Merging High Temporal Resolution Data of SO$_2$ Emissions and Seismicity from Soufriere Hills Volcano, Montserrat

Project Summary

The degassing behavior of a volcanic system is an integral part of the seismicity it generates. Volcanic monitoring has relied heavily on the use of seismic networks and regular measurements of sulfur dioxide degassing to evaluate the state of the magma body and the potential for future eruptions. These methods have helped improve understanding of magma dynamics and eruption forecasting, but have been limited by the fact that gas measurements cannot be taken at similar temporal resolution as continuous seismicity. Thus, these methods, have remained somewhat independent of each other relaying on observing distinct changes or trends (“ramping up “) in activity as indicators of future events. However both decreasing and increasing trends in SO$_2$ emissions may signal impending eruption, and a closer link between seismic and degassing information would give scientists and new tool with which to mitigate volcanic hazards. In January 2002, the Montserrat Volcano Observatory (MVO) installed a new gas monitoring system at Soufriere Hills Volcano (SHV) composed of two Differential Optical Absorption Spectrometers (DOAS); these new sensors allow continuous retrieval of sulfur dioxide spectra from the emitted plume, and gas flux values every 1-6 minutes over the course of a working day. These data enable, for the first time, a close merging of gas and seismic datasets.

The proposal features:
- Calibration of the timing of SO$_2$ degassing and seismic activity, and correlation of changes in emitted SO$_2$ fluxes to seismic triggers from subsurface and near-surface motions.
- Development of a magnitude scale for SHV seismic events, based on the MOV seismic network database. This magnitude scale will be used to constrain magnitude-frequency relationships for SHV events (long-period and hybrid earthquakes, and rockfalls).
- Correlation of volcanic SO$_2$ fluxes to seismic event type, magnitudes, seismic amplitude and timing by merging the SO$_2$ and seismic data over active periods for SHV.
- Support for MVO’s automated gas measurement system, by providing rigorous evaluations of daily degassing fluctuations, noise, and system errors.

The intellectual merits include:
- Merging of high temporal resolution datasets will allow better understanding of magma dynamics and evaluate current theories of volatile and seismic characteristics.
- Improved eruption prediction capabilities, by linking gas and seismic behavior to precursory activities in a highly active volcanic system.

Outreach and broader impacts include:
- Establishing baseline trends and methodologies for most effective uses of gas flux data, as rapid SO$_2$ measurement systems are incorporated into other volcano monitoring efforts.
- Support for MVO’s hazard mitigation infrastructure, through exploration of the potential for a gas alert derived from automated gas flux data.
- Develop a stronger, long-term collaboration between Michigan Tech and MVO, featuring student research projects.
**Project Description:** Merging High Temporal Resolution Data of SO₂ and Seismicity from Soufriere Hills Volcano, Montserrat

**Project Objectives**

The purpose of this work is to take advantage of the growing archive of high-temporal resolution SO₂ data from Soufriere Hills Volcano, Montserrat to explore detailed relationships between seismicity and sulfur dioxide degassing in volcanic systems. The Montserrat Volcano Observatory (MVO) operates and maintains a 9 station, short period and broadband seismic network, collecting continuous seismic data. In January 2002, MVO installed two Differential Optical Absorption Spectrometers (DOAS) near the volcano that automatically collect a continuous spectrum that is utilized to retrieve SO₂ amounts based on its unique absorption at ultra-violet wavelengths. For the first time it is possible to compare SO₂ and seismic data on similar temporal scales for an extended, continuous period. These data will allow us to investigate detailed relationships between seismicity and SO₂ degassing on an active volcanic dome, and to improve interpretations of magma dynamics and eruption forecasting.

Key features of our study are:

- *Correlation of simultaneous, near-continuous gas and seismic data.* Time series’ of DOAS SO₂ emission fluxes will be calibrated to continuous seismic data collected during the same time periods on the MVO short-period and broadband seismic network.
- *Development of a catalog of seismic event type, magnitude and location.* A well-calibrated, automated magnitude scale will be developed, and used to help constrain physical characteristics of source processes for each seismic event type.
- *Relationships of SO₂ degassing to characteristic seismic activity.* Gas data will be correlated to event type (long period and hybrid earthquakes, rockfalls), event magnitude, hypocenter location, spectral signature, and long term seismic trends. These correlations will be evaluated with respect to current models of Soufriere Hills magma dynamics.
- *Advancement of real-time dissemination of gas monitoring products.* Our work will help provide background and plume spectra boundary conditions, to investigate the feasibility of a real-time SO₂ alert as part of the MVO’s hazard mitigation efforts.
- *Collaboration with the Montserrat Volcano Observatory.* This project solidifies and expands the working relationship between Michigan Tech and MVO experts in seismic and gas monitoring. We will use our expertise in data merging and analysis to generate quantitative analyses of these complementary datasets.

**Background**

Sulfur dioxide (SO₂) gas is measured at active volcanoes because it is relatively abundant in volcanic plumes (2-12% molar mass - Symonds et al., 1994), atmospheric background concentrations are minimal (Andres and Rose, 1995), and it can be detected and measured remotely (Millan et al., 1976). From a volcano monitoring and hazard standpoint, establishing SO₂ baseline emissions, followed by detection and interpretation of deviations from that baseline, is an on-going objective. Changes in SO₂ emissions from background levels have, in past monitoring efforts, indicated major changes in the volcanic system, often foreshadowing a
change in eruptive activity. For example, the onset of \( \text{SO}_2 \) emissions from an otherwise dormant volcano has advertised the ascent of gas-rich, juvenile magma towards the surface such as at Pinatubo (Daag et al., 1996) and Montserrat (Gardner and White, 2002). Increased \( \text{SO}_2 \) emissions often precede and/or accompany an escalation in eruptive activity (Malinconico, 1979; Young et al., 1998). On the other hand, a decrease in \( \text{SO}_2 \) has revealed the influence of hydrothermal systems on magma degassing (Doukas and Gerlach, 1995), the capping or plugging of the volcanic conduit (Stix et al., 1993; Casadevall et al., 1994), and the slow degassing of a batch of magma that has stalled on ascent (Andres et al., 1993; Gardner and White, 2002).

Many of the scientific advances in the past three decades regarding volcanic \( \text{SO}_2 \) relied on the correlation spectrometer (COSPEC) to measure \( \text{SO}_2 \) concentrations in volcanic plumes (Stoiber et al., 1983). COSPEC was a major change from direct gas sampling, trading some individual measurement accuracy for safety and increased sampling frequency, and thus greatly improving the ability to evaluate degassing trends. The COSPEC is an ultra-violet (uv) spectrometer that takes advantage of the selective absorption of uv light by \( \text{SO}_2 \), and measures the line-of-sight \( \text{SO}_2 \) burden as a concentration-path length product (Millan et al., 1976). The method utilizes the daytime sky as a background and source for uv light. COSPEC surveys are conducted either by scanning through the plume from a fixed position on the ground, or by traversing beneath the plume using an automobile, boat, or aircraft.

COSPEC suffers from several inherent limitations such as wind speed determination (Stoiber et al., 1983), non-selective absorption and scattering of other particles or molecules in the volcanic plume (Millan, 1980), and geometric errors in plume width determination (Shannon et al., 2001). However, one of the biggest limitations has been the inability to acquire consistent, high-temporal resolution data. In the past, COSPEC deployment efforts have typically been either 1) long-term (months to years) monitoring averaging about one measurement per day, or 2) short-term deployments of days to weeks consisting of daily to hourly (rapid) measurements (Andres and Rose, 1995). This is because the instrument is relatively cumbersome, and measurements and data processing are both labor intensive and time consuming. Consequently, volcanic degassing phenomena that have been studied or postulated are those that occur on time scales that can be "seen" with low temporal resolution COSPEC data (i.e. days, weeks, months).

In 2001, a new, compact ultraviolet spectrometer was field tested at Masaya volcano, Nicaragua (Galle et al., 2003). This instrument, the Differential Optical Absorption Spectrometer (DOAS), featured an updated electronic design using optical fibers and a linear CCD array detector (Edmonds et al., 2003a). The success of this effort led to field trials on Montserrat in August 2001, with good correlation between DOAS and COSPEC sensors. MVO installed two DOAS sensors in January 2002. The DOAS system represented a major advance in \( \text{SO}_2 \) monitoring, as it enabled the continuous, automatic collection of \( \text{SO}_2 \) absorption spectra. Depending on cloud geometry, the system could retrieve and derive \( \text{SO}_2 \) fluxes on the order of minutes throughout daylight working conditions. For the first time, \( \text{SO}_2 \) data could be used to monitor rapid changes in volcanic degassing (Edmonds et al., 2003a).

Seismic data collected at active volcanoes shows a multitude of activity occurring on the order of hours, minutes, and seconds. Seismic data have generally been the foundation of
monitoring efforts because many forms of volcanic activity generate detectable seismic waves that can be measured and recorded continuously with expendable, automated instrumentation networks. Volcanoes produce a plethora of seismic waveforms that are generally categorized based on frequency and waveform. These include volcano-tectonic, long period, hybrid and explosion earthquakes and rockfalls.

Modeling shows that the frequencies and waveforms characteristic of long period and hybrid earthquakes are generated from the excitation and resonance of a fluid magma body surrounded by an elastic medium (Ferrazzini and Aki, 1987; Chouet, 1988; Chouet et al., 1994; Chouet, 1996; Benoit and McNutt, 1997; Neuberg et al., 2000). However, among the variables that may govern the observed seismic wavefield (i.e. conduit geometry, topography, impedance contrast at fluid/solid interface, velocity model source mechanisms), modeling by Benoit and McNutt (1997) and Neuberg et al. (2000) show that the gas content of the magma also has an affect on the observed seismic waveforms generated from magmatic oscillation. For a given depth, the acoustic seismic wave velocity is controlled by the pressure, gas-liquid density, and gas volume fraction. An increase in the amount of gas (bubbles) results in a decrease in seismic velocity, therefore affecting the observed spectra generated from low-frequency resonance. A change in gas content causes a shift in spectral frequencies and may explain "gliding" spectral lines observed during long period and hybrid swarms (Neuberg et al., 1998; Baptie et al., 2002; Neuberg and O'Gorman, 2002). A number of scenarios may cause changes in gas concentrations within the conduit: 1) pressurization of the system, caused by the plugging of the conduit by a slug of stalled magma; 2) depressurization resulting from increased gas and ash venting, or the loss of overburden pressure as a result of overlying material collapse; or 3) the introduction of new, gas-rich magma at the bottom of the magma chamber. Resulting changes in the magma gas content could manifest themselves as changes in the spectral content of low frequency earthquakes, and also in degassing trends observed at the surface.

In addition to models, field observations and measurements collected during swarms of long period and hybrid earthquakes suggest gas-related volcanic processes are coincidentally involved. For instance, long period and hybrid earthquakes are often precursors to explosive activity (Endo et al., 1981; Harlow et al., 1996; Miller et al., 1998), behavior which necessitates the build-up of pressure, presumably in part by exsolution of magmatic gases.

On Montserrat, long period and hybrid earthquake swarms correlate with inflation and deflation cycles as measured by tilt meters (Voight et al., 1998; White et al., 1998). The cycles are interpreted as a series of repetitive events in which: 1) a degassed plug of magma inhibits conduit flow, 2) pressure builds beneath the plug as a result of exsolution of gases from underlying magma, 3) pressure causes the edifice to inflate, and 4) eventually overburden pressure is exceeded, the plug is forced out, gases escape, and the dome deflates (Voight et al., 1999). High-temporal resolution (one month of daily sessions, consisting of 1-8 measurements, 15-30 minutes apart) COSPEC data collected during a portion of these cycles found that high SO₂ emission rates correlated with maximum deformation gradients and peaks in hybrid seismicity (Watson et al., 2000). Also on Montserrat, long period events have been recorded during coincidental visual observations of ash and gas venting at the surface, and immediately precede rockfalls (Luckett et al., 2002). The combined signal observed includes a long period
component preceding and sometimes mixed in with the high frequency rockfall signal. These events have been termed "long-period rockfalls".

**Summary.** Gas and seismic monitoring have become standard operations at volcano observatories, but in practice their primary predictive uses rely on recognizing patterns of “ramping up” of activity (e.g., Kerr, 2003). There have been a number of intriguing studies which link degassing to magmatic movements, and it is clear that the degassing behavior of a magma body is an integral part of the seismicity it generates. As not all increases in degassing or seismic strength/frequency lead to eruptions (and in fact, decreased gas fluxes may precede eruptions), there is significant value in understanding the linked behavior of the two measurements. For example, models and limited field observations indicate that, among the diverse seismic signals observed at volcanoes, long period and hybrid earthquakes are thought to be related to volcanic phenomenon involving gases. However, owing to disparities in sampling resolution, there has not been an adequate opportunity to study degassing and seismicity over long time periods for the variety of volcanically active phases. With the development of the DOAS sensor, relationships between volcanic gas emissions and earthquakes can be more directly compared and understood and therefore utilized as an additional forecasting tool.

**Montserrat Volcano Observatory (MVO)**

Soufriere Hills Volcano (SHV) is located on the island of Montserrat in the Lesser Antilles volcanic arc island chain (Figure 1). SHV is a complex of andesitic lava domes that dominate the topography of the southern third of the island, rising to an elevation of approximately 1000 meters. The current eruption of SHV began in 1995 and continues to the present (Kokelaar, 2002). Most activity consists of the extrusion of viscous, andesitic lava resulting in the formation of a large, steep-sided volcanic dome. The current dome has been building since the last major sector collapse in July 2001, which involved 45x10^6 m^3 of material. Associated activity includes frequent rockfalls, pyroclastic flows, lahars, sector collapses, degassing of volatiles (mostly H₂O, CO₂, SO₂, and HCl), and a variety of seismic events. The volcano is monitored 24 hours a day by staff at the MVO using techniques that include seismicity, deformation, SO₂ and HCl gas measurements, and visual observations (Aspinall et al., 2002).

Seismic monitoring at SHV is accomplished with both an analog and a 24-bit digital seismic network. The analog network is composed of 6 short period sensors. The digital network consists of three broadband sensors and four short period sensors. Four stations on the digital network are co-located with stations on the analog network, giving a total of nine independent seismic stations (Figure 2). All data are transmitted via UHF or VHF radio telemetry to the observatory for processing. Triggered and continuous raw data are recorded in addition to derived data including real-time seismic amplitude measurement (RSAM) and preliminary magnitudes.

Two DOAS instruments are used to measure SO₂ concentrations in the volcanic plume. The DOAS instrument is composed of an Ocean Optics S2000 spectrometer with a linear 2048-element linear CCD array. Light enters the spectrometer via a fiber optic cable and is dispersed over the CCD array by a diffraction grating. The DOAS at Montserrat is unique in that the data collection has been automated. Both spectrometers have been housed in weatherproof boxes and placed permanently in scanning positions. These positions were strategically picked based on
prevailing wind conditions (Figure 2). A 90° prism is rotated by a stepper motor and directs light via lenses and a telescope to the fiber optic cable, which subsequently transfers the light to the spectrometer. The prism steps through 360° of rotation in 0.9° increments. A spectrum is collected every 5-6 seconds. These spectra are telemetered via 24-bit UHF radio modem to the observatory for processing, allowing an SO$_2$ plume flux to be calculated approximately every 1-6 minutes (Edmonds et al., 2003a). The gas data collection periods range from 0800 to 1600 daily, with the best data typically recovered during the mid-morning and afternoon owing to optimum sunlight conditions.

Figure 1: Location of the island of Montserrat in the Lesser Antilles island arc (from Kokelaar, 2002)

Meteorological data, namely windspeeds and directions, are required for gas flux determinations. The MVO currently maintains a weather station on St. George’s Hill (Figure 2; elevation 308 m), which collects continuous measurements of wind speed, direction, relative humidity, temperature and pressure; this station was installed in September, 2002. These real-time data are telemetered to the MVO; the raw data are transformed into 1-minute averages and incorporated into the DOAS SO$_2$ flux processing.

Work Plan

Dataset description and acquisition. We have already targeted a representative dataset of an active period for Soufriere Hills volcano. During a recent period as a Visiting Scientist, Jeremy
Shannon and proposal Participants Marie Edmonds and Glenn Thompson selected the period from July 1 to August 3, 2002 as an initial study. This one-month time period is ideal for this study because seismicity remains relatively low throughout the first three weeks of July, but then increases significantly toward the end of the month. During dynamic periods, relationships between SO$_2$ degassing and seismicity may be more apparent.

![Map of Montserrat](image.png)

**Figure 2:** Map of the island of Montserrat including locations of seismic and gas monitoring instrumentation, and the two meteorological stations referred to in the text. Station locations are approximate. MVO is currently located on Mongo Hill (modified from Aspinall et al., 2002).

For this project we have begun analysis of these 34 consecutive days of DOAS data. Each day contains an average of 6000-7000 spectra, with each spectrum consisting of intensity data.
from 280-420 nm. The corresponding seismic data set consists of 1161 recorded events and were classified by MVO seismic technicians into the following categories: 811 rockfalls, 71 long period rockfalls, 54 hybrids, and 225 long period earthquakes.

Subsequent dataset acquisitions are planned, with selection periods building upon our initial correlation study. We anticipate that these will focus on periods of elevated long period earthquakes, hybrid earthquakes, and rockfalls in order to study and verify initial correlations in detail. A time series of each will also be used to examine if and how the evolving magma system affects the gas/seismic correlations.

Data processing. The SO$_2$ spectra are acquired and processed using internal software written by MVO senior volcanologist Dr. Richard Herd. Individual spectra are analyzed by subtracting a dark spectrum and a reference spectrum, and then fitting it to a laboratory-measured SO$_2$ spectrum to derive concentration path-length product (Edmonds et al., 2003a). Only the spectra that contain SO$_2$ concentrations above background levels are considered. These concentrations are then weighted based on the scan angle and plume height at the time of measurement, and then summed to obtain a plume cross-section. Multiplying the plume cross-section by the wind speed results in a plume flux (reported in kgs-1 or tonnes per day). Wind speed data for the July 2002 monitoring period were provided from the Montserrat Heliport located at Gerald's Bottom (Figure 2).

MVO uses the software package Seisan to evaluate seismic data; Seisan will also be used in this study. Spectral data for these events also exist, but not in a suitable form for comparison, and programs will be developed to reformat these data. MVO technicians classify general events as part of the routine MVO processing, which will need to be verified, with subclasses assigned as well.

Analyses. Our preliminary analyses comparing long-period (LP) earthquakes and SO$_2$ fluxes are shown in Figure 3a-c. July 19 marked the shift in seismicity resulting in an increase of LP earthquakes. These comparisons demonstrate some of the background variability in the DOAS data; with more analyses we will be able to better determine if filtering or smoothing would be beneficial (e.g., Edmonds et al., 2003a). It can be seen also that it is crucial to calibrate the timing in order to make meaningful correlations between the two phenomena. Although there appear to be some general correlations on July 19 and 20, it is clear that not every seismic trigger can be linked to a change in degassing.

We plan to initially focus the project on the basic needs in correlating gas and seismic data, followed by a shift towards science and monitoring applications: (1) identify and catalog basic features in each; (2) establish temporal calibration between the two datasets; (3) correlate the gas and seismic signals to explore the physical processes involved in magma dynamics, and (4) help MVO develop an automated system for rapidly calculating and disseminating gas flux data.

(1) The gas flux data will be catalogued with respect to noise, wind-dependence, and solar intensity dependence. Edmonds et al. (2003a) detail errors in the DOAS system and methodology, the largest of which is, as for COSPEC, a function of the uncertainty in wind speed. We will perform a rigorous evaluation of the magnitude and trend of fluctuation
Figure 3. Comparison of DOAS SO$_2$ fluxes and long-period seismic event triggers: a) July 19, 2002; b) July 20, 2002; c) July 23, 2002.
observed in the individual flux measurements (Figure 3), as a means to recognize and quantify non-volcanic influences (e.g., wind speed and direction, meteorological clouds, solar zenith angle). The variability may also be the result of “puffing” gas releases, which we can investigate through MVO’s video surveillance of the vent summit. Edmonds et al. (2003a) note periods of high background noise in the early morning and late afternoon, which can be observed in Figure 3. We will examine the magnitude of the wind speed influence through comparison of peak SO\textsubscript{2} concentrations versus wind speed throughout daily cycles. For example, when fluxes increase are they influenced by wind speed/direction, or truly a measure of increased gas concentration in the plume?

In order to compare gas flux to seismicity in a quantitative way, we need to develop a well-calibrated, easily automated magnitude scale for the SHV seismic events. Approximately 90% of events are “rockfalls” and 9% are “long-period earthquakes”. These cannot be located precisely, so an assumption about location needs to be made. Previous work by MVO has provided an estimate of the degree of attenuation for each station. For each station on the network, an independent estimate of magnitude can then be made. Outliers will be removed and a weighted mean constructed (some of the seismic stations produce more consistent and reliable data than others). To calibrate the scale, magnitude data for Montserrat events recorded by regional agencies in the Caribbean will be obtained and analysed. We will then compute magnitudes for all events in our dataset.

The seismic data will also need to be characterized with respect to the distribution of events versus magnitude. A temporal “b-value” study will be undertaken to help to constrain physical characteristics of the source process for each event type. The b-value numerically defines the relationship between earthquake frequency and magnitude. The first part of this study would be to determine if each type of event (e.g. “rockfall”, “long-period earthquake”, “hybrid earthquake” etc.) obeys a power law distribution, or an exponential distribution. To make that possible, magnitudes would have to be calculated for a long sample of the MVO event catalog (e.g. at least 1 year), in order to get a statistical robust b-value. Shorter variations in b-value could then be analysed and interpreted with respect to observed activity and models of the SHV system.

(2) We will determine the temporal relationships of the gas to seismic signals. Clearly, any gas flux measurement will represent the end result of a process which began in the subsurface. The pathway for a gas “parcel” is likely to vary, even if the geochemical process is basically the same. Therefore, we will need to establish an empirically-based calibration scale for linking the gas fluxes to seismic events. To do this we will need to identify anomalies in the gas fluxes, and compare these to the timing of event triggers in the seismic data. We anticipate that the seismic/gas correlations (see #3) can therefore be more robust. The consistency of the calibrations, or the precision of the scale will dictate to what extent we may determine lead and lag processes between magma degassing and seismicity.

(3) The time series of SO\textsubscript{2} measurements will be compared with a number of parameters derived from the seismic monitoring network. General correlations between gas fluxes and long-period and hybrid earthquakes (e.g., Young et al., 1998; Watson et al., 2000; Gardner and White,
2002; Edmonds et al., 2003a), rockfalls (Luckett et al., 2002), and deformation (Gardner and White, 2002; Watson et al., 2000) have been established. The selection of parameters is based upon these broader-based comparisons between gas fluxes and seismic activity, and our preliminary analyses. The seismic parameters we will focus on include:

a) Event type: events recorded and classified at Montserrat during July 2002 include long period, hybrid, rockfall, and long period rockfall. Here we will examine specifically which events appear to influence, or are influenced by, degassing at SHV. We will also examine event clusters, or swarms, to determine if SO$_2$ outputs change in proportion to the number of events occurring over a given time.

b) Event magnitude. We will examine relationships between earthquake magnitude and the magnitude of change observed in SO$_2$ measurements, for each event type. We will investigate whether individual seismic events can trigger a change in SO$_2$ degassing.

c) RSAM: Real-time Seismic Amplitude Measurement – this is the average seismic amplitude sampled each minute; we will examine sulfur dioxide fluxes for correlation during all seismic trigger events. Preliminary work by Edmonds et al. (2003a) show some strong, but not entirely consistent, correlations between SO$_2$ flux and RSAMs during June 2002, a relatively quiet period; during July we can examine the relationships as activity shifts towards a more active phase.

d) Peak Spectral Frequency: dominant frequency at which the peak amplitude (energy) occurs for each event (Baptie et al., 2002). We will examine changes in SO$_2$ output as a function of shifts in peak spectral frequencies. This information could help in constraining models of magma movement, and deformation processes at SHV.

e) Frequency-Magnitude Relationship: b-value; trend in the number of earthquakes vs. magnitude. Correlations between SO$_2$ and seismicity at this temporal scale may shed light on the source mechanisms of low frequency earthquakes.

(4) A final portion of our study is somewhat high risk, but with significant value if successful. The MVO has developed a web-based dissemination system (http://www.mvo.ms/), which allows a rapid broadcast (and archive) of volcanic conditions and data for both scientists and the public. Currently, the DOAS system requires operator processing time before the data can be released. As described earlier, the operator is responsible for defining a background and cloud-free portion of the spectrum to use a deconvolution method for quantifying the signal attenuation by plume SO$_2$ absorption. We believe it is possible to derive a fairly robust set of diurnal conditions based on a long-term analysis of daily spectra.

If we are able to determine adequate background conditions through long-term studies of the SHV gas fluxes, this would support the development of a simple, automated SO$_2$ “alarm” system for MVO, based on the change in peak values exceeding a prescribed threshold. While unsuitable to accurate retrieval of SO$_2$ fluxes, this would alert the MVO personnel to rapidly changing conditions, which may not otherwise be evident.
Table 1. Project Timeline

<table>
<thead>
<tr>
<th>Year 1</th>
<th>Key Tasks</th>
<th>Personnel*</th>
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|        | -Analyze gas data for background noise, diurnal and wind dependencies  
-Calibrate timing of gas fluxes to seismic signals  
-Catalog seismic data | Bluth, Edmonds, Shannon  
Bluth, Shannon  
Bluth, Shannon, Thompson  
Shannon, Thompson |
| Year 2 | -Calculate magnitudes of all trigger events (e.g., rockfall, long-period, hybrid)  
-Begin b-value magnitude/frequency study  
-Correlate SO₂ to seismic event energy, type, magnitudes, spectral frequencies | Shannon, Thompson  
Bluth, Edmonds, Shannon  
All |
| Year 3 | -Acquire new datasets for specific event-based processing  
-Continue SO₂/seismic event correlations  
-Continue b-value study  
-Develop automated gas threshold alert | Edmonds, Thompson  
All  
Shannon, Thompson  
Bluth, Edmonds, Shannon |

*in alphabetical order; these represent the main efforts by personnel but are not exclusive.

Expected Significance

Relationships between magma degassing and generation of seismicity have been inferred from studies of many different volcanic systems. As magma migrates toward the surface, temperature and pressure regimes fluctuate causing dramatic changes in the character of magma as a result of volatile and heat loss. Magma interactions with overlying hydrothermal systems also dictate the character of volcanic activity and associated hazards. Volcano monitoring, therefore, requires the collection and integration of many types of data that represent different processes in the volcanic system.

In this research, we investigate relationships between volcano seismicity and SO₂ degassing. In the past, these relationships have either been postulated from modeling, or speculated based on irregular and inconsistent field observations. The new DOAS system at Montserrat provides a drastic improvement over past SO₂ monitoring efforts. As many as 100 SO₂ measurements per day (derived from continuous gas burden spectra) can now be compared directly with continuous seismic data. The implications of this technology affect our investigations into both short-term (minutes, hours) and long term (months, years) volcanic processes.

We anticipate the following main impacts through this study:

-**Improved interpretation of magma dynamics.** Comparing SO₂ measurements with seismicity on these time scales will shed new light on magmatic movement and degassing, as well as the source mechanisms and influence of low frequency seismicity.

-**Development of a physical basis to interpret monitored seismic and gas data for SHV.** Correlations between SO₂ flux and levels of rockfalls, long-period earthquakes or hybrid
earthquake will mark a significant progression from earlier studies, allowing more accurate correlations and the ability to identify potential eruption precursors. Models of SHV’s eruption dynamics will benefit from increased understanding of these new, relatively more sensitive and continuous gas flux data.

- **Improve MVO’s monitoring capabilities.** A better understanding of the source process that generates long-period earthquakes, and hybrid earthquakes, may lead to a breakthrough in MVO’s ability to forecast activity. A tangible improvement in the MVO’s mitigation mission is the development of a magnitude scale for SHV earthquakes. The development of a simple “gas-alert” system would correspondingly add another tool for early warning of changes and potential activity at SHV.

– **Applications to other volcanic monitoring units.** Methods of rapid gas measurement, such as DOAS, will inevitably become established at other volcano observatories, as these allow vast improvements in monitoring capabilities over current COSPEC-based systems. This project will provide vital data for implementation of monitoring programs, for example with respect to optimum gas data collection, potential errors, and processing methodologies. The development of correlative data interpretation at SHV should provide a significant improvement over the standard “ramping-up” activity predictions, leading to more robust forecasting of volcanic eruptive activity.

**Relevance**

This work supports the ongoing interests of the PI and Participants by advancing their interests in the study of active volcanic systems and hazard mitigation. The work at SHV builds upon past volcanological experience in Guatemala (Bluth), Etna (Edmonds) and Alaska (Thompson). The PI has long held interests in merging geophysical datasets to explore eruptive activity, stemming from earlier studies with Dr. William Rose pioneering the use of ultraviolet and infrared satellite data to map and quantitatively retrieve ash and gas species in drifting volcanic clouds.

Soufriere Hills Volcano has been the focus of intense study since eruptive activity began in 1995. Two journal issues have been devoted to the many scientific efforts involved: 1998 in Geophysical Research Letters (Young et al., eds.), and 2002 in The Geological Society, London (Druitt and Kokelaar, eds.). Despite the strong interests in links between gas emission and seismicity, there has never been an opportunity to study these two diverse data types at compatible scales for extended time periods. Correlations between the two data sets have been restricted to field sampling, and daily measurements by field spectrometers. The DOAS system at MVO in early 2002 has generated roughly 7000 SO$_2$ cloud spectra per day since January 2002; this enormous dataset presents a unique and valuable opportunity to improve understanding of magma dynamics.

This project is in direct support of the MVO mission to mitigate volcanic hazards through improved forecasting, and will be building upon earlier work by Edmonds and Thompson and others at MVO to compare SO$_2$ emissions and seismic signatures at SHV (e.g., Edmonds et al., 2003a; 2003b).
Results of Prior NSF Support

Volcano-atmosphere interactions: the first week; Award # EAR 0106875; $259,000 from 5/01/01-4/30/03; W.I. Rose, G.J.S. Bluth and I.M. Watson.

The focus of our project has been to apply all of our current methods for satellite-based sensing of volcanic clouds to two recent eruptions, the February 2000 Hekla event and the February-March 2001 eruption of Cleveland. Advances in satellite retrievals enable us to get quantitative estimates of SO$_2$ (three different methods), ash, ice and sulfate for volcanic clouds during periods lasting from hours to days. They also allow mapping of the 2D positions of volcanic clouds and the separations of ash and SO$_2$. Tangible results from this project were four major publications: 1. A comprehensive paper in the AGU Volcanism/Climate volume about the February Hekla eruption, including results from many satellite-based volcanic cloud sensors and the research aircraft validations (Rose et al., in press). 2. A paper about MODIS results on volcanic clouds (Watson et al., in press) is completed. 3. A paper about the development of the forward model of radiative transfer of volcanic clouds is completed (Watson et al., in press) and 4. The demonstration of a new scheme for atmospheric corrections of IR ash size and mass retrievals (Yu et al., 2002) is in JGR. In addition, this project has supported the doctoral research of two students, one who studied the fallout of fine ash from earth's atmosphere (Colleen Riley, 2002) and the second (Song Guo) who is in progress doing an evaluation of remote sensing data for the 1992 Pinatubo eruption, the largest of the satellite era.

The Hekla study includes the most significant science results. A small (80,000 km$^2$) stratospheric volcanic cloud formed from the 26 February 2000 eruption of Hekla, Iceland. Three different algorithms (TOMS UV, MODIS & TOVS 7.3 micron IR and MODIS 8.6 micron IR) were used to quantitatively measure (about 0.2 Tg) and map SO$_2$, and they produced remarkably comparable data for this initial effort. The mass of sulfate aerosol in the cloud, estimated from multispectral MODIS IR data during the first 3 days was 0.003-0.008 Tg. MODIS and AVHRR remote sensing showed that the particles in the volcanic cloud were mainly ice and reached a peak mass of about 1 Tg about 10 hours after eruption, but a small (0.1 Tg) mass of ash was detected in the initial dense volcanic plume measured during the early explosive phase of the eruption. Repetitive TOVS data were used to measure the loss of SO$_2$ from the cloud which decreased from 0.2 Tg to values below TOVS detection in about 3.5 days. The stratospheric height of the volcanic plume and resulting cloud may have been explained by a large release of magmatic water vapor early during the explosive phase of the eruption beginning at 1819 UT on 26 February, which led to the ice-rich volcanic cloud. A serendipitous research aircraft encounter with the top part of the volcanic cloud at 0514 UT on 28 February, 35 hours after eruption, gave us important information to validate the various algorithms. Comparisons among different SO$_2$ algorithms during the drifting of the cloud illuminate some of the environmental variables (e.g., meteorology, underlying background, altitude, water vapor content) which affect the quality of results. Overall this is the most robust data set ever analyzed to assess the first few days of stratospheric residence of a volcanic cloud.

Geology of Utah’s National Parks and Monuments: Education Materials for Earth Science Courses. Award # 9950213; $428,131 from 7/15/99 to 6/30/03; J.E. Huntoon, G.J. Bluth, and W.A. Kennedy.

Funds are used to develop, evaluate, and disseminate three components of an introductory
earth science multimedia laboratory(\url{http://www.ehr.nsf.gov/PIRSWeb/Doc/9950213.htm}). This project is developing CD-ROM based activities that integrate the components of a field course taught in the National Parks and Monuments of southeastern Utah. The course and the CD incorporate a variety of teaching methods to communicate fundamental geologic principles and concepts (Bluth and Huntoon, 2001). The materials target lower division undergraduate students and K-12 teachers. The multimedia laboratory is designed to help university undergraduates and secondary school earth science teachers to understand information using an earth system approach. The content of the multimedia laboratory encourages problem-solving on the part of users and the ability to integrate information from a variety of sources. Quantitative and qualitative assessment vehicles, including diagnostic learning logs, pre-test/post-test attitude surveys, and an instrument to measure higher-order cognition are used by students and teachers who participate in the project to determine the materials success at teaching basic geologic concepts (Huntoon et al., 2001).

The tangible products consist of a CD-ROM "virtual" field course, extensive lesson plans, rock samples, and an instructional video covering in greater detail some of the field techniques used by students and teachers in this course. Project dissemination has included 6 publications and 7 presentations on project results. Participants in the field project have included undergraduate students, pre-service teachers, in-service teachers, minorities, and graduate students. The major research and education activities have been tested in part by the PI's during the field-based version of the course. Based on participant assessments, the material presented in this project has consistently produced a significant (>20%) increase in scores on technical skills, scientific concepts, and open-ended concepts. If this trends holds for larger sample sizes, this project would form the basis for meaningful, quantitative assessments for field-based learning. Quantitative assessments are continuing throughout this project.
References Cited


