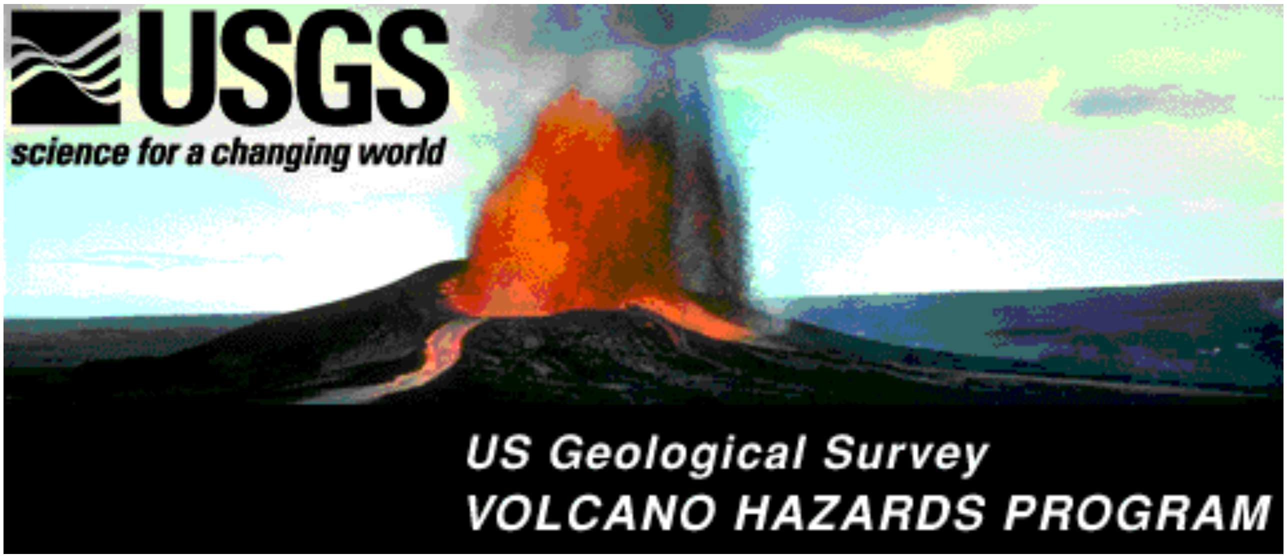

FIVE-YEAR SCIENCE PLAN
1998 to 2002

July 1997

Visit our WWW site at http://volcanoes.usgs.gov

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PROGRAM MISSION

The United States has 65 active and potentially active volcanoes. During the twentieth century, volcanic eruptions in Alaska, California, Hawaii, and Washington have devastated thousands of square miles of land and caused substantial economic and societal disruption and, in the worst instances, loss of life. The Volcano Hazards Program (VHP) seeks to lessen the harmful impacts of volcanic activity by monitoring active and potentially active volcanoes, assessing their hazards, responding to volcanic crises, and conducting research on how volcanoes work. To fulfill a Congressional mandate (P.L. 93-288) that the USGS issue “timely warnings” of potential geologic hazards to responsible emergency-management authorities and the populace affected, the VHP strives to obtain the best possible scientific information about volcanic hazards and to communicate it effectively to the authorities and the public in an appropriate and understandable form.

PRINCIPAL ELEMENTS OF THE PROGRAM

Volcano Monitoring—Nearly all volcanic eruptions are preceded by measurable changes in seismicity, ground deformation and/or other geophysical and geochemical parameters. Vigilant, sustained monitoring of these signals provides the data needed to detect the initial stages of volcanic unrest, forecast eruptions, and understand volcanic processes. The VHP monitors active and potentially active volcanoes primarily through a network of volcano observatories, whose staffs collaborate with other domestic and foreign agencies as appropriate.

Volcano Crisis Response—The USGS is the only agency with the mandate and ability to provide a comprehensive scientific response to volcanic crises. The VHP maintains capabilities and protocol for the rapid deployment of staff and monitoring equipment during times of volcanic crisis in the United States and abroad. Response readiness is a key underpinning of the VHP.

Volcano Hazard Assessments—The record of a volcano's past eruptions provides the scientific principal rationale for assessing its future behavior. Information obtained through geologic mapping, dating of eruptive products, analysis of volcanic deposits, geophysical analysis, and hydrologic investigations is compiled in hazard-zonation maps, digital databases, and probabilistic recurrence and inundation models. These assessments are updated as new data become available and serve as critical input for public policy on land-use planning and emergency preparedness.

Topical Investigations of Volcanic Processes—An effective volcano monitoring and hazard assessment program must be rooted in accurate and comprehensive knowledge of magmatic and volcanic processes. The VHP conducts field, laboratory, and theoretical studies that promote understanding of basic mechanisms that control the origin of magmas, their ascent, their degassing and interaction with crustal rocks and fluids, and their eruption.

Scientific Outreach and Information Dissemination—The results of volcano-hazard studies must be effectively conveyed to the community they are intended to serve. The VHP works closely with other scientists, Federal and State officials, public-safety officials, community planners, developers, business leaders, educational institutions, and citizen groups. Information is disseminated through briefings, workshops, published reports and maps, videos, digital databases, web sites, interviews with media, and weekly newspaper columns.

PROGRAM STRUCTURE

The study of volcanoes is a multidisciplinary endeavor requiring the talents of geologists, seismologists, geophysicists, hydrologists, geochemists, petrologists, computer scientists, and electronics specialists. The VHP funds work in both the Geologic and Water Resources Divisions. In FY 1997, 24% of Volcano Hazards Program funding (gross) was spent within the Water Resources Division, and ~8% was spent on cooperative agreements with state and university partners. Within the Geologic Division, the Volcano Hazards Program maintains close ties with the Earthquake Hazards Reduction Program, whose regional earthquake monitoring networks provide the framework for more localized volcano-monitoring networks. Research and development of seismic and geodetic monitoring instrumentation and data-processing techniques also are of mutual interest to the two programs.

Most staff members are located in one of VHP's three volcano observatories or in the Western Regional Center in Menlo Park, California.

- The Alaska Volcano Observatory (AVO) is a cooperative effort of the USGS Volcano Hazards Program, the University of Alaska Fairbanks Geophysical Institute (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS). AVO monitors the more than 40 active volcanoes of Alaska (Fig. 1), which threaten not only local populations but also aircraft and travelers using the major air routes across the North Pacific. AVO also is responsible for disseminating warnings and information on dangerous eruptions and ash clouds from Kamchatkan volcanoes in the Russian Far East.

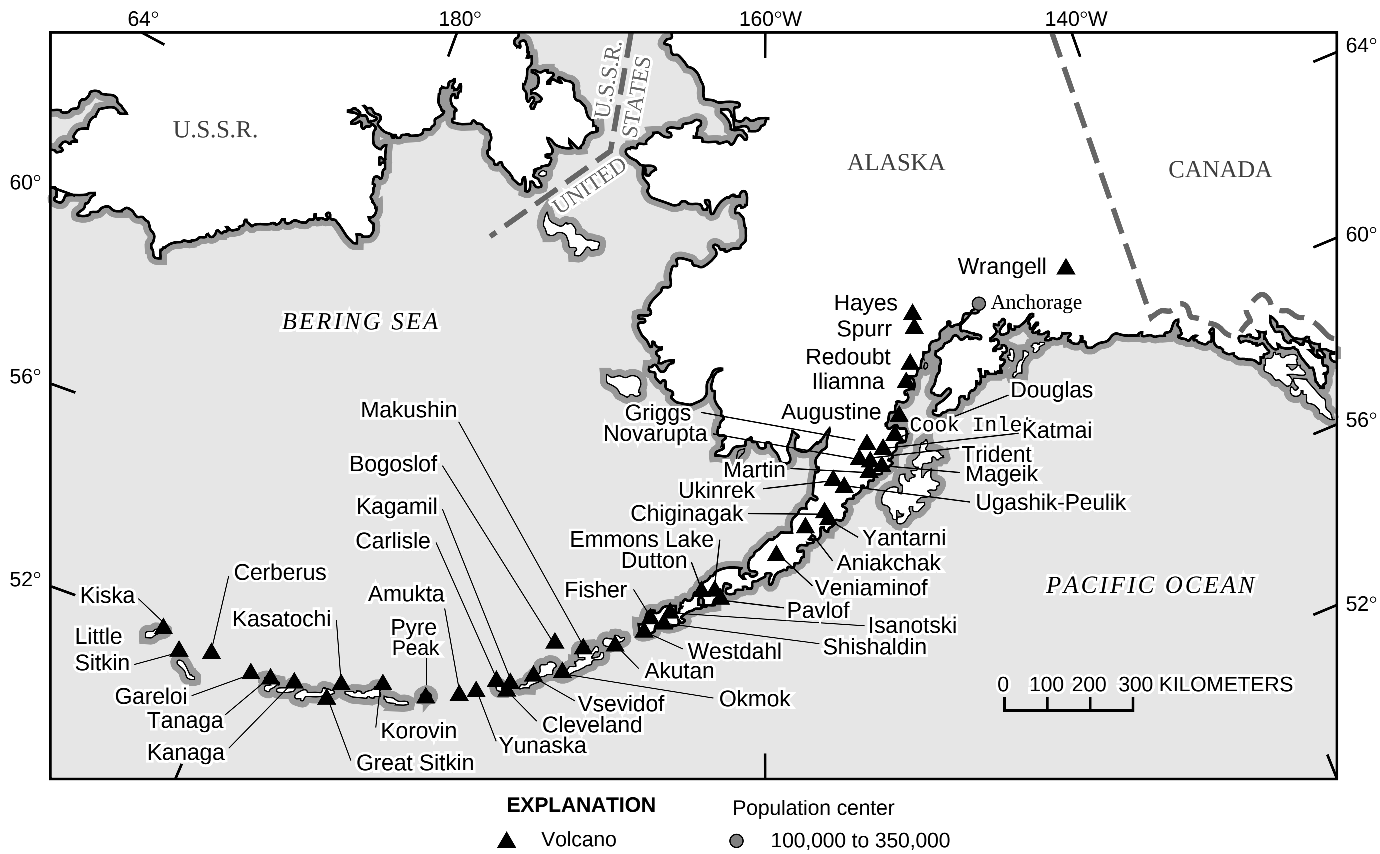

Figure 1.—Map of volcanoes in the State of Alaska, located in the Aleutian Islands, Alaska Peninsula, and Cook Inlet regions.

- The Hawaiian Volcano Observatory (HVO) carries on an intensive program of seismic, gas, geodetic, and observational monitoring of the frequently active volcanoes of the State of Hawaii (Fig. 2). For example, the most recent eruption of Kilauea Volcano began in 1983 and has continued into 1997. Frequent accessible eruptions, combined with HVO's long record of comprehensive seismic, gas, and geophysical monitoring, has made HVO a nationally and internationally utilized center for volcanologic field experimentation and instrument design and testing.

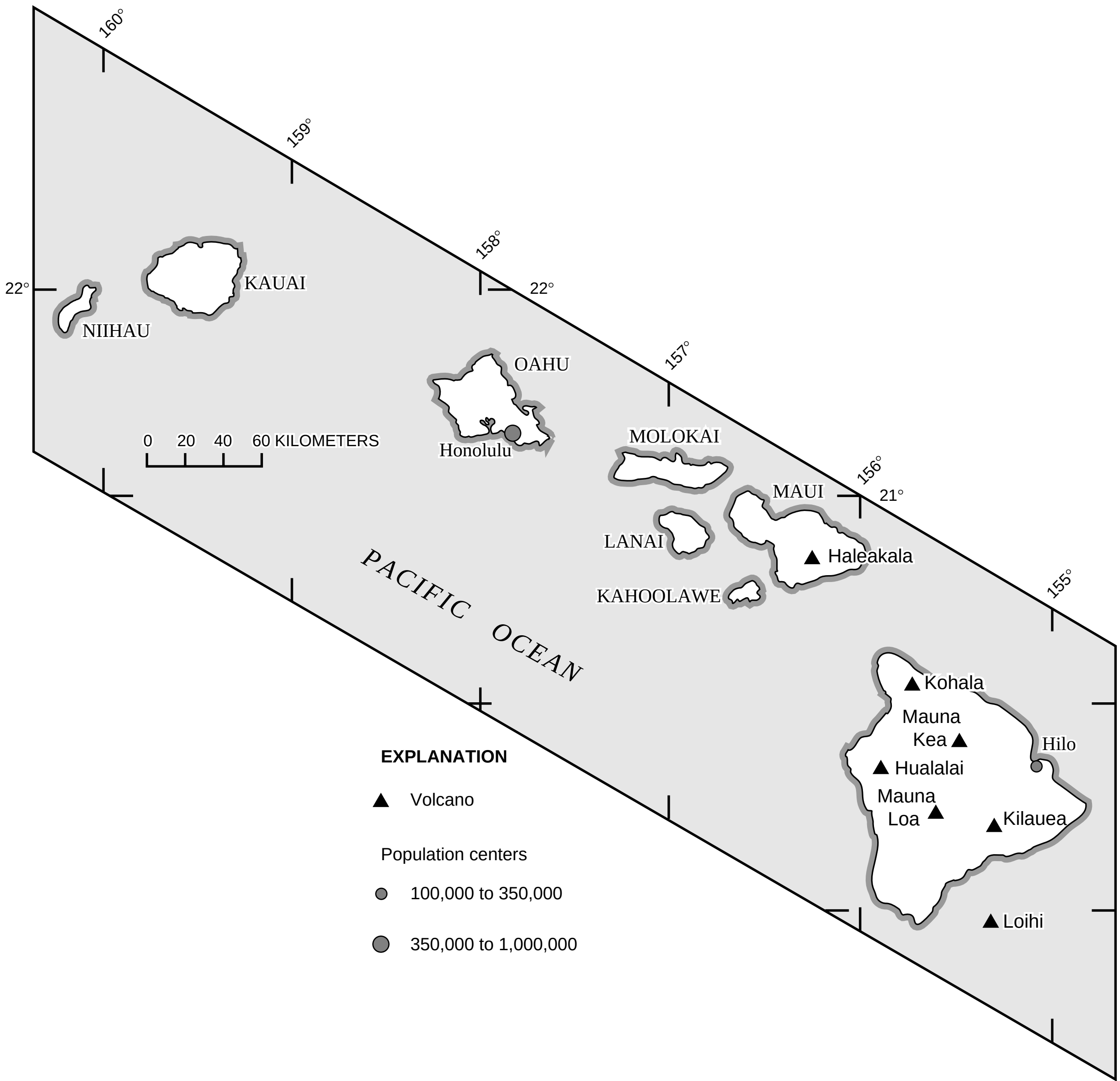

Figure 2.—Volcanoes of the State of Hawaii.

- The Cascades Volcano Observatory (CVO) in Vancouver, Washington, monitors and assesses hazards from the volcanoes of the Cascade Range of Washington, Oregon, and California (Fig. 3). The responsibility for seismic monitoring of the Cascade volcanoes is shared with the USGS center in Menlo Park, California (for northern California) and the Geophysics Program of the University of Washington in Seattle (for Washington and Oregon). CVO also is home to the Volcano Disaster Assistance Program.
- Through the Volcano Disaster Assistance Program, a joint effort with the US Agency for International Development (USAID), the Volcano Hazards Program operates the world's only mobile volcano observatory to respond to selected volcanic crises around the world. At the request of host countries and working through USAID, program scientists rapidly respond with a portable cache of monitoring equipment to determine the nature and possible consequences of volcanic unrest. The USGS has benefited from these international responses by refining monitoring methods and applications for use in domestic volcanic crises (e.g., in Alaska in 1989 and 1992).

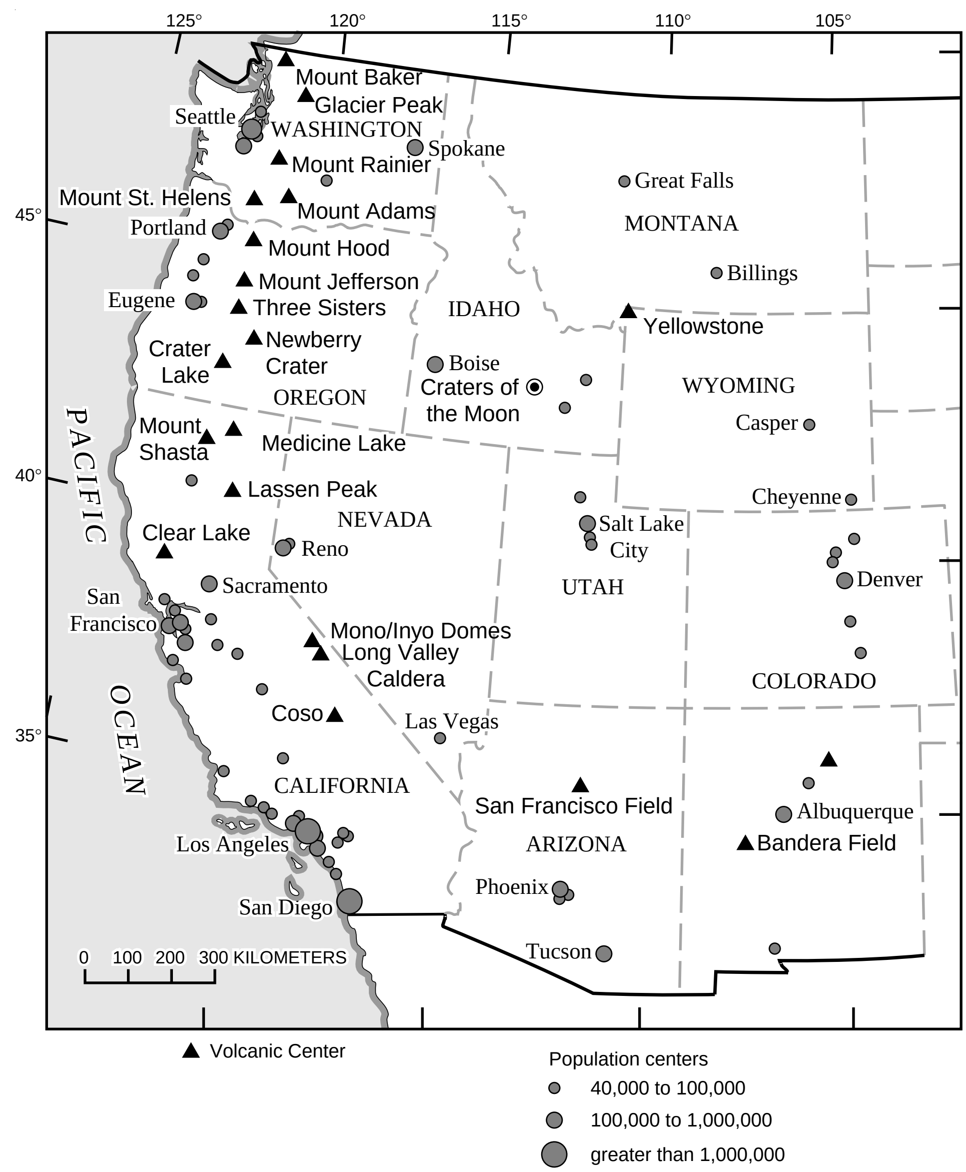

Figure 3.—Volcanic centers of the western United States.

- The Western Regional Center in Menlo Park, California, conducts topical volcanologic studies and hazard assessments, often in concert with staff from one or more of the observatories. Seismic, deformation, and gas monitoring at Long Valley caldera in California is carried out primarily from Menlo Park, in effect constituting the Long Valley Observatory (LVO).
- The VHP also supports USGS personnel in Denver, Colorado; Flagstaff, Arizona; Reston, Virginia; and Seattle, Washington, as well as seismic monitoring of the Yellowstone volcanic region in partnership with the University of Utah.

BRIDGES TO OTHER AGENCIES AND INSTITUTIONS

Hazards related to domestic volcanoes are of vital concern to other government agencies, as well as the private sector, and the VHP strives to maintain and enhance these important partnerships (Appendix 1). The Federal Emergency Management Agency, federal managers of public lands (U.S. Forest Service, National Park Service, Bureau of Land Management, U.S. Fish and Wildlife Service), state and county civil defense authorities, and local businesses all rely on information provided by the VHP. The VHP works closely with the Federal Aviation Administration and the National Weather Service to protect air passengers and freight from the dangers of volcanic-ash clouds dispersed into air-travel routes, and in recent years the program has expanded contacts with the commercial aircraft industry, the National Transportation Safety Board, the Office of the Federal Coordinator for Meteorology, and the International Civil Aviation Organization. The VHP also cooperates with the National Oceanographic and Atmospheric Administration on volcanogenic tsunami hazards. The Department of Energy supports VHP research on the hydrothermal systems associated with volcanic systems, and the Environmental Protection Agency frequently requests assistance from VHP geochemists to sample and analyze hydrothermal fluids and run-off waters from abandoned mines. Looking to the future, the VHP needs to build a stronger relationship with National Atmospheric and Space Administration, an agency which has claimed terrestrial natural hazards as within its purview.

In addition, the VHP maintains numerous international partnerships. The Volcanic Disaster Assistance Program is conducted by the VHP with joint funding from USAID's Office of Foreign Disaster Assistance. USAID also has funded geothermal investigations by the VHP to promote world-wide clean energy development. The program has ties to many foreign volcano observatories (for example, the Kamchatka Volcanic Eruption Response Team and the Philippine Institute of Volcanology and Seismology), and VHP staff are leaders in many international training programs, such as the International Training Course in Volcano Hazards Monitoring at the University of Hawaii, Hilo.

The VHP also maintains close ties to university groups concerned with volcano-related research. Examples include those between CVO and the University of Washington's Volcano Systems Center, between AVO and the University of Alaska and Michigan Technological University, between the Menlo Park regional center and Stanford University, and between HVO and both the Hawaii Center for Volcanology and the Center for the Study of Active Volcanism at the University of Hawaii. In addition, the VHP has a long history of fruitful collaboration and data sharing with the Global Volcanism Project of the Smithsonian Institution.

PROGRAM ACTIVITIES—1998 to 2002

Over the next five years the Volcano Hazards Program will continue to conduct integrated scientific activities that provide essential information on the nature of volcanic processes and associated hazards to public officials who must deal effectively with volcanic crises. An overview of anticipated program activities is outlined below.

VOLCANO MONITORING

Data collected by volcano-monitoring networks make possible the early detection of volcanic unrest and are indispensable for interpreting volcanic processes, anticipating eruptions, and estimating likely impacts of eruptions. Experience gained worldwide indicates that the most effective monitoring is achieved by applying a combination of techniques (seismic, geodetic, other geophysical, hydrological, geochemical, and remote satellite analysis) on a continuous near-real-time basis. Monitoring contains an inherent research component by providing fundamental observations and measurements that are used to develop and test models of volcanic processes and to improve monitoring methods. Over the next few years, the Volcano Hazards Program intends to maintain and upgrade networks, work toward a more effective blending of existing monitoring techniques, examine new technologies, and better integrate topical research studies with monitoring activities.

Seismic Networks—Seismic detection of volcanic earthquakes remains the primary tool for eruption monitoring. By early 1997, 37 U.S. volcanoes had at least a minimal amount of seismic coverage. Alaska poses the most urgent example of the need to increase the number of seismically monitored volcanoes. Currently, 14 volcanoes in Alaska—near Anchorage, in the Alaskan Peninsula–Katmai region, and in the central Aleutian Islands—are seismically instrumented. More than 30 other dangerous volcanoes in the Aleutians, many of which could threaten commercial air traffic, are not instrumented.

In addition to increasing the number of volcanoes that are seismically monitored, there also is a critical need to augment certain networks and to enhance instrument sensitivity. Some of the recent eruptions in Alaska (1989 Redoubt, 1996 Pavlof) showed that some precursory earthquake swarms are too small to be reliably detected and located by our existing networks. To provide early warnings, detection capabilities must be enhanced to identify small precursory earthquakes at high-risk volcanoes.

Broad-band seismometers provide greatly enhanced capability over that of short-period seismometers in common use. They are able to record seismic waveforms not captured by existing networks, and such signals have important ramifications for understanding volcanic processes and evaluating hazards (an example is the cause and meaning of rapid fluctuations in tilt at Kilauea Volcano). Broad-band instruments will be installed as funds permit at dangerous volcanoes.

Geodetic Networks—A geodetic network measures the changing shape of a volcano's surface caused by the pressure of magma and/or associated fluids moving underground. With some exceptions, geodetic monitoring traditionally has been carried out in episodic campaigns spaced days to years apart. The only continuously recording geodetic device in common use is the electronic tilt meter. The growing emphasis in the VHP is on developing, testing, and implementing better continuously recording systems, which are less labor-intensive than the traditional instrumentation and afford real-time assessment and notification capabilities. Over the next five years, VHP plans to expand the use of continuously recording, permanent GPS (Global Positioning System) receivers and borehole tilt meters and strain meters, particularly in Hawaii and Long Valley. Improved means of transmitting field data and more automated data analysis and archiving schemes must be developed to support this shift toward real-time deformation monitoring.

Volcanic Ash and Aviation Safety—Volcanic ash is highly hazardous to jet aircraft because it can erode compressor blades, melt onto critical engine parts, and cause loss of engine thrust power; particularly susceptible are the new long-range aircraft that employ larger, hotter running engines. Hazardous concentrations of volcanic ash can drift at air-traffic altitudes for hundreds to thousands of miles downwind following a volcanic eruption. Worldwide, about 80 jet aircraft in the past 15 years have accidentally entered volcanic-ash clouds, putting thousands of passengers at risk. In a dramatic incident in 1989, a Boeing 747 lost all thrust power after entering an ash cloud from the eruption of Redoubt Volcano. The plane dropped from an altitude of 28,000 feet to 14,000 feet before the engines could be restarted. Fortunately, the airliner landed safely in Anchorage but sustained damage from the ash cloud costing more than $80 million to repair.

Within U.S.-controlled airspace, the ash-aviation issue is especially important in the North Pacific region, where many active and potentially active Alaskan volcanoes are overflown daily by commercial and military aircraft on heavily traveled international and domestic air routes (Fig. 4). AVO is working closely with the Federal Aviation Administration (FAA) and National Weather Service (NWS) to provide real-time reports of volcanic activity that may pose a threat to air traffic; using AVO's information, the NWS tracks eruption clouds and the FAA warns pilots to route air traffic around ash clouds. In FY 1996 and FY 1997, the FAA gave a total of $4 million to AVO to expand its seismic monitoring to include several volcanoes in the Central Aleutian Islands. Among the highest priorities of the VHP is the work of AVO to improve aviation safety. Accordingly, to the degree that funding allows and in cooperation with the University of Alaska at Fairbanks Geophysical Institute and the State of Alaska Division of Geological and Geophysical Surveys, the VHP is committed to maintaining the expanded monitoring capability of Alaska Volcano Observatory. To the extent that funding and technology make possible, the VHP also recognizes the need to monitor volcanoes in the Western Aleutians and improve techniques to detect, track, and predict the path of volcanic ash plumes.

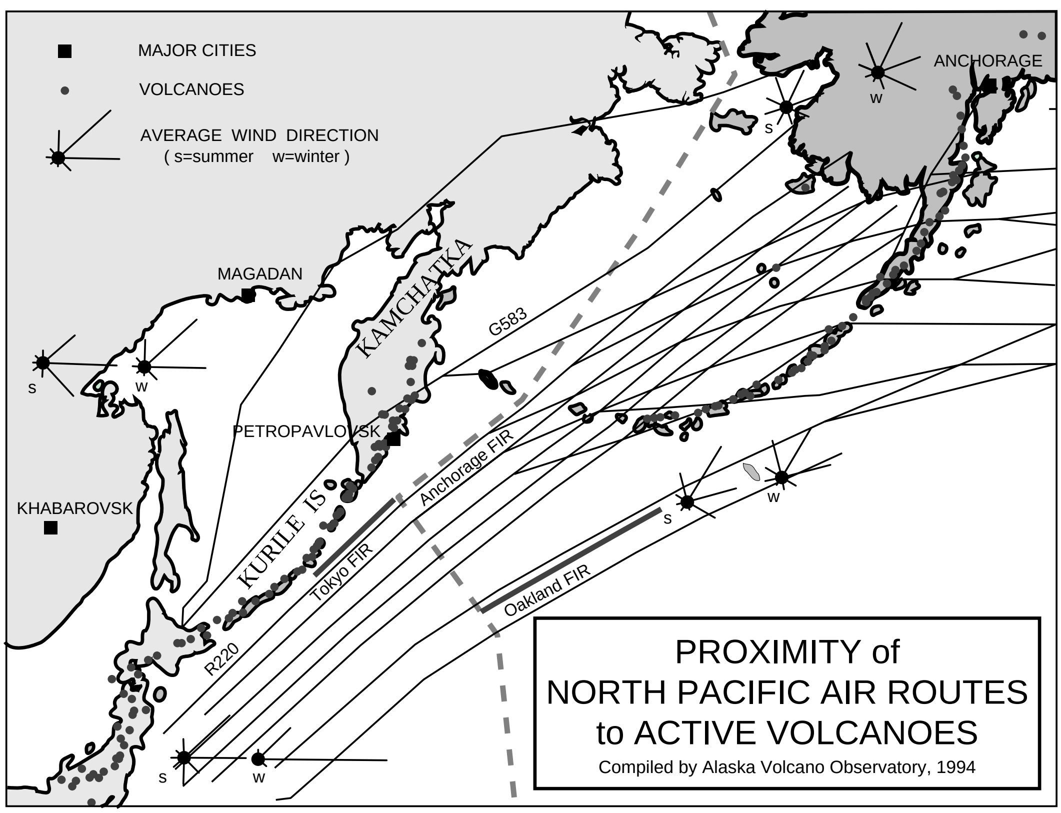

Figure 4.—Map of North Pacific air routes and their proximity to more than 135 active volcanoes of Alaska (>40), Kamchatka (30), the Kurile Islands (30), and Japan (>35).

InSAR Technology—Interferometric Synthetic Aperture Radar (InSAR) is a new, unclassified technique that uses satellite-radar images to map the Earth's surface in exceptional detail. InSAR technology promises broad-scale rendering of temporal changes in topographic relief at high precision and could revolutionize the field of ground-deformation monitoring. A thrust in the VHP in the next five years will be to cultivate partnerships with other agencies and universities in order to have access to the capabilities to process and analyze InSAR data for selected volcanoes.

Automated Eruption-Detection Stations—Automated eruption-detection stations are used to identify the onset of an eruption in remote or restricted areas where network coverage or visual confirmation is limited or impractical. Prototype units exist that host single-channel seismic sensors, pressure-transient counters and/or lightning detectors and that transmit data via the low-baud GOES satellite system. Over the next five years, similar GOES-based stations need to be constructed and field tested for possible deployment in the Western Aleutians and the Cascades. The VHP must also be prepared to take advantage of the proposed network of low earth orbit (LEO) commercial satellites that will be providing coverage for the growing cellular telephone market in the near future. The LEO system promises a broad-band, high-baud alternative to GOES technology, but usage costs initially may be high.

Volcanic Gas Monitoring—Changes in volcanic-gas flux and composition furnish important signals in identifying the presence of subsurface magma reservoirs and assessing eruption potential. Sulfur dioxide emissions, for example, increased ten-fold before the 1991 eruption of Pinatubo Volcano in the Philippines. Volcanic gases also kill vegetation, corrode machinery, and pose a health threat to livestock and humans. For example, in Hawaii, the ongoing eruption of Kilauea Volcano creates a volcanic smog (called “vog”) that on 69 occasions since 1987 has exceeded the 24-hour health standard set by the Environmental Protection Agency for sulfur dioxide exposure.

Over the next five years, the VHP will continue baseline measurements made at fumaroles, gas plumes, thermal springs, wells, and crater lakes. The program must look for ways to better integrate seismic and geodetic monitoring with gas measurements, improve techniques to quantify gas emissions (e.g., CO_2/SO_2 ratios) to better evaluate volcanic unrest, institute continuous in-situ monitoring at selected volcanoes, explore the growing field of remote airborne and space-based technology, and collect air-quality data needed to assess the environmental and health effects of volcanic gases.

Geophysical Monitoring—Non-seismic geophysical monitoring using gravity, self-potential, resistivity, and magnetic field surveys may provide important indicators of volcanic unrest, especially in instances when magma transport occurs aseismically or without measurable ground deformation. Self-potential measurements, for example, detected the slow, aseismic intrusion that preceded the 1983 onset of the current eruption of Kilauea Volcano, Hawaii, and pinpointed the eventual site of vent opening. Geophysical monitoring of changes in groundwater temperature, pore pressure, and depth are also important in detecting unrest and in assessing the potential for steam explosions or hydromagmatic eruptions. At present, only Hawaii and Long Valley have adequate non-seismic geophysical surveillance. Critical geophysical surveys need to be undertaken for the highest risk volcanoes in Alaska and the Cascades.

Remote Monitoring Using Classified Data—High-resolution classified satellite imagery may have substantial potential for detecting the onset of an eruption in real-time, for tracking ash plumes, and for monitoring ground deformation and lava-dome growth. VHP scientists will participate in a two-year interagency feasibility study to “ground-truth” results and establish collaboration protocols.

VOLCANO CRISIS RESPONSE

Since 1980, the Volcano Hazards Program has provided major responses to 10 volcano-related emergencies in the United States—Augustine, Redoubt, Spurr, Akutan (Fig. 5), and Pavlof volcanoes in Alaska; Long Valley in California; Kilauea, Mauna Loa, Loihi in Hawaii; and Mount St. Helens in Washington. In addition to domestic activities, the Volcanic Disaster Assistance Program (VDAP) has responded to 15 volcanic crises abroad (notably, Mt. Pinatubo, Philippines; Rabaul, Papua New Guinea; Popocatepetl, Mexico; Soufriere Hills, British West Indies). These international responses serve to advance U.S. foreign-policy objectives and also directly benefit domestic efforts in volcanic-hazards mitigation by providing opportunities to learn from diverse eruptive scenarios and test new monitoring equipment and emergency protocols.

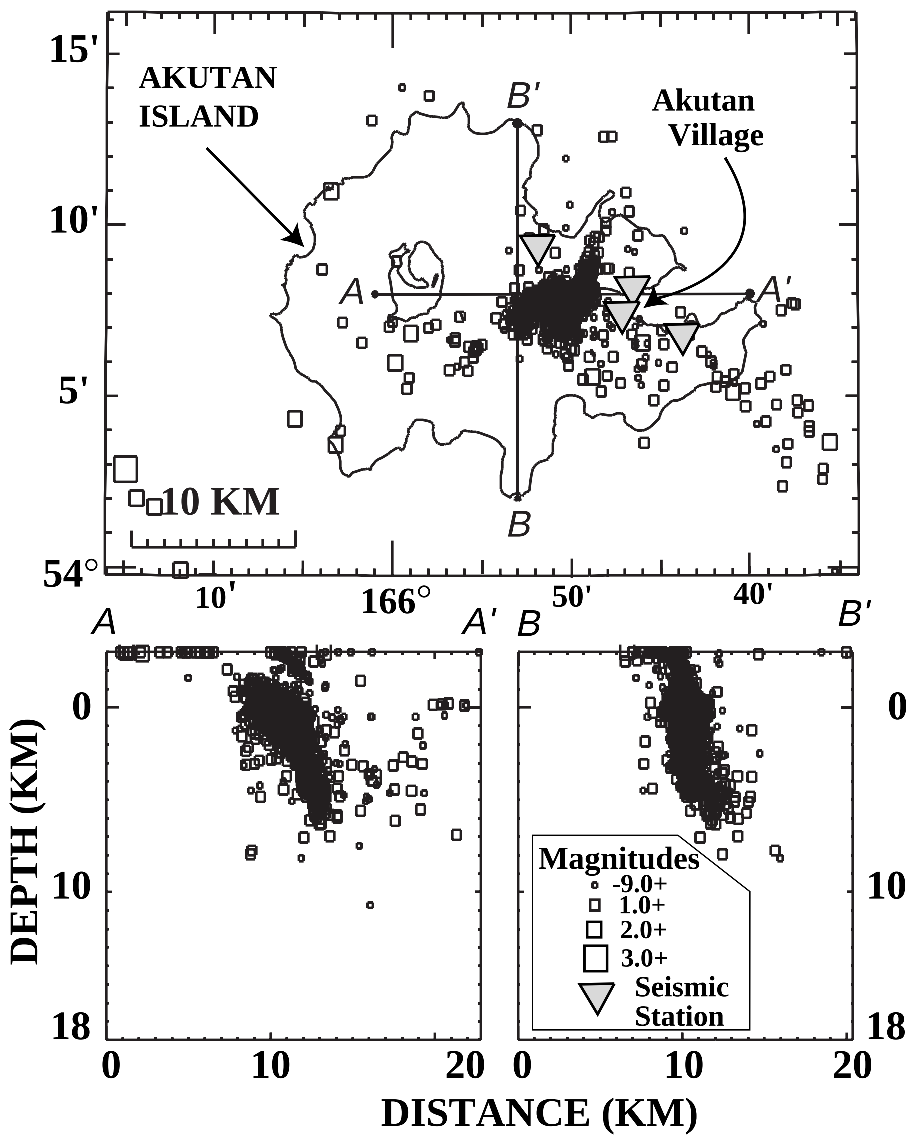

Figure 5.—Seismicity at Akutan Island, Alaska, during the crisis period of 18 March to 23 July 1996. Map view (above) and two cross sections (below, A–A' and B–B') show that micro-earthquakes were along a NE-dipping structure rather than beneath the volcano summit. Information from earthquake intensities, focal depths, and waveforms indicated that a major eruption was not likely, averting expensive and disruptive evacuation procedures.

On the basis of demonstrated successful VDAP deployments, the VDAP-style mobile volcano-monitoring system is now designated within the Volcano Hazards Program as the explicit mode of response planned for future unrest in the Cascades, Long Valley, parts of Alaska, and elsewhere in the western US. Over the next five years, the Volcano Hazards Program will maintain its ability to respond to domestic and foreign volcanic emergencies, will continue to integrate VDAP activities with the rest of the program, and will continue to gather and analyze information on global occurrences of volcanic unrest and eruptive potential.

Staff Available for Crisis Response—Recent emergency responses have placed great demands on VDAP's staff. At present, the core VDAP group consists of six staff members, all of whom have half-FTE support from USAID. Through in-house workshops and technical training sessions VHP intends to increase the number of staff available for both foreign and domestic emergency response.

VDAP-Type Cache of Research-Grade Seismic Equipment—Some types of seismic investigations at volcanoes require more data than are needed for traditional monitoring purposes alone. Over the next five years, VHP will look for opportunities to deploy portable, three-component, broad-band, digital seismic sensors along with standard VDAP equipment during crisis response. In order for data from such instruments to be useful in a crisis, however, software engineering is needed to integrate digital broad-band seismic data into the VDAP data-acquisition and analysis system.

Crisis-Response Chronicling—Successful eruption responses rely on the ability to recognize and interpret the complex, often subtle signals of volcanic unrest. Volcanoes that erupt frequently (e.g., Kilauea) offer unparalleled opportunities for testing data-analysis techniques and prediction models. Those that erupt less frequently are often more explosive, more variable in their behavior, and consequently are the subject of great uncertainty. For both foreign and domestic responses, the Volcano Hazards Program must carefully document actual volcanic crises and responses—i.e., the sequence of volcanic events that occurred, how data were used to interpret and forecast volcanic behavior, and how the scientific information was used to mitigate hazards. Such documentation can be used to prepare contingency plans for high-risk volcanoes and will help identify likely outcomes as long-dormant volcanoes reawaken.

VOLCANO HAZARD ASSESSMENTS

When volcanic unrest culminates in eruption, information from monitoring networks is combined with analysis of the volcano's past activity to evaluate the most likely hazards and their impact on a day-to-day basis during the course of the eruption. In addition to responding to eruption crises with real-time hazard assessments, the VHP also maintains a longer-term view of volcanic hazards. The geologic record of past eruptions provides the only practical guide to assess future hazards and the frequency of their recurrence. The spatial distribution of volcanic hazards is displayed via hazard-zonation maps (Fig. 6), which provide an essential basis for design of monitoring networks, long-term eruption forecasts, land-use planning, or short-term emergency plans.

Over the next five years, the VHP will continue its approach of preparing and updating hazard assessments based on field studies that integrate diverse geoscience disciplines and methods. Topical hazard-assessment will be investigated, such as edifice stability and potential for sector collapse, probabilistic methods of assessing hazards, and new ways of communicating and displaying hazard-assessment results.

Integrated Field Studies—Accurate and detailed geologic maps of volcanic centers are the foundation of hazard assessments. Geologic mapping and stratigraphy, combined with geophysical, geochronological (K/Ar, $^{40}Ar/^{39}Ar$, ^{14}C, and dendrochronology), paleomagnetic, and geochemical/petrographic methods are used to decipher the volcanic history of an area, eruption-recurrence intervals, eruptive style of the volcanic system, characteristic patterns of eruptive ejecta, debris avalanches, and lava flows, and subsurface structures.

Figure 6.—Hazard-zonation map for the area around Mount Rainier, Washington, including metropolitan Tacoma. Similar maps are available or being prepared for many Cascades and Alaskan volcanoes and are a useful tool for decision makers, planners, land managers and local officials.

Volcanic hazard assessments prepared by the VHP also incorporate information about a volcano's hydrologic regime, because hydrologic factors can strongly influence the nature of volcanic hazards. Hot volcanic material can rapidly melt large volumes of snow and ice to form debris flows and mudflows. Post-eruptive debris flows are generated when loose volcanic deposits on steep slopes are remobilized by earthquakes or heavy rainfall. The ground-water regime of a volcano can cause an initially benign eruption of lava to develop into an explosive eruption of significantly greater hazard. Accordingly, hazard assessments must incorporate information on the geometry and recharge/discharge properties of hydrologic basins, the volume of snowpack or ice available for melting, soil and rock type, and topography. Such data, when combined with fluid-dynamic models, can be used to predict the travel time and potential inundation area of primary or secondary debris flows.

In the current program, hazard-zonation maps have been completed for volcanoes in Washington and Oregon. Detailed geologic maps, upon which any future revisions of hazard assessments would be based, are underway or nearing completion for Cascade and Hawaiian volcanoes and several high-priority volcanoes in Alaska, and are expected to be published within the next five years. Program plans for the next few years are to start hazard-assessment mapping at Haleakala Volcano in Hawaii and Three Sisters Volcano in Oregon, make progress on hazard-assessment work in Alaska started in conjunction with the Central Aleutian monitoring expansion, and integrate detailed field studies of volcanic centers in California into hazard-assessment reports.

Edifice Stability—Volcanoes are inherently unstable geologic structures. They may ride atop active faults and other near-surface structures, have steep edifices, and often are composed of layers of poorly consolidated materials that have been weakened by centuries of reaction with acidic gases and hydrothermal waters. We now realize that large parts of the flanks of volcanoes can collapse, even in the absence of a triggering eruption. In the Cascade Range, flank collapse is documented at Mount Shasta in the Pleistocene, at Mount Rainier in the Holocene, and at Mount St. Helens in 1980. Very large failures of volcanic edifices have occurred in the Hawaiian Islands, where parts of many volcanoes have slid into the ocean, sometimes abruptly enough to generate giant tsunamis that affected the circum-Pacific rim. Over the next five years the VHP will work to identify those parts of U.S. volcanoes susceptible to major collapse. Remote-sensing geophysical techniques (e.g., high-resolution aeromagnetic surveys) offer rapid and cost-effective means of identifying deep alteration zones and locating buried faults that cut and destabilize volcanic edifices. Selected mineralogical and geochemical studies should be conducted to complement these geophysical studies.

Probabilistic Modeling—Probabilistic modeling is a growing area of hazard and risk research, one which offers promise as information on eruption frequencies and patterns increases. Particular topics to be explored over the next five years include eruption-recurrence intervals, lava-flow and mudflow inundation probabilities, risk assessment, and decision-tree analysis (e.g., given certain symptoms of unrest, what are the probabilities of various sequences of outcomes?).

Digital Maps and Databases—The success of current and future assessment projects hinges on VHP's ability to bolster technical support for the development of digital geospatial databases. GIS allows ready integration of geologic, geophysical, seismic, and hydrologic data with topographic, cultural, and environmental data. The Federal Emergency Management Administration (FEMA) is close to completing a nationwide GIS infrastructure and census database for use in natural hazard and risk assessment. VHP hazard maps and probabilistic hazard estimates must conform with usage of FEMA's database.

TOPICAL INVESTIGATIONS OF VOLCANIC PROCESSES

USGS volcano-monitoring strategies and analyses of precursory unrest are founded on an understanding of magmatic processes and eruption dynamics. The Volcano Hazards Program utilizes many tools from seismology, geophysics, geochemistry, field geology, and hydrology to acquire fundamental knowledge about how volcanoes work. Major programmatic research interests pertain to volcanic seismicity and deformation, vigor and style of eruptions, magmatic evolution of volcanic systems, the circulation of thermal fluids in and around magma bodies, magmatic degassing and eruption dynamics, and interaction of magma and eruptive products with ground and surface water.

In the coming years, the VHP will be challenged to better integrate topical investigations with monitoring and forecasting activities by focusing research at volcanoes with data from pre-eruptive and syn-eruptive events, particularly volcanoes with potential for explosive eruptions such as Long Valley, Alaskan centers, and selected foreign volcanoes. Topical studies of greatest interest to the VHP include those designed to discriminate if seismic and other signals actually are precursors to eruption or signify temporary fitfulness or intrusion without eruption; to determine what triggers eruptions and whether a volcanic system is waxing or waning; and to identify what factors control the explosivity of an eruption.

Volcanic Seismicity and Deformation—Combined seismic and deformation monitoring is routinely used to track volcanic unrest. However, our interpretations of seismic waveforms and deformation patterns and the processes that cause them are incomplete. For example, at Long Valley deep long-period earthquakes appear to be related to an incompletely understood process of release of volcanic gases perhaps during magma movement. To understand the significance of long-period earthquakes, which are characteristic of active volcanic areas, field experiments are needed to distinguish between seismic and deformation signals generated by magmatic and hydrothermal sources.

Vigor and Style of Volcanic Eruptions—At present, we have only a rudimentary understanding of the parameters that determine eruption intensity and style. Conduit geometry, magma-ascent rate and volume flux, and the density, viscosity, crystallinity, and gas content of the magma all appear to be important. Furthermore, the diverse character of volcanic eruptions is determined not only by the processes taking place in magmatic systems at depth, but also by near-surface and surficial hydrologic processes during eruption—e.g., quenching magma, or, alternatively, generating phreatomagmatic eruptions; routing mudflows down drainages. A combination of field, laboratory, and theoretical studies is needed to truly understand the interplay between the various magmatic and hydrologic factors that control the type and size of eruptions and resulting deposits.

Magmatic Evolution of Volcanic Systems—Each volcano has a history of physicochemical evolution that is revealed through field and laboratory studies of its erupted products. Well-designed geochemical and isotopic studies, combined with petrographic and textural data, are used to interpret the dynamics of magma mixing, cooling and crystallization, degassing, and the time frame through which each process occurs; new microbeam technologies (e.g., ion microprobe) that decipher the physicochemical evolution of a magma in great detail, may yield new insights on these subjects. Within the VHP, future topical studies on magmatic evolution need to focus more explicitly on eruption potential of different stages of magmatic evolution for various types of volcanic systems.

Magmatic Degassing—Magmatic degassing strongly influences the style, frequency, and intensity of volcanic eruptions, the release of volatiles to the atmosphere and hydrothermal systems, and the origin and dispersal of pyroclasts and ash during explosive eruptions. Degassing phenomena are assessed through ground- and air-based emission measurements, investigations of volatile solubility and diffusivity in volcanic rocks and minerals, modeling of exsolution and vesiculation dynamics, and quantitative textural analysis of ash and pyroclasts. These types of studies will be undertaken in the next several years in order to assess the environmental and health hazards posed by volcanic gases, evaluate the influence of degassing mechanisms on eruption intensity and lava-dome collapse, and refine our ability to use gas-emission data to help predict eruptions.

Hydrothermal Systems—As magma cools and degasses beneath the Earth's surface, heat and fluids are released that interact with the surrounding country rock. The resulting interactions may cause alteration and weakening of the volcanic edifice, and, in favorable instances, result in precipitation of metals to form volcano-hosted ore deposits. These same processes may create reservoirs of thermal fluids that are suitable for generating electricity with conventional technology (geothermal energy). Investigations using methods such as seismic tomography, gravity, aeromagnetic and other geophysical techniques provide insight into the size, location, and three-dimensional structure of magma bodies and associated hydrothermal systems. Exposed volcano-plutonic complexes can be useful analogues to present-day systems. Mechanical models and laboratory studies of the material properties of rocks and melts (e.g., shear strength, temperature, permeability, pore pressure) can be used to explore the conditions under which rocks fracture, facilitating the transport of magma and hot fluids. Hydrologic and thermal models supported by geophysical and geochemical data from deep wells provide insight into the transfer of heat and fluids in volcanic systems.

In the field of geothermal research, the Volcano Hazards Program will continue a few core activities, *viz.* characterization of the geochemical and isotopic signature of hydrothermal fluids, alteration minerals and fluid inclusions; investigations of a few geothermal systems in response to expressed needs of other government agencies (DOE, BLM, USFS) and industry, mathematical modeling of flow systems that develop above magma bodies, relationship of crustal heat and stress, and participation in key drilling projects into magmatic/hydrothermal systems.

SCIENTIFIC OUTREACH AND INFORMATION DISSEMINATION

As the 1985 eruption of Nevado del Ruiz Volcano (Colombia) that killed more than 22,000 people tragically demonstrated, an improved understanding of volcanic processes is in itself insufficient to mitigate volcanic hazards. The acquisition of knowledge must go hand in hand with effective, timely information dissemination. Ongoing communication with public officials is an essential part of the operation of the Volcano Hazards Program. During volcanic crises, program personnel work directly with authorities responsible for public safety. The VHP publishes hazard assessments, including hazard-zonation maps, and general-interest publications on volcanic phenomena; booklets describing volcano hazards in lay terms are available for several volcanic areas. Other activities, conducted in a non-crisis atmosphere, include media briefings on volcanic processes and their associated hazards, local forums and newspaper articles to discuss the hazards of a specific area, and meetings with public officials responsible for long-range planning. Videos and short focused fact sheets are produced. Scientific results are dispersed to other volcanologists for stringent peer review and corroboration. Data, reports, and photographic materials are increasingly becoming available to the public via the Internet.

The scientific outreach goals for the VHP are to expand its product formats to take advantage of new digital technologies and Internet services, to make better use of regional workshops to provide hazard information, and to create sophisticated GIS databases that encompass the breadth of VHP products and data on volcanic centers.

<u>Scientific Manuscripts, Maps, and Bulletins</u>—The Volcano Hazards Program must continue to report its scientific work in peer-reviewed venues, such as journals of professional societies and USGS maps, bulletins, and open-file reports. It is through this process of documentation and scrutiny that VHP efforts receive accreditation and that scientific models advance and improve. Without a foundation of solid, published scientific results, derivative outreach products ultimately become less effective and lose endorsement by the broad scientific community.

Over the next five years, VHP intends to make greater use of new digital technologies and Internet services and develop an online publication venue. The program should increasingly take advantage of the remarkable possibilities available by digital publishing on the World-Wide Web. The WWW is not only a place for depositing data but also for publishing research results, complete with color illustrations, interactive models, and hyperlinks to relevant source materials and related studies. Paper publications will always be with us, but in time more and more of our best products will be placed on the WWW.

Communication with Public Officials—The VHP will continue to issue timely warnings of potential hazards to the responsible authorities and to seek ways of streamlining the process, particularly with the FAA and NWS for eruption reports and ash-cloud detection and characterization. The program also recognizes the need to improve communications within the federal sector (e.g., BLM, NPS, USFS) inasmuch as most U.S. volcanoes are located on federally managed lands (Table 1). The VHP also will make more use of workshops at which observatory staff explain the significance of hazard assessments to regional and local land managers and emergency-response officials.

Table 1.—Representative List of U.S. Volcanoes, their Most Recent Eruption or Seismic Crisis, Location, and Land Manager

[NPS = National Park Service, U.S. Department of Interior; F&W = Fish and Wildlife Service, U.S. Department of Interior; FS = Forest Service, U.S. Department of Agriculture; DOD = U.S. Department of Defense]

Volcano	Last Activity	State	Land Manager
Augustine	A.D.1986	AK	State of Alaska
Spurr	A.D.1992	AK	State of Alaska
Redoubt	A.D.1989	AK	NPS, Lake Clark
Iliamna	A.D. 1996	AK	NPS, Lake Clark
Aniakchak	A.D. 1931	AK	NPS, Aniakchak
Trident	A.D.1964	AK	NPS, Katmai
Mageik	A.D. 1946	AK	NPS, Katmai
Katmai/Novarupta	A.D.1912	AK	NPS, Katmai
Akutan	A.D.1996	AK	F&W, AK Peninsula NWR
Pavlof	A.D. 1996	AK	F&W, AK Peninsula NWR
Kilauea	A.D.1997	HI	NPS, Hawaii Volcanoes
Hualalai	A.D. 1801	HI	NPS, Hawaii Volcanoes
Mauna Kea	YBP 4000	HI	NPS, Hawaii Volcanoes
Mauna Loa	A.D. 1984	HI	NPS, Hawaii Volcanoes
Haleakala	A.D. 1790	HI	NPS, Haleakala
Mt. Baker	A.D. 1870	WA	FS, Mt. Baker Snoqualmie
Glacier Peak	pre- A.D. 1800	WA	FS, Mt. Baker Snoqualmie
Mt. Rainier	A.D.1946	WA	NPS, Mt. Rainier
Mt. Adams	YBP 3500	WA	FS, Gifford Pinchot
Mt. St. Helens	A.D.1991	WA	FS, Gifford Pinchot
Mt. Hood	A.D. 1865	OR	FS, Mt. Hood
Mt. Jefferson	YBP 50,000	OR	Warm Springs Indian Res. + FS, Deschutes, Willamette
Three Sisters	~A.D. 950	OR	FS, Deschutes, Willamette
Newberry	~A.D. 600	OR	FS, Deschutes
Crater Lake	~ YBP 4000	OR	NPS, Crater Lake
Mt. Shasta	A.D. 1786?	CA	FS, Mt. Shasta
Medicine Lake	A.D. 1065	CA	FS, Klamath
Lassen	A.D.1914-17	CA	NPS, Lassen Volcanic
Clear Lake	unknown, Holocene?	CA	Private
Long Valley	~A.D. 1400	CA	FS, Inyo and Private
Sunset Craters	A.D. 1065	AZ	NPS, Sunset Craters
Coso	~ YBP 40,000	CA	DOD, China Lake

Digital Geospatial Databases—In 1997, the VHP began development of the US Volcanism Database, an electronic geospatial database (GIS) that will organize the wealth of USGS data on volcanic centers into a common structure for use as a research tool and scientific-outreach vehicle. The database will allow diverse, cartographically based datasets and products (including seismic and geodetic data from monitoring networks, geologic and hazard-assessment maps, geochemical and geochronological data, gravity and aeromagnetic surveys, heat flow, remote-sensing imagery, and cultural data) to be easily accessed, combined, and analyzed. Efforts to build this unique, cutting-edge database will intensify over the next several years. As a related endeavor, the Volcano Hazards Program will participate in the USGS's multi-program Digital National Atlas Project.

General-Interest Publications, Videos, Personal Outreach, and Websites—The VHP will continue to produce a variety of print products to provide information needed to increase public awareness about and reduce the risk of volcano hazards in the United States. This effort will include general-interest publications like the popular *Volcanic and Seismic Hazards on the Island of Hawaii*, *Eruptions of Mount St. Helens, Past, Present, and Future, Living with Active Volcanoes*, and Fact Sheets. The latter have proven to be a very cost-effective and efficient means for providing current, needed information to the public, Congress, and local communities. Beginning in 1997, the wide distribution of VHP's video program, *Perilous Beauty—The Hidden Dangers of Mount Rainier*, demonstrated the effectiveness of high-quality educational videos in delivering information to communities. Additional video programs will be produced in the future. The VHP will continue to take advantage of the opportunity to work with partners and educators to develop volcano interpretive exhibits for the public, train naturalists of the National Park Service and Forest Service, conduct volcano-awareness workshops, consult with media producers, and develop up-to-date materials for educators. For the new Forest Service Johnston Ridge Observatory visitor center, which is expected to draw well over one million visitors each year, a VHP scientist will give hundreds of interpretive talks and guided walks about volcanoes during the summer months beginning in late 1997. A new VHP website went online in 1997, with links to the four observatory websites. The program website provides information about results of VHP's scientific investigations, current volcanic activity, and general volcano topics, and it also will eventually link to the U.S. Volcanism Database. The VHP strives to make its websites the authoritative source of accurate and current information on U.S. volcanoes and volcanology by continually adding new relevant information on each site.

Web Sites for the Volcano Hazards Program and Associated Networks

Volcano Hazards Program:	http://volcanoes.usgs.gov
Alaska Volcano Observatory:	http://www.avo.alaska.edu
Cascades Volcano Observatory:	http://vulcan.wr.usgs.gov
Hawaiian Volcano Observatory:	http://hvo.wr.usgs.gov
Long Valley, California:	http://quake.wr.usgs.gov/VOLCANOES/LongValley
University of Utah:	http://www.seis.utah.edu
University of Washington:	http://www.vsc.washington.edu

REALITY AND CHALLENGES IN THE 21ST CENTURY

As the Volcano Hazards Program moves into the 21st Century, it faces a number of daunting challenges associated with the operational issues of funding, staffing, and facilities, as well as with underlying issues of increased volcanic risk and preservation of scientific credibility.

FUNDING

Since FY 1995, funding to the VHP has declined by about $3 M, and level funding is assumed by many to be the future trend.

FY 1995: $20 M
FY 1996: $19 M
FY 1997: $17.1 M
FY 1998: $17.1 M (President's budget as proposed to Congress in Feb. 1997)

Continued level funding will present a serious challenge to the Volcano Hazards Program as salary, space, and operational costs continue to escalate. Moreover, expensive improvements in monitoring networks, data analysis and interpretation, and hazards-information dissemination are required. Long-term maintenance and operation of the newly installed seismic networks at Aleutian volcanoes, establishment of continuous real-time GPS networks, expansion of geochemical monitoring, enhancements in seismic networks, and deployment of geophysical field experiments are all OE-intensive efforts that will strain program financial resources. With level funding, new work can be undertaken only incrementally with the scaling down or completion of ongoing work and by redirection of work within existing projects.

STAFFING

To conduct its priority activities, the VHP will need additional expertise in volcano seismology, physical volcanology, electronic engineering, geochemistry, geodesy, remote-sensing, and GIS design. Unfortunately, even given salary funds freed up by staff attrition, the VHP will confront a conflict in the coming years between the need to hire new expertise and the need for operating expenses.

The VHP also must maintain a minimum level of scientific expertise in the study of magmatic heat sources and surrounding hydrothermal zones, to be well positioned to undertake geothermal investigations if interest in environmentally benign (e.g., low-CO_2) non-fossil fuels again influences national energy policy.

FACILITIES

The three volcano observatories and the Long Valley monitoring project will remain major foci for programmatic activities. Accordingly, the VHP must continue to have a presence in Hawaii, Washington (Vancouver and Seattle), Alaska (Anchorage and Fairbanks), and California (Menlo Park). However, gradual diminution of the number of VHP staff in Menlo Park can be anticipated as people retire and the majority of new hires are located elsewhere.

The Geologic Division of the USGS is in the throes of evaluating how shared laboratory facilities in the regions should be funded and administered. For the VHP, the crucial issue is to have affordable access to a geochronology lab capable of dating very young volcanic rocks. Without the capability to get reliable, rapid, high-quality dating, the program cannot prepare hazard assessments and geologic maps or investigate the genesis, development, and eruptive potential of magmatic systems.

INCREASED VOLCANIC RISK

With growing population pressure in the western United States and expanding commercial air traffic between Asia and the United States, volcanic risk to human enterprise is increasing. Increased volcanic risk creates need for intensified risk-mitigation activities, such as real-time monitoring and event-notification systems, that the USGS Volcano Hazard Program is uniquely qualified to provide. The outcome of recent volcanic events in the United States and abroad where the VHP has been involved all indicate that the benefit derived from volcano monitoring, hazards evaluations, and warning systems far outweigh the cost of providing them.

The VHP has been remarkably successful in carrying out its mission of providing timely notice of volcanic hazards to the American public. The VHP's ability to provide value for funding received is further demonstrated by the approximately $2.6 million per year that the program has received on a recurring basis from other agencies, primarily the FAA and USAID, to address problems of significant societal concern. Strong efforts will continue to secure reimbursable support for work related to the overall objectives of the program. However, the ability of the program to conduct the full breadth and depth of its mission in the long term ultimately requires an increase to its base Congressional funding.

To fully carry out its mission into the next century, the Volcano Hazards Program needs to be a $25-million program.

SCIENTIFIC CREDIBILITY AND PUBLIC TRUST

Even as the Volcano Hazards Program deals day-to-day with the above described realities and challenges, it also must work diligently to continue to nurture fundamental investigations of how volcanoes work. Over the decades, high-quality data and research studies accrued from such investigations have established the USGS as a leader in the study of volcanic phenomena and associated hazards. This long-standing leadership role has underpinned the scientific credibility of, and public trust in, the VHP activities and products. Without these two paramount attributes, the USGS devolves into another mere “contractor” competing for public funds, and the effectiveness of the program with respect to ensuring public safety is seriously damaged.

APPENDIX 1.—List of Agencies and Organizations with which the Volcano Hazards Program has Working Relationships

FEDERAL

- Federal Aviation Administration
- NOAA -- National Weather Service
- NOAA -- Tsunami Warning Centers
- NOAA -- Satellite Analysis Branch
- Office of the Federal Coordinator for Meteorology
- U.S. Agency for International Development
- U.S. Forest Service
- U.S. Army
- U.S. Air Force
- U.S. Coast Guard
- U.S. Fish and Wildlife Service
- Bureau of Land Management
- Federal Emergency Management Agency
- Smithsonian Institution
- Department of Energy
- Los Alamos National Laboratory
- Jet Propulsion Laboratory
- Environmental Protection Agency
- Central Intelligence Agency
- National Photographic Interpretation Center
- National Park Service
  - Hawaii Volcanoes National Park
  - Haleakala National Park
  - Puu Kohala Heiau National Historic Site
  - Kaloko-Honolulu National Historic Site
  - Mount Rainier National Park
  - Crater Lake National Park
  - Lassen Volcanic National Park
  - Yellowstone National Park
  - Katmai National Park
  - Lake Clark National Park

U.S. UNIVERSITIES

- California State University, Sacramento
- Michigan Technological University
- Pennsylvania State University
- Stanford University
- University of Alaska, Fairbanks
- University of California, Berkeley
- University of California, Los Angeles
- University of Hawaii at Manoa and Hilo
- University of Oregon
- University of Utah
- University of Washington
- University of Wisconsin

INTERNATIONAL

- International Association of Volcanology and Chemistry of the Earth's Interior World Organization of Volcano Observatories
- Swiss Disaster Relief Organization
- International Civil Aviation Organization
- UNESCO
- Japan Meteorological Agency
- Geological Survey of Japan
- Institute of Volcanic Geology and Geochemistry (Kamchatka Volcanic Eruption Response Team)
- Philippine Institute of Volcanology and Seismology
- National Center for Disaster Prevention, Mexico
- British Geological Survey
- Australian Geological Survey Organization
- Volcanological Survey of Indonesia
- Geological Survey of Canada
- Canadian Meteorological Centre
- Rabaul Volcanological Obs., Papua New Guinea
- National University of Mexico
- Volcanological Obs., Univ. of Colima, Mexico
- National Geological and Mines Service, Chile
- National Polytechnical University, Ecuador
- National Inst. of Geology and Mining, Colombia
- Volcanological and Seismological Observatory of Costa Rica
- Center for Geotechnical Investigations, El Salvador
- National Institute for Territorial Studies, Nicaragua
- National Institute of Seismology, Volcanology, Meteorology, and Hydrology, Guatemala
- Vesuvius Observatory, Italy
- Institute of International Volcanology, Italy
- Institute of Physics of the Globe, France
- Nordic Volcanological Institute, Iceland

APPENDIX 1.—Continued

STATE AND LOCAL

Alaska Division of Geological and Geophysical Surveys
Alaska Division of Emergency Services
Municipality of Anchorage
Anchorage International Airport
Alaska State Troopers
Kenai Economic Development District
Cook inlet Regional Corporation
Aleut Regional Corporation
Akutan Corporation
Ounalashka Corporation
City of Akutan
City of Unalaska
Pierce County and City of Orting, Washington
Washington State Department of Natural Resources
Washington State Department of Emergency Management
Oregon Department of Geology and Mineral Industries
Hawaii County Civil Defense
Hawaii County Planning Department
Hawaii State Civil Defense
Hawaii State Planning Department
Hawaii State Department of Education
Hawaii State Department of Land and Natural Resources
Hawaii State Department of Health
California Office of Emergency Management
City of Mammoth Lakes, California

INDUSTRY

Numerous airlines and air delivery companies
Geothermal Resources Council
Hawaii Islands Economic Development Board
Long Valley Hydrologic Advisory Committee
Union Oil
Oxbow Geothermal Corporation
Puna Geothermal Ventures