Understanding Volcano Hazards and Preventing Volcanic Disasters

A Science Strategy for the Volcano Hazards Program, U.S. Geological Survey, 2004-2008

Executive Summary

With more than 169 geologically active volcanoes, the United States is among the most volcanically active countries in the world. During the twentieth century, volcanic eruptions have caused substantial economic and societal disruptions. Hazardous volcanic activity will continue to occur in the U.S., and, because of rising populations, development pressures, and expanding national and international air traffic over volcanic regions, risks to life and property through exposure to volcano hazards continue to increase. Moreover, rapid globalization makes U.S. businesses, financial markets, and government interests vulnerable to volcano hazards throughout the world.

The mission of the U.S. Geological Survey (USGS) Volcano Hazards Program (VHP) under the Disaster Relief Act (P.L. 93-288) is to enhance public safety and reduce losses from volcanic events through effective forecasts and warnings of volcanic hazards based on the best possible scientific information. The VHP conducts four major science activities to reduce volcanic risk in the Nation: (1) monitoring volcano unrest and eruption, (2) preparing volcano hazard assessments, (3) conducting research on volcanic processes, and (4) providing reliable forecasts, warnings, and volcano-hazard information. These activities address the U.S. Department of the Interior's (DOI) Serving Communities strategic goal of protecting lives, resources, and property by making information available to communities to use in developing volcano hazard mitigation, preparedness, and avoidance plans, and support the Geology Strategic Plan (2001-2010) goals of conducting geologic hazards assessments for mitigation planning and providing short-term prediction of geologic disasters and rapidly characterize their effects.

The VHP was reviewed in 2003 as part of the overall Geologic Hazards Program for the purpose of implementing the Program Assessment Rating Tool (PART). The Office of Management and Budget (OMB) found that the VHP role is clearly defined and unique from other Federal, State, local, or private entities. Three intermediate outcome measures are now tracked in support of the intermediate outcome of providing information to assist communities in managing risks from natural hazards. These outcome measures are (1) use rate of products, (2) percent of at-risk communities served with DOI science on hazard mitigation, and (3) adequacy of information. Output measures for which targets are now established in support of achieving the intermediate outcome goal include (1) maintenance of one hazard monitoring network, (2) delivery of risk assessments to customers, (3) presentation of formal workshops or training to customers, and (4) expanding the number of sites (mobile or fixed) monitored for ground deformation to identify volcanic activity.

To address the growing national risk from volcanic activity, the VHP must monitor all hazardous U.S. volcanoes in real time so that data can be acquired, processed, interpreted, and disseminated rapidly. In the past decade, with new funding from Congress, the VHP and partners have built new monitoring networks in Alaska and expanded existing networks in Hawaii, Long Valley caldera, California, and Yellowstone's enormous volcanic system. However, significant gaps and deficiencies in monitoring capability remain at numerous, hazardous volcanoes, and nineteen

volcanoes that pose a significant threat to air traffic completely lack the ground sensors necessary for basic monitoring. Furthermore, monitoring sensors currently deployed are becoming outdated, and many dangerous volcanoes are only monitored at a minimal level with regional networks of sparsely spaced seismometers. Consequently, the VHP must deploy adequate monitoring equipment when a volcano exhibits signs of significant activity, and scientists and civil authorities are placed in the position of “playing catch up” as a volcano's unrest increases, with scientists trying to install instruments and civil authorities struggling to develop and implement civil-defense measures before the situation worsens. Inevitably, this manner of response results in failing to monitor the early stages of volcanic unrest, which provide crucial, timely information needed to forecast the behavior of the volcano.

The Office of Management and Budget (OMB) evaluated VHP in 2003 to establish the use of PART to track program performance. The OMB found that the VHP role is clearly defined and unique from other Federal, State, local, or private entities. As a result of the PART evaluation, three intermediate outcome measures and four intermediate output measures are now tracked in support of the intermediate outcome of providing information to assist communities in managing risks from natural hazards. Also, in the course of the evaluation, it was recommended that the VHP develop plans for a National Volcano Early Warning System (NVEWS) to prioritize and coordinate the future investment required for the Nation's volcano-monitoring infrastructure. As a first step, a report released in April 2005 assessed the relative threat posed by 169 geologically active volcanic centers within the United States and summarized a gap analysis of the monitoring level at each volcanic center in light of the threat assessment.

<u>The 5-year goals of the VHP for the period FY2004–FY2008 comprise eight priority goals and objectives:</u>

1.0 Complete NVEWS planning and install new, and develop existing, geophysical and geochemical monitoring networks on dangerous volcanoes commensurate with the threat each poses to ensure reliable, real-time information on critical parameters such as earthquake activity, ground deformation, and emission of volcanic gases.

2.0 Conduct detailed geological field investigations of volcanoes and use Geographic Information System (GIS) technology to enhance hazard assessments, hazard-zonation mapping, probabilistic eruption forecasting, and an overall understanding of volcanologic, magmatic, and hydrologic processes.

3.0 Conduct experiments and systematic studies to establish a sound theoretical and empirical basis for understanding volcano processes and related hydrothermal and surface flowage processes.

4.0 Utilize Interferometric Synthetic Aperture Radar (InSAR) data to systematically characterize the deformation field at hazardous volcanoes and volcanic regions. This goal will be achieved through partnerships with other USGS programs and other agencies.

5.0 Reduce volcano risk abroad through the Volcano Disaster Assistance Program (VDAP), an interagency partnership between USGS and USAID Office of Foreign Disaster Assistance

(OFDA), by infrastructure development, technology transfer, and training in volcano monitoring, geological investigations, and hazard assessment in other countries.

6.0 Build and expand databases on volcanism in the U.S. and abroad, suitable for use in assessing potential volcanic activity and threat. Databases include historical information about volcanic unrest and eruptions, maps, geochemical and geophysical data, hazards analyses, and populations and infrastructure at risk.

7.0 Deliver effective products and services and provide timely access to VHP information.

8.0 Conduct strategic hiring and strengthen partnerships and communication with universities to maintain core capabilities, enhance scientific and technical coordination and exchange, and promote educational opportunities for students.

These goals are built on recent scientific accomplishments and advances in technology, and present important opportunities to further advance scientific understanding through multi-disciplinary research and, as a consequence, reduce our Nation's growing volcanic risk. The goals are interlinked and relate directly to the VHP PART measures by enhancing the ability of the VHP to provide information to assist communities in managing risks from natural hazards. Development for an NVEWS and databases on volcanic unrest and impacts (Program Goals 1 and 6) will expedite access and analysis of data during periods of crisis so that information can be more rapidly provided to the public (Program Goal 7). Real-time seismic monitoring at distant, but frequently active, volcanoes and expanded monitoring networks enhanced with broadband seismometers, continuous GPS and tiltmeters, InSAR, and other sensors (Program Goals 1 and 4) will provide new insight into (1) how distant earthquakes trigger volcanic activity, (2) how magmatic and hydrothermal processes produce volcanic uplift and subsidence, and (3) where migration paths of magma and hydrothermal fluids are located beneath volcanoes. Similarly, our understanding of volcanic processes will be advanced by developing methods to remotely analyze multiple species of volcanic gases, by determining precise ages of prehistoric volcanic events, by studying magma ascent paths and eruption triggers, by predicting flowage paths and stability of slopes, by assessing event probabilities, and by analyzing field data with GIS (Program Goals 2 and 3.) The improved understanding of volcanic processes generated by these activities will translate into more accurate assessments, better interpretation of volcanic unrest, and more reliable eruption forecasts (Program Goal 7). To achieve these goals, the VHP must maintain appropriate expertise and expand capabilities through partnerships and strategic hiring (Program Goals 5 and 8).

Introduction

Within the United States, 169 volcanic centers have erupted within the last 10,000 years and are deemed capable of eruption in the future. In the past 200 years alone, more than 50 of these volcanoes have erupted, many repeatedly. In the twentieth century, volcanic eruptions in Alaska, California, Hawaii, and Washington have caused significant economic disruption, long-term environmental damage and loss of life. Several of these eruptions led to the creation of national parks and monuments that are among the most popular in the Nation. In other countries, eruptions have caused great loss of life, displaced large numbers of people and wildlife, induced short-term climate perturbations, and affected U.S. investments and international relations. Hazardous volcanic activity will continue to occur, and the threat to lives and property is increasing with the growth in population and development near volcanoes, and the increase in national and international air traffic over volcanic regions.

Volcanic eruptions create hazardous conditions, which severely affect people and human infrastructure, near the volcano, in downstream valleys, and thousands of miles away.

Pinatubo Tephra. Clark Air Base, Phillipines. Photograph taken in 1991 by Ed Wolfe (USGS).

Lahar damage. Philippines from Mt. Pinatubo (1991)

Ash-covered DC-10, Cubi Point Naval Air Station, Philippines. Photograph by R.L. Roberts

Lava flow west of Royal Gardnes subdivision, Hawaii. Photograph taken in 1983 by R.W. Decker.

Before (4/23/1990) and after (6/13/1990) photographs of Kalapana Store in area inundated by lava flows from Kilauea Volcano in 1999, Kalapana, Hawaii. Photographs by J.D. Griggs, USGS.

Bicyclist wearing dustmask in Anchorage, Alaska, following eruption of Mount Spurr and tephra fall in city. Photograph taken in 1992 by Richard Emanuel.

The capability of the USGS in the field of volcano hazards has increased dramatically since the explosive eruption of Mount St. Helens, Washington, in 1980 and the contemporaneous volcanic unrest of Long Valley caldera, California. Prior to these events, the only U.S. volcano observatory was in Hawaii and only two volcanoes, Kilauea and Mauna Loa, were monitored at a significant level. By the end of 2003, the VHP supported five volcano observatories and monitored 46 of the Nation's dangerous volcanoes with real-time instrumented networks. The creation of the Volcano Disaster Assistance Program in 1986, an interagency cooperative program between the USGS and USAID Office of Foreign Disaster Assistance (OFDA), has helped 16 countries reduce volcanic risk during 20 significant volcano emergencies, most notably the 1991 eruption of Mount Pinatubo in the Philippines, where tens of thousands of lives and hundreds of millions of dollars in U.S. assets were saved.

This 5-year plan builds on this increased capability, and addresses the U.S. Department of the Interior's (DOI) Serving Communities strategic goal of protecting lives, resources, and property by making information available to communities to use in developing volcanic hazard mitigation, preparedness, and avoidance plans, and support the Geology Strategic Plan (2001-2010) goals of conducting geologic hazards assessments for mitigation planning and providing short-term prediction of geologic disasters and rapidly characterize their effects. When realized, the plan will enable the VHP to (1) more accurately interpret volcanic unrest and forecast eruptive behavior, (2) identify and assess volcano hazards, and (3) better understand the magmatic precursors of eruptions in the diverse tectonic settings of the nation and the world.

The continuing scientific quest of the VHP is to learn to distinguish signs of volcanic activity that lead to eruptions from those of intermittent unrest; discern more clearly the factors that determine the onset, duration, style (explosivity), and end of eruptions; and develop better methods for assessing and communicating long- and short-term hazard potential.

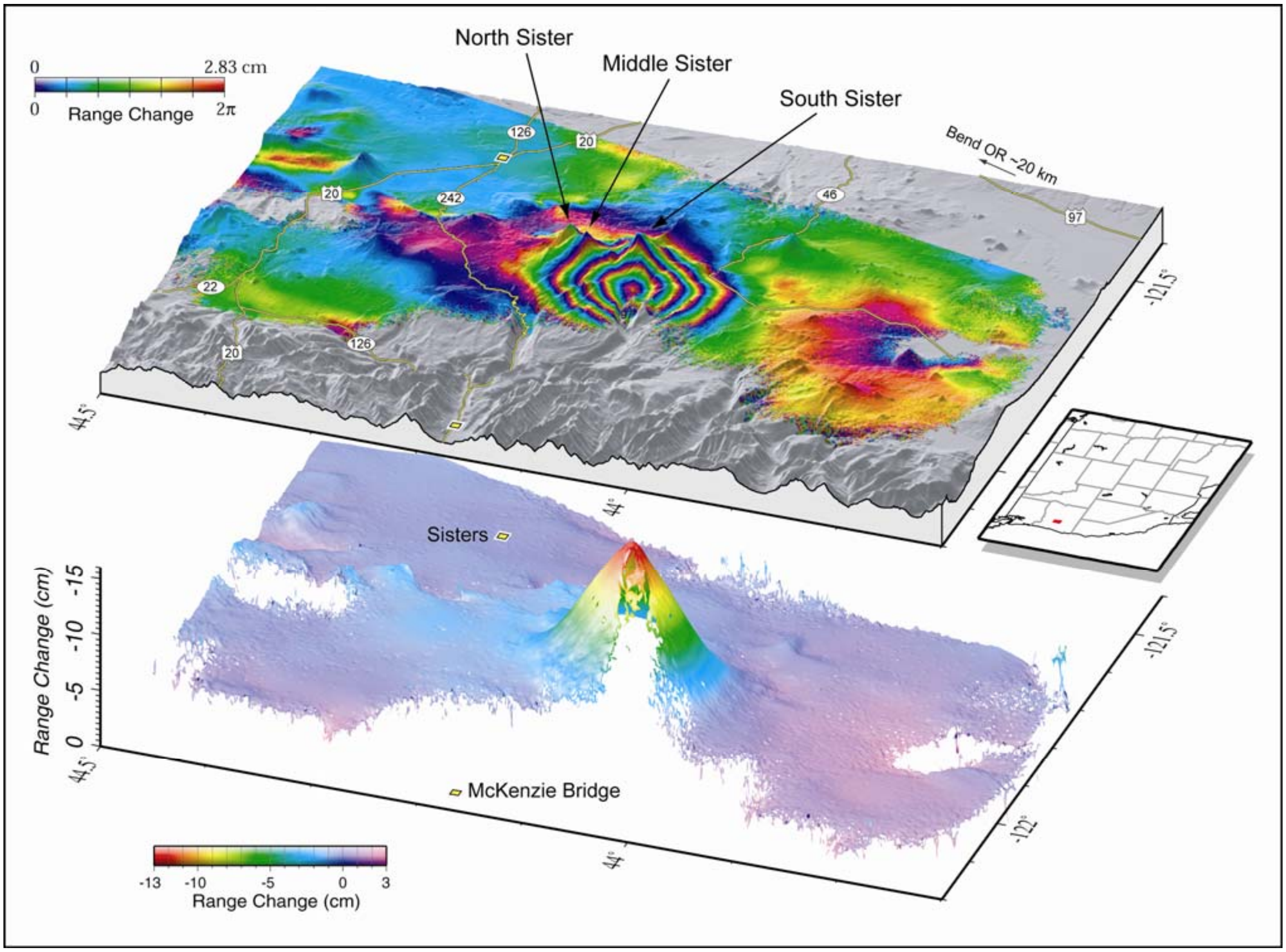
New volcanic unrest and eruptions, including significant changes in ongoing eruptions, quickly modify short-term objectives and priorities of the VHP and partners on short notice. For volcanoes with an existing monitoring network, a period of heightened unrest may require the installation of additional instruments in order to better track the activity. Work plans may be redirected to deal with short-term hazards, provide warnings, and disseminate general information about the activity. When a volcano that lacks an adequate network of real-time instruments awakens, the VHP must establish an adequate network if feasible. Internal review, collaboration with partners and universities, and a clear understanding of VHP's mission facilitate a sudden redirection of resources when necessary.

New episodes of activity are, in essence, unplanned opportunities to test hypotheses of magma migration and to analyze eruptive processes and hazards. Eruptions and magma intrusions allow scientists to examine and develop new models of volcanic behavior and to develop and test new tools for monitoring active volcanoes. Dramatic improvements to scientific understanding of volcanoes are the result of careful observations and analysis of volcanic activity. Thus, modern volcano-monitoring networks and scientific capability to document new eruptive activity on the ground are crucial in improving the reliability of eruption forecasts.

The VHP must expand partnerships and adjust the scientific balance in its workforce to implement and maintain an NVEWS. The program has a long tradition of applying diverse scientific and technical specialties to meet its mission, and will continue to build on this strength by better integrating its activities with those of other groups within and outside the USGS.

Restless activity triggers response, Three Sisters, Oregon

In April 2001, a broad area of ongoing uplift centered 5 km west of South Sister volcano in the central Oregon Cascade Range was detected, using newly proven satellite-based Interferometric Synthetic Aperture Radar (InSAR). The discovery of more than 15 cm uplift since 1998 resulted in an immediate enhanced monitoring effort (2001 to present). This effort is directed toward identifying the cause, tracking subsequent ground movement, earthquakes, and chemical changes in spring water and keeping Federal land managers and State and county officials informed about the status of the activity and potential volcano hazards. The area of uplift is located in the Three Sisters Wilderness, which requires detailed planning with the U.S. Forest Service for the installation and maintenance of radio-telemetered instruments and conducting ground surveys with minimal or no impact to this sensitive area. Monitoring data suggest the ongoing uplift results from the slow accumulation of magma 5 to 7 km below the surface. A hazard assessment, "Volcano Hazards in the Three Sisters Region, Oregon," which was published in 1999, provides context for evaluation of potential hazards. Continued vigilance is necessary to detect additional activity that is certain to occur should magma rise to the surface.



Wrapped (above) and unwrapped (below) interferograms for the Three Sisters area for the period 1995 to 2001. Each fringe (color band) in the upper image represents 2.83 cm of satellite-to-ground range change (mostly uplift).

Acknowledgments

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Authorizations

On May 22, 1974, Congress enacted the Disaster Relief Act of 1974 as Public Law 93-288 (88 Stat. 143), also known as the Stafford Act. Through this act and subsequent Executive orders, the USGS was granted specific responsibility for providing technical assistance on volcanic hazards and assigned authority to issue volcano warnings.

Through Executive Order 11795 entitled "Delegating Disaster Relief Functions Pursuant to the Disaster Relief Act of 1974" (30 FR 25939, July 11, 1974) and subsequent actions (as reported in 40 FR 52927, November 13, 1975, and 49 FR 213938, 1984), the President delegated responsibility to the Secretary of the Department of the Interior to empower the Director of the U.S. Geological Survey "to exercise the authority, functions, and powers granted by Section 202 of the Disaster Relief Act of 1974 with respect to disaster warnings for an earthquake, volcanic eruption, landslide, mudslide, or other geological catastrophe."

Accordingly, the mission of the USGS Volcano Hazards Program (VHP) is to enhance public safety and reduce losses from volcanic events through effective forecasts and warnings of volcanic hazards based on the best possible scientific information. VHP warnings, expertise, and products are used by other government agencies, the private sector, the public, universities, and the global community.

The VHP mission is reflected in the USGS Geologic Discipline's first two strategic goals for the period 2000-2010: *Goal 1 - Conduct geologic hazard assessments for mitigation planning and Goal 2 - Provide short-term prediction of geologic disasters and rapidly characterize their effects.* The VHP 5-Year Plan provides additional information for these goals and translates them into more specific objectives and tasks, which define priorities and allow for tracking progress.

PART Review and Outcome Measures

OMB evaluates program performance quarterly through the use of a Program Analysis and Rating Tool (PART), which is linked to annual goals and measures established under the Government Performance and Results Act (GPRA). The VHP was reviewed in 2003, as part of the overall Geologic Hazards Program for the purpose of implementing the Program Assessment Rating Tool (PART). As described in the Office of Management and Budget (OMB), the VHP role is clearly defined and unique from other Federal, State, local, or private entities. The VHP Five-Year Plan, a critical component for the OMB evaluation, links annual PART and GPRA evaluations to long-term program and USGS bureau goals. Three intermediate outcome measures are now tracked in support of the intermediate outcome of providing information to assist communities in managing risks from natural hazards. These outcome measures are (1) use rate of products, (2) percent of at-risk communities served with DOI science on hazard mitigation, and (3) adequacy of information. Output measures for which targets are now established in support of achieving the intermediate outcome goal include (1) maintenance of one hazard monitoring network, (2) delivery of risk assessments to customers, (3) presentation of formal workshops or training to customers, and (4) expanding the number of sites (mobile or fixed) monitored for ground deformation to identify volcanic unrest. Appendix H presents outcome and output measures with goals projected 5 years into the future and also summarizes the relationship between program goals and PART outcome and output measures.

History of the VHP

With roots in the world's second volcano observatory, the Hawaiian Volcano Observatory (HVO), founded in 1912 atop Kilauea Volcano on the island of Hawaii, the VHP today supports five U.S.

volcano observatories, a world-renowned volcano-response capability, and a multidisciplinary team focused on mitigating volcano hazards and advancing the science of volcanology.

The 1980 eruption of Mount St. Helens brought a tenfold increase in funding to USGS's volcano-focused projects and authorization of a line item in the USGS budget for the VHP. The Cascades Volcano Observatory (CVO), Vancouver, Washington, was formally created in 1982 to continue a long-term monitoring and hazard-assessment program for Cascade Range volcanoes. Focused initially on the continuing eruptive episodes at Mount St. Helens, in partnership with the University of Washington Geophysics Program, CVO quickly built an unmatched record of accurate warnings as far as 3 weeks in advance for 19 of 21 eruptive episodes between June 1980 and October 1986. CVO also became a center for tracking extremely high sediment yields in eruption-impacted river valleys heading on Mount St. Helens, especially the Toutle River, and water levels in lakes that formed behind unstable debris dams along the margins of the giant landslide that slid into the North Fork Toutle River.

Within 1 week of the destructive May 18, 1980, eruption of Mount St. Helens, four M6 earthquakes in Long Valley caldera, California, heralded the beginning of more than 20 years of unrest marked by earthquake swarms and ground uplift in the middle of the caldera. This unrest was caused by rise of magma beneath the caldera and slip on a series of faults. The most recent eruptions in the area took place 250 to 550 years ago, which raised concern about the potential for eruption within a few miles of the town of Mammoth Lakes and other resort communities in eastern California. In 1989, magma intruded beneath Mammoth Mountain, a volcano on the caldera's west rim and site of a major ski resort. Although magma did not erupt, the intrusion released carbon dioxide gas that destroyed more than 100 acres of forest during the subsequent 2 years. Increased monitoring of the caldera by USGS and the university community eventually led to formal organization of the Long Valley Observatory (LVO) in the late 1990s as a major VHP project.

The Alaska Volcano Observatory (AVO) was created in 1988, following the 1986 explosive eruptions of Augustine Volcano in Cook Inlet, Alaska, which generated eruption clouds that disrupted regional air traffic. The AVO is a partnership between the USGS, University of Alaska Fairbanks Geophysical Institute, and the Alaska Division of Geological and Geophysical Surveys. The 1989-90 eruption of Redoubt Volcano and 1992 eruptions of Mount Spurr demonstrated the value of AVO's monitoring capability to provide eruption warnings for Cook Inlet volcanoes and to help prevent aircraft from encountering volcanic ash along routes between Asia and Europe and the U.S. and air routes in the conterminous U.S.

Beginning in 1996, with new Congressional funding, AVO began an aggressive effort to install volcano-monitoring networks at active volcanoes on the Alaska Peninsula and Aleutian Islands. At the end of FY2003, 27 volcanoes were monitored in real time, with seismic networks, satellite remote-sensing, and a growing number of geodetic-monitoring instruments.

To facilitate warnings for volcanoes beyond the Aleutian Islands in Russia, AVO also collaborates with the Kamchatkan Volcanic Eruption Response Team (KVERT), created in 1993 by the Russian Academy of Sciences Institute of Volcanic Geology and Geochemistry and the Kamchatkan Experimental and Methodical Seismological Department.

The tragic deaths of more than 23,000 people on November 13, 1985, from lahars triggered by a moderate-sized explosive eruption of Nevado del Ruiz, Colombia, led the U.S. Agency for

International Development (USAID) and the USGS VHP to jointly fund a new Volcano Disaster Assistance Program (VDAP). The program supports a team of scientists who rapidly respond to volcano emergencies in the U.S. and abroad with a portable cache of volcano-monitoring equipment. Foreign responses are conducted at the request of other nations and the U.S. State Department. Since 1986, the VDAP team has deployed teams in response to 20 volcano emergencies and provided monitoring equipment and technical assistance for 59 volcanoes in 18 countries.

A key mission of VDAP is to assist other nations build and maintain their own capacity to monitor volcanic activity, assess hazards, and reduce volcanic risk. Monitoring equipment, technical assistance, and training are provided at no cost to developing countries. VDAP also supports scientific investigations required for volcano hazards assessments, technology transfer, infrastructure development, and training in volcano monitoring and hazards assessment in other countries. With USGS funding, VDAP develops and maintains a cache of modern equipment for U.S. volcano emergencies, assists during domestic eruptions, and helps expand monitoring networks in the U.S. Through these diverse activities, VDAP provides essential experience needed by the program to fulfill its domestic mission, as well as contributing to the foreign assistance goals of USAID.

In FY1995, the USGS's long-lived Geothermal Investigations Program was merged into the Volcano Hazards Program, bringing both funding (about $4.5 M) and expertise in geothermal-energy resources. From FY1996 to FY1997, the geothermal component of the combined program was cut substantially. Much of the remaining geothermal project work was redirected to volcano hazard-assessment studies in the Cascade Range and Alaska, and on the interaction between hydrothermal and magmatic systems, important studies to understand episodes of unrest at the large volcanic systems of Yellowstone caldera, Wyoming-Idaho-Montana and Long Valley caldera, California.

In 1989, HVO and the University of Hawaii formed the Center for the Study of Active Volcanism (CSAV), chartered to assist in the mitigation of volcano hazards worldwide, with special emphasis on the circum-Pacific area. In addition to its role in fostering cooperation among universities and national and State agencies, CSAV conducts a highly successful training program. With significant support from VDAP, the program assists developing nations and U.S. scientists in monitoring volcanoes and conducting volcanologic research.

The Yellowstone Volcano Observatory (YVO) was created in May 2001 by the USGS, University of Utah, and Yellowstone National Park based on the long-term monitoring and geologic investigations of the Yellowstone volcanic system, dating back to the 1959 Hebgen Lake M7.5 earthquake. This is the largest active magmatic system in North America and the world's first national park. YVO will further strengthen scientists' abilities to track activity that could result in hazardous hydrothermal, seismic, or other volcano-related activity.

The increased capability of the VHP to issue effective warnings and assess hazards for a growing number of volcanoes stems directly from an improved understanding of how volcanoes work and a proven monitoring and research program. At the beginning of the twenty-first century, with an experienced team, effective partnerships, and advances in monitoring technology, the VHP is well positioned to further reduce volcano risk in the United States and abroad. A challenge of the next 5 years will be to maintain adequate levels of expertise and to expand program capabilities in order to meet the increasing need for volcano hazards information.

<u>Scientific accomplishments and highlights</u>

The 5-Year Program Plan developed for FY1999 to FY2003 identified a range of major programmatic activities as priority targets, which were achieved with small modifications made during the VHP's annual planning activities (appendix A).

The period between 1999 and 2003 included these major accomplishments:

- Timely information updates and warnings for seven episodes of restless activity and three eruptions, including the 1983-present eruption of Kilauea Volcano (appendix B).

- Increased geophysical, geochemical, and remote-monitoring capabilities required for volcano warnings and corresponding research, especially along the 1,800-mile-long chain of volcanoes in Alaska.

- Multidisciplinary studies at more than 10 volcanic fields to decipher the evolution of contrasting magmatic systems and improve hazards assessments.

- Scientific results published in more than 300 papers and maps in peer-reviewed journals, monographs, books, and map series, and volcano-hazard information disseminated through Web sites, fact sheets, exhibits, posters, public presentations, meetings, workshops, and the news media.

- Establishment and maintenance of the Web-based Weekly Volcanic Activity Report, in partnership with the Smithsonian Institution's Global Volcanism Program.

- Direct assistance to mitigate volcano hazards in 17 countries through VDAP (appendix D) and the Commonwealth of the Northern Mariana Islands (CNMI).

- Strengthening of scientific and emergency partnerships nationally and internationally, resulting in increased capabilities, products, and services that are more responsive to customer and community needs. For example, VHP co-sponsored the “Cities on Volcanoes III” international meeting in 2003 to bring together scientists and emergency managers to focus on strategies for reducing volcanic risk in communities near active volcanoes.

Selected highlights for the period of the last 5-year plan, 1999 to 2003, are presented in appendix D.

<u>Scientific directions, challenges and partnership opportunities</u>

National Volcanic Early Warning

As a consequence of the 2003 PART review of the VHP, OMB recommended that the VHP develop plans for a National Volcano Early Warning System (NVEWS) to prioritize and coordinate the future investment required for the Nation's volcano-monitoring infrastructure. The VHP is working through the Consortium of U.S. Volcano Observatories (CUSVO) to respond to this request. As a first step, USGS Open-File Report 2005-1164, released in April 2005, presented an assessment of the relative threat posed by 169 geologically active volcanic centers within the United States and a gap analysis of the monitoring level at each volcanic center in light of the threat assessment. Based on the NVEWS analysis and volcanic activity as of April 2005, the highest priority targets for monitoring improvements are

- *5 volcanoes that currently are erupting (Mount St. Helens in Washington, Anatahan in the Mariana Islands, Kilauea in Hawaii) or exhibiting precursory unrest (Mauna Loa in Hawaii, Mount Spurr in Alaska*).
- *13 very high-threat volcanoes with inadequate monitoring (9 in the Cascade Range and 4 in Alaska).*
- *19 volcanoes in Alaska and the Mariana Islands that have high aviation-threat scores and no real-time ground-based monitoring to detect precursory unrest or eruption onset.*

An additional 21 under-monitored volcanoes in Washington, Oregon, California, Hawaii, Alaska, the CNMI, and Wyoming also are priority NVEWS targets. The physical aspects of NVEWS involve installation of modern instrumentation arrays with data links to the volcano observatories and facilities of the CUSVO partners. Monitoring improvements at these volcanoes would entail new capital costs for equipment as well as recurring expenses for operation and maintenance and would take several years to implement, requiring a substantial investment beyond the current resources of the USGS Volcano Hazards Program and its affiliate partners.

Along with enhancing instrumentation capabilities, NVEWS proposes to institute a 24x7 National Volcano Watch Office to improve alerting and forecasting capabilities and provide authoritative information on volcanic activity. Duties at the watch office would be shared among all the observatories in a distributed fashion. Implementing NVEWS and a National Volcano Watch Office will require significant investment in IT hardware and software to handle continuous archiving and sharing of data from monitoring networks. The IT system would increase inter-operability among observatories and permit all data streams from monitored volcanoes to be accessed in real time at multiple locations.

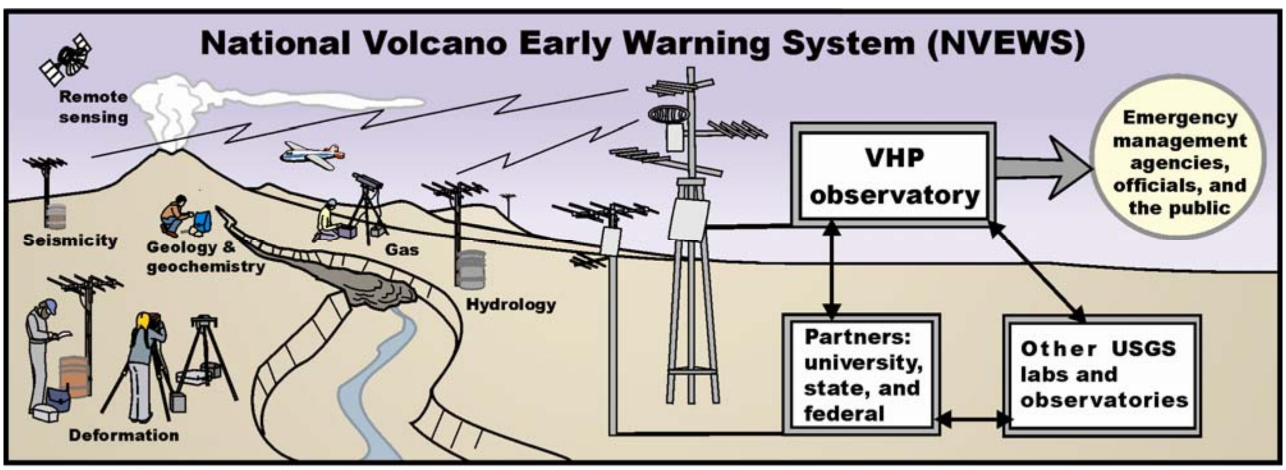
A fully implemented NVEWS, when combined with current monitoring capabilities, will provide

- A much richer body of observations and data on volcanic activity, as the basis for more reliable eruption forecasts and a range of derived information products from real-time graphical and map depictions of data to peer-reviewed research papers.
- Minimized risk of a surprise eruption at a dangerous volcano.
- Real-time hazard analysis and rapid event notification during periods of escalating unrest and eruption at well-monitored volcanoes, aiming for 5-minute notification by volcano observatories to the FAA of major explosive eruptions.
- The hardware, software, and networking infrastructure to enable scientists to view and analyze all data streams from monitored volcanoes in real time at multiple locations.
- A 24x7 National Volcano Watch Office for full alerting capabilities and authoritative information about unrest and eruptive activity throughout the U.S. and more general situational awareness of volcanic activity globally.

- A National Volcano Data Center to archive all the diverse kinds of NVEWS data.
- An NVEWS Web site with a daily status report covering all monitored volcanoes.
- Efficient coordination of volcano-monitoring resources across agencies and institutions.

An NVEWS will greatly facilitate mitigation of volcanic hazards through earlier detection of unrest and through greater understanding of magmatic processes beneath volcanic centers. Comprehensive monitoring will allow us to (1) track seismic activity, deformation, and degassing through entire eruptive cycles and (2) relate characteristics of unrest to magma composition and processes. As we increase the number of volcanoes monitored for deformation by InSAR and ground-based measurements, numerical modeling will play a greater role in inferring the behavior of the magmatic plumbing. Ultimately, forecasting volcanic activity will be dramatically improved through modeling geodetic, seismic, and geochemical observations on the basis of geologic processes and geologic records of previous eruptions.

As a next step, the USGS Volcano Hazards Program will convene workshops beginning in 2005 to review and refine the proposed implementation framework. A workshop will be held with the full CUSVO membership and other scientific stakeholders to establish data and operational policies and launch topical working groups. At another workshop, a broader group including other Federal agencies, State and County emergency management agencies, and business and private organizations, will be consulted about their specific information requirements.



Schematic diagram illustrating the major components of a National Volcano Early Warning System (NVEWS). Real-time (and near-real time) data acquired through automated monitoring of seismicity, ground deformation, hydrology, and gas geochemistry are telemetered from networks of instruments on volcanoes to Volcano Hazards Program (VHP) observatories and partners. Observatory scientists rapidly analyze and interpret these data, often in consultation with colleagues at other observatories and labs. Such analysis takes into account additional information on geology, geochemistry, hydrology, and hazards. The state of unrest and the potential hazard is then communicated to emergency managers, officials, and the public. When there is elevated risk, established telephone "call-down" lists are used for immediate notification, and formal USGS hazards advisories are issued under the authority of the Stafford Act.

Volcano monitoring and volcano hazard assessments in the Commonwealth of the Northern Mariana Islands

Within the Commonwealth of the Northern Mariana Islands (CNMI), nine islands host active volcanoes that pose a significant hazard to air traffic and to planned settlement and economic development. Within just a small area of airspace immediately surrounding the Mariana Islands, there are approximately 25,000 large commercial passenger flights per year, and more than 1,000,000 flights of large commercial aircraft transit from Asia to Australia and New Zealand, passing through air space potentially affected by eruptions in the Marianas. On the ground, the volcanoes of the CNMI directly threaten expanded settlement and development.

In collaboration with the Emergency Management Office (EMO) of the CNMI, the VHP plans to install a volcano-monitoring network for the Mariana Islands during the next 5 years. The core of the Northern Mariana Islands volcano-monitoring system would be a satellite-telemetered seismic network. Monitoring data would be received at the EMO and shared via the Internet to USGS volcano observatories in real time with analysis of the data carried out by the EMO and USGS volcanologists. Parallel with the installation and commissioning of the monitoring system, the USGS would conduct field studies and laboratory research with the aim of defining and evaluating seismic and volcanic hazards associated with eruptions in the Northern Mariana Islands. In addition, a program will be implemented to increase public awareness and education, and to develop a strategy for mitigating volcanic hazards to Northern Islands residents and infrastructure.

The Marianas arc remains relatively unstudied although it is one of the world's best examples of an island arc developed solely on a basement of oceanic crust. It is anticipated that, in addition to contributing to public safety, monitoring and hazard assessment of the Marianas volcanoes will contribute fundamental scientific understanding on the processes involved in the formation and evolution of island arcs.

Expansion of Alaska Volcano monitoring and studies of the Aleutian Island Arc

Continued expansion of volcano monitoring in Alaska is a high priority identified by the NVEWS analysis. A challenge over the next 5 years will be to maintain the appropriate balance in funding and staffing needed to meet the requirements for both continued expansion and maintenance of the Alaska volcano monitoring networks, while also devoting adequate resources for the scientific opportunities that will be created by the Alaskan expansion.

The Aleutian arc provides an outstanding opportunity to better understand the origins and characteristics of island arc volcanoes because of its geologic and tectonic diversity and its high rate of volcanic unrest and frequency of eruptions. All major types and compositions of arc volcanoes are present and potentially active, ranging from basaltic maar volcanoes to andesitic and dacitic stratovolcanoes and calderas. Older basement rocks underlying the volcanoes, continental in character beneath the Alaskan Peninsula, become mainly oceanic farther to the west; sediment loads the Aleutian trench near the continent, yet the trench is sediment-starved in the west. Plate convergence along the arc is head-on in the east but transitions to highly oblique in the west. The arc-trench gap, the distance between the offshore oceanic trench and the volcanic axis, spans most of the range seen on Earth, from 100 km at the narrowest to 500 km at the widest. All of these factors play a role in controlling the locations, sizes, and frequency of eruptions, types of erupted products, and the potential explosiveness of future eruptions from volcanoes. In addition to these large-scale factors, there is a series of equally important smaller-scale questions, ranging from the spacing of volcanoes along the arc to the effect of local controls on eruptive processes and on the geometry and longevity of magma reservoirs. Because of the high rate of eruption (on average, one eruption and numerous periods of volcanic unrest each year), the Aleutian Arc provides an opportunity to advance the understanding of volcanic processes and hazards through investigations of many eruptions from volcanoes with diverse chemical compositions.

Major advances in the understanding of volcanic processes and their hazards often take place during, and immediately after eruptions, such as was observed after the eruption of Mount St. Helens, Washington; Redoubt Volcano; Alaska; and Mount Pinatubo, Philippines. In the next 5 years, the Alaska Volcano Observatory will enter a phase in which a 10-year-long rapid network expansion and first-time geologic investigations will gradually shift to (1) upgrades and maintenance of existing instruments, telemetry, and data-acquisition systems, and (2) more comprehensive scientific investigations of eruptive histories, processes, and new episodes of unrest and eruption. These studies will involve teams of USGS scientists and university colleagues.

KVERT and the Northern Pacific Arcs

The Kamchatkan Volcanic Eruption Response Team (KVERT) is a cooperative program of the Institute for Volcanic Geology and Geochemistry and the Kamchatka Experimental and Methodical Seismological Department in Petropavlovsk-Kamchatsky. KVERT monitors active Kamchatkan volcanoes and provides status reports and eruption notifications through the Alaska Volcano Observatory. A significant new scientific opportunity is emerging for cooperation among American, Russian, and Japanese scientists for expanding volcanic monitoring and scientific studies to the Kurile Islands, thereby providing volcano monitoring across the extent of the entire North Pacific volcanic arc system.

Through AVO, the USGS partners with the KVERT provide notifications of eruptions from the 29 active volcanoes in Russia’s Kamchatkan Peninsula. Several eruptions each year in Kamchatka produce ash clouds that threaten the safety of air travel across the North Pacific, including travel between the United States and Russia and Japan.

Eruption of Sheveluch Volcano, Kamchatka, on May 19, 2001. Photograph courtesy of Yuri Demyanchuk, Kamchatka Experimental Methodical Seismological Department, Geophysical Service.

Advancing Volcanology through University Partnerships

Earthscope is a decade-long $356 million experiment designed to advance basic research in the solid earth sciences through the deployment of hundreds of geophysical instruments in North America. As a partner in Earthscope, USGS brings its unique Federal role in applying earth science to reducing risk from natural hazards. Components of Earthscope that directly contribute to the mission of the VHP are the Plate Boundary Observatory (PBO) and Interferometric Synthetic Aperture Radar (InSAR).

PBO is a suite of high-precision geodetic instruments (GPS, strainmeters, and borehole tiltmeters) deployed along the North American and Pacific plate boundary from Alaska to Mexico. Instrument deployment for PBO is funded by the National Science Foundation (NSF), and the NSF and the USGS will fund their own research projects to analyze and interpret the resulting data sets. Integration of data appropriate PBO instruments into the VHP monitoring networks is actively occurring and USGS scientists have participated in PBO planning workshops beginning in 1999. Through this interaction, the VHP has contributed to the PBO Deployment Plan for Studying Diverse Magmatic Systems Along the Western North America Plate Boundary (http://volcanoes.usgs.gov/pbo/).

The InSAR component has been proposed through NASA as a satellite mission, and the USGS and NSF will provide funding for research, science applications, and data management. Although the InSAR component is not yet operational, the VHP has been collaborating with USGS colleagues (EROS Data Center, the Land Remote Sensing Program, Earthquake Hazards Program, and the Ground Water Resources Program), NASA, and the NSF to conduct a pilot program to acquire, archive, and distribute InSAR data quickly from existing non-U.S. satellite systems for use in monitoring volcanoes, fault zones, and ground-water basins. Advancing volcano geodesy with

InSAR and integration of InSAR as one tool in a National Volcano Early Warning System will be a program objective over the next 5 years.

Center for the Study of Active Volcanoes

The Volcano Hazards Program supports the Center for the Study of Active Volcanoes (CSAV)–a cooperative program of the University of Hawaii and HVO, chartered in 1989. The mission of CSAV is to assist in the mitigation of volcanic hazards worldwide, with special emphasis on the circum-Pacific area. CSAV seeks to develop training programs in volcanology, assist developing nations, expand cooperation among universities and government agencies, and foster cooperation with other volcano observatories, scientific organizations, and universities. In its first decade, CSAV developed volcanology training courses, provided technical assistance to HVO, and worked with the VDAP to provide training programs for observatory staff from other countries. In 2003, CSAV proposed to expand its role on behalf of the program through enhanced technical assistance and hazards assessment activities and through volcano hazards database development. Strengthening the CSAV partnership through coordination with the other U.S. and international volcano observatories poses a significant opportunity.

Potential Science and Technology Centers

The National Science Foundation's Science and Technology Centers (STC) Integrative Partnerships program was established in 1987 to support innovative research and education projects of national importance that require a center mode of support to achieve the research, education, and knowledge-transfer goals shared by the partners. STCs conduct world-class research in partnerships with academic institutions, national laboratories, industrial organizations, and (or) other public and private entities to create new and meaningful knowledge of significant benefit to society. Although previous volcano STC proposals to NSF have not been successful, the Volcano Hazards Program will continue to work with the university community toward the development of future proposals, which seek to advance volcano science and reduce volcano risk.

Developing a common alert-level system

Several alert-level schemes have been used in the past two decades to characterize the degree of volcano unrest and likelihood of hazardous activity and eruption, and, for the aviation community, to indicate the potential height of an eruption cloud either expected or in progress. With greater national emphasis placed on the coordination of emergency management and contingency planning for mitigation of natural disasters, the creation of the international system of Volcanic Ash Advisory Centers (within the National Weather Service (NWS)), and the development of a color code for terrorism by the Department of Homeland Security, the VHP recognizes the need for a common volcano hazards alert-level system. The program will review current alert-level systems used at its observatories and develop a more uniform approach in collaboration with its key customers. An effort to review current alert-level schemes was begun by VHP in FY2003 and a revised national-level system will be implemented within the next few years.

Program Mission and Long-Term Activities

Mission

The USGS's Volcano Hazards Program (VHP) enhances public safety and reduces losses from volcanic events through effective forecasts and warnings of hazards based on a comprehensive understanding of volcanic processes. Other government agencies, the private sector, the public, universities, and the global community use VHP warnings, expertise, and products.

Long-term activities

Monitor volcano unrest and eruption

Nearly all volcanic eruptions are preceded by measurable changes in seismicity, ground deformation, and 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 improve scientific understanding of volcanic processes. The VHP monitors active and potentially active volcanoes primarily through five volcano observatories with partners, and maintains the capability and protocol for the rapid deployment of staff and monitoring equipment during times of escalating unrest and eruption in the U.S. and abroad. A significant effort to improve access, delivery, archiving, and processing of monitoring data during the next 5 years will be the development of a National Volcanic Monitoring System; continued improvement and maintenance of this IT-based system will become a long-term program activity.

Prepare and keep current volcano hazards assessments (long term and during unrest)

The detailed record of a volcano's past eruptions provides the scientific rationale for assessing its likely future activity. This information is obtained through geologic mapping, dating of eruptive products, physical and chemical analysis of volcanic deposits, and high-resolution topographic mapping of the landscape to produce detailed digital elevation models. These data are integrated and analyzed using Geographic Information Systems (GIS) and numerical models to produce hazard zonation maps, which may include probabilistic information on recurrence and inundation. Hazards assessments are updated as new mapping data and modeling results are generated, and they serve as critical inputs for public policy on land-use planning, emergency plans, and preparedness activities.

Conduct research (topical investigations of volcanic processes)

Comprehensive knowledge and understanding of magmatic and hydrothermal processes taking place beneath the ground as well as volcanic and hydrologic activity at the surface and in the atmosphere are essential for reliable interpretation of monitoring data and preparation of volcano hazards assessments. Research utilizing extensive monitoring data, controlled experiments in the laboratory and field, and stratigraphic relations of eruptive products is directed toward improving models of magma storage, evolution, and ascent; eruption triggers; and the flowage of volcanic materials, including lava flows, debris flows, landslides, pyroclastic flows, and high-sediment discharge in watersheds affected by volcanic activity. Research is also directed to identify processes that lead to volcanic unrest on the basis of geochemical and petrologic studies of eruption products. These analyses can help determine whether a given magmatic system is waxing, waning, or in steady state and provide insight into the long-term eruption potential of volcanoes.

Provide reliable warnings, forecasts, and other information

The results of volcano monitoring, research, and hazards assessments must be conveyed effectively and in a timely manner to the communities and other customers they are intended to serve. The VHP works closely with other scientists, Federal and State officials, public safety and emergency managers, community planners, business leaders, educational institutions, and citizens groups to disseminate volcano warnings, forecasts, and other information through briefings, workshops, published reports and maps, videos, digital databases, Web sites, media, and weekly newspaper columns.

<u>Five-year goals, 2005-2009</u>

The VHP must continue to enhance existing partnerships and develop new ones with other USGS programs and non-USGS organizations to extend and augment its expertise in order to reduce future volcano risk in the Nation and abroad and achieve the goals identified in this 5-year plan. The VHP has a long tradition of applying diverse scientific and technical specialties to meet its mission and will continue to build on this strength by better integrating its activities with those of other groups both within and outside the USGS.

1. Complete NVEWS planning and install new, and develop existing, geophysical and geochemical monitoring networks on dangerous volcanoes commensurate with the threat each poses to ensure reliable, real-time information on critical parameters such as earthquake activity, ground deformation, and emission of volcanic gases. This goal is tracked by PART efficiency measures that track maintenance of the overall monitoring network, number of sites monitored for ground deformation, and number of volcanoes for which information supports public safety decisions (appendix H).

On the basis of NVEWS analysis and volcanic activity as of April 2005, the highest priority targets for monitoring improvements are

- *5 volcanoes that currently are erupting (Mount St. Helens in Washington, Anatahan in the Mariana Islands, Kilauea in Hawaii) or exhibiting precursory unrest (Mauna Loa in Hawaii, Mount Spurr in Alaska*).
- *13 very high-threat volcanoes with inadequate monitoring (9 in the Cascade Range and 4 in Alaska).*
- *19 volcanoes in Alaska and the Mariana Islands that have high aviation-threat scores and <u>no</u> real-time ground-based monitoring to detect precursory unrest or eruption onset.*

An additional 21 under-monitored volcanoes in Washington, Oregon, California, Hawaii, Alaska, the CNMI, and Wyoming also are priority NVEWS targets.

Increased deployment of ground-based monitoring systems for U.S. volcanoes is tracked under PART.   Important aspects of this goal are to establish and maintain the real-time flow of critical data during evolving volcanic activity and to optimize the spatial and temporal resolution of network components as much as possible to both develop and test conceptual models for geological structures, magma dynamics, and related hydrothermal processes.

Cooperative funding agreements with universities (University of Alaska at Fairbanks, University of Hawaii, University of Washington, and University of Utah) are critical for maintaining, improving, and increasing seismic and geodetic networks for volcano monitoring and research purposes, for which $1.7 million was provided to these universities in FY2003. The VHP is strongly linked to the USGS Earthquake Hazards Program (EHP) through shared responsibilities for geophysical (seismic and geodetic) monitoring of crustal processes in active tectonic zones and volcanic regions, including the design of field instrumentation and telemetry, and data acquisition, storage, and analysis systems. The VHP also collaborates with many other universities for volcano monitoring, including Stanford University, University of California at Berkeley, Duke University, Caltech, University of California at Los Angeles, University of Nevada at Reno, Washington University, University of Wisconsin, and the University of Oregon. Additional collaboration is expected through Earthscope's PBO and USARRAY to fully achieve this goal. VHP also collaborates with the USGS Landslide Hazards Program on real-time monitoring of debris flows and on developing models of debris flows and landslides.

General objectives:

- Complete a science and implementation plan for an integrated National Volcano Early Warning System (NVEWS), including data standards, communication, and security protocols, physical components, staffing needs, and links between VHP facilities and partners.
- Deploy new monitoring networks and improve and maintain existing monitoring networks at hazardous volcanoes; use enhanced monitoring data for interpretation of volcanic, magmatic, and hydrologic processes.
- Continue development and testing of new monitoring systems and methods to improve and extend capabilities in seismologic, geodetic, and hydrologic monitoring.
- Continue development and implementation of new software systems for integrated display and analysis of disparate types of monitoring data at all U.S. volcano observatories and VDAP's mobile volcano observatory; make systematic improvements based on user feedback; and evaluate them for inclusion in the NVEWS.
- Conduct campaign-style surveys of deformation, gravity, and gas emissions at priority volcanoes to complement and constrain data of the real-time monitoring networks (for example, Long Valley and Yellowstone calderas, Kilauea and Mauna Loa Volcanoes).
- Develop new multi-species, open-path Flow-Through-Infrared (FTIR) gas-monitoring methods.
- Develop airborne capability for direct measurement of plume CO_2/ SO_2 ratios in order to obtain CO_2 emission rates with less data processing time.

- Coordinate with Earthscope's PBO to optimize new installations of GPS, strainmeter, and borehole tiltmeter instruments at U.S. volcanoes and volcanic centers.

- In collaboration with USGS Geography Discipline, maintain access to and continue use of classified remote-sensing assets for evaluating volcanic unrest and hazards in support of VHP activities and archive classified remote-sensing data for use in future evaluations of volcanic unrest and hazards assessment.

- In collaboration with NOAA and other partners, enhance capabilities to detect and track eruption clouds (consisting of volcanic ash and sulfur aerosols), primarily in Alaska and the North Pacific, in near real-time, using remote-sensing data from civilian meteorological satellites.

<u>Volcano-specific objectives:</u>

- Continue to implement plans to install multiple monitoring instruments (borehole tiltmeters, strainmeter, three-component seismometer, temperature sensor, pore-pressure sensor) between 2- and 3-km depth in the 3-km-deep Long Valley Exploratory Well (LVEW) in Long Valley caldera, California.

- Integrate Long Valley caldera fluid-pressure data set into interpretations of volcanic and seismic activity in the caldera and establish procedures and data-processing systems to provide fluid-pressure information in a timely way during periods of unrest.

- Continue high-precision deformation monitoring using real-time broad band borehole strain, ground tilt, ground acceleration, pore pressure and velocity during magmatic intrusive events, triggered seismicity, and general volcano unrest, principally at Long Valley caldera, California, and Kilauea and Mauna Loa Volcanoes, Hawaii.

- Develop and implement a CO_2-gas monitoring system that will serve as proxy for tracking the rate of magma supply, expand continuous monitoring capabilities for SO_2 and CO_2, and implement remote SO_2 measurement networks at Kilauea with the new mini-UV spectrometer technology.

- Continue monitoring air quality at Hawaii Volcanoes National Park, atmospheric CO_2 gas at Long Valley, California, and CO_2, SO_2, and H_2S gas-emissions at volcanoes in the Aleutian arc and Cascade Range, Yellowstone caldera, Mammoth Mountain, and Kilauea Volcano.

- Collect and analyze river waters in Yellowstone caldera for Cl, S, HCO_3, and other anions to constrain the flux of magmatic and other volatiles issued from the Yellowstone hydrothermal system, and conduct geochemical reconnaissance studies in and around the Yellowstone caldera to corroborate the inferred growth of a large gas pocket that causes seismic anomalies in the Madison Plateau, west of the Norris geyser basin.

- Evaluate methods for detecting deformation that may be occurring at the north end of Yellowstone Lake.

2. Conduct detailed geological field investigations of volcanoes and use Geographic Information System (GIS) technology to enhance hazards assessments, hazard-zonation mapping, probabilistic eruption forecasting, and greater understanding of volcanologic, magmatic, and hydrologic processes. This goal is tracked by PART efficiency measures for a number of hazard assessments delivered to customers, number of areas for which geophysical models exist and allow interpretation of data, and percentage of hazardous volcanoes with published hazard assessments (appendix H).

2.1 Prepare geologic maps, GIS, and related reports that describe the eruptive history, geologic structure, and geomorphic evolution of targeted volcanoes. These are multi-authored studies that can take 5 to 10 years to complete.

<u>Objectives:</u>

2.1 a Begin new multidisciplinary studies at the following volcanoes:

- Alaska: Peulik, Chiginagak, Ukinrek Maars, Cerebus, Little Sitkin, Vsevidof, Kiska.

- Synthesis study of Cascades volcanism (compare and contrast eruptive styles and products).

2.1 b Complete primary field phase of mapping studies at the following volcanoes:

- Alaska: Veniaminof, Emmons Lake/Pavlof, Black Peak, Okmok, Gareloi, and Tanaga.

- Cascade Range (Washington, Oregon, Northern California): Glacier Peak and Mount St. Helens, Washington; Mount Hood, Three Sisters, and Newberry Volcano (extensive flows originating on north flank), Oregon.

- Hawaii: southwest rift zone, Kilauea Volcano.

2.1 c Complete compilation of geologic maps (not for all volcanoes) and related reports for the following volcanoes:

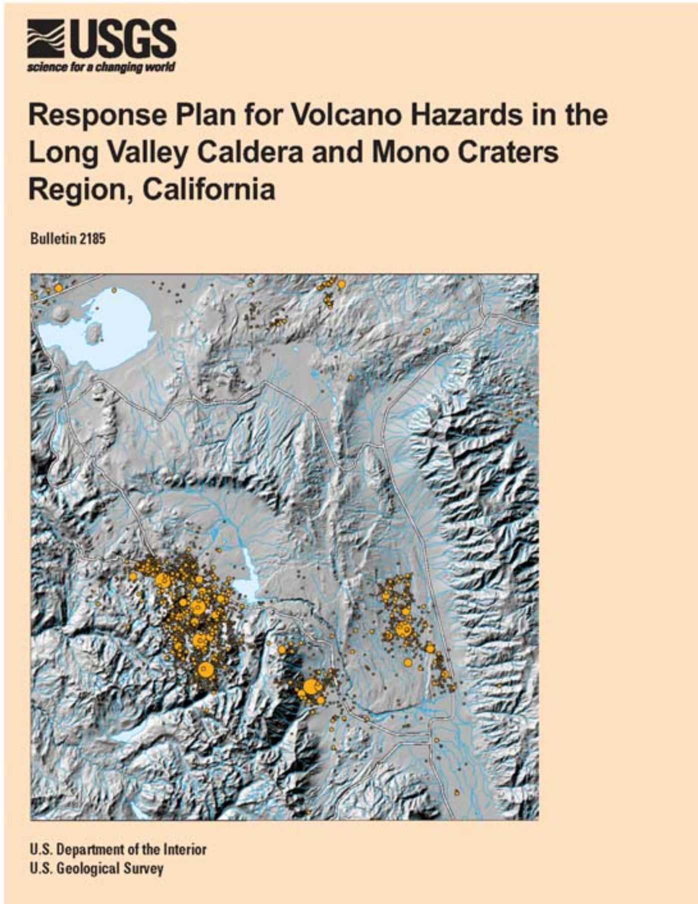
- Alaska: Veniaminof, Emmons Lake/Pavlof, Okmok, Dutton, Peulik, Gareloi, and Tanaga.

- Cascade Range: Mount Baker, Mount St. Helens, and Mount Rainier, Washington; Mount Hood and Crater Lake, Oregon; and Mount Shasta, Medicine Lake, and Lassen Peak, California.

- Hawaii: East Maui Volcano (Haleakala, Maui); Mauna Loa Volcano (2 of 5 sections completed by FY2004), and southwest rift zone, Kilauea Volcano.

2.2 Produce new and updated hazard assessments and hazard-zonation maps of U.S. volcanoes and volcanic centers needed for mitigation planning. An increase from 19

(FY1999 baseline) to 33 (FY2008) volcanoes with hazards assessment information is planned under PART.



Levels of Concern Color Code

GREEN	**No eruption anticipated.** Volcano is in quiet, "dormant" state.
YELLOW	**An eruption is possible in the next few weeks and may occur with little or no additional warning.** Small earthquakes detected locally and (or) increased levels of volcanic gas emissions.
ORANGE	**Explosive eruption possible within a few days and may occur with little or no warning. Ash plume(s) not expected to reach 25,000 feet above sea level.** Increased numbers of local earthquakes. Extrusion of a lava dome or lava flows (non-explosive eruption) may be occurring.
RED	**Major explosive eruption expected within 24 hours. Large ash plume(s) expected to reach at least 25,000 feet above sea level.** Strong earthquake activity detected even at distant monitoring stations. Explosive eruption may be in progress.

Under the authority of the Stafford Act, the USGS issues formal volcanic hazard assessments and warnings. Assessments include information on the eruptive frequency and extent of past eruptions, as well as evaluations of hazards and potential impacts of future eruptions. Emergency responders, land managers, and a wide variety of communities use these assessments to develop crisis response plans and mitigate risk through evacuation, zoning, land-use planning, and education. Notification of the status of volcanic unrest, such as illustrated by AVO's color-code system, is used widely in the private and public sectors. Key among uses are evacuations of hazardous areas and, coupled with ash-cloud tracking by NOAA's Volcanic Ash Advisory Centers, re-routing of aircraft to avoid volcanic ash clouds, which are extremely hazardous to aircraft.

Objectives:

- Hazards assessment of Alaska volcanoes, Veniaminof, Emmons Lake/Pavlof, Okmok, Dutton, Gareloi, Tanaga, Peulik, and an integrated report on Cook Inlet Volcanoes.

- Hazards assessment of Yellowstone volcanic system conducted through the Yellowstone Volcano Observatory.

- Hazards assessment of Cascade Range volcanoes, including Mount Shasta, Lassen Peak, and Medicine Lake Volcano; revise existing assessments, as appropriate, when significant new information becomes available.

- Revise the 1983 hazards assessment of Long Valley caldera and the Mono-Inyo Craters volcanic chain (including volcano, earthquake, and landside hazards).

- Probabilistic hazards assessment report for the island of Hawaii.

- Maps showing potential lava-flow inundation zones for Kilauea and Hualalai volcanoes, Hawaii, and maps showing lavasheds for entire island of Hawaii.

- A new hazards assessment for Mauna Loa Volcano, including a probabilistic map of lava flow inundation and evaluations of hazards from earthquakes, ground rupture, and explosive eruption.

3. Conduct experiments and systematic studies to establish a sound theoretical and empirical basis for understanding volcano processes and related hydrothermal and surface flowage processes.

3.1 Conduct studies focused on the physical and chemical processes that lead to magma ascent and eruption to optimize volcano-monitoring strategies and improve hazards assessments.

Basic field and lab research into volcanic processes is an essential element in a national volcano hazards program. Studies such as these help define what types of eruptions are possible at individual volcanoes, how explosive and long-lived they are likely to be, and how extensive the affected areas will be.

In the magma dynamics laboratory, specialized high-temperature furnaces and pressure vessels subject silicate melt to the conditions magma encounters as it travels to Earth's surface. The entire eruptive process can be examined in a succession of carefully planned and executed experiments, allowing scientists to identify the factors that control eruption explosivity. Photograph shows pressure vessel as it is removed from furnace at the end of experiment (temperatures and pressures of the magma inside the vessel reach 1050 ^{o}C and 200 MPa). Photograph taken in 2003 by Ben Hankins (USGS).

Objectives:

- Determine and evaluate physical and chemical controls on eruption triggers, intensity, and impact through a combination of experimental, field, and theoretical studies. Emphasis is on the interplay between time-dependent magma properties (viscosity, density, crystallinity, and vesicularity) and magma storage and ascent characteristics (storage depth, residence time, magma rise rate, volume flux, and conduit geometry).

- Evaluate compositional controls on eruptive behavior with experimental studies of samples from volcanoes in the Cascades and Alaska.

- Utilize the growing network of broadband seismometers to investigate the relation between volcano-tectonic and long-period events and very long-period signals accompanying magma migration and eruption, develop high-resolution models of the three dimensional P- and S-wave velocity structure of volcanoes, and characterize the location, orientation, and geometry of the magma pathway system using very long-period data.

- Improve models of eruptive processes by incorporating results from developing theories and experimental results (for example, magma rheology, degassing, seismic resonance, and conduit dynamics).

- Improve models to simulate deformation time-series data generated by episodes of magma intrusion (magma-reservoir inflation and emplacement of shallow dikes), and hydrothermal fluid migration. These models will be tested with data gathered from VHP and Earthscope geodetic-monitoring networks.

- Improve understanding of the locations, geometries, and evolution of magma reservoirs from the synthesis of geophysical and geologic data.

- Integrate hydrothermal flux, climatological data, and geodetic measurements to understand the relation between seismic and aseismic deformation and migration of thermal waters within Yellowstone caldera.

- Investigate causes and effects of hydrothermal explosions in the past 12,000 years at Yellowstone caldera using stratigraphic data from sediment cores.

3.2 Conduct studies on the properties of mass movements and other volcano-related flows, including edifice stability and flow-inundation models.

Objectives:

- Improve assessment of mass-movement hazards (for example, lahars and landslides) through continued development of quantitative techniques that provide information on event location, timing, size, speed, and areas of impact; conduct large-scale experiments at the USGS debris-flow flume necessary for testing mathematical models of flow behavior.

- Assess factors controlling the instability of volcanic cones, such as the three-dimensional slope stability of volcanoes in the Cascades.

- Characterize the origin and distribution of fluids in the shallow subsurface of volcanic systems, and develop better models of heat and multiphase fluid flow in volcano-hosted hydrothermal systems during cycles of intrusion, eruption, and dormancy, and test these models with hydrologic and geochemical monitoring of selected volcanoes.

- Extend current capability to estimate inundation of lahars using LAHARZ to other flowage phenomena, such as non-volcanic debris flows, rockfalls, and pyroclastic flows; evaluate and test inundation models for basaltic lava flows.

- Investigate and model the effects of tsunamis generated by eruptions at Alaskan volcanoes to assess future potential tsunami caused by volcanic activity.

3.3 Evaluate the severity and impact of accelerated sedimentation in rivers disturbed by volcanic eruptions.

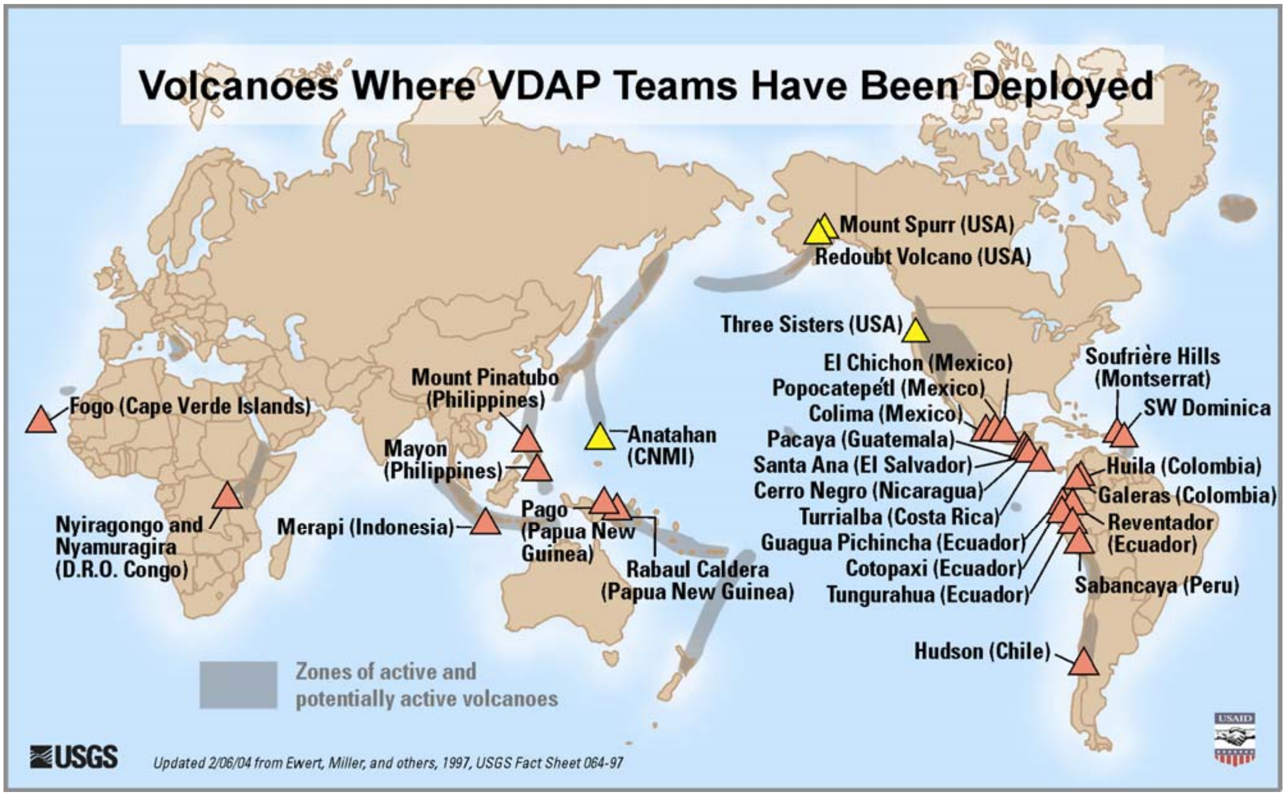
- Continue studies and development of forecasts of long-term sedimentation and its impacts on watersheds surrounding selected Cascades and Alaskan volcanoes, such as at Mount St. Helens, where sediment yields in some valleys remain approximately 100 times above background levels. Such high and persistent yields following volcanic eruptions pose significant hazards that can threaten downstream fisheries, flood protection, public works, commerce in distal communities, and geomorphic behavior of major Northwest river systems.

4. Use satellite Interferometric Synthetic Aperture Radar (InSAR) data to systematically characterize the deformation field at hazardous volcanoes and volcanic regions. This goal will be achieved through partnerships with other USGS programs and other agencies.

Objectives:

- Continue to acquire, interpret, distribute, and archive InSAR data for volcanoes using existing satellite systems, expanding coverage to volcanoes as funding permits.
- Continue participation in the InSAR component of Earthscope to assess the potential of InSAR data for tracking and interpreting subtle ground deformation of volcanoes.
- Continue participation in a consortium of government and university research users of Synthetic Aperture Radar (SAR) to promote open access to, and use of, SAR data for scientific and natural hazards applications.

5. Reduce volcano risk abroad through VDAP, an interagency partnership between USGS and USAID Office of Foreign Disaster Assistance, by infrastructure development, technology transfer, and training in volcano monitoring, geological investigations, and hazards assessment in other countries.



The USGS Volcano Disaster Assistance Program (VDAP) maintains a staff of experienced scientists and a cache of volcano monitoring equipment, which can be deployed globally within 48 hours to 1 week to assist other nations in dealing with volcanic unrest. This map shows volcanoes where VDAP teams have been deployed since the program began in 1986. As of 2004, VDAP has provided equipment or technical assistance to respond to hazards at 55 international volcanoes through a partnership with the U.S. Office of Foreign Disaster Assistance and at 4 domestic volcanoes.

Installation of telemetered tiltmeter at Soufriere Hills volcano, Montserrat,British West Indies. Photograph taken in 1995 by C. Dan Miller August (USGS).

<u>Objectives:</u>

- Maintain in operational readiness a rapid-response team for volcanic activity in the U.S. and developing countries, staffed by technically qualified experts who can work effectively to mitigate volcano emergencies.

- Maintain in operational readiness a dedicated, modern volcano-monitoring equipment cache for rapid deployment and use in volcano emergencies in the U.S. and developing countries.

- Provide training and technical assistance in support of national and regional centers for volcano-hazards mitigation, principally in Latin America, and to a lesser extent, in the Western Pacific (for example, Papua New Guinea, Indonesia, Philippines, and Pacific Islands).

- Collaborate with appropriate international organizations and donor institutions and promote inter-country cooperation, data exchange, and technical assistance.

- Maintain existing, and develop new liaisons with appropriate host-country officials, institutions, and agencies associated with volcano monitoring, volcano-emergency planning and preparedness, and crisis management, with international volcanologic institutions, and with other providers of volcanological assistance.

- Continue sustainable volcano-risk management in Central America through the 3-Year Central American Mitigation Initiative (CAMI) supported by OFDA, including hazards assessments at high-risk volcanoes, installation of new telemetered seismic stations, training of personnel, and database development on Latin American volcanoes.

6. Build and expand databases on volcanism in the U.S. and abroad, suitable for use in assessing potential volcanic activity and threat. Databases include historical information about volcanic unrest and eruptions, maps, geochemical and geophysical data, hazards analyses, populations, and infrastructure at risk.

Objectives:

- Continue collaboration with national and international partners and the World Organization of Volcano Observatories (WOVO) to advance the development of a distributed database, called WOVODAT, to include monitoring data on episodes of volcanic unrest and Internet accessibility to facilitate evaluation of volcano unrest worldwide.

- Expand database of effects of volcanic ash on aircraft and airports, linked to the worldwide volcanism database of the Smithsonian Institution's Global Volcanism Program.

- Continue updating bibliographic databases in Hawaii, Alaska, and other volcanic regions.

- Continue expansion of the Latin America and Caribbean database on potentially active volcanoes.

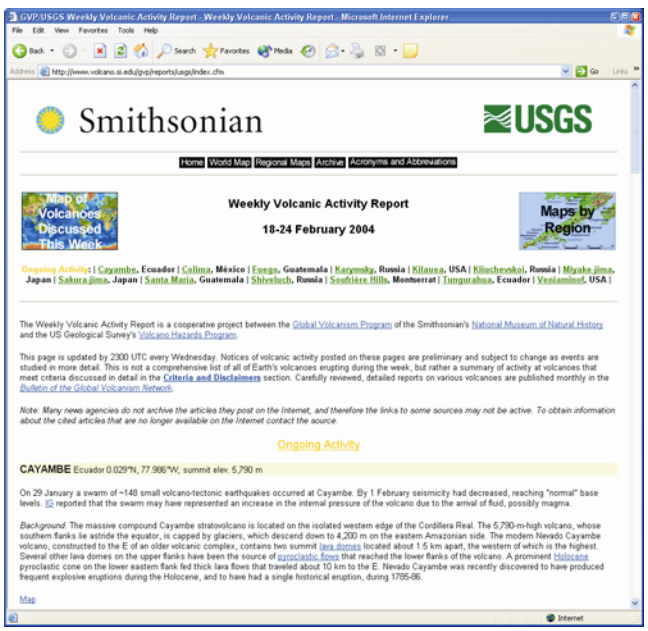
- Establish Geologic Database of Information on Volcanoes in Alaska (GeoDIVA) as the future backbone of a database-driven website. Designed for use in research, crisis response, and public information, GeoDIVA is planned to include eruptive histories, catalogues of maps and reference materials, images, sample information, and summaries of seismic and remote sensing data.

7. Deliver effective products and services and provide timely access to VHP information.
This goal is tracked by:

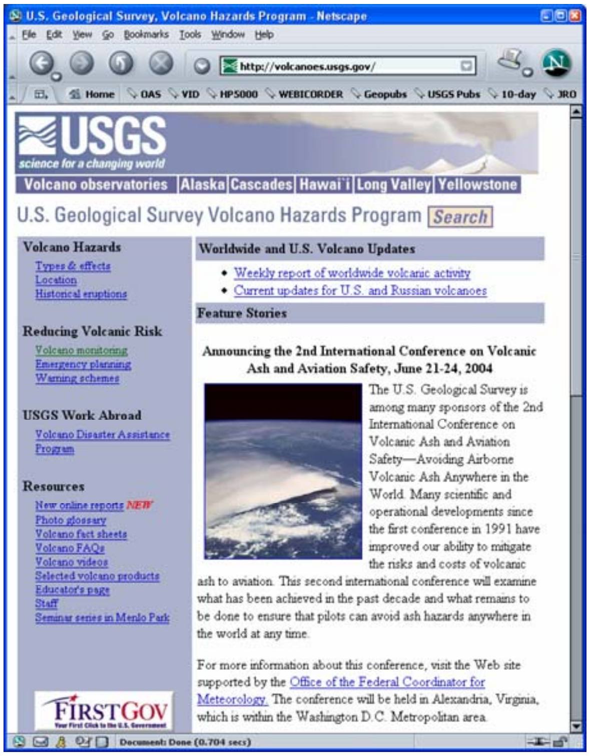
- PART End Outcome Measures for percents of communities using DOI science on hazard mitigation, percent of customers whose needs for information were met to achieve reduced risk.
- PART Intermediate Outcome Measures for percent of communities using DOI science on hazard mitigation, preparedness, and avoidance, and percent of sampled stakeholders reporting adequacy of science base to informed decisionmaking.
- PART Efficiency Measure for number of formal workshops or training provided to customers.

7.1 Improve the accessibility and availability of volcano information to the public, including emergency information, and to other Federal, State, and local agencies.

Information on hazards, forecasts, and warnings are only of use if they are effectively communicated and used. In addition to formal publication and hazard notification, VHP maintains close contact with regulatory agencies and the public and assists in the development of community response plans and risk mitigation strategies.



Volcanic activity reports worldwide are updated weekly and posted on a Web page managed in partnership by the Smithsonian and the USGS.



Volcano Hazards Program Web page.

During an intense swarm of earthquakes beneath Akutan Volcano, Alaska, USGS scientists were on hand to provide updates and evaluations of the seismic unrest – preventing the unnecessary evacuation of 1,000 residents and the shutdown of a $10 million per month fishing industry. Photograph taken in 1996 (USGS).

Mount Rainier Volcano-Hazards Workgroup meeting, 2003. Photograph by Carolyn Driedger (USGS).

Objectives:

- Adopt the Common Alerting Protocol (CAP) standards.
- Post daily U.S. volcano warnings and information updates on an NVEWS Web site.
- Maintain close collaboration and effective communication with the USAID Office of Foreign Disaster Assistance (OFDA) concerning international volcano unrest.
- Continue preparation of worldwide weekly volcano reports in collaboration with the Smithsonian Institution's Global Volcanism Network (GVP) for distribution on the Web.
- Publish scientific and technical results of investigations in peer-reviewed journals, maps, and books.
- Spotlight scientific results of VHP and partner volcano studies on Web sites.
- Produce fact sheets on volcano hazard topics, eruptive histories at specific volcanoes, and new results of scientific investigations.
- Support video programs on volcano hazards generally and (or) regarding specific volcano centers.

- Collaborate with the National Park Service, U.S. Forest Service, and museums for developing volcano-related exhibits, specimens, and multi-media presentations.

- Provide products and services to educators, interpretive programs of the National Park Service and U.S. Forest Service and non-government organizations, and media representatives including field excursions, public lectures, interpreter-training workshops, and education material.

- Provide GIS products and other geologic mapping information of volcanoes in national parks to the Geologic Resource Division, National Park Service.

7.2 Engage in frequent communication, enhance notification procedures with Federal, State, and local emergency-management agencies and communities.

Objectives:

- Increase the number of volcano-related notification plans and contingency plans developed in collaboration with Federal, State, and local agencies and communities. New target volcanoes include Mount Shasta, Lassen Peak, Medicine Lake, California; Three Sisters area, Oregon; and Yellowstone volcanic system, Yellowstone National Park, Wyoming-Idaho-Montana.

- Regularly update existing volcano notification and contingency plans in collaboration with Federal, State, and local agencies and communities.

- Participate in meetings, workshops, table-top exercises, and training sessions intended to improve volcano-hazard awareness and promote preparedness activities.

- Evaluate the effectiveness of existing VHP alert-level notification schemes for unrest and eruptions in collaboration with national partners and customers and national and international aviation industry.

- Conduct emergency response activities in foreign countries and conduct training in coordination with the OFDA.

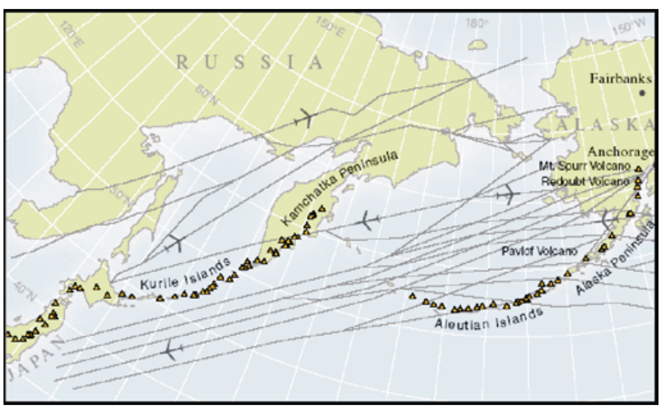
- Continue evaluation of new volcanic-event-tree probability analysis tool developed by VHP scientists during future episodes of unrest and eruption for analysis of different scenarios.

- Work with partners to develop a more consistent system for volcanic hazard alerts, notices, watches, and warnings.

7.3 Promote coordinated, rapid release of critical information when volcanic ash potentially threatens aircraft and airports, in collaboration with National Weather Service, Federal Aviation Administration, airline industry, and national and international organizations, including Volcanic Ash Advisory Centers, the International Civil Aviation Organization, and volcano observatories abroad.

More than 80 commercial aircraft have unexpectedly encountered volcanic ash in flight and at airports in the past 15 years. Seven of these encounters caused in-flight loss of jet engine power, which nearly resulted in the crash of the airplane. A range of damage may occur to airplanes that fly through an eruption cloud depending on the concentration of volcanic ash and gas aerosols in the cloud, the length of time the aircraft actually spends in the cloud, and the actions taken by the pilots to exit the cloud.

Image from NASA space shuttle of wedge-shaped eruption-cloud from Rabaul, Papau New Guinea, September 19, 1994.



North Pacific and Russian Far East air routes (gray lines) pass over or near more than a hundred potentially active volcanoes (triangles). Aircraft flying along these routes, some of the busiest in the world, carry more than 10,000 passengers and millions of dollars of cargo each day to and from Asia, North America, and Europe. In the North Pacific region, several explosive eruptions occur every year. Ash from these eruptions, which has caused jet engines to fail, is usually blown to the east and northeast, directly across the air routes. (USGS Fact Sheet 030-97)

Objectives:

- Co-sponsor Second International Symposium on Volcanic Ash and Aviation Safety.
- Develop an interagency operating plan for volcanic eruption clouds originating in the Pacific Northwest and California.

8.0 Conduct strategic hiring and strengthen partnerships and communication with universities to maintain core capabilities, enhance scientific and technical coordination and exchange, and promote educational opportunities for students.

Objectives:

- Continue active participation in the USGS Mendenhall Post-Doctoral and National Research Program post-doctoral appointment programs as means to diversify staff expertise.

- Hire new staff members as appropriate to maintain critical capabilities and fill gaps in critical areas of research and technical support.

- Expand partnerships with other USGS programs, where missions are complementary. Examples include the USGS Landslide Hazards Program, which also conducts research to understand landslide and mass-movement processes and triggering mechanisms; the National Research Program, which seeks to improve understanding of hydrologic processes; the Land Remote Sensing Program, which develops new remote-sensing technology, data delivery, processing and archiving; the Mineral Resources Program, which evaluates the role of hydrothermal fluids in mineral deposition at volcanoes; and the National Cooperative Geologic Mapping Program, which conducts multidisciplinary geologic mapping and geologic map and GIS database development.

- Expand role of The Center for the Study of Active Volcanoes (CSAV), a partnership of the Hawaiian Volcano Observatory and the University of Hawaii, for the mitigation of volcano hazards in the circum-Pacific area, including education and training in volcano hazards and contributions to volcano-monitoring databases.

- Continue participation and leadership within working groups in the scientific community, such as U.S. ARRAY, PBO, and InSAR components of Earthscope.

- Assist the university community in developing partnerships to advance the science of volcanology (for example, participation in NSF grants, collaborative research programs, and initiatives).

- Promote communication, sharing data and experience, and common approaches to strengthen VHP partnerships involving Federal, State, and academic representatives of the five U.S. volcano observatories.

Program Review

2003 PART Review

The VHP was reviewed in 2003, as part of the overall Geologic Hazards Program for the purpose of implementing the Program Assessment Rating Tool (PART). As described in the Office of Management and Budget (OMB) found that the VHP role is clearly defined and unique from other Federal, State, local, or private entities. Three intermediate outcome measures are now tracked in support of the intermediate outcome of providing information to assist communities in managing risks from natural hazards. These outcome measures are (1) use rate of products, (2) percent of at-risk communities served with DOI science on hazard mitigation, and (3) adequacy of information. Output measures for which targets are now established in support of achieving the intermediate outcome goal include (1) maintenance of one hazard monitoring network, (2) delivery of risk assessments to customers, (3) presentation of formal workshops or training to customers, and (4) expanding the number of sites (mobile or fixed) monitored for ground deformation to identify volcanic activity.

Reviews of Program Activities

The VHP has a vigorous and thorough review process for ensuring that its work is relevant to the Nation's needs and reflects priority science objectives. Reviews to examine the scientific and hazards mitigation activities of the VHP and determine whether research results and national and local needs are effectively integrated into future work plans are regularly accomplished through (1) the preparation of an annual prospectus describing the scope of VHP work and corresponding review of project proposals and project status by the Program Coordinator and an internal panel; (2) frequent meetings and workshops with stakeholders on specific topics and issues, including the Consortium of U.S. Volcano Observatories (CUSVO); (3) annual reviews with partners of the Alaska Volcano Observatory and Long Valley Observatory to review accomplishments, challenges, and priorities of the upcoming year; (4) external review of VHP science goals and capabilities, most recently completed in 1999 and published in 2000 by the National Research Council (NRC); (4) external and internal review of 5-year plans; (5) frequent evaluations of new and ongoing responses to volcano unrest and eruption among volcano observatories, VDAP, and stakeholders; and (6) peer review of all reports and publications of projects supported by VHP.

Review of Volcano Disaster Assistance Program

VDAP is reviewed every year through an annual work plan and budget proposal submitted to OFDA, and through annual meetings with OFDA managers to summarize recent and ongoing work and accomplishments, and to plan future goals and objectives of USGS, OFDA, and VDAP. Also, OFDA sometimes requires an external review of VDAP, as it did in 1993, when a consulting firm was hired by OFDA to review VDAP. VDAP is supported by OFDA through a Participating Agency Service Agreement (PASA). The first PASA to support VDAP operated from 1986 to 1999. In FY2000 a second PASA was developed with the scope of work expanded to encompass current and anticipated VDAP activities. In the next 5 years, a new PASA may be prepared to further define the goals and scope of work of VDAP with internal and external input. OFDA and USGS management would review any new PASA.

National Academy of Sciences Review

In 1999, the NRC of the National Academy of Sciences conducted a review of the VHP. The NRC formed a committee of 10 members, representing academia, and County and Federal agencies, to address two questions:

- Do the activities, priorities, and expertise of the VHP meet appropriate scientific goals?

- Are the scientific investigations and research results throughout the VHP effectively integrated and applied to achieve mitigation?

The committee concluded that for the VHP to continue meeting its mission, "its staff size must be significantly increased and (or) better leveraged through partnerships." As outlined in the following sections of this plan, since 1999, the VHP has expanded partnerships and hired new staff. The program must continue to do both in the next five years. The wide-ranging recommendations of the NRC and corresponding steps taken by the VHP are summarized in Appendix E.

Staff Capabilities and Facilities

Current capabilities

A broad range in scientific skills is required to assess volcanic hazards and to properly monitor and interpret volcanic unrest. The VHP core workforce comprises geologists, seismologists, geodesists, hydrologists, remote-sensing specialists, geochemists, and administrative and support staff housed by the Volcano Hazards Team, the Alaska Volcano Observatory, the Eastern Earth Surface Processes Team (Reston), and the Water Resources Discipline (CVO and Menlo Park). This workforce is augmented as required by part-time support from seismologists and support staff of the Earthquake Hazard Team (Menlo Park), and by geologists in Denver in the Central Mineral Resources and Central Earth Surface Processes Teams, who receive partial support from VHP. The EROS Data Center (Sioux Falls) has provided crucial collaboration in the application of remote sensing to volcano monitoring. Crucial supporting skills for VHP activities include GIS, electronics and engineering for equipment maintenance and development, computer support including database management, and outreach. In addition, VHP laboratories and field projects require technical support from physical science technicians and operational scientists. Additional scientific support is provided through partnerships with the University of Alaska, the Alaskan Division of Geological and Geophysical Surveys, the University of Washington, and the University of Hawaii.

The VHP core workforce will be moderately reduced by retirement within the next 5 to 10 years. However, retirements will significantly deplete the group’s scientific leadership, especially in geology, which has historically been the dominant skill in the VHP. The program already relies heavily on emeriti for physical volcanology and geologic mapping in support of hazard assessments.

In 1999, VHP managers and scientists undertook an analysis of future needs and updated the program’s staffing plan. Subsequently, program and team managers closely monitored staffing and funding levels and used this plan to guide hiring and facility improvements. As a consequence, new remote-sensing capabilities were developed at the Alaska Volcano Observatory and National Center in Reston, Virginia, and staff positions were filled in volcano seismology, geodesy, and GIS. In addition, since 2001, post-doctoral appointments made through USGS Mendenhall and National Research Council Fellowships, and additional term or permanent appointments, have added expertise in geodesy, hydrology, petrology, seismology, and communications/outreach. In addition, a new partnership with the Smithsonian Institution's Global Volcanism Program was created to better communicate world volcanic activity, and critical vacancies in geochronology and volcanic geology were filled. However, technical support needs remain critical program issues--issues that will be compounded over the next 5 years as the VHP expands its capabilities in monitoring and information technology in support of the National Volcanic Early Warning System. The resulting staffing and facilities plan will serve as the framework for hiring and for laboratory and facility investments over the next 5 years.

Future Needs

In its 1999 review of the program, the National Research Council concluded that the VHP is facing a "crisis of continuity" in staffing. The program has addressed this issue with actions to increase efficiency, such as expanding partnerships, focusing work more directly on program goals and strategic hiring to meet critical needs (appendix F). However, demographics of the current workforce indicate that the "crisis of continuity" will remain as an outstanding issue for VHP management in the near future. Additional hiring to replace critical vacancies and augment capabilities in under-represented specialties will be required to fulfill the program's public safety mandate under the Stafford Act, and to meet goals outlined in this 5-year plan. In particular, it is imperative that the program maintain a cadre of scientists who not only have diverse research capabilities, but also have real-world experience in dealing with volcanic hazards and effectively communicating with public officials during crisis situations.

In addition to maintaining critical expertise, the future VHP workforce must increase staff with the skills necessary to deploy and maintain a comprehensive National Volcano Early Warning System. Increased emphasis will be placed on real-time monitoring of current activity and, consequently, it is anticipated that the greatest need for increased scientific expertise will be in the fields of seismology, geodesy, numerical modeling, remote sensing, and gas geochemistry. Similarly, support staff will need increased expertise in electronics and telemetry to maintain an expanded monitoring system; increased GIS support will be required to facilitate forecasting and communication of developing hazards during rapidly evolving unrest and eruption; and increased expertise in database management will be required to support the enormously increased data stream from the ground-based and satellite monitoring systems. Geologists, who constitute the largest single group in VHP today, are critical for completion of hazard assessments, research on volcanic processes, and evaluation of unrest based on geologic records. Historically, VHP geologists have been world leaders in volcanology and igneous petrology, integrating geologic, seismic, geodetic and geochemical data into comprehensive models of magmatic systems. High-level, research geologists will always be critical to the VHP to perform integrated studies of volcanic centers and processes, and to interpret volcanic unrest in light of the geologic record. However, implementation of a National Volcano Early Warning System will require that future hiring focus on increasing expertise in seismology, geodesy, numerical modeling, remote sensing, and gas geochemistry.

To some extent, a shift in the workforce can be accommodated through retirement of the geologic staff coupled with strategic hiring in seismology, geodesy, remote sensing, numerical modeling, technical support in electronics and telemetry, and GIS. However, these actions alone are unlikely to establish an appropriate skill mix in the VHP within the next 10 years, and filling the workforce gap will likely depend on increased use of the expertise in other USGS groups, especially the Earthquake Hazards Team for seismology and the EROS Data Center for remote sensing. Contracting would be a useful mechanism to fill gaps in electronic, computer, and GIS support. Academic partnerships are expected to continue to be important for the maintenance of monitoring networks and, following the example set by AVO, could be extended to enhance research in the VHP.

Facilities

The VHP will continue to require support for (1) volcano observatory facilities in Alaska (Anchorage), Washington (Vancouver), Hawaii (located in Hawaii Volcanoes National Park), and California (Menlo Park and Mammoth Lakes); (2) National Center in Reston, Virginia; (3) Western Region facility in Menlo Park, California; (4) a Bureau-supported infrastructure for public Web sites (currently, the NatWeb system); and (5) various shared laboratory facilities within USGS and among partners.

Primary facility issues facing VHP in the next 5 years include

- analytical capabilities for chemical and isotopic analysis of volcanic samples, currently met through shared USGS lab facilities which serve VHP's and other programs' requirements; and
- IT infrastructure to support expansion of volcano monitoring networks and data archiving systems as part of the National Volcano Monitoring System.

Analytical capabilities are currently met through USGS laboratories in cases where the process of analysis constitutes an integral component of discovery and research (for example, ion- and electron-microbeam analysis, specialized rock, water, and sediment analysis, geochronology, and paleomagnetics); collaboration with colleagues from universities, and, for routine data, through contracts with commercial labs. VHP also co-funds USGS laboratories with other programs to meet its research needs and uses working capital funds for anticipated future expenditures, such as contributing to replacement in FY2003 of a mass spectrometer for the Ar-Ar geochronology laboratory in Menlo Park, California.

In addition to volcano monitoring networks and back-up equipment maintained by the observatories, through VDAP, the program maintains a cache of seismic and GPS monitoring equipment for rapid response to volcanic unrest. This cache has two funding components: a domestic cache, funded by congressional appropriations to VHP, and an international cache, funded by OFDA. As international and domestic demands fluctuate, instruments are cycled to maintain both caches in operational readiness. Annual appropriations, as well as funds accumulated over multiple years through the USGS working capital fund process, are used to purchase new instruments for use to maintain and expand observatory networks and, periodically, to replenish the VDAP domestic cache. Additional funding for expansion of Alaskan and Hawaiian monitoring networks has been provided by Congress in recent years, both through direct appropriations to USGS and thorough the FAA. As annual appropriations for network maintenance and expansion have continued for a number of years and networks are still incomplete, it is anticipated that this funding will continue. Each of the volcano observatories prepared a multi-year network maintenance and expansion plan in FY2003. These plans are being revisited in the context of planning for a National Volcanic Early Warning System, which will be the framework for a capital asset plan (OMB 300b plan), as requested by OMB for future volcano monitoring network investment by the Federal Government.

Concluding Statement

The USGS Volcano Hazard Program is a relatively young Federal program with a demonstrated record of effective application of scientific information to reduce risk and save lives. This success grew in response to domestic and international volcanic crises in the 1980s, and the value and validity of the VHP has been repeatedly demonstrated over the past 20 years. The program faces major opportunities, as well as challenges, over the next 5 years. Fulfilling the goals outlined in this plan will require significant expansion of monitoring networks and development of a National Volcano Early Warning System--a major effort to organize, standardize, and plan future volcano monitoring in the United States. InSAR, which has demonstrated remarkable promise as a remote monitoring technology, will become operational for many of the highest risk volcanoes. GIS and database technology, numerical modeling and probabilistic assessment will significantly improve forecasting of volcanic hazards. Capabilities for volcanic risk reduction in developing countries will be improved and lives saved through contributions by VDAP. New research will contribute theories and models that will improve our understanding of volcanic processes and their hazards.

These goals are not without challenges; paramount among these is a critical need to expand staff capabilities in a Federal workforce, which, at the broadest level, continues to shrink. The VHP has met this challenge during the past decade through high levels of performance, increased efficiency, innovative partnerships, persistent efforts to build critical capabilities, and administrative and Congressional priorities in the area of natural hazards and risk mitigation. We anticipate continued innovation, as well as persistence, as the program's managers and staff pursue these public-safety-based science goals to prevent volcanic crises from becoming volcanic disasters.

Appendix A

Priority Activities, USGS Volcano Hazards Program 1999-2003	
Priority Activities	Accomplishments
1. Expansion of real-time seismic monitoring to provide coverage of volcanoes in the western Aleutian Islands of Alaska. Incorporation of broadband seismometers into volcano monitoring networks at Long Valley caldera in California, Mauna Loa Volcano on Hawaii Island, and selected Cascade volcanoes in Washington, Oregon, and northern California.	1a. Completed installation of seismic networks at Kanaga, Great Sitkin, Veniaminof, Okmok, Tanaga, and Gareloi. 1b. Three-component, borehole digital seismometers installed in three 100-m-deep drillholes on Mauna Loa and at summit of Kilauea (1999). 1c. Two three-component, borehole digital seismometers installed near north and south rim of Long Valley caldera (1999) and two broadband seismometers installed in caldera (2002). 1d. Broadband seismometer installed on Mount Hood and short-period seismometers installed in Three Sisters uplift, Oregon, and Glacier Peak, Washington (2000-2002). 1e. 15 strong-motion and 5 broadband seismometers installed on island of Hawaii (supported by the USGS Earthquake Hazards Program).
2. Expanded use of real-time geodetic techniques (continuous GPS, borehole strainmeters, and tiltmeters), particularly in Hawaii and at Long Valley in California, along with improved modeling of strain data.	2a. Real-time GPS stations installed on Kilauea (2 new) and Mauna Loa volcanoes (5 new); Three Sisters uplift, Oregon; Mount St. Helens, Washington; Akutan, Veniaminoff, Okmok, and Augustine, Alaska. 2b. Borehole tiltmeters and strainmeters installed in three 100-m-deep drill holes on Mauna Loa and one deep drillhole near the summit of Kilauea (1999); 15 tiltmeters installed in 3-m-deep holes on Kilauea and Mauna Loa. 2c. Two new borehole dilatometers and borehole tiltmeters installed near north and south rim of Long Valley caldera (1999) and real-time GPS network expanded to 16 stations.
3. Further development and testing of the capability to access and process data collected by Interferometric Synthetic Aperture Radar (InSAR) at selected volcanoes.	InSAR successfully used to quantify deformation at Yellowstone National Park; South Sister, Oregon; and Akutan, Westdahl, Peulik, and Augustine Volcanoes in Alaska; InSAR is recommended for future monitoring of volcanoes.

4. Better integration of seismic and geodetic monitoring with airborne and continuous measurements of volcanic-gas emissions. Collection of data to assess the health and environmental effects of volcanic gases such as sulfur dioxide and carbon dioxide.	4.1 Air-quality monitoring system installed in Hawaii Volcanoes National Park and public notification protocols established. 4.2 Airborne gas monitoring system developed; provides concurrent digital data at 1-s intervals for CO_2, H_2S, SO_2, air temperature, barometric pressure, latitude, longitude, and altitude logged on a common time base. 4.3 Continuous monitoring soil-CO_2 sensor network at Mammoth Mountain detected CO_2 degassing events, which coincided with frequent long-period earthquakes under Mammoth Mountain in 1997, and determined that CO_2 concentrations build up in tree-kill areas as snow accumulates and drop precipitously as snow melts in the spring, causing intense carbonic acid loading of tree-kill soils and depleting soil fertility.
5. Evaluation of the use of classified remote-sensing data as an additional tool for volcano monitoring.	5.1 Classified imagery used successively to support volcano eruption response and hazards assessment activities. Products released to USGS volcano scientists include sketch maps of often-ephemeral volcanic features (domes, ash deposits) and provision of dimensional information (size of lava domes or new craters, area of active flows). 5.2 Generated a large archive of imagery of recent eruptions (both domestic and foreign), as well as baseline imagery of selected domestic volcanoes, in cooperation with USGS National Mapping personnel.
6. Development of a prototype system at Mount Rainier for automatic detection and notification of large lahars.	6.1 Designed and installed an automated lahar-detection system in the Puyallup and Carbon River valley, including redundant base stations at Pierce County Law Enforcement Support Agency in Tacoma and Washington Emergency Operations Center at Camp Murray (in 2003). 6.2 Provided training to Pierce County staff, who will take over operation and maintenance of the system.
7. Preparation of hazard-assessment reports and zonation maps at all monitored volcanoes, with improved application of probabilistic methods where appropriate.	Completed reports at the following volcanoes: Iliamna, Aniakchak, Mukushin, Katmai cluster, Mount Hayes in Alaska; Mount Jefferson and Three Sisters area, Oregon; lower northeast rift zone hazard assessment and lava-flow inundation zone maps for Mauna Loa, Hawaii.

8. Preparation of new and revised operational plans for responding to U.S. volcanic crises.	8a. Interagency plans completed for Mount Rainier (2001) and Mount Baker and Glacier Peak, Washington (2003); plans initiated for Mount Hood, Oregon (2002). 8b. Alaska Interagency Operating Plan for Volcanic Ash Episodes, updated (2000, 2002). 8c. USGS response plan revised for Long Valley caldera and Mono Craters Region (2002). 8d. Hawaii lava-flow mitigation plan approved by Hawaii State Civil Defense (2002).
9. Creation of digital content for an electronic geospatial database that will allow diverse, cartographically based datasets and products to be easily accessed, combined, and queried. (Note: more specific databases subsequently identified as priorities, indicated by accomplishments 9.2-9.6).	9.1 Volcano information made accessible online via USGS GEO-DATA Explorer (http://geode.usgs.gov), and the Volcano Weekly Report (http://www.volcano.si.edu/gvp/reports/usgs/index.cfm) prepared by USGS and Smithsonian Institution's Global Volcanism Program. 9.2 Volcano risk database of active and potentially active volcanoes in Latin American and Caribbean created by VDAP for rapid consultation and response to unrest and eruption; data-base proved critical for immediate assessment of potential threat to reports of unrest in Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama. 9.3 VALVE (Volcano Analysis and Visualization Environment) developed and tested to display and analyze real-time and archived data from various instruments and surveys. 9.4 Participated in several meetings to plan WOVO.DAT, a proposed database of worldwide volcano monitoring data, sponsored by the World Organization of Volcano Observatories (WOVO). 9.5 Bibliographic database of volcanism in EndNote: created for Long Valley caldera and associated volcanic fields (2000); existing database updated annually for Hawaii's volcanoes. 9.6 Augmented Global Volcanism Database of the Smithsonian Institution to include known volcanic ash effects to airports and aircraft during flight.

10. Research on the diverse factors that determine the onset, duration, style, end of eruptions, and post-eruption hazards.	Scientific results published in more than 300 papers and maps in peer-reviewed journals, monographs, books, and map series. Accomplishments were made in the following categories and results were used in volcanic hazard assessments and forecasts: 10.1 Studies of volcanic seismicity used to resolve fluid and magma movement beneath volcanoes. 10.2 Geodetic and remote sensing studies documented and modeled active volcanic deformation. 10.3 Geologic and stratigraphic studies, mapping, and GIS analysis, supported by petrology, geochemistry, geochronology, paleomagnetics and geophysical surveys, used to determine style, frequency, and magnitude of past eruptions and subvolcanic structures. 10.4 Petrologic experiments reproduced conditions of eruptions, magma reservoirs, and zones where magmas originate and were used to constrain eruptive dynamics and magmatic plumbing. 10.5 Field and laboratory investigations of water and volcanic gas geochemistry documented and modeled role of fluid transport of magmatic components and importance of CO_2, H_2S, and additional gas species as indicators of degassing. 10.6 Modeling of flowage processes and volcano edifice stability enables prediction of areas susceptible to landsliding and flow inundation. 10.7 Studies of geomorphology, fluvial hydrology, and sedimentology documented and modeled long-term post-eruption impacts on watersheds.
11. Studies of processes at volcanoes that lead to post-eruptive hydrologic hazards.	Studies of geomorphology, fluvial hydrology, and sedimentology documented and modeled long-term post-eruption impacts on watersheds: 11.1 Greater than normal rainfall in the late 1990s in the Pacific Northwest resulted in suspended-sediment yield from the Mount St. Helens 1980 debris-avalanche deposit in the North Fork Toutle River 100 times above typical background preeruption levels, temporarily reversing the nonlinear decline in suspended sediment yields. 11.2 Comparative studies demonstrate that the magnitude and duration of extraordinary post-eruption sediment transport can persist for decades, requiring that mitigation measures designed to reduce downstream sediment delivery remain functional for that duration or more. 11.3 Investigations along the lower Columbia River found that episodic high input of volcanic sediment from Cascade volcanoes over at least the past few thousand years has significantly affected channel morphology and streamflow hydraulics of the Columbia River.

Appendix B

Volcano Unrest and Eruptions in U.S., 1999-2003			
Volcano	**Year**	**Unrest**	**Unrest and Eruption**
Kilauea Volcano, Hawaii	1999-2003		Continuous eruption of lava flows since 1983 covered 115 km^2 of land and created volcanic smog (known as vog); new vent in 2002 sends lava flows in new direction in Hawaii Volcanoes National Park, burying 1 km of Chain of Craters Road, igniting forest fires, forming new land, and drawing hundreds of thousands of visitors from around the world to view lava up close. Also, two episodes of intrusion were detected along east rift zone in 1999 and 2000.
Long Valley caldera, California	1999-2003	Low seismicity and continued inflation of the resurgent dome.	
Yellowstone caldera, California	1999-2003	Uplift of central caldera with different source areas, small seismic swarms, hydrothermal explosions, and expanding fumarole fields.	
Shishaldin Volcano, Alaska	1999		Seismicity, including volcano tremor, precedes and accompanies eruption, which generates multiple eruption clouds in April and May.
Mount Hood, Oregon	1999, 2001, 2002	Small earthquake swarms consisting of a few dozen events <M4.5 were reported in information statements.	
Mount St. Helens, Washington	2001	Shallow swarm of small earthquakes (<M2) follows seismic swarm and elevated discharge of carbon dioxide gas in 1998.	
Cleveland Volcano, Alaska	2001		Cleveland not monitored with seismic network; remote sensing analysis detected first signs of eruption cloud in Feb.; analyses four times daily continued through April.
Three Sisters, Oregon	1997-2003	Broad area of uplift detected with InSAR, about 2.5 cm/year, beginning in 1997, but not detected until 2001.	

Mauna Loa Volcano, Hawaii	2002-2003	New real-time GPS network detects deformation of summit caldera, indicating renewed inflation of magma reservoir; reported to Hawaii County Civil Defense and Hawaii Volcanoes National Park, and public.	
Veniaminof Volcano, Alaska	2002-2003	New seismic network detects anomalous volcano tremor and earthquakes; reported in AVO Weekly Updates.	

Also in the period 1999-2003, detection and tracking of eruption clouds from eruption of Russian volcanoes Kliuchevskoi, Bezymianny, Sheveluch, and Karymsky, in collaboration with the Kamchatkan Volcano Eruption Response Team (KVERT).

Appendix D

Selected Highlights of the Volcano Hazards Program, 1999-2003

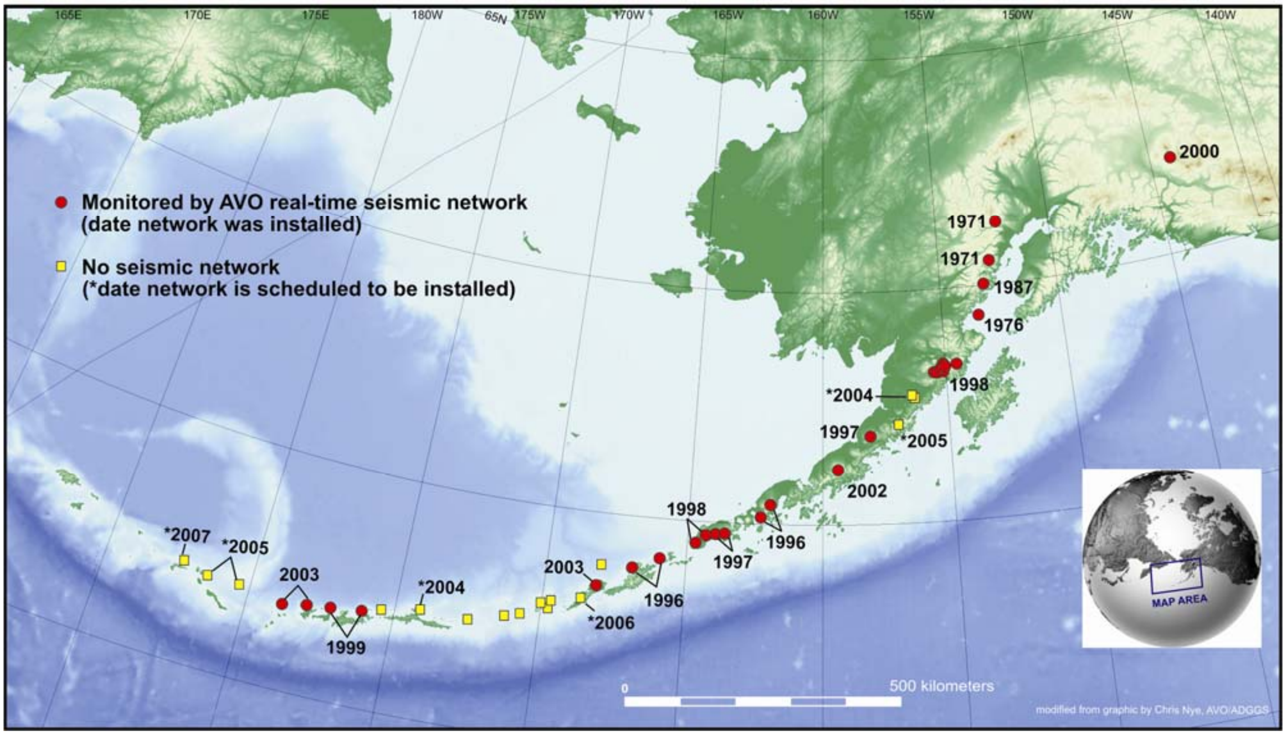
InSAR effective for detecting volcano deformation

Interferometric Synthetic Aperture Radar (InSAR) is now a proven technique for mapping ground deformation using data from aircraft and satellites. Since 1997, USGS scientists have used InSAR to measure deformation at the Yellowstone caldera, Mauna Loa, volcanoes in Alaska, and the Three Sisters area in the central Oregon Cascade Range. Several processes are responsible for the observed deformation, including fluid migration (Yellowstone), magma intrusion (Akutan, Westdahl, Peulik, Three Sisters, and Mauna Loa), tectonic strain (Akutan), and compaction of pyroclastic deposits (Augustine). This work demonstrates that InSAR can detect inflating magma bodies at otherwise quiescent volcanoes (Westdahl, Peulik, Three Sisters). Although unable to provide real-time monitoring because of the 3-week return time for InSAR satellites, the techniques can detect subtle ground movement long before an eruption, and continued application of InSAR is expected to increase our knowledge of eruption precursors, enabling earlier awareness of volcanic unrest, and allowing scientists and public officials more time to prepare.

Monitoring expansion in Aleutians results in effective volcano warnings

Spurred by near-disastrous encounters between aircraft and volcanic ash in the early 1990s and the demonstrated benefits from real-time monitoring of Alaska's 43 historically active volcanoes, VHP has received new Congressional appropriations and new funding from the Federal Aviation Administration (FAA) to expand its volcano monitoring program in Alaska. As of September 2003, AVO established seismic monitoring networks on 27 volcanoes, extending from the Alaska Range to the central Aleutian Islands. AVO is currently extending volcano monitoring to the far western Aleutian Islands. As the monitoring networks have pushed westward, so have the scientific investigations, with team investigations of volcanic history and hazards at Katmai, Aniakchak, Veniaminof, Emmons Lake, and Okmok calderas, Akutan Volcano and Unimak Island (Fischer caldera and Shishaldin Volcano). The expanding monitoring network in Alaska beginning in 1996 is yielding far more timely and accurate hazards information about restless and erupting volcanoes than has ever been possible. At Shishaldin, a seismic network installed in 1997 and 1998 enabled seismologists to detect early warning signs as much as 1 year before an eruption in 1999 and steady seismic unrest 3 months before it began. Timely information updates and eruption warnings were issued regularly for the 1999 eruption, in sharp contrast to the volcano's 1995-1996 eruption, when scientists issued information only after the eruption began based on reports from local observers. In 2002, only months after a seismic network was installed at Veniaminof, scientists issued information about increased activity at the volcano and were able to track the level of activity during subsequent months. The network also allowed scientists to critically evaluate reports from observers in the nearest town (22 miles away). The new Veniaminof network enabled scientists to issue accurate updates about the status and likelihood of eruptions of Veniaminof.

Historically Active Alaskan Volcanoes

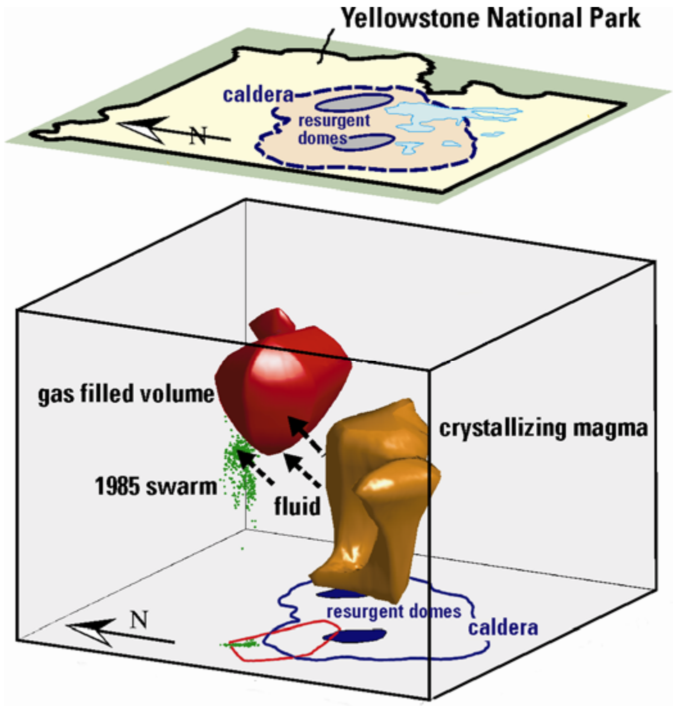


Map illustrating the expansion of real-time seismic volcano monitoring by the Alaska Volcano Observatory, beginning with the 4 Cook Inlet volcanoes (Spurr, Redoubt, Iliamna, and Augustine) and expanding to include 27 of the 43 historically active volcanoes of Alaska by 2003. The rapid expansion during the last decade was in response to the recognition of the hazard that volcanic ash clouds pose to aircraft on the busy North Pacific jetways.

Quantitative volcano seismology identifies source mechanisms and subsurface structures

Quantitative characterization of subsurface volcanic structures and processes has been greatly enhanced in the past 5 to 10 years by the advent of portable broadband seismic instrumentation, digital networks with wide dynamic range, and powerful analysis techniques. Examples of recent accomplishments include (1) tomographic mapping of the subsurface, revealing the distribution of magma, hydrothermal fluids, and rock units beneath Yellowstone and Kilauea calderas; (2) identification of shallow volcanic tremor and long-period earthquakes at Kilauea in February 1997 as a response of the caldera's hydrothermal system to increased discharge of gases from the underlying magma conduit; (3) use of very long-period seismic data to identify the source mechanisms of gas-release explosions at Stromobli Volcano, Italy; (4) use of very long-period seismic data to identify ground deformation at Kilauea caldera produced by gas-jetting from the summit magma reservoir through a gas- and magma-filled crack; and (5) successful comparison of the complex frequencies of long-period earthquake signatures at volcanoes with those predicted by a fluid-filled resonating crack model.

The emergence in the past 5-10 years of new seismic instrumentation and analysis techniques has led to increasingly quantitative characterization of subsurface volcanic structures and processes.



(Block diagram courtesy of Stephan Husen and Robert Smith, (University of Utah) and Greogory Waite (USGS))

This three-dimensional block diagram shows the modeled locations of magma and hot volcanic gas beneath Yellowstone caldera. The diagram is approximately 100 km on a side and 25 km deep, and underlies much of Yellowstone National Park, as illustrated on the accompanying map. The block diagram was created using seismic tomography, a modeling method in which many earthquakes are used to determine seismic wave velocities along different subsurface paths. The resulting three-dimensional velocity map is then used to identify areas where seismic waves are attenuated or delayed by the presence of fluids.

Submarine exploration of Hawaiian Islands provides insights on volcano growth, generation of massive underwater landslides, and resulting tsunamis

Collaboration with Japanese scientists on the study the submarine flanks of Hawaiian volcanoes is yielding new ideas about the long-term growth of Kilauea, Mauna Loa, and other volcanoes in Hawaii, and about processes that lead to massive landslides from the flanks of Hawaiian volcanoes. At no cost to the USGS except salaries, six VHP scientists have participated in research cruises sponsored by the Japan Marine Science and Technology Center in 1998, 1999, 2001, and 2002 using new research vessels, deep-diving submersibles, and remotely operated vehicles. Results indicate that Kilauea began erupting on the southeast submarine flank of Mauna Loa instead of on the deep sea floor. Both the southeast flank of Mauna Loa and the south flank of Kilauea are gradually moving seaward under the influence of gravity and intrusion. Kilauea is younger than previously recognized and not associated with any previous major slope failure; but continued seaward movement of its south flank may lead to slope instabilities and landslides in the future.

Explosive history of Kilauea Volcano, Hawaii

Work in the 1990s showed that the most recent large explosions of Kilauea Volcano, Hawaii, thought to have taken place in 1790, were caused by water interacting with magma when the caldera was deep, and near the water table. Other research in the early 1990s on recent faulting in the Koae fault system south of Kilauea's caldera unexpectedly discovered evidence for powerful explosive eruptions 1,200 to 1,400 years ago. A re-examination of Kilauea's explosive history led to the realization that explosions previously thought to have taken place only in 1790 actually occurred sporadically during the preceding 300 years. At least one powerful explosion during the 1,200 to 1,400-year period, and possibly one in about 1700, were apparently caused by expansion of gas dissolved in magma and not by steam produced from ground water. We now know that Kilauea can erupt explosively as frequently as many other explosive volcanoes--and not necessarily only when the caldera is deep. Ongoing work is leading to an improved hazards assessment of Kilauea.

Relation between Kilauea and Mauna Loa

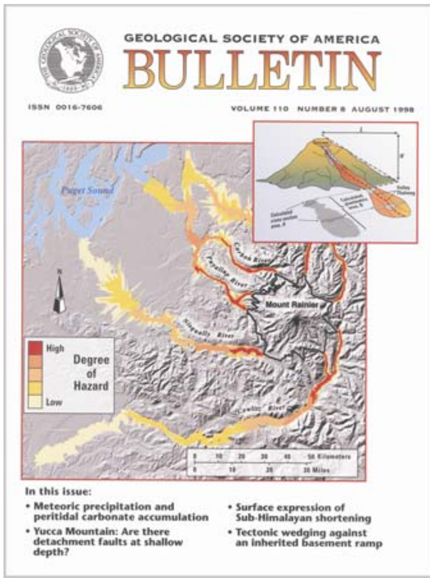
Two of the world's most active volcanoes are adjacent to each other, and one might think, intuitively, that there is some direct relation between them. Such a relation has long been discussed, and the general consensus has been that the two volcanoes are not related, because they erupt chemically different lava and have demonstrably different plumbing systems. In early May 2002, however, a new vent opened on the southwest flank of Puu Oo, Kilauea, with attendant ground deformation, while, at about the same time, the summit of Mauna Loa began to swell. This correspondence in time suggests that the two volcanoes are linked after all, but in a more subtle way than formerly considered. Stresses in one volcano may impose themselves on the other, causing changes despite the first-order differences between the two volcanoes.

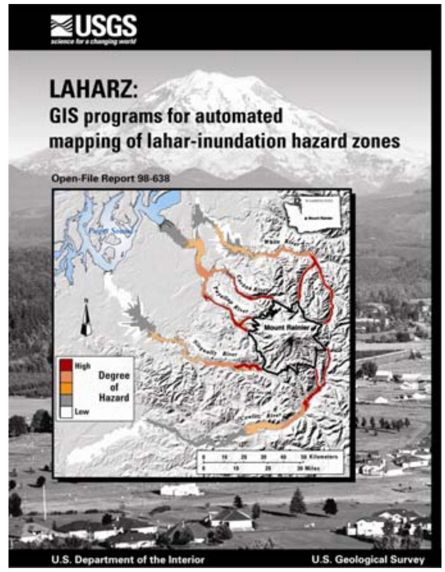
Mount Rainier: Geologic mapping and geophysical surveys improve hazards assessment

Detailed geologic mapping of Mount Rainier's cone begun in the mid-1990s, and high-resolution airborne magnetic and electromagnetic surveys in 2000 have shown that collapse-prone altered sections of the volcano are localized to known narrow regions and do not threaten all valleys around the volcano as previously reported. The mapping and age measurements also show that large, destructive lahars have generally been restricted to episodes of volcanic eruption for which precursory warning signs can be anticipated. These new results significantly improve the assessment of volcano hazards from Mount Rainier and provide the framework for hazards monitoring and mitigation strategies.

Modeling runout of debris flows and rock avalanches

Two new approaches to modeling the runout of debris flows and rock avalanches have improved forecasting of flow hazards in lowlands adjacent to volcanoes. One approach, based on the governing physical conservation laws and tested through intensive experimentation, simulates nearly all details of avalanche and debris-flow motion. This approach has the advantage of complete generality but demands intensive computation. A more expeditious approach utilizes statistically calibrated semi-empirical runout equations to generate probabilistic hazard maps. This approach has been widely applied in situations where hazards assessments are required but human and financial resources are limited. Both approaches continue to be extended and refined and together they provide effective tools to model, assess, and visualize flow hazards in valleys that head on volcano flanks.





Using high-resolution Digital Elevation Models (DEMs) of the terrain surrounding volcanoes and empirical data from deposits, VHP scientists have developed computer code to model downslope movement of potential volcanic mudflows (lahars) and display the results in Geographic Information Systems (GIS). The resulting maps have been instrumental in evaluating hazards, establishing crisis response plans, and reducing risks to downstream populations. Next generation numerical models are under development, which will improve resolution and extend these applications to other types of hazardous flows.

Magmatic and hydrothermal fluids play role in unrest at Long Valley caldera, California

Upward movement of hydrothermal fluid beneath the south moat of the caldera is indicated by seismic data and by the elevation of ground-water levels in thermal wells. Vertical migration of hot fluid is believed to have occurred during a dramatic period of uplift and increased seismicity in late 1997 and early 1998. Moreover, fluid pressure and continuous borehole strain data at the times of large distant earthquakes, including those that have triggered microseismicity at Long Valley, exhibit transient signals that closely resemble those recorded during the late 1997 unrest. These findings have at least two important implications. They suggest ways in which the movement of hydrothermal fluid can be distinguished from the more dangerous movement of magma, based on seismograms and hydrologic observations. They also show that seismic waves from distant earthquakes increase fluid pressure in the Long Valley hydrothermal system, a valuable clue to the mechanism of remotely triggered microseismicity and the means by which earthquakes and volcanoes interact.

Simulating volcanic eruptions in the laboratory

The VHP Magma Dynamics Laboratory employs specialized high-temperature furnaces and custom-designed high-pressure containment vessels to reproduce the extreme conditions of volcanic eruptions, magma reservoirs, and the mid-crustal to upper-mantle regions where magmas originate. Laboratory efforts have focused on the general topics of vesiculation (gas bubble formation) during eruptive magma ascent, and on the origins and characteristics of magmas that dominate explosive eruptions. Water- and carbon dioxide-rich gases vesiculate in magmas that ascend toward the surface; however, the rate of vesiculation depends on the composition of the silicate melt within the magma. If gases escape continuously over much of the ascent distance, the magma can erupt quiescently, forming a lava flow or dome. If kinetic factors delay vesiculation, the gases escape violently at shallow depths, causing explosive eruptions and forming pumice, ash, or scoria. Experiments have established that a significant kinetic barrier impedes the formation of gas bubbles in rhyolitic melt but that a negligible barrier exists for dacitic melt. A consequence is that rhyolitic melt can ascend much closer to the surface without degassing, where it vesiculates suddenly, whereas dacitic melt degasses continuously as it rises toward the surface. The kinetic barrier to vesiculation in rhyolite may explain why nearly all pumice contains rhyolitic glasses. This discovery has clear hazards implications, as it defines a characteristic feature of magmas that erupt explosively from those that do not.

Magmatic intrusions revealed in hydrologic studies

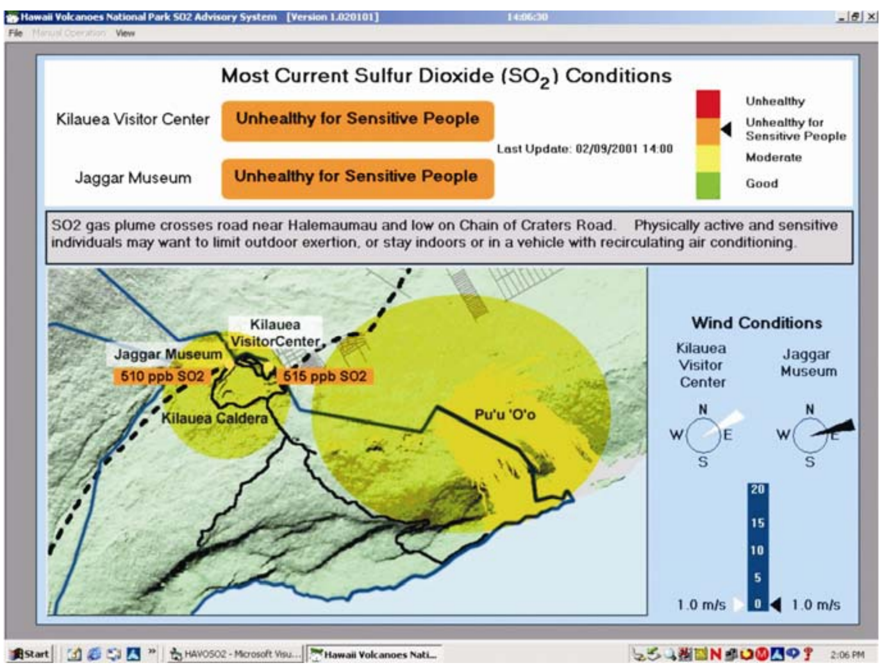
Much of the heat and gas released from shallow magmatic intrusions is absorbed by ground water. Hydrologic investigations provide information on intrusion rates in much the same way that geologic mapping constrains the eruptive history at a given volcano. Studies at Mammoth Mountain and Three Sisters suggest that small intrusive events, similar in size to those recently inferred from geophysical techniques, must occur about once per century to account for the heat and gas discharges measured in springs. These studies found that low-temperature ground water often transports most of the gas and even some of the heat away from the intrusion. A new time-series analysis of hot springs at Yellowstone, Lassen, and Long Valley shows that total discharges of heat and chloride are generally unresponsive to volcanic or tectonic unrest and are thus suited to evaluating long-term intrusion rates. Advances in numerical code development and numerical modeling enable rigorous calculation of mass and heat transport rates to the point that thermal or chemical anomalies in ground water can be tied to specific incidents of unrest.

Measuring carbon dioxide gas critical for volcano monitoring strategies

Sulfur dioxide is the most commonly monitored plume gas, but it can be dissolved (scrubbed) virtually entirely by ground water (meteoric or hydrothermal) and never make it to the surface. Gas models predict extensive scrubbing of strongly acidic volcanic gases (SO_2, HCl, HF), and the role of scrubbing in the early stages of eruptions has been documented through case studies at Mount St. Helens, Washington; Mount Spurr, Alaska; and Mount Pinatubo, Philippines. The results underscore the risk in the customary practice of relying solely on acid gases in volcanic gas monitoring. Scrubbing can mask the release of these gases from subvolcanic magma intrusions at “wet” volcanoes. Thus, low SO_2 emission rates do not necessarily imply low rates of intrusion and degassing. Scrubbing is an especially significant concern in monitoring the “wet” volcanoes of the Cascades and Aleutian arcs. Gas monitoring should be based on major magmatic volatiles that have a low solubility in magma and a low susceptibility to scrubbing. The best candidate is CO_2, followed by H_2S.

The first accurate CO_2 emission rate determined for Kilauea Volcano–about 8,500 tons per day–is three to four times greater than previous estimates, and among the highest observed to date for passively degassing volcanoes. Furthermore, the CO_2 emission rate is relatively steady, compared to SO_2 emission rates, and could potentially be used to monitor the supply rate of primary magma from the mantle. The results confirm that all magma supplied to Kilauea passes first through a summit reservoir, from which about 95 percent of the total CO_2 emission is degassed. Almost all CO_2 in the primary magma is exsolved vapor at summit reservoir depths; consequently, primary magma is buoyant and mixes turbulently with reservoir magma, thus preventing its frequent eruption in the summit area. However, increased CO_2 flux at the summit is a direct indicator of new magma entering the reservoir–a necessary condition for continued eruption.

The Hawaiian Volcano Observatory operates an automated volcanic gas monitoring system. Data from the system are used to produce near-real-time VOG hazard maps for Hawaii Volcanoes National Park and surrounding areas, which are used to alert visitors and employees of air quality and hazardous conditions, as illustrated by this National Park Service Web page. At Long Valley caldera, near Mammoth Mountain Ski Area in California, we monitor volcanic emissions of carbon dioxide. Accumulation of this relatively dense gas in soil has killed trees and poses a hazard to life in low-lying depressions. In both cases, close working relation with land management agencies and other officials has been important to public safety.



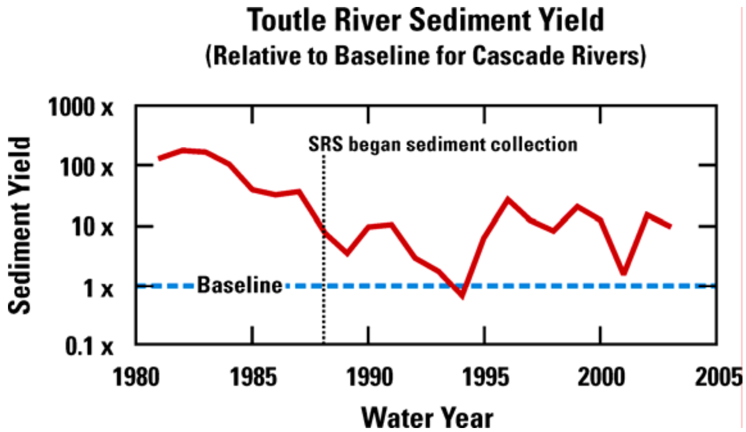
Web page showing current gas hazard areas in and near Volcanoes National Park, Hawaii.

Forest area killed by emissions of carbon dioxide at Horseshoe Lake, Long Valley caldera, California. Photograph taken in 1999 by Ken McGee (USGS).

Sediment yields remain extraordinary high decades after eruptions

Continued monitoring of post-eruption streamflow hydrology and sediment transport at Mount St. Helens reveals that peakflow water discharges are temporarily amplified by tens of percent and that persistent sediment yields can remain elevated above pre-eruption yields by as much as 100-fold for decades. Comparative studies with other volcanoes show that such extraordinary sediment delivery commonly leads to drastic aggradation of riverbeds and valley floors. Extraordinary aggradation typically buries or severely damages infrastructure, triggers channel instability, reduces the ability of channels to convey water, and leads to substantially increased flood hazards. The magnitude and duration of such extraordinary post-eruption sediment transport varies mainly with the nature of volcanic disturbance, but also by interannual and interdecadal hydrologic fluctuations. Sediment delivery is greater and more persistent from basins with severely disturbed channels than from basins with mainly disturbed hill slopes. These and earlier studies demonstrate that mitigation measures designed to reduce downstream sediment delivery must be designed to remain functional for decades. At a broader scale, investigations along the lower Columbia River found that episodic high input of volcanic sediment from Cascade volcanoes over at least the past few thousand years has significantly affected channel morphology and streamflow hydraulics of the Columbia River. Persistent sediment yield in rivers can remain elevated for decades after volcanic eruptions, posing long-term problems for fisheries and navigation.

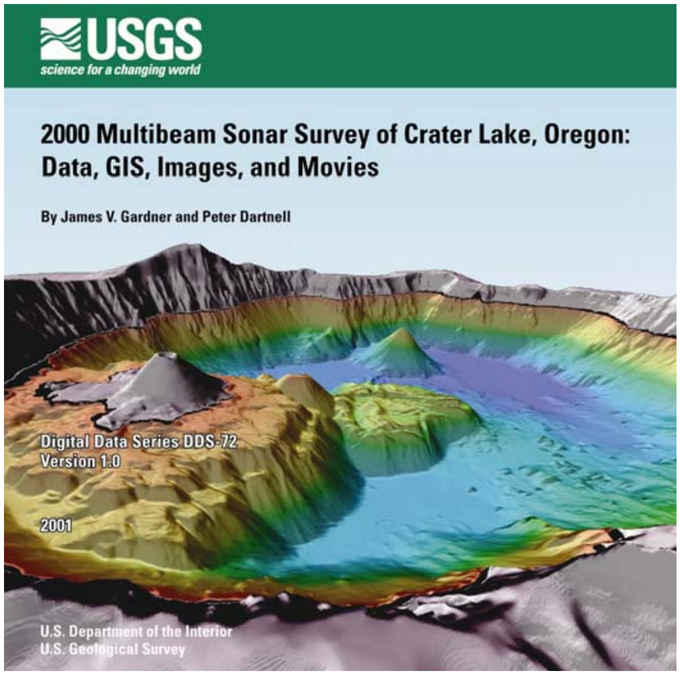
Aerial view looking upstream at Sediment Retention Structure (SRS) built by the U.S. Army Corps of Engineers in the mid-1980s on the Toutle River, Washington. Mount St. Helens is visible in background. Photograph by U.S. Army Corps of Engineers.



Annual sediment yields from Toutle River, downstream of Mount St. Helens, Washington from 1980 to 2003. The baseline (dashed blue line) represents the median sediment yield from western Cascade Range rivers. During the first few years after the 1980 eruption of Mount St. Helens, sediment yield was several hundred times greater than the pre-eruption levels (baseline). 23 years after the eruption (and 15 years after the Sediment Retention Structure (SRS) began collecting sediment), sediment levels in the Toutle River remain 10 times greater than the pre-eruption level.

New bathymetry of Crater Lake reveals evidence concerning most recent eruptions

New high-resolution bathymetry of Crater Lake, Oregon, has led to a more detailed chronology of its geologic history following the climactic eruption of Mount Mazama 7,700 years ago. The high-resolution multibeam echo sounding, conducted in 2000 by a team from the USGS, the University of New Hampshire, C and C Technologies, Inc., and the National Park Service, revealed, in striking detail, many landforms resulting from volcanism in rising water, extensive landslide deposits, submerged beaches, and rock outcrops that define the structural boundary of the collapsed caldera floor. The bathymetry and new eruption chronology also allowed calculation of minimum eruption rates for the post-caldera volcanism. The most recent volcanism occurred about 5,000 years ago, when a lava dome was emplaced beneath the lake on the flank of Wizard Island vent.



New high-resolution lake-bottom bathymetry, developed in cooperation with the USGS Coastal and Marine Geology Program, has helped define the locations and extents of the most recent eruptions within this large and still-potentially active Cascade volcano. This type of information on size and frequency of past eruptions is the basis for evaluation of future hazards.

Forecasting volcanic events using rapidly deployed seismic networks

Rapid deployment of short-period seismic networks at newly restless volcanoes throughout the world has proved invaluable for recording volcano-tectonic (VT) earthquake swarms and long-period seismicity associated with magma intrusion and episodes of gas transport beneath volcanoes. Key to the success is the recognition that off-vent VT swarms, which can spread as far as a few tens of kilometers from a volcano, result from unclamping and slippage on preexisting faults, as high pore pressures generated by magmatic intrusion lower normal stresses in the regions surrounding the volcano.

In the past 5 years, comparative analysis of such seismicity and corresponding volcanic activity has led to (1) successful forecasts of eruptions at Guagua-Pichincha and Tungurahua (Ecuador) and Telica (Nicaragua) in 1999; (2) successful recognition of magma intrusion at Turrialba (Costa Rica) in 2000; and Cotopaxi (Ecuador) in 2001; (3) early recognition after the onset of eruption, that eruptive activity at the initially unmonitored volcanoes Mt. Pago (Papua New Guinea) and Anatahan Volcano, (Commonwealth of the Northern Mariana Islands) and the poorly monitored Reventador Volcano (Ecuador) and Fuego Volcano (Guatemala) was unlikely to soon increase to more explosive levels; and (4) recognition that the sudden appearance of earthquake swarms, long-period events and (or) harmonic tremors were not, in themselves, cause for immediate alarm at San

Vicente (El Salvador) in 1999; Apoyo and Masaya calderas (Nicaragua) in 2000; Apoyeque (Nicaragua) in 2001; Cotopaxi and Cayambe (Ecuador), Machin (Colombia), Cosiguina (Nicaragua), and Mt. Hood (Oregon) in 2002; and Concepcion and Telica (Nicaragua) and Turrialba (Costa Rica) in 2003.

Remarkable magmatic plumbing beneath the Valley of Ten Thousand Smokes, Katmai National Park

The largest eruption in the twentieth century took place in June 1912 in what is now Katmai National Park, Alaska, an area with the tightest clustering of active volcanoes (7) in North America. Through geologic mapping and a series of field and lab investigations completed by VHP during the past 5 years, we now have an enhanced understanding of the events of 1912, as well as the eruptive histories and magmatic relationships between the volcanoes in the Katmai cluster. The 1912 eruption broke through flat-lying sedimentary rocks and formed a new vent (Novarupta), where virtually all of the 1912 magma was erupted. However, Novarupta is located 10 km from the summit of Mount Katmai, which collapsed to form a dramatic 1-km-deep caldera during the eruption. Fourteen earthquakes with magnitude greater than M6, including one M7 event, occurred during caldera collapse. The distance between the site of caldera collapse at Mount Katmai and the vent at Novarupta has long been a puzzle for volcanologists, one with obvious implications for volcanic hazards. We now know that the 1912 magmas are compositionally distinct from other recent eruptive products in the Katmai cluster, arguing against separate shallow magma reservoirs to explain the 1912 events. Instead, a model has been presented in which magma from a large reservoir beneath Mount Katmai intruded laterally and intersected the surface to form the new vent at Novarupta. Lateral transport of magma during the 60-hour-long eruption partially drained the reservoir beneath Mount Katmai, accounting for collapse of the summit to form the caldera.

Professional Paper establishes framework for future hazards assessment of Yellowstone

In 2001, the USGS published a benchmark professional paper including a detailed geologic map of the Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana. This product documents the geology and eruptive history of one of the largest active volcanic systems on Earth and provides the spatial and temporal framework for a modern volcano and seismic hazards assessment, which is now being undertaken through the new Yellowstone Volcano Observatory. Several of the largest eruptions in geologic history took place in the region of Yellowstone National Park. Three gigantic volcanic eruptions, 2.1, 1.3, and 0.64 million years ago, each ejected hundreds to thousands of cubic kilometers of magma and formed enormous crater-like calderas. The youngest of these, the Yellowstone caldera, is nearly 80 km long. Subsequent to the last of these giant eruptions, the core of the caldera has been uplifted, and rhyolite lavas as young as about 70,000 years have nearly filled the caldera. The well-known geysers and other hydrothermal features of Yellowstone attest to exceptionally high heat flow and the continued presence of magma at depth under the region. Although it is not yet possible to quantify probabilities, the geologic history and present state of the volcanic field indicate three general categories of possible future volcanic activity: (1) further rhyolite eruptions within the caldera or in a radial fault zone to the north as the third major volcanic cycle continues to decay, (2) basaltic eruptions on the margins, or even eventually within, the caldera, or 3) a major new magmatic insurgence, initiating a fourth cycle and leading toward climatic ash-flow eruptions and caldera formation.

Appendix D [See Appendix G for a complete list of acronyms used in this appendix]

Assistance Provided by Volcano Disaster Assistance Program, 1999-2003			
Country	**Year**	**Volcano or Agency**	**Assistance Provided**
Chile	2002	Villarica, unrest	Seismic telemetry instrumentation.
Colombia	2002	Machin, unrest	Seismic instrumentation.
	2003	Ruiz, Huila, unrest	Training in U.S. for Colombian scientists to operate lahar detection and warning system; additional lahar detection instrumentation and seismic data acquisition system.
Costa Rica	1999-2001	Turrialba, unrest	Monitoring equipment and training to host scientists.
	1999-2003	OVSICORI	Volcano monitoring workshops co-produced each year for Central American participants.
	2003	Turrialba, Irazu, Arenal, Poas, and so on.	Seismic monitoring and data acquisition and analysis system (for national seismic network).
Democratic Republic of the Congo	2001-2003	Nyiragongo, eruption crisis	Monitoring equipment; consultation and onsite collaboration; training for scientists in U.S.
Dominica	1999	Seismic unrest	Technical assistance to Seismic Research Unit, UWI; preliminary evaluation of volcano hazards.
Ecuador	1998-2003	Tungurahua, eruption crisis	Consultation and onsite collaboration; seismic deformation, and lahar warning instrumentation.
	1998-2001	Guagua Pichincha, eruption crisis	Consultation and onsite collaboration; seismic and lahar warning instrumentation.
	2001-2003	Cotopaxi, unrest	Monitoring equipment; hazards consultation and onsite collaboration (in response to first anomalous seismic activity since 1975).
	2002-2003	Reventador, eruption crisis	Monitoring equipment and consultation (in response to sudden explosive eruption and heavy ash fall across Ecuador).
	2002-2003	Cotopaxi, unrest Reventador, eruption Cayambe, unrest,	On-site GIS training (to aid lahar hazards evaluation).
El Salvador	1999	San Vicente, unrest	Consultation regarding seismicity (eruptive history and experience showed earthquakes unrelated to volcano unrest; no emergency response taken).

	2001	Santa Ana, unrest	Seismic monitoring instrumentation; onsite inspection of summit crater lake (prompted by M7 earthquake and earlier reports from nearby residents of sulfur dioxide gas emissions).
	2003	Santa Ana	Volcano hazards assessment (CAMI).
	2003	Ilopango	Volcano hazards assessment (CAMI).
	2002-2003	San Miguel, Santa Ana, Conchagua, Ilopango, Usulutan	Seismic field instrumentation and data acquisition and analysis system, integrated with National Seismic Network--CAMI Program. Moved and wired new observatory
France	2002	Guadeloupe	Training in installation and operation of seismic data acquisition system.
Great Britain	1999	Soufriere Hills, Montserrat	Assistance to MVO with hazard and risk evaluation.
	2002	Soufriere Hills, Montserrat	Training in installation and operation of seismic data acquisition system.
Guatemala	2003	Atitlan	Volcano hazards assessment (CAMI).
	2003	San Pedro	Volcano hazards assessment (CAMI).
	2003	Atitlan caldera	Volcano hazards assessment (CAMI).
	2003	Toliman	Volcano hazards assessment (CAMI).
	2003	Pacaya	Volcano hazards assessment (CAMI).
	2003	Fuego, Acatenango, Santiaguito, Pacaya, Atitlan, Toliman, Tacana	Seismic and lahar warning instrumentation; integration with national seismic network—(CAMI).
Indonesia	2003	Merapi, unrest/eruption monitoring	Telemetered tiltmeter instrumentation; base station data acquisition and analysis system.
	2003	DVGHM	Training in US in volcano hazards mitigation for DVGHM staff; plan for long-term collaboration in N. Sulawesi.
Mexico	1998-2001	Colima, unrest, eruption monitoring	Seismic data acquisition and analysis system; tiltmeters; assistance with hazard evaluation.
	1994-2001	Popocatepetl	Collaboration in hazards assessment and monitoring systems (seismic, deformation, and gas monitoring); use of Doppler radar for all weather eruption notification.
	2003	El Chichon	Collaboration in seismic monitoring and data acquisition; seismic and base station instrumentation.

Nicaragua	1997-2003	Momotombo, San Cristobal, Telica, Cerro Negro, etc.	Seismic instrumentation and data acquisition and analysis system; integration with national seismic network.
	2000	Momotombo, unrest	Consultation and onsite briefing; no emergency response measures taken.
	2003	Momotombo	Volcano hazards assessment, CAMI Program.
	2003	Telica	Volcano hazards assessment, CAMI Program.
	2003	Cosiguina	Volcano hazards assessment, CAMI Program.
	2002	Various	Onsite GIS training (to aid lahar hazards evaluation).
Papua New Guinea	2002-2003	Pago volcano, eruption crisis	Installation of GPS and seismic-networks. Collaboration on hazards assessment and mitigation.
	1999-2003	Rabaul caldera, unrest, eruption monitoring	Upgrades to data acquisition and analysis systems; installation of real-time GPS network, tide gages, seismic stations.
Peru	2003	El Misti	Collaboration on volcano hazards assessment of Misti; in-country training in volcanology.
Philippines	2001	Pinatubo (crater lake)	Advice and assistance resulted in controlled breaching of crater lake rim--severe hazard to 40,000 people eliminated.
	1999-2001	Mayon, unrest, eruption monitoring	Assistance to PHIVOLCS in monitoring; telemetered tiltmeters and base station; collaborative research on unrest with Univ. of Washington graduate students.
Russia	2000-2003	Kamchatkan volcanoes.	Funding support for monitoring and hazard mitigation activities in Kamchatka, Russia.

Other volcano work abroad by VHP scientists (not supported through VDAP) 1999-2003			
Canada	2002-2003	Mt. Revelstoke and Glacier National Parks (no volcanoes)	Technology transfer of debris-flow monitoring system for hazard zone along Trans-Canada Highway.
Cameroon	2001-2003	Lake Nyos	Installation of carbon dioxide degassing and monitoring systems.
	2003	Lake Manoun	Installation of carbon dioxide degassing and monitoring systems.
Chile	1999-2003	Planchon	Debris avalanche and lahars hazard studies with SERNAGEOMIN.
Commonwealth of the Northern Mariana Islands	2001	Anatahan, Pagan, and others	Survey of previously installed geodetic networks and improvements to seismic stations and radio telemetry.

	2003	Anatahan	Onsite consultation with Emergency Management Office (to evaluate seismic activity of first historic eruption and evaluate future monitoring needs).
El Salvador	1999	San Vicente, lahar hazards	Lahar hazards assessment report (Hurricane Mitch Program).
	2001	San Salvador, lahar hazards	Lahar hazards assessment report (Hurricane Mitch Program).
	2001	San Miguel, lahar hazards	Lahar hazards assessment report (Hurricane Mitch Program).
Great Britain	2003	Soufriere Hills, Montserrat	Review of monitoring and hazard assessment program at Montserrat Volcano Observatory.
Guatemala	2001	Fuego and Acatenango, unrest/ lahar hazards	Volcano hazards assessment report (Hurricane Mitch Program).
	2001	Santiaguito	Lahar hazards assessment report (Hurricane Mitch Program).
	2001	Agua	Lahar hazards assessment report (Hurricane Mitch Program).
	1999-2003	Tacana	Volcano hazards assessment with scientists from INSIVUMEH and UNAM.
Japan	2003	Iwo Jima	Investigation of caldera unrest.
Mexico	1999-2000	Colima	Debris avalanche hazard investigations with National University (UNAM) scientists.
	1999-2003	El Chichon	Investigation of natural dam formed by 1982 eruption with UNAM scientists.
New Zealand	2001-2003	Ruapehu	Consultation with Department of Conservation (on lahar hazards and installation of automated lahar-detection system).
Nicaragua	2001	Concepcion	Lahar hazards assessment report (Hurricane Mitch Program).
	2001	Mombacho	Lahar hazards assessment report (Hurricane Mitch Program).
	2001	San Cristobal/ Casita	Lahar hazards assessment report (Hurricane Mitch Program).
Nicaragua, El Salvador, Guatemala	2001	Various	Week-long GIS technology transfer workshop on the use of LAHARZ modeling procedures (Hurricane Mitch Program).
Peru	2001		Post-earthquake hazards evaluation.

Appendix E (not yet referenced to text)

VHP Supported Hazards Assessment Reports and Zonation Maps, 1999-2003			
Region	**Volcano**	**Year**	**Revised**
Alaska	Iliamna	1999	
	Aniakchak	2000	
	Makushin	2000	
	Spurr	2001	
	Katmai cluster	2001	
	Hayes	2002	
	Kanaga	2002	
	Shishaldin	2003	
	Great Sitkin	2003	
Cascades	Jefferson	1999	
	Three Sisters	1999	
Hawaii	Mauna Loa	2003	
	Mauna Loa, lower northeast rift zone	1999	

Appendix F

National Research Council Review Recommendations and Actions Taken by Volcano Hazards Program			
Priority Area	**NRC Assessment of Need**	**NRC Recommended Solution**	**VHP Response**
Basic research	Improve and rebuild research capabilities in VHP.	Focus all basic research on program goals. Collaborate more with labs and universities. Design extramural grant program.	Research is focused on 5-year goals. Geothermal projects refocused on hydrothermal volcanic systems and hazards. Cooperative grants with universities expanded. Hired new staff and made multiple post-doc appointments.
Basic research-quantitative modeling	Strengthen modeling and probabilistic approaches in assessment.	Integration of hydrologic and modeling and probabilistic assessment of hazards.	Empirical LAHARZ model developed and numerical method application for debris flows being developed at CVO. Modeling and hydrologic hazards integrated into assessments. Decision-tree analysis developed through VDAP and integrated in domestic and international responses.
Monitoring, in situ	Improve seismic-deformation monitoring.	Expand existing nets and upgrade instruments.	Vigorous monitoring network expansion underway: Aleutian Expansion continues; YVO established; priorities for upgrading networks for monitoring Cascade volcanoes established; networks expanded for monitoring of Mauna Loa; pilot program for InSAR monitoring defined; LVEW instrumented. NVMS planning approved by OMB and underway.
Monitoring, remote	Remote eruption detection.	Field test and deploy.	Existing networks in place for this purpose. New remote sensing monitoring systems established and being used (for example, Reston, AVO).
Monitoring, partnerships	Leverage with others to enhance monitoring.	Work closer with NASA, DOE, DOD, NOAA, NSF-consortia such as UNAVCO, IRIS to develop new instruments and approaches.	Expanded partnerships with NSF through EarthScope (for example, especially through PBO and InSAR), NASA (InSAR), NOAA (Aircraft Ash Hazards and 2nd International Workshop).
Monitoring, volcanic gas	Improve gas monitoring capabilities in VHP	Reestablish in-house gas geochem. capability. Obtain new generation of ground-based CO_2 and other gas instruments, or collaborate with developers of these	Volcanic Gas Project established, automated analyzers deployed at HVO. Airborne gas monitoring capability developed and deployed, FTIR experiments conducted, CO_2 monitoring

		instruments.	methods developed and deployed. New low-cost SO2 (Flyspec, Mini-DOAS) systems being tested.
	Increase use of gas geochemistry & remote sensing in gas studies	Increase collaboration with labs and universities.	New post-doc utilizing FTIR, beginning in January 2004.
Data management	Increase ease and timeliness of access to data.	Archive & publish data during crisis response. Explore/develop standards and ways to apply data from one response to another. Observatories work toward real-time data release. Establish appropriate time-lag for release of sensitive data. Embrace universal and prompt data access, such as in meteorology & seismology. Address liabilities through leadership in defining standards for release.	New databases and monitoring data systems being implemented: EarthWorm implemented at observatories and through VDAP, VALVE (Volcano Analysis Visualization Environment) developed and implemented for displaying and analyzing muli-parameter data; WOVOdat under development in partnership with IAVCEI; and US National Volcanic Monitoring System (NVMS) is planned.
Program Management/internal	Focus program more effectively on stated goals. Improve integration of hydrologic and volcanologic studies.	Install more formal mechanism for prioritizing activities and aligning with pgm goals. USGS management should integrate geologic and hydrologic parts of VHP.	Projects aligned with Program Goals thru BASIS+, annual prospectus and annual project reviews, and five year plan. New integrated geology-hydrology management structure adopted at CVO. BASIS+ enables co-funding of projects; funding for geologic and hydrologic components of program remains split by fixed percentage legacy.
	Increase project efficiency	Institute collaborative prioritization- team approach, e.g., as at AVO, CVO. End one-volcano/one scientist project approach.	New team-based volcanic assessment/mapping projects utilized for new work in Aleutians, Mount St. Helens and elsewhere.
Program Management/ interagency	Improve multi-program efficiency	Improve outside communication with other agencies and improve integration with them. (e.g., as have done with local civil defense officials).	Productive collaboration with NASA, NSF on research initiatives (e.g., EarthScope and InSAR resulted in resources for volcanic hazard research and monitoring). Collaboration with NOAA (NESDIS/NWS) & FAA on aircraft-ash hazard warnings continues as essential public safety partnership.

	Resolve policy conflicts regarding volcano hazards research and monitoring in wilderness areas.	Seek high-level interagency agreement and priority.	National level policies for emergency response exist through Stafford Act and interagency MOU's. Additional agreements not deemed necessary at present. Federal land management agencies delegate many essential authorities to regional and local levels. Effective working relations exist and are maintained at these levels by volcano observatories. In addition, National workshop with National Park Service on volcano hazards in September 2001 and MOU with Yellowstone National Park in 2001 for Yellowstone Volcano Observatory have enhanced communications and established mutual priorities.
Program Mangement/ Outreach	Improve rewards for outreach publications.	USGS management should remove disincentives, allow VHP to retain proceeds of publication sales	Outreach activities and publications are encouraged and rewarded by program and team managers. Publication sales policy is being addressed at USGS bureau level.
Program Management/ publications	Improve timeliness of publications.	Set high priority on timeliness of scientific pubs (especially hazard assessments)	Overall publication productivity is high. Hazard assessments are GPRA goals- program has consistently met or exceeded goals.
Program Management/ hazard assessments	Improve timeliness and consistency of hazard appraisals for individual volcanoes.	Use team approach as at Rainier.	Not a factor, appraisals are now timely and involve team efforts- see recent AVO examples, LVO assessment/response plan, Central America VDAP series.
Program Management/ training	Strengthen mentoring/training for crisis response.	Formalize process for selecting new participants in VDAP.	Formalization may not be appropriate. VDAP is including new personnel.
Program Management/VDAP	Increase funds & personnel for VDAP	Wider involvement of non-VDAP personnel to add depth to response team and to increase and pool of talent	VDAP core staff has been expanded. VDAP routinely taps qualified expertise from other parts of VHP. However, additional attention is needed, especially to fill under-represented staff positions (e.g., Electrical Engineering) and to develop additional staff with crisis response experience.
	Inability of VDAP members to publish results.	Judge success of VDAP responses not only in mitigation of eruption	Some misunderstanding by NRC panel of VDAP role is evident. First, many VDAP results are

		impacts, but also in dissemination of information.	published; especially through joint publications with host country scientists. Information dissemination is also focused in ways to most effectively meet U.S. AID/OFDA foreign policy goal of building capabilities in developing countries, and involved frequent one-to-one technical assistance, in-country visits, workshops and training.
Program Priorities	Aleutian volcanoes	Maintain/Increase funds for AVO. Expedite studies to allow instruments to be placed.Use team approach.	Funding for Aleutian expansion strongly supported by program and USGS leadership. Funding levels continue to increase annually and monitoring network continues to expand. Program continues to seek additional support from Department of Interior.
Program Priorities	Hydrologic monitoring	Explore ways to monitor groundwater flow & pore pressure within volcano edifices.	Ongoing thru collaboration with Landslide Hazards and Mineral Resources Programs, and through new projects at CVO.
Program Priorities	Numerical modeling	Include numerical models in evaluation of processes and hazards.	A program priority is the ongoing effort to develop and improve numerical models for debris flowage and mass movement.
Remote Sensing	Improve and develop satellite based methods for volcano monitoring	Continue development of near real-time remote sensing of remote volcanoes and ash clouds. USGS to work with NASA to support InSAR satellite specifically designed for hazards monitoring.	VHP added a new staff position in remote sensing at AVO, and has developed partnerships with NOAA (NESDIS) for monitoring ash clouds, with Michigan Tech. University to develop new methods, and with the USGS Geography Discipline for use of advanced remote sensing systems. In addition, VHP is working with other USGS and academic parthers and with NASA to develop volcano monitoring using satellite based InSAR.
Remote Sensing	Improve satellite monitoring.	Avoid HSS and CINDI, establish closer tie to NASA programs.	Both CINDI and HSS discontinued by USGS. Close ties with NASA's Earth Science Enterprise program established.
Staffing	Crisis of continuity.	Hire, partner, re-train, establish grants-program.	VHP has added ~10 new staff members since 1999. These include post-doctoral appointments, term and permanent positions. In addition, partnerships with the

			observatories' university partners (through cooperative grants) have been expanded.
Staffing	Crisis of continuity.	Increase coordination and collaboration with other parts of USGS, other feds, academics and industry. Convince USGS management that such collaboration is important.	Closer coordination is taking place between geologic and hydrologic parts of the program. New partnerships & staff support through EROS Data Center for InSAR monitoring underway. USGS management strongly supports these efforts.
Staffing	Enable multiple simultaneous VDAP deployments	Expand VDAP	VDAP maintains capability to respond to two simultaneous crises of small to moderate size, or to one large scale crisis. Additional USGS funding and bureau endorsement is required for expansion.
Staffing	Failure to hire.	Prepare strategic hiring plan based on science plan.	Done- priorities established within program in 1999, largely met thru post-docs and collaboration by FY-03. New Staffing Plan being established thru new 2004-2009 5-Year Plan.
Staffing	Ability of program to respond to increasing risk.	Increase staff size or do less. Without staff additions, program needs to focus on monitoring and crisis response .	VHP has grown in both funding and staff since 1999, through increases in USGS line item and reimbursable funding and through collaboration and leveraging of resources with partners. VHP managers disagree with the NRC panel regarding their alternative recommendation, that without such increases, the program should focus only on monitoring and crisis response. USGS science policy is to maintain a balance of basic and applied research. Maintaining high-quality research capabilities as an "in house" resource is, and will remain as a critical component of VHP.

Appendix G

Acronyms

ASC	Alaska Science Center
AVO	Alaska Volcano Observatory
CAMI	Central American Mitigation Initiative
CAP	Common Alerting Protocol
CINDI	Center of Integrated National Disaster Information
CSAV	The Center for the Study of Active Volcanoes
CUSVO	Consortium of U.S. Volcano Observatories
CVO	Cascades Volcano Observatory
DVGHM	Directorate of Volcanology and Geological Hazards Mitigation (Indonesia)
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOD	U.S. Department of Defense
EDC	EROS Data Center
EHP	Earthquake Hazards Program
EROS	Earth Resources Observation System
FAA	Federal Aviation Administration
FTIR	Flow-Through-Infrared
GIS	Geographic Information System
GeoDIVA	Geologic Database of Information on Volcanoes in Alaska
GPRA	Government Performance and Results Act
GPS	Global Positioning System
GVP	Smithsonian Institution’s Global Volcanism Network
HSS	Hazards Support System
HVO	Hawaiian Volcano Observatory
IAVCEI	International Association of Volcanology and Chemistry of the Earth’s Interior
InSAR	Interferometric Synthetic Aperture Radar
INSIVUMEH	Institute of Seismology, Volcanology, Meteorology, and Hydrology
IRIS	Incorporated Research Institutions for Seismology
IT	Information Technology
JAMSTEC	Japan Marine Science and Technology Center
KVERT	Kamchatkan Volcanic Eruption Response Team
LAHARZ	GIS software for modeling downslope movement of volcanic mudflows (lahars)
LVEW	Long Valley Exploratory Well
LVO	Long Valley Observatory
MOU	Memorandum of Understanding
MVO	Montserrat Volcano Observatory
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data and Information Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NVMS	National Volcanic Monitoring System

NWS	National Weather Service
OFDA	Office of Foreign Disaster Assistance
OMB	Office of Management and Budget
OVSICORI	Observatorio Vulcanologico y Sismologico de Costa Rica
PART	Program Analysis and Rating Tool
PASA	Participating Agency Service Agreement
PBO	Plate Boundary Observatory
SAFOD	San Andreas Fault Observatory at Depth
SAR	Synthetic Aperture Radar
SERNAGEOMIN	National Service of Geology and Mining (Chile)
STC	Science and Technology Centers
UCLA	University of California Los Angeles
UNAM	University of Mexico
UNAVCO	University of NAVSTAR Consortium
USAID	U.S. Agency for International Development
US ARRAY	U.S. Seismic Array
USGS	U.S. Geological Survey
VALVE	Volcano Analysis Visualization Environment
VDAP	Volcano Disaster Assistance Program
VHP	Volcano Hazards Program
VT	Volcano-tectonic earthquakes
YVO	Yellowstone Volcano Observatory
WOVO	World Organization of Volcano Observatories
WOVO.DAT	World Organization of Volcano Observatories Data Base

Appendix H: Volcano Hazard Program Performance Metrics

End Outcome Goal: SEO.1. Protect Lives, Resources and Property							
End Outcome Measures	**2002 Actual**	**2003 Actual**	**2004 Plan/ Budget**	**2004 Revised Final Plan**	**2005 Plan**	**Change in Performance – 2004 to Planned 2005**	**Long-term Target (2008)**
Hazards: X% of communities using DOI science on hazard mitigation, preparedness and avoidance for each hazard management activity (based on 256 total) **(SP)**	**UNK**	58.6	63.3%	63.3%	66.4%	+3.1%	80%
Decisionmaker Satisfaction: Met need for information to help achieve goal of reduced risk **(SP)**	UNK	UNK	≥80%	≥80%	≥80%	0	≥80%
Intermediate Outcome: Provide information to assist communities in managing risks from natural hazards							
Use Rate: Volcanoes: X% of communities using DOI science on hazard mitigation, preparedness, and avoidance for each hazard management activity (based on 256 total) **(NK)**	**UNK**	58.6%	63.3%	63.3%	66.4%	+3.1%	80%
Adequacy: Percent of sampled stakeholders reporting adequacy of science base to inform decision-making for each hazard management activity (volcanoes, earthquakes, etc.) **(SP)**	**UNK**	97%	≥80%	≥80%	≥80%	0	≥80%
PART Efficiency Measures or other Outputs	**2002 Actual**	**2003 Actual**	**2004 Plan/ Budget**	**2004 Revised Final Plan**	**2005 Plan**	**Change in Performance – 2004 to Planned 2005**	**Long-term Target (2008)**
# of hazards monitoring networks maintained **(BUR)**	1	1	1	1	1	0	1
# of risk/hazard assessments delivered to customers **(BUR)**	5	2	0	0	2	+2	+5
# of formal workshops or training provided to customers **(BUR)**	4	4	4	4	4	0	4/year
# of sites (mobile or fixed) monitored for ground deformation to identify volcanic activity **(BUR)**	**UNK**	75	75	85	85	0	130
# of areas or locations for which geophysical models exist that are used to interpret monitoring data **(PART)**	**6**	6	6	6	6	0	8
# of volcanoes for which information supports public safety decisions **(PART)**	45	**48**	48	49	50	+1	56
% of potentially hazardous volcanoes with published hazard assessments (based on a total of 70) **(PART)**	58.6%	61.4%	61.4%	61.4%	64.3%	+3.1%	68.6%
Data processing and notification costs per unit volume of input data from geophysical sensors in monitoring networks (in cost per gigabyte)(**PART**)	UNK	UNK	TBD	TBD	TBD	TBD	TBD

Target Codes:
SP = **Key Strategic Plan measures**
NK = **Non-Key measures**
TBD = **Targets have not yet been developed**
NA = **Long-term targets are inappropriate to determine at this time**
PART = **PART measures**
UNK = **Prior year data unavailable**
BUR = **Bureau specific measures**