Collaborative Studies Target Volcanic Hazards in Central America

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Central America is the second-most consistently active volcanic zone on Earth, after Indonesia. Centuries of volcanic activity have produced a spectacular landscape of collapsed calderas, debris flows, and thick blankets of pyroclastic materials. Volcanic activity dominates the history, culture, and daily life of Central American countries.

January 2002 marked the third consecutive year in which a diverse group of volcanologists and geophysicists conducted focused field studies in Central America. This type of multi-institutional collaboration reflects the growing involvement of U.S. and international universities and organizations in Guatemala and El Salvador (Table 1).

The work includes many ground-based, geophysical field studies in conjunction with satellite remote sensing. The university contingent works closely with the local volcanological and hazard mitigation agencies, and all benefit from the sharing of manpower, resources, and technical and field expertise.

When graduate volcanology programs do volcanic hazards work in developing countries, research turns toward mitigating real problems and building local infrastructure. A single university is unlikely to be able to maintain the needed broad base of expertise in these areas. One of the advantages of the MTU-lead research is that, when the academic community collaborates, teams of researchers can draw on their strengths to attack problems relevant to their disciplines. At the same time, students are trained by top scientists in diverse, yet complementary fields.

Local Agencies

Currently, two main agencies within Guatemala deal with volcano hazards. INSIVUMEH (Instituto Nacional de Sismologia, Vulcanologia, Meteorologia, E Hidrologia) is a scientific and technical agency that works with both the private sector and government. It is responsible for monitoring natural hazards, conducting basic research, and developing and maintaining a hazards data base. It operates instrument networks for monitoring volcanic activity primarily through seismic stations, but it also has a network of field workers who maintain small observatories and observe the volcanoes, reporting daily by radio. INSIVUMEH consists of roughly 100 scientists/engineers, technicians, and staff.

CONRED (COordinadora Nacional para la REduccion de Desastres) is concerned with overall disaster mitigation. It develops and implements disaster reduction strategies related to ash falls, lava and debris flows, flooding, mud flow, and relocation hazards. This agency is responsible for hazard education, as well as recommending evacuation routes and relief shelters.

In El Salvador, a series of natural disasters --Hurricane Mitch in 1998, major tectonic earthquakes, and associated landslides in 2001-have led to a reorganization of the government agencies that deal with natural hazards. A new agency called SNET (Servicio Nacional de Estudios Territoriales) is being created to centralize and help prioritize monitoring and mitigation efforts in the country. The agency, within the Ministerio de Ambiente, has a geological service headed by Carlos Pullinger, who did a hazards study of the Santa Ana Volcanic Complex as an

M.S. thesis at MTU in 1997. This service is aimed at involving the academic community in hazards efforts, and there is an effort by all who have worked in El Salvador to try to help. A publication about natural hazards in El Salvador is being published as a GSA Special Paper (http://www.geo.mtu.edu/~raman/GSASalvador.html).

Volcanic Hazards and Field Studies

The volcanic hazards in Guatemala and El Salvador (Figure 1) are diverse and ominous: steep, unstable slopes, seasonal transport of volcanic debris, volcanic dome collapse, and of course, the many primary and secondary threats from explosive eruptions themselves. Neither country has a strong natural hazard mitigation effort, but both have participated in international hazards mitigation efforts focused on volcanoes within their own country.

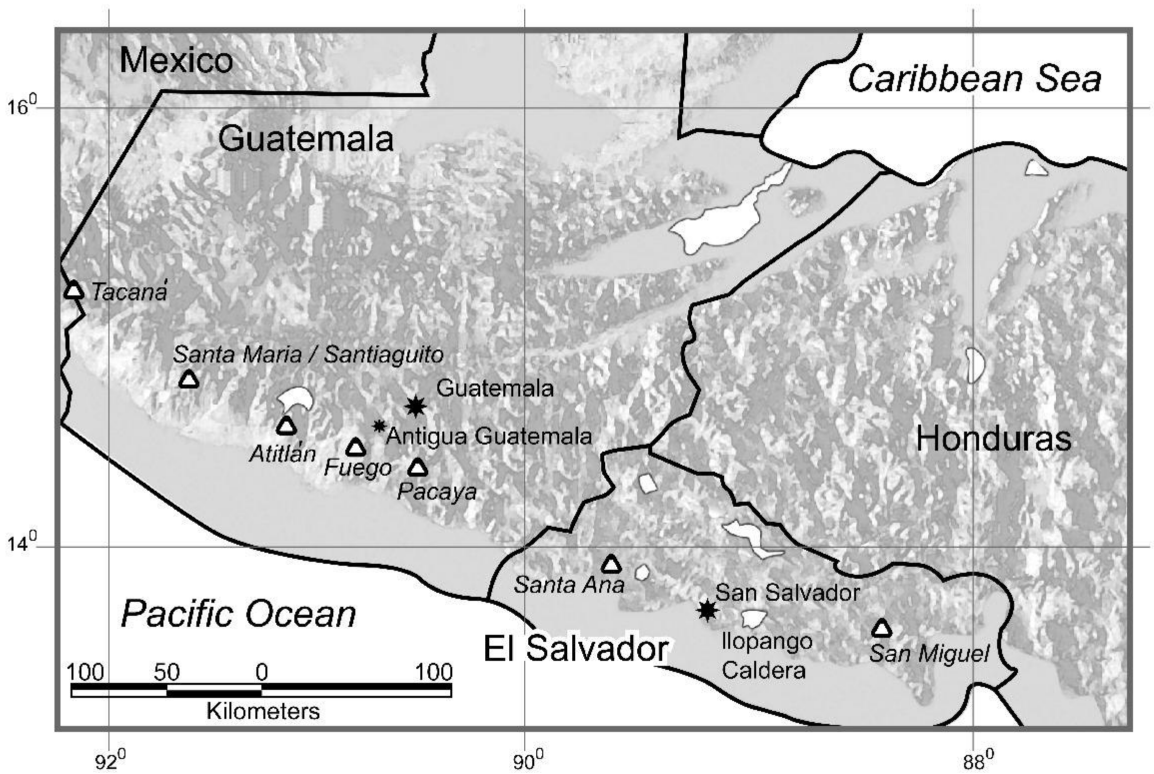

Fig. 1. This map of Guatemala and El Salvador notes volcanoes from collaborative studies.

Guatemala

Pacaya volcano lies 30 km south of Guatemala City, which has a population of ~2 million. Air routes for La Aurora International Airport, just south of the capital city, routinely pass through Pacaya's airspace. During the past several decades, and most recently in early 2000, Pacaya has produced many strombolian eruptions, lava flows, and occasionally, more explosive eruptions. The current summit geometry suggests the risk of over-steepening around the high-level, basaltic magma body, which may be the locus of a future major collapse. Fuego volcano has been the site of more than 60 historic eruptions that produced extensive ash falls and many basaltic pyroclastic flows. Its eruptions affected large areas along the Guatemalan highlands and coastal plain in 1971 and 1974. It was inactive from about 1978 until 1999, when its vertical conduit re-opened. In early 2002, its restlessness increased, with small ash eruptions and lava flows and the threat of lahars [*Vallance et al.,* 2001].

Fuego's proximity to the country's main airport and Antigua Guatemala, a major tourist and cultural center, means that ash eruptions could affect tourism and business significantly. Atitlán caldera is the tourist centerpiece of Guatemala, a high-elevation caldera lake surrounded by indigenous populations that is considered by many to be one of Earth's most beautiful places. The hazards presented by future volcanic activity are compounded by the closely-spaced density of historically active vents and by the presence of the great lake itself. Santa María volcano produced one of the largest eruptions of the 20th century in 1902 and devastated much of southwestern Guatemala, killing at least 5000 people and leaving behind a 1-km diameter crater. The dacitic Santiaguito volcano lava-dome complex has been growing episodically at the base of the crater since 1922, accompanied by almost continuous minor explosions and periodic lava extrusion, larger explosions, pyroclastic flows, and lahars [*Rose*, 1987].

Hazards generated from Santiaguito activity are mainly directed toward the southwest, affecting an important agricultural region and disrupting major ground transportation routes. The near-constant output of pyroclastic material is transported, sometimes catastrophically, downstream through several major river channels during the rainy season (Figure 2). A block lava flow extends more than 2 km from Santiaguito, generating hazards from the potential collapse and generation of lahars, both at the flow front and at the vent itself [*Harris et al.,* 2002]. Collaborative fieldwork has included SO_2 emission surveys of Pacaya, Fuego, and Santiaguito volcanoes, using INSIVUMEH's Correlation Spectrometer (Cospec) and key resources from CONRED. These data provide a framework for validating a satellite-based volcanic SO_2 survey method using Moderate-Resolution Imaging Spectrometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite data.

Fig. 2. This helicopter view of El Palmar shows Santiaguito in the background, debris deposition, downcutting by Rio Nima I, and damaged structures. From 1983 to 1997, the town of El Palmar was largely destroyed by lahars, debris flows, and associated downcutting through unconsolidated material by the main rivers. Prior to the debris flows, El Palmar extended across the lower portion of the photo.

Led by the University of Hawaii group, a deformation-measurement network was designed and set up on Pacaya in 2000-2001, employing a kinematic Global Positioning System (GPS).

GPS surveys of lava flows (Pacaya) and debris flows (Santiaguito; Figure 3) were completed and will be used to calculate material volumes of unprecedented accuracy, and to establish base levels for future activity. Suites of rock samples from individual flows and deposits have been collected and catalogued for future petrographic, age-dating, and compositional studies. A Geographic Information System (GIS) data base for the Santiaguito region is being constructed that will facilitate the development of a long-range, several decades-long plan for hazard mitigation and infrastructure development. The GIS includes digital topography supplemented by the kinematic GPS results, model lahar simulations contributed by the U.S. Geological Survey, and approximately 30 cloud-free Landsat Thematic Mapper (TM) satellite images spanning the past 20 years. Hazard mapping is well underway for the Atitlán region, and we have begun compilations of the past 30-40 years of activity for Pacaya and Fuego.

Fig. 3. The kinematic GPS base station for surveying debris flow volumes. Santiaguito volcano is in the background. From left to right: Luke Flynn, Mark Davies, and Gregg Bluth.

El Salvador

El Salvador has had far less historic activity than Guatemala; however, it may be even more vulnerable to volcanic hazards [*Major et al.*, 2001] because the country's infrastructure is located more completely on or near volcanoes, and because the historic time period has been unusually quiet and people are not as aware of potential hazards as are their Guatemalan neighbors. Rather, the hazards of civil war, earthquakes, landslides, and hurricanes are at the forefront of people's memories. Santa Ana Volcano, a volcanic complex in El Salvador, consists of a silicic caldera, an andesitic stratovolcano (Volcán Santa Ana, proper) and several satellitic mafic cones.

Rarely active in historic times, the complex has been developed as a tourist center and agricultural resource. Santa Ana has a summit crater lake and a prominent plume. In recent years, and particularly following the earthquake of January 2001, local residents complained of increased acidity of the plume and were concerned about a volcanic crisis. Ilopango Caldera is a Quaternary caldera located at the eastern edge of San Salvador, El Salvador's capital of >1 million people. Ilopango's last activity was a major phreatoplinian event that devastated the whole country in A.D. 301. The deposit of this great eruption, called the Tierra Blanca Joven

(TBJ), is one of the world's most important geological records of an explosive eruption through a caldera lake. Deposits are found all over the city and for many kilometers surrounding it. Basaltic San Miguel volcano towers above El Salvador's second city of San Miguel. It has had several minor ash eruptions since 1970, and has active SO_2 emission from a deep summit crater.

A team of MTU investigators worked with INSIVUMEH scientists and Salvadorans to develop a baseline for Santa Ana's and San Miguel's SO_2 emissions (Figure 4). A systematic series of sampling visits to the Santa Ana crater lake and its associated fumaroles was made by Demetrio Escobar and by crater lake expert Alain Bernard. Results have led to a complete description of the crater lake and its geochemistry, helping to fashion a new understanding of Santa Ana's activity. SO_2 declined markedly after the 2001 earthquakes and the crater lake temperatures also declined, so it is possible that the quakes promoted temporary increased degassing of the volcano's hydrothermal system. A team of scientists from El Salvador and the Smithsonian Institution in the U.S. worked to finish a comprehensive debris avalanche study on Santa Ana. Work on Ilopango by Bruce Houghton, University of Hawaii, and the McGill University group has focused on the stratigraphy, physical volcanology, and ages of the Tierra Blanca deposits.

Fig. 4. A Cospec survey of Santa Ana volcano. From left to right: Alain Bernard, Gustavo Chigna, Demetrio Escobar, and Oto Matías.

A field team of Salvadorans has extensively sampled and mapped the many San Miguel flows. Geochemical analysis and age dating is now underway. Two field seasons have provided the basic geological data needed for a modern hazard assessment.

Organizing Collaborative Field Work

Our field work in Guatemala and El Salvador requires close collaboration and coordination from several university and government agencies, which is clearly a huge effort. However, the benefits are equally large, and these types of multi-institutional efforts are well worth developing. How do students, researchers, and the local infrastructure benefit from these multidisciplinary efforts?

The 10-15 students involved in this work received on-site training in various volcanic hazards methodologies (Table 1); these studies provided abundant opportunities for in-depth experience in instrument calibration, data collection, and processing. Students make valuable professional contacts from fellow universities and gain international experience. While some of this would be expected from a single university, the breadth of skills, research approaches, and collaborators are beyond the typical research experience.

The academic professionals benefit from comprehensive approaches to the study of volcanic hazards, linking related but technologically diverse skills such as gravity and gas measurements. They gain access to regular monitoring from local observatories, with vast knowledge of volcanic behavior and past activity. Additionally, many of our research efforts simply require energetic manpower to complete work in reasonable timeframes.

Civic Benefits to Host Countries

The Guatemalan and El Salvadoran government agencies involved have been highly receptive to these field studies, and they likewise have benefited from multidisciplinary field efforts. These excursions have provided a focus for inter-agency collaboration, mechanisms for education and training in new monitoring techniques, and in several cases, the opportunities to attend geoscience-intensive institutions and obtain higher academic degrees.

Table 1. Summary of Field Efforts, 2000-2002

Investigators	***Institution***	***Research Areas***
Bill Rose, Gregg Bluth, Matthew Watson	Michigan Technological University	Gas emissions, field and GIS hazard mapping, remote sensing of gas emissions
Andy Harris, Luke Flynn, Mark Davies	University of Hawaii, Oahu	Field and satellite thermal studies, lava and debris flow volume measurements, gravity surveys
Lee Siebert, Paul Kimberly	Smithsonian Institution	Debris avalanches, mapping
Jim Vallance	McGill University, Montreal, Canada	Debris flow mapping; volume and composition measurements
Simon Carn	JCET, University of Maryland Baltimore Campus	Gas emissions, remote sensing
Oto Matías*, Gustavo Chigna	INSIVUMEH, Guatemala	Gas emissions, volcanic hazards
Rudiger Escobar Wolf	CONRED, Guatemala	Geophysical studies
Carlos Pullinger, Demetrio Escobar**	SNET, El Salvador	Volcanic hazards
Alain Bernard	Université Bruxelles, Belgium	Crater lake studies
Craig Chesner	Eastern Illinois University	San Miguel volcanic hazards
John Stix	McGill University	Caldera studies, volcanic gases
Lina Patino	Michigan State University	Geochemistry of volcanic rocks

*currently in the Bachelor's program at Michigan Tech

**currently in the Master's program at Michigan Tech

How have the cross-disciplinary efforts helped improve understanding of the volcanic hazards? At present, some of the most pressing needs for effective hazards mitigation in Central America include compilations of historic and recent activity and generation of baseline data.

Many of our efforts focus on generating comprehensive, long-term evaluations of volcanic activity, including gas and lava emissions, debris flow mobilization and remobilization during the rainy seasons, sub-surface magma movement, and the use of remote sensing to correlate temperature anomalies and the effects of emissions on the environment. Repetitive field studies---at Pacaya volcano, for example---provide perspective for our relatively short-term studies, largely by helping us understand what volcanic activity might happen next. Combining deformation studies from 2001 and 2002 with coincident thermal and gas flux measurements will yield key information relating sub-surface motion and degassing. The GPS, gravity, and remote sensing work will help us learn about changes in the Pacaya magma body, which will be useful in forecasting hazards. The timing of these field excursions has maximized the use of satellite-based data, including ETM+ imagery and also various infrared satellite systems such as MODIS, ASTER, and Geostationary Operational Environmental Satellite (GOES).

Future Work

A large group of people can collaborate to tackle problems that address both the new research ideas of academic scientists and the practical needs of hazard mitigation agencies. We intend to continue these studies over the next several years because the significance of most of this work is amplified through time. Involvement of graduate students in this work has added an important subject to their education: the practical problems of volcanic hazard mitigation in a developing country. Through this program we have helped to develop the infrastructure of hazards mitigation abroad while also advancing volcanic research. We encourage communication and participation by others in this rewarding effort.

Acknowledgments

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