. Geologic and hydrologic fieldwork necessary for hazards mapping, and the interpretation of monitoring data cannot be done by sophisticated instruments or computer software alone, nor can a GIS printout substitute for human interaction and judgment during a volcanic crisis. We also recognize the need to develop simple, low-cost, and rugged ("low-tech") instruments and techniques that complement the increasingly sophisticated and expensive "high-tech" approaches.

Volcanoes with their eruptions and other related hazards have long been regarded in this country as exotic phenomena found only in remote corners of the world. In 1980 when Mount St. Helens demonstrated a wide spectrum of nature's fury that perception changed dramatically. Now that we have (1) a much better understanding of hazardous processes at volcanoes, (2) new advances in monitoring and computer technology, (3) the fresh awareness of what volcanoes can do in the minds of people around the world, and (4) the IDNDR with its opportunities for scientific exchange, the 1990's are ripe for significant progress in reaching the goals of the Volcano Hazards Program. The USGS is ready to meet the ongoing challenge of understanding volcanic hazards to mitigate and, when possible, prevent volcanic disasters.

PHOTOGLOSSARY OF VOLCANIC HAZARDS

The following photographs illustrate different kinds of eruptive activity and the associated hazards for selected volcanic areas within the United States

Pyroclastic fallout (ash fall or tephra fall). Volcanic ash (material less than 2 millimeters in diameter) or tephra (material greater than 2 millimeters in diameter) is formed when magma is finely fragmented by vesiculation or when previously solidified rocks are shattered by the explosion of ground water into steam. Ash falls are deposited beneath an eruption column and for many kilometers downwind; the ash fall becomes finer grained with increasing distance from the volcano. Vigorous eruption plumes can carry the finest ash into the stratosphere, where strong winds distribute it over many thousands of kilometers. Even a small ash fall poses a serious nuisance to people, crops, machinery, and computers. When thick or wet, it can cause roofs to collapse. Windborne ash is a serious threat to aircraft.

Ash-laden eruption plume *from Mount St. Helens rising into the stratosphere and moving eastward with the prevailing winds (July 22, 1980). Photograph by Mike Doukas.*

Ash falling in Yakima, Washington, on May 18, 1980, following the eruption of Mount St. Helens. Photograph courtesy of Yakima Herald-Republic. Used with permission.

*Channeled **aa lava** flow from Mauna Loa, March 1984. Photograph by Toni Duggan.*

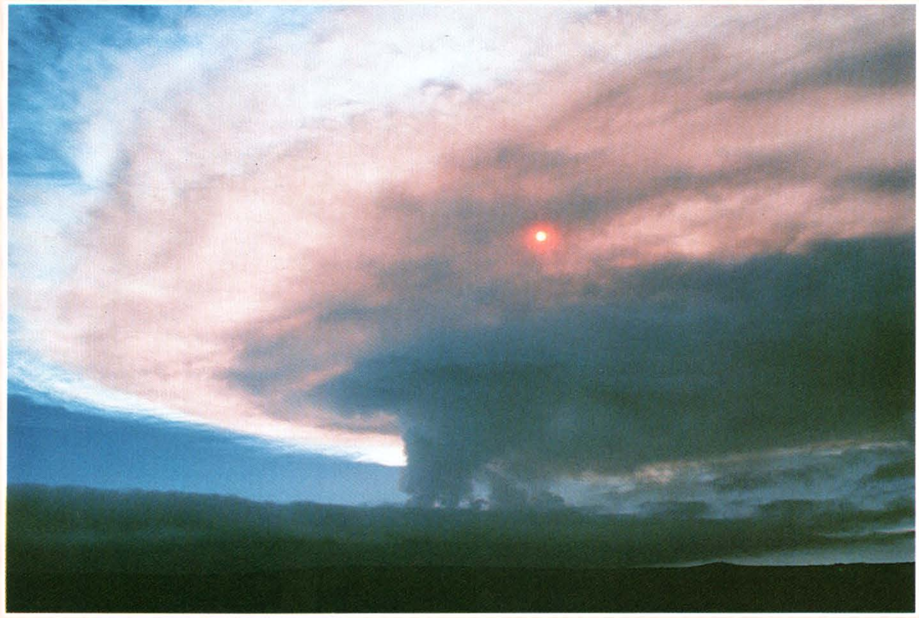
***Lava dome** of Novarupta, Katmai National Monument, Alaska. Photograph by Gene Iwatsubo.*

Lava flows. Streams of molten rock that either effuse quietly from a vent or are fed by lava fountains. Fluid **basalt** flows can move at velocities from 15 to as high as 50 kilometers per hour on steep slopes and travel up to tens of kilometers from their source. Viscous **andesite** flows move only a few kilometers per hour and rarely extend more than 8 kilometers from their vent. Lava flows destroy everything in their path, but most move slowly enough that people can escape. **Lava domes.** Lava (usually **dacite** or **rhyolite**) that is too sticky to flow far from its vent forms steep-sided mounds called **lava domes**.

*Destruction of the National Park Service Wahaula Visitor Center on June 22, 1989, by **pahoehoe lava** from Kilauea. Photograph by J.D. Griggs.*

PHOTOGLOSSARY OF VOLCANIC HAZARDS

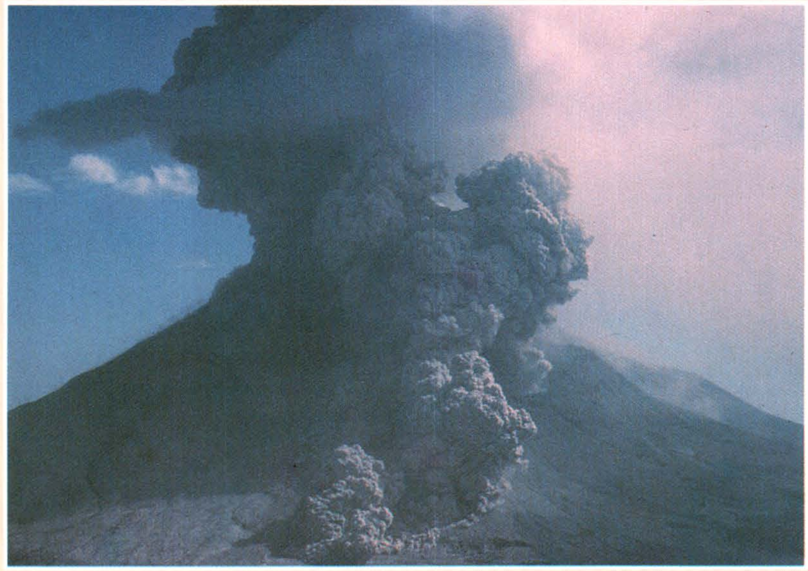
Volcanic gases. The most common gases associated with active volcanoes are water vapor, carbon dioxide, sulfur dioxide, hydrogen sulfide, hydrogen, helium, carbon monoxide, and hydrochloric acid. Lesser amounts of hydrofluoric acid, nitrogen, argon, and other compounds are commonly associated with active volcanoes as well. Volcanic gases rarely reach populated areas in lethal concentrations, although sulfur dioxide can react with the atmosphere downwind and fall as acid rain to cause corrosion and a host of other effects. People with respiratory or heart diseases are especially susceptible to volcanic gases (**fume**). Carbon dioxide is heavier than air and tends to collect in depressions, where it can occur in lethal concentrations and cause suffocation. On occasion, toxic concentrations of fluorine from hydrofluoric acid have been adsorbed onto ash and ingested by livestock or leached into domestic water supplies.



***Volcanic gas plume** from Puu Oo cone, Kilauea east rift zone, April 1985. Photograph by J.D. Griggs.*

*Broccoli plants wilted by **volcanic fume** from the ongoing eruption at Kilauea. Photograph by J.D. Griggs.*

Pyroclastic flows and **pyroclastic surges**. Mixtures of hot rock fragments and gases can sweep away from their source vents at hurricane velocity. Pyroclastic flows are dense and most are confined to valleys around a volcano; the largest ones can travel tens or even hundreds of kilometers beyond a volcano. Pyroclastic surges are turbulent, low-density variants of pyroclastic flows. Some unusually rapid pyroclastic flows or surges originate from laterally directed explosions from a vent. Because of their high speed and high temperature, pyroclastic flows and surges kill or destroy virtually all that is in their path.



***Pyroclastic flow** moving downslope at Mount St. Helens, August 1980. Photograph by Rick Hoblitt.*

The town of St. Pierre, Martinique, following the eruption of Mont Pelée in 1902. Pyroclastic flows completely destroyed the town of 65,000 people. Photographer unknown.

PHOTOGLOSSARY OF VOLCANIC HAZARDS

Volcanic landslide *that marked the beginning of the Mount St. Helens eruption, May 18, 1980. The landslide itself, obscured by the eruption plume, is represented by the missing sector of the volcano, which slid away just prior to the explosion producing the eruption plume. Photograph courtesy of Keith Ronnholm. Used with permission.*

Volcanic landslides. Gravity-driven slides, often rapid, of a mass of rock and soil that can occur in all sizes, from those involving a small amount of loose debris on the surface of a volcano to massive failures of the entire summit and (or) the flanks of a volcano. Volcanic landslides need not be associated with eruptions; heavy rainfall or a large earthquake can trigger landslides on steep volcanic slopes. Landslides that have evolved into a chaotic tumbling flow are termed **debris avalanches**.

Debris avalanche *deposit in North Fork Toutle River valley following the May 18, 1980, eruption of Mount St. Helens (in the distance). Valley is approximately 2.4 kilometers wide. Photograph by Lyn Topinka.*

Waning stage of May 18, 1980, volcanic **debris flow** in Toutle River valley. Woody debris covers banks and fluid surface; mud slurry contains nearly two-thirds rock fragments by volume. Photograph by Don Swanson.

Volcanic debris flows (mudflows or lahars). Flowing mixture of water-saturated debris, intermediate between a debris avalanche and a water flood, typically moves at speeds of several tens of miles per hour on steep slopes, slowing to less than 10 mi per hour on gentle slopes. Debris flows can travel tens of miles down valley and devastate distant unsuspecting communities, as in Colombia during the 1985 eruption of Nevado del Ruiz.

Aerial view of Crater Lake showing depression (**caldera**) left by destruction of ancestral Mount Mazama and subsequent collapse. Photograph by Roland Emetaz, U.S. Forest Service. Used with permission.

Caldera. Large depression commonly formed by collapse of the ground following explosive eruption of a large body of stored magma. Calderas at Yellowstone and Long Valley are associated with eruption of silicic magma as pyroclastic flows that covered large areas around and within the caldera. Kilauea caldera, by contrast, is thought to be associated with draining of basaltic magma from beneath Kilauea's summit. The caldera now filled by Oregon's Crater Lake was produced by an eruption that destroyed a volcano the size of Mount St. Helens and sent volcanic ash as far east as Nebraska.

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Appendix 1. Active and potentially active volcanoes in the United States

Volcano	Eruption type(s)	Number of eruptions in the past 200 years	Latest activity (in years before present or year(s) A.D.)	Remarks
			HAWAII	
Loihi	Lava	Not known	Not known	Submarine volcano; seismically active; youngest lava less than 1,000 years old.
Kilauea	Lava, most common; ash, rare.	47	Ongoing from 1983	Explosive eruption at Kilauea summit in 1790 killed approximately 80 Hawaiian warriors. Eruptions presenting lava-flow hazard to coastal areas: 4 in the 19th century; 5 in the 20th century.
Mauna Loa	Lava	30	1984	Eruptions presenting lava-flow hazard to coastal areas: 8 in the 19th century; 8 in the 20th century.
Hualalai	Lava, ash	1	1800–01	High hazard due to unusually fluid lava.
Mauna Kea	Lava, ash	0	4,000 years ago	Frequency of activity before latest eruption is estimated to be about 300 years.
Kohala	Lava, ash	0	120,000 years ago	Volcanic cycle may not be completed, but eruption probability is low.
Haleakala	Lava, ash	1	1790	In last stage of Hawaiian volcanic cycle. Expected recurrence rate estimated to be about 200-600 years.
			ALASKA	
			Eastern Alaska	
Wrangell	Ash	1?	1902?	Emission of gases and vapors from vents (fumarolic activity).
			Cook Inlet	
Mount Hayes	Ash	0	450?	
Mount Spurr	Ash	1	1953	
Redoubt Volcano	Ash, dome	4	Ongoing	Eruption began December 1989.
Iliamna Volcano	Ash	?	?	
Augustine Volcano	Ash, dome	5	1986	
			Alaska Peninsula	
Katmai Group	Ash, lava			
Mount Mageik		4	1946	
Mount Martin		7	1990	
Novarupta		1	1912	The world's largest 20th century eruption.
Trident Volcano		1	1964	
Mount Ugashik—Mount Peulik (Ukinrek Maars).	Ash	1	1977	Ukinrek Maars formed 1.5 kilometers south of Becharof Lake, 12 kilometers from Peulik.

Appendix 1. Active and potentially active volcanoes in the United States—Continued

Volcano	Eruption type(s)	Number of eruptions in the past 200 years	Latest activity (in years before present or year(s) A.D.)	Remarks
		Alaska Peninsula—Continued		
Yantarni Volcano[1]—Mount Chiginagak.	Ash	2	1971	
Aniakchak Crater	Ash, dome	1 (or 2?)	1931	
Mount Veniaminof	Lava, ash	7	1983–84	
Mount Emmons—Pavlof Volcano.	Ash, lava	30	1987	Pavlof is most frequently active volcano in Alaska.
Mount Dutton	Ash, lava	0	?	
		Aleutian Islands		
Kiska Volcano	Ash, lava	7	1990	Steam and ash emission.
Little Sitkin Volcano[1]	Ash, lava ?	1?	1900?	
Mount Cerberus (Semisopochnoi).	Ash, lava ?	1	1987	Possibly from Sugarloaf, satellitic vent on south flank.
Mount Gareloi	Ash, lava	6	1987	
Tanaga Volcano	Lava, ash	1	1914	
Kanaga Volcano	Lava	2	1933	
Great Sitkin Volcano	Ash, dome	6	1974	
Kasatochi Island	?	1	1828	
Korovin Volcano	Ash	7	1951?	
Pyre Peak (Seguam).	Ash, lava	5	1977	Eight lava fountains, as high as 90 meters.
Amukta Volcano[1]	Ash, lava	3	1987	
Yunaska Island	Ash	2	1937	Minor ash emission.
Carlisle Volcano	?	1	1987	Probable small steam and ash eruption, possibly from Cleveland.
Mount Cleveland	Ash, lava	10	1987	1945 eruption resulted in only known fatality from Alaska volcanism.
Kagamil Volcano	?	1	1929	
Mount Vsevidof	Ash	1	1957	
Okmok Caldera	Ash, lava	11	1988	
Bogoslof Volcano[1]	Ash, dome	6	1951	
Makushin Volcano	Ash	7	1980	

Appendix 1. Active and potentially active volcanoes in the United States—Continued

Volcano	Eruption type(s)	Number of eruptions in the past 200 years	Latest activity (in years before present or year(s) A.D.)	Remarks
		Aleutian Islands—Continued		
Akutan Peak	Ash, lava	21	1988	
Westdahl Peak	Ash, lava	2	1978	
Fisher Dome	Ash	0	1830	
Shishaldin Volcano.	Ash, lava	About 18	1987	
Isanotski Peaks	Ash, lava	0	1845	
		CASCADE and COAST RANGES		
		Washington		
Mount Baker	Ash, lava	1?	1870	Increased heat output and minor melting of summit glacier in 1975; some debris flows not related to eruption. History of extensive pyroclastic flows.
Glacier Peak	Ash	More than 1?	Before 1800	
Mount Rainier	Ash, lava	1?	1882 (?)	History of massive debris avalanches and debris flows. Occasional very shallow seismicity.
Mount Adams	Lava, ash	0	More than 3,500 years ago.	Debris flows are the most recent events.
Mount St. Helens	Ash, dome, lava.	2–3	1980-present	Continuing intermittent volcanic activity.
		Oregon		
Mount Hood	Ash, dome	2?	1865	Occasional seismic swarms.
Mount Jefferson	Ash, lava	0	More than 50,000 years ago.	Debris flows in 1934, 1955; young basaltic flows in nearby area.
Three Sisters	Ash, lava	0	950?	Debris flows in this century.
Crater Lake	Ash, lava, dome.	0	4,000 years ago	Largest known eruption from Cascade Range volcano. Catastrophic, caldera-forming eruption 7,000 years ago; post-caldera lava and domes.
Newberry Crater	Ash, lava	0	600	Latest eruption was obsidian flow.
		California		
Medicine Lake	Ash, lava	0	1065	Latest eruption formed Glass Mountain.
Mount Shasta	Ash, dome	1	1786?	Debris flows in this century.
Lassen Peak	Ash, dome	1	1914–1917	Lateral blast occurred in last eruption.
Clear Lake[2]	Lava, ash	0	Not known	Geothermal energy and long-period (volcanic) seismicity suggest "active" status.

Appendix 1. Active and potentially active volcanoes in the United States—Continued

Volcano	Eruption type(s)	Number of eruptions in the past 200 years	Latest activity (in years before present or year(s) A.D.)	Remarks
CONTINENTAL INTERIOR				
California				
Long Valley Caldera.	Ash, dome, ashflow.	3?	About 1400	Youngest activity represented by nearly simultaneous eruptions of rhyolite at several of the Inyo craters; currently restless, shown by seismicity and ground deformation.
Coso Peak	Lava, ash, dome.	0	About 40,000 years ago.	Geothermal energy production and seismic activity suggest "active" status.
Arizona				
San Francisco Field.	Lava	2	1065–1180	Sunset Crater; disrupted Anasazi settlements.
New Mexico				
Bandera Field (McCarty's Flow).	Lava	1	About 1000	Most voluminous lava within past 1000 years.
Idaho, Montana, and Wyoming				
Craters of the Moon, Idaho.	Lava	About 1	2,100 years ago	Youngest activity in the Snake River Plain.
Yellowstone Caldera, Wyoming, Montana, and Idaho.	Ashflow	0	70,000 years ago	Numerous hydrothermal explosions, geysers, geothermal activity; currently restless, shown by seismicity and ground deformation.

[1]Informal name, not officially recognized by the Board on Geographic Names.

[2]California Coast Ranges.

Appendix 2. Status of hazard evaluation for volcanoes in the United States

[Volcanoes included on the same map are grouped together]

Volcano	Geologic map	Petrologic study	Hydrologic study	Monitoring: Seismic	Monitoring: Geodetic	Monitoring: Gas	Monitoring: Other[1]	Hazard assessment
HAWAII								
Loihi	Yes (preliminary)	Yes	No	Yes	No	Little	No	No
Kilauea	Yes	Yes	Incomplete[2]	Yes	Yes	Yes	Yes	Yes
Mauna Loa	Yes	Yes	No	Yes	Yes	Yes[3]	Yes[3]	Yes
Hualalai	Yes	Yes	No	Yes	Yes[3]	No	No	Yes
Mauna Kea	Yes	Yes	No	Yes	Yes[3]	No	No	Yes
Kohala	Yes	Yes	No	Yes	No	No	No	Yes
Haleakala	Yes (needs revision).	Yes	No	Yes	No	No	No	Yes
ALASKA								
Eastern Alaska								
Wrangell	No	Incomplete[4]	Incomplete[4]	No	No	No	No	No
White River	No	No	No	No	No	No	No	No
Edgecumbe	Yes	Yes	No	No	No	No	No	Preliminary
Cook Inlet								
Hayes	No	No	No	No	No	No	No	No
Spurr	In progress	Yes	Yes	Yes	No	No	No	In progress
Redoubt	In progress	In progress	In progress	Yes	Yes	Yes	No	In press
Iliamna	In progress	In progress	No	Yes	No	No	No	No
Augustine	In progress	Yes	No	Yes	Yes[3]	Yes[3]	No	Preliminary
Alaska Peninsula								
Ugashik-Peulik	In progress	In progress	No	No	No	No	No	No
Yantarni-Chiginagak	No	No	No	No	No	No	No	No
Aniakchak	In progress	In progress	No	No	No	No	No	No
Black Peak	In progress	No	No	No	No	No	No	No
Veniaminof	In progress	In progress	No	No	No	No	No	No
Dana	In progress	No	No	No	No	No	No	No
Emmons Lake-Pavlof	In progress	In progress	No	Yes	No	No	No	No
Dutton	In progress	In progress	No	Yes	No	No	No	No

Appendix 2. Status of hazard evaluation for volcanoes in the United States—Continued

Volcano	Geologic map	Petrologic study	Hydrologic study	Monitoring				Hazard assessment
				Seismic	Geodetic	Gas	Other[1]	
Alaska Peninsula—Continued								
Katmai group (includes Martin, Mageik, Novarupta, Trident, Katmai)	Yes[5]	Novarupta only	No	Yes	Novarupta only[3]	No	No	No
Aleutian Islands								
Reconnaissance geologic maps exist for about one-third of the Aleutian volcanoes, but these lack the details necessary for deciphering eruptive history. Only a few petrologic studies, hydrologic studies, and monitoring studies have been made of Aleutian volcanoes.								
CASCADE and COAST RANGES								
Washington								
Mount Baker	Outdated	Incomplete	Incomplete	Yes	Yes[3]	Yes[3]	No	Preliminary[6]
Glacier Peak	Outdated	Incomplete	Incomplete	Poor	No	No	No	Preliminary[6]
Mount Rainier	Outdated	No	Yes	Yes	Yes[3]	No	No	In progress
Mount Adams	In progress	In progress	Incomplete	Poor	No	No	No	Partial
Mount St. Helens	In progress	Incomplete	Yes	Yes	Yes	Yes	No	Needs updating
Oregon								
Mount Hood	Outdated	Incomplete	Incomplete	Yes	Yes[3]	Yes[3]	No	Preliminary[6]
Mount Jefferson	In progress	In progress	Incomplete	Yes	No	No	No	No
Three Sisters	Partial	Incomplete	Incomplete	Yes	Yes[3, 7]	No	No	In progress[8]
Newberry Crater	Yes	In progress	Incomplete	Yes	Yes[3]	No	No	No
Crater Lake	In progress	In progress	Incomplete	Yes	Yes[3]	No	No	No
California								
Medicine Lake	In progress[9]	Yes	Incomplete	Yes	Yes[3]	No	No	In progress[10]
Mount Shasta	In progress	In progress	Incomplete	Yes	Yes[3]	Yes[3]	No	Preliminary[6]
Lassen Peak	In progress	In progress	Incomplete	Yes	Yes	Yes	No	Preliminary[6]
Clear Lake	Yes	Yes	Incomplete	Yes	No	No	No	No
CONTINENTAL INTERIOR								
California								
Long Valley	Yes	Yes	Yes	Yes	Yes	Yes	No	Preliminary
Coso Field	Yes	Yes	Yes	Yes	No	No	No	No

Appendix 2. Status of hazard evaluation for volcanoes in the United States—Continued

Volcano	Geologic map	Petrologic study	Hydrologic study	Monitoring: Seismic	Monitoring: Geodetic	Monitoring: Gas	Monitoring: Other[1]	Hazard assessment
Arizona								
San Francisco Field	Yes	Yes	No	Yes	No	No	No	No
New Mexico								
Bandera Field	Yes	Yes	No	No	No	No	No	No
Montana, Idaho, and Wyoming								
Craters of the Moon	Yes	Yes	Incomplete	Yes	No	No	No	Preliminary
Yellowstone, Montana Idaho, Wyoming.	Yes	Yes	Incomplete	Yes	Yes	Yes	No	No

[1]Electrical geophysics, magnetics, and gravity.

[2]Extensive mapping of the local water table and fresh water-seawater interface using resistivity soundings and geophysical logs from one deep drill hole.

[3]Limited coverage or infrequent remeasurement.

[4]Field studies have been completed, but the volcano has not been thoroughly and systematically studied using modern techniques.

[5]No mapping of individual volcanoes.

[6]Hydrologic component of assessment not yet complete.

[7]No monitoring of North Sister, Middle Sister, or Mount Bachelor.

[8]Geologic component of assessment only.

[9]Geologic map (covering approximately 10 percent of the volcano) of Lava Beds National Monument published.

[10]Both geologic and hydrologic components need updating.

TASKS FOR THE 1990'S

Future tasks and activities of the Volcano Hazards Program can be described in five elements, which also serve as the framework of the accompanying text.

1. Eruption prediction

2. Volcanic hazard assessment

3. Research in volcanic process

4. Effective communication

5. Working in the world laboratory

The first four elements are carried forward from the program's previous long-range plan (Bailey and others, 1983); the fifth is an explicit recognition that the program exists in a shrinking world in which international sharing is of great mutual benefit.

Below, we describe each element and the principal activities that are presently planned for the 1990's. Many activities are a continuation of those in the 1980's; others are new and reflect advances in our understanding of the behavior of volcanoes. Specific activities will be adjusted as new eruptions and new insights demand.

ELEMENT 1. Eruption prediction

Eruption prediction is fast becoming a reality. Virtually every eruption has measurable precursors and the recognition and interpretation of those precursors is improving yearly. Volcanoes that erupt frequently offer many chances for testing predictions; those which erupt infrequently (and often dangerously) are the subject of the greatest uncertainties and are the most challenging. It is also important to recognize and predict the *end* of eruptions, so activities and business in communities around volcanoes can return to normal.

Priority activities in the 1990's are:

- Continue intensive monitoring of the Nation's most restless volcanoes and volcanic areas, including Kilauea, Mauna Loa, Mount St. Helens, Mount Rainier, Long Valley Caldera, Yellowstone Caldera, Augustine, and Redoubt Volcano. Monitors on the west flank of Mauna Loa will be upgraded. At other hazardous volcanoes, continuous seismic monitoring will be combined with periodic remeasurement of ground-deformation, gas, and other baseline parameters to anticipate renewed activity.

- Use new digital seismic instrumentation to monitor preeruption signals such as volcanic tremor. These will supplement, not replace, conventional seismic networks.

- Extend seismic coverage to more volcanoes, especially in Alaska. Networks will be installed around the more active and accessible volcanoes (for example, active volcanoes on the Alaska Peninsula). Simpler, event-counting, satellite-telemetered seismometers will be installed on active but remote volcanoes, so that eruptions and ash hazard to aircraft can be anticipated.

- Expand use of Global Positioning System monitoring on U.S. volcanoes to obtain real-time records of ground movement.

- Develop new geophysical and geochemical monitors whose data can be collected and cross-correlated continuously.

- Seismic and ground-deformation monitoring of those volcano flanks thought likely to collapse and (or) generate large earthquakes, for example, Kilauea, Mauna Loa, and Mount Rainier.

ELEMENT 2. Volcanic hazard assessment

Long-range planning for land use and emergency response complement eruption prediction and are important tools in volcanic risk reduction. Volcanic hazard assessments by the USGS are the primary scientific basis for this planning by land managers and emergency response officials.

Priority activities in the 1990's include:

- Integrate geologic mapping, detailed stratigraphic information, petrologic studies (especially of petrologic change during eruptions and from one eruption to the next), hydrologic factors, historical and current unrest, and interpretative models of how each volcano works into a new generation of comprehensive volcanic hazard assessments.

- Work toward greater quantification of volcanic hazard assessments.

- Increase use of Geographic Information System (GIS) technology, both for analysis and dissemination of information.

- Conduct additional studies of explosive eruptions at Hawaiian volcanoes, including field studies of their deposits, the role of ground water, and theoretical studies of magma-ground water interaction.

- Compile detailed geologic maps of Mount Hood, Mount St. Helens, Mount Rainier, and Mount Baker.

- Complete geologic maps and hazard assessments for individual volcanic centers of the Cook Inlet (Spurr, Redoubt, Iliamna, and Augustine) and selected volcanoes of the Alaska Peninsula and the Wrangell Mountains.

- Evaluate of the impacts of volcanic eruptions and degassing on human health and agricultural productivity, using observations from a worldwide sample of volcanoes.

- Study how volcanic ash threatens jet aircraft and passenger safety and determine how that threat can be minimized.

Several of these activities complement, and will be complemented by, work under the Volcano Emissions activity of the U.S. Global Change Research Program.

ELEMENT 3. Research in volcanic processes

State-of-the-art eruption predictions and long-range hazard assessments require a solid understanding of processes before, during, and following eruptions. With such an understanding, we can anticipate specific changes, such as imminent ascent of magma or incorporation of stream-bank sediment into debris flows, rather than wait to observe and recognize them.

Priority projects in the 1990's are:

- Study the occurrence and significance of long-period earthquakes and volcanic tremor, which are promising parameters for eruption prediction.

- Study the accumulation and release of gases from magma, including the rapid release of gases during explosive eruptions.

- Explore relation between regional tectonic strain and volcanic eruptions.

- Model in detail the ground-water system at one or more selected volcanoes to improve our understanding of how ground water influences eruptions and what effect it has on weakening the volcanic edifice.

- Model, both theoretically and experimentally, how hot rock interacts with snow and ice, and how glacial outburst floods originate at volcanoes.

- Model how volcanic debris flows develop, flow, and abate.

ELEMENT 4. Effective communication

Even the most reliable scientific information about volcanoes and their impacts will be of little use unless it is presented in terms that are useful to planners, emergency management officials, businesses, and citizens. Outreach measures to ensure public safety from volcanic eruptions begin long before an emergency develops, especially with volcanic hazard assessments and public education, and continue through periods of volcanic unrest and eruptions with forecasts, predictions, and real-time tracking of eruptive activity.

Priority activities in the 1990's are:

- Integrate volcanic hazards information into Geographic Information Systems used by State and local planners.
- Expand public education programs, using a variety of media including video, general-interest publications, and school curriculum materials. Conduct workshops for public officials, teachers, news media, and citizens.
- Work with the FAA, NOAA, and the airline industry to develop an effective system for detecting and tracking ash plumes in real time, initially in the Cook Inlet, but extend the system to other parts of the U.S. as soon as possible.

ELEMENT 5. Working in the world laboratory

International collaboration offers opportunities to learn more about hazardous volcanism than we can learn in the U.S. alone and to share what we learn with others. Many more eruptions occur abroad than in the U.S., and many advances in volcanology are being made abroad. Increasingly, scientific advances and successful volcanic crisis management will involve collaboration between scientists from different countries, sharing observation techniques and interpretations.

Priority international activities during the 1990's are:

- Participate in multidisciplinary, multinational hazard-mitigation projects on selected "Decade Volcanoes," as part of the International Decade for Natural Disaster Reduction. Three Decade Volcanoes are within the U.S., where U.S. volcanologists will be joined by foreign colleagues; an additional 10 to 20 Decade Volcanoes are located in other countries, where U.S. volcanologists will join by invitation if the activity contributes to program goals.
- Assist developing nations faced with volcanic crises that seek USGS expertise. The program seeks to continue the Volcanic Disaster and Early-Warning Assistance Program (VDAP), in cooperation with USAID's Office of Foreign Disaster Assistance. Initially, activities will be focused in Latin America, as now; later, some activities may be added in Southeast Asia and Africa.
- Conduct investigations on foreign volcanoes or in foreign laboratories to address specific topics of import to U.S. hazards mitigation, for example, how snow and ice are melted by pyroclastic flows to form debris flows, or processes of caldera unrest. New collaboration is already planned with Japan and the USSR. Such collaboration is likely with Italy and other countries.
- Participate in global information exchanges among volcanologists. This will most easily be accomplished by working with the World Organization of Volcano Observatories and with the Smithsonian's Global Volcanism Project.

VISIONS FOR THE 21ST CENTURY

Today's dream is tomorrow's reality, and the Volcano Hazards Program aims to overcome a number of technical and scientific limitations by the 21st century. Examples of what might be accomplished by early in the next century include:

- Place monitoring instruments on every potentially active U.S. volcano
- Set up a real-time data base of unrest at U.S. volcanoes, and link it to a comparable data base for regional seismicity.
- Set up continuous GPS monitoring of deformation at many volcanoes.
- Use geostationary satellites to conduct, multispectral, high-resolution surveillance of U.S. volcanoes.
- Use artificial intelligence (AI) to analyze volcanic unrest and improve the logical rigor of eruption predictions.
- Build experimental apparatuses that will reproduce eruptions of laboratory-produced magma to test the influence of various factors (such as composition, temperature, and gas content) on style of eruption.
- Conduct experiments to test models of the initiation and hydraulics of debris flows.
- Monitor continuously, in real time, sediment movement in streams draining active volcanoes.
- Map and monitor, in real time, ground water in volcanoes.
- Identify and monitor, in real time, potentially unstable sectors of volcanic edifices.
- Link data networks among the USGS volcano observatories and link volcanologists around the world using networked telecommunications.
- Conduct a lively continuing education program that effectively transfers information about volcanoes from scientists to public officials, using new communications technology.
- Place interactive, user-friendly GIS workstations in county and State emergency response offices, on which public officials can request information about various hazards over various time frames, overlay this information on risks, and see the effects of various mitigation options.

Judging from the pace of progress in the 1980's and the increasing challenges from technology and world population growth, the 1990's and the 21st century will be a challenging and busy time for the Volcano Hazards Program.

Appendix 4. Participants in the workshop "Volcano Hazards Program Directions for the 1990's," held November 13-15, 1989, at the Cascades Volcano Observatory, Vancouver, Washington

U. S. Geological Survey

Norman G. Banks	Cynthia A. Gardner	Thomas L. Murray
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Ernest D. Cobb	Malcolm J. Johnston	Cinthia M. Stine
John E. Costa	Peter W. Lipman	Donald A. Swanson
Paul T. Delaney	John P. Lockwood	Robert I. Tilling
Michael P. Doukas	Jon J. Major	Randall G. Updike
Daniel Dzurisin	Jeffrey N. Marso	Richard B. Waitt
Elliot T. Endo	Kenneth A. McGee	Joseph S. Walder
John W. Ewert	C. Daniel Miller	Craig S. Weaver
Gary L. Gallino	Thomas P. Miller	Edward W. Wolfe

Non -USGS

Name	Organization
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David Pieri	Jet Propulsion Laboratory, Pasadena
Tom Simkin	Smithsonian Institution, Washington
Barry Voight	Pennsylvania State University

Back cover: *Snow-covered Mount Rainier, rising behind Tacoma, Washington. Because of its historical activity and proximity to major population centers, Mount Rainier is targeted for intensified study during the International Decade of Natural Disaster Reduction (IDNDR). Photograph by Lyn Topinka.*

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