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Tracking Pyroclastic Flows at Soufrière Hills Volcano

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Explosive volcanic eruptions typically show a huge column of ash and debris ejected into the stratosphere, crackling with lightning. Yet equally hazardous are the fast moving avalanches of hot gas and rock that can rush down the volcano's flanks at speeds approaching 280 kilometers per hour. Called pyroclastic flows, these surges can reach temperatures of 400°C. Fast currents and hot temperatures can quickly overwhelm communities living in the shadow of volcanoes, such as what happened to Pompeii and Herculaneum after the 79 C.E. eruption of Italy's Mount Vesuvius or to Saint-Pierre after Martinique's Mount Pelée erupted in 1902.

The ability to detect volcanic explosions and track pyroclastic flows in a timely fashion is crucial to volcano monitoring operations and can positively affect risk management on many volcanoes, particularly those where collapsing lava domes tend to trigger pyroclastic flows.

Increasingly, monitoring active explosive volcanoes involves studying infrasound. Infrasound is the low-frequency component of sound, ranging from 0.001 to about 20 hertz, below the human threshold of hearing. Many natural phenomena such as earthquakes, avalanches, landslides, tornadoes, and tsunamis are efficient sources of infrasound. Volcanoes are especially prolific infrasonic radiators: On active explosive volcanoes, volumetric sources rapidly expanding in the atmosphere produce infrasound, providing valuable insights into eruption dynamics. In particular, volcanoes characterized by lava dome growth exhibit infrasound generated by nonexplosive sources related to dome collapses, such as pyroclastic flows [*Yamasato,* 1997], rockfalls [*Moran et al.,* 2008], and lahars. Such acoustic monitoring is fast becoming a standard technique on active volcanoes worldwide because of its potential to rapidly assess eruptive activity.

By M. Ripepe, S. De Angelis, G. Lacanna, P. Poggi, C. Williams, E. Marchetti, D. Delle Donne, and G. Ulivieri

The Soufrière Hills volcano (SHV), on the West Indies island of Montserrat, represents one of the best examples of a hazardous volcano that can be readily monitored through infrasonic studies. After several centuries of quiescence, SHV explosively erupted in 1995 and has since followed a characteristic cycle of dome growth and collapse activity accompanied by explosions and pyroclastic flows [*Young et al.,* 1998].

Large domes and kilometers-high explosive columns have collapsed multiple times, generating large and devastating pyroclastic density currents that thus far have killed 19 people, destroyed the capital city of Plymouth, overrun its airport, forced its total evacuation, and prompted more than half of the island's population to leave. At present, a lava dome with a volume of about 200 million cubic meters stands at the summit of SHV [*Scientific Advisory Committee,* 2008].

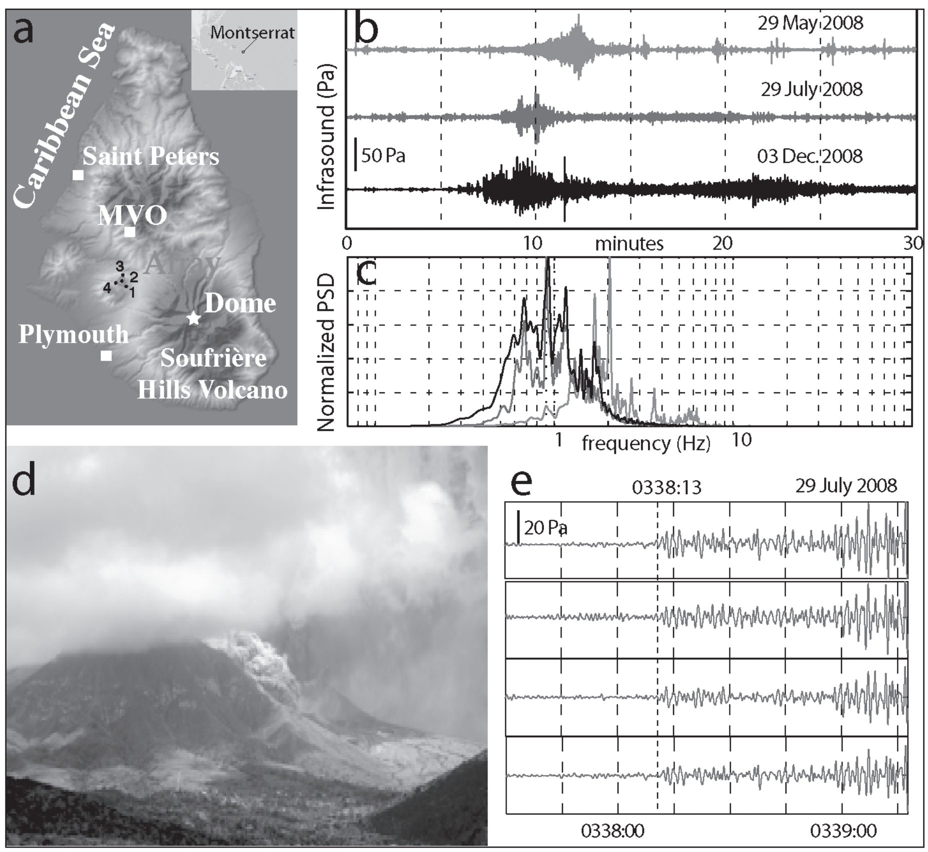

Fig. 1. (a) Location of the array on Montserrat and its proximity to the cities of Saint Peters and Plymouth as well as to the lava dome on Soufrière Hills volcano. (b) Infrasound, measured in pascals (Pa), associated with Vulcanian eruption and pyroclastic flows on 29 May 2008 (red line), 29 July 2008 (blue line), and 3 December 2008 (black line). (c) Power spectral density (PSD) of infrasonic waveform associated with pyroclastic flow events on 29 May 2008 (red curve), 29 July 2008 (blue curve), and 3 December 2008 (black curve). The infrasound generated by the large flows in July and December 2008 peaked at 0.9 hertz. The smaller event in May peaked at 2 hertz. (d) Pyroclastic flow observed from Montserrat Volcano Observatory (MVO) on the western side of SHV on 13 May 2008. Image courtesy of MVO. (e) Infrasound of 29 July starts with a clear onset and coherent signals across the array microphones. Original color image appears at the back of this volume.

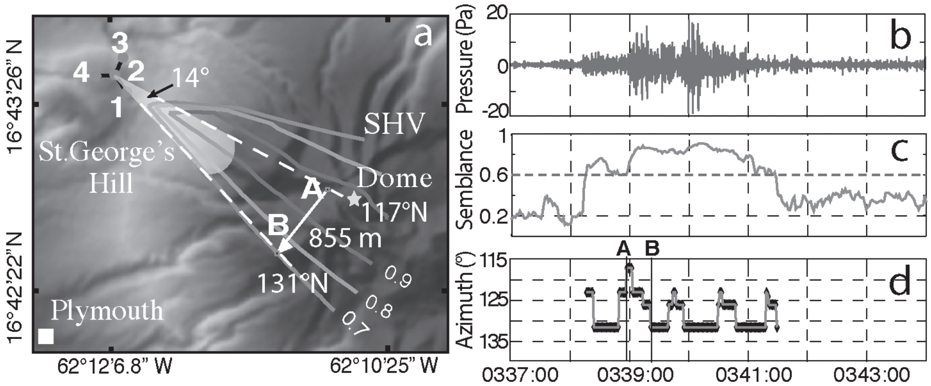

Fig. 2. (a) Map showing the position of the array on Saint George's Hill and tracking of the pyroclastic flow on 29 July 2008 by real-time array location. The plot shows that the direction to the infrasonic source changed with time, shifting an angle of 14° from A (117° from north) to B (131° from north) with respect to the array as a result of the movement of the flow toward the south-southeast. Contour lines (0.9, 0.8, and 0.7) represent the distribution of the semblance indicating the direction from where sound is propagating (back-azimuth). (b) Infrasonic signal, measured in pascals (Pa), associated with the flow propagation as recorded at sensor 2 of the array. (c) Distribution of multichannel semblance as a function of shifting direction (back-azimuth) and time. The blue dashed line indicates the threshold used to localize the source. (d) Repeated variations of the changing angle (azimuth) of the infrasonic signals during the main flow phase, showing clear pulses in flow along the volcano's flanks. Locations A and B are marked for reference. Original color image appears at the back of this volume.

It is capable of collapsing and exploding at any time.

To help provide adequate warning of volcanic hazards, the monitoring system at SHV was recently enhanced with the installation of a permanent small-aperture infrasonic array less than 3 kilometers away from the lava dome. This array has already proved its ability to detect explosive eruptions and track pyroclastic flows in real time, improving the efficiency of the response of the Montserrat Volcano Observatory (MVO) during eruption crises and providing useful data that will help to constrain theoretical models aimed at unraveling the complex dynamics of pyroclastic flow propagation.

Volcano Monitoring by Infrasonic Array

Volcano acoustic studies, to date, have dealt mostly with analyzing different types of volcanic explosions, including those where ash jets high into the atmosphere (Plinian and sub-Plinian eruptions), those where lava and ash fountain to modest altitudes (Strombolian eruptions), and those where lava fragments are ejected in frequent cannon-like bursts due to the presence of water in the magma chamber (Vulcanian eruptions). Infrasonic arrays at regional distances have also been used to detect and track atmospheric injection of volcanic ash [*Garcés et al.,* 2007].

Little is known about the infrasonic wavefield associated with the emplacement of pyroclastic flows and other density currents (such as avalanches and landslides), all of which are characterized by nonstationary, extended infrasonic sources that introduce a high level of complexity in data processing schemes and theoretical modeling.

The infrasonic array on Montserrat represents the first effort to tackle data processing issues by using state-of-the-art technology to monitor and track pyroclastic flows in real time. The infrasonic array was installed at a distance of about 3 kilometers from the active lava dome on SHV, at the Saint George's Hill site (Figure 1a). The full deployment of the array required 4 days of work by a team of five people. The array, with a total installation cost similar to that of two digital broadband seismic stations, has an aperture of 200 meters and a "star" geometry of three satellite sensors located 100 meters from a central station that includes two additional absolute pressure sensors along with the array receiver unit.

Each of the satellite sensors is linked to the receiver unit by fiber-optic cables. The use of fiber-optic technology provides optimal signal-to-noise ratio (SNR) and ensures network integrity against atmospheric agents such as lightning. Strong winds, blowing mainly from east to west, introduce large noise contamination to signals. These were reduced by burying the sensors 1 meter underground. A gooseneck pipe, open at both ends, provides coupling of the infrasonic sensors to the atmosphere.

Each satellite element of the array is equipped with a sensitive infrasonic microphone as well as temperature and voltage sensors. The high-resolution data acquired are sent, via radio modem, to the MVO offices where they are processed in real time and archived. The array works as a sonic antenna detecting small-amplitude pressure waves and providing the direction (back-azimuth) from which the sound emanates (Figure 2a).

The source position of infrasonic signals is resolved by use of a grid search algorithm that calculates the statistical correlation (semblance) between predicted and observed time delays across the array (Figure 2c). On other volcanoes characterized by explosive degassing (e.g., Italy's Stromboli and Etna, Vanuatu's Yasur, and Chile's Villarica), this location procedure has proved to be able to detect in real time up to several million infrasonic events per year [*Ripepe et al.,* 2007]. On Montserrat, this technique has been adapted to detect and track pyroclastic density currents in a real-time fashion.

Infrasound of Pyroclastic Flow Activity

Beginning in May 2008, SHV has produced small to intermediate explosions accompanied by the emplacement of pyroclastic flows that descended the western flanks of the volcanic edifice (Figure 1d).

The SHV infrasonic array recorded clear signals lasting about 400–1500 seconds (Figure 1b) associated with the explosions and the propagation of pyroclastic fronts. Coherent infrasound across the array (Figure 1e) generally started with an impulsive onset and reached peak amplitudes of 20–30 pascals during the most vigorous phase of the event. The infrasound recorded at SHV is relatively broadband (0.4–7 hertz); the frequency of the dominant spectral peak scaled inversely to the size of the flow (Figure 2c), reflecting variable propagation dynamics and grain composition of the density currents.

One of the most remarkable events occurred at 0338:13 UTC on 29 July 2008, when a large Vulcanian eruption produced a 12-kilometer-high ash column and set off significant pyroclastic activity on the western flanks of the volcano. Tracing back the infrasonic signals identified an initial source located on the western sector of the summit lava dome (Figure 2a).

The most energetic phase of the flow was characterized by several rapid changes in the direction of infrasound propagation (Figure 2d), indicating that the pyroclastic front was moving away from the dome, toward the south-southwest, in the direction of Plymouth (Figure 2a). Analysis of the changing source of infrasonic signals shows that the flow traveled 855 meters in 24 seconds—a rate of roughly 35 meters per second.

Variations to infrasound were observed multiple times (Figure 2d) during the high-amplitude infrasonic phase, reflecting distinct pulses in flow activity. The estimated speed of each flow ranged between 35 and 75 meters per second, in good agreement with previous measurements of pyroclastic flows calculated at Japan's Unzen volcano [*Yamasato,* 1997].

The Potential of Infrasound

For many years, real-time monitoring of the activity at SHV has been based solely on the interpretation of seismic records and visual observations. Visual observations during the night are limited; the huge gas and ash columns towering above the edifice during large Vulcanian explosions and the hazardous pyroclastic flows running from the summit along the flanks of the volcano are not visible to the human eye. Thus, infrasonic monitoring at SHV has proven its great value, especially during severe weather conditions when visual observations were precluded and alternative means for identifying the onset of an eruption were limited, as during the 29 July 2008 eruption.

The use of infrasound technology has positively influenced monitoring operations at MVO, allowing scientists to be able to make more informed decisions during eruptive crises. Thus far, flows have run in the direction of Plymouth, now a ghost town. But pyroclastic flows could run northeast toward inhabited villages—in such a case, quick detection and a precise monitoring system will allow MVO researchers to resolve some ambiguities in the assessment of the eruptive activity.

Local infrasound monitoring exhibits a great potential for integration with other geophysical measurements, particularly seismic, and may assist with their interpretation by yielding information on the mechanisms of eruptions and the propagation of density currents [*Moran et al.,* 2008]. Its continued use can yield important dividends in the assessment of volcano-related hazards and the management of civil protection operations on Montserrat, as well as at other volcanoes worldwide.

Acknowledgments

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References

Garcés, M., D. Fee, D. McCormack, R. Servranckx, H. Bass, C. Hetzer, M. Hedlin, R. Matoza, and H. Yepes (2007), Prototype ASHE volcano monitoring system captures the acoustic fingerprint of stratospheric ash injection, *Inframatics, 17,* 1–6.

Moran, S. C., R. S. Matoza, M. A. Garcés, M. A. H. Hedlin, D. Bowers, W. E. Scott, D. R. Sherrod, and J. W. Wallace (2008), Seismic and acoustic recordings of an unusually large rockfall at Mount St. Helens, Washington, *Geophys. Res. Lett., 35,* L19302, doi:10.1029/2008GL035176.

Ripepe, M., E. Marchetti, and G. Ulivieri (2007), Infrasonic monitoring at Stromboli volcano during the 2003 effusive eruption: Insights on the explosive and degassing process of an open conduit system, *J. Geophys. Res., 112,* B09207, doi:10.1029/2006JB004613.

Scientific Advisory Committee (2008), Assessment of the hazards and risks associated with the Soufriere Hills volcano, Montserrat: Tenth report of the Scientific Advisory Committee on Montserrat volcanic activity—Part I: Main report, 19 pp., Montserrat Volcano Obs., Flemmings, Montserrat. (Available at http://www.montserratvolcanoobservatory.info/)

Yamasato, H. (1997), Quantitative analysis of pyroclastic flows using infrasonic and seismic data at Unzen volcano, Japan, *J. Phys. Earth, 45,* 397–416.

Young, S. R., R. S. J. Sparks, W. P. Aspinall, L. L. Lynch, A. D. Miller, R. E. A. Robertson, and J. B. Shepherd (1998), Overview of the eruption of Soufrière Hills volcano, Montserrat, 18 July 1995 to December 1997, *Geophys. Res. Lett., 25*(18), 3389–3392.

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A Global Ground-Based Magnetometer Initiative

eGY
Electronic Geophysical Year

PAGES 230–231

With the motto “Knowledge is the common wealth of humanity,” the 2007–2008 Electronic Geophysical Year (eGY) advocated that scientists have the responsibility to create and implement strategies that utilize the full potential of digital capabilities in providing information for present and future generations.

Although eGY has officially ended, the geomagnetic research community continues to support the goals of eGY through a global ground-based magnetometer initiative. This initiative, called SuperMAG, helps scientists have easy access to measurements of the Earth’s magnetic field.

What Is SuperMAG?

SuperMAG is a worldwide collaboration of organizations and national agencies that currently operate more than 200 ground-based magnetometers. It provides measurements of magnetic field perturbations from all available stations in the same coordinate system, with identical time resolution and a common baseline removal approach.

SuperMAG utilizes vector measurements of the magnetic field, which represent a variety of file formats, temporal resolutions, units, and coordinate systems, and are provided with or without baseline subtracted. SuperMAG resamples the raw data to 1-minute temporal resolution and converts all units into nanoteslas (nT). Artifacts and errors are removed by automated as well as manual correction routines. Data are then rotated into a local geomagnetic coordinate system, and finally the baseline is subtracted by an automated technique.

Why Is SuperMAG Needed?

Before SuperMAG, global or even local studies required painstaking and labor-intensive data handling, which effectively limited research. Analysts faced several inherent complications: confusing or even unknown coordinate systems, a multitude of data artifacts and errors, unknown baselines, and even difficulties obtaining data. These problems have resulted in a serious underutilization of data from magnetometers. Now the collected and processed high-quality ground-based magnetic field data provide an easier way to globally study magnetic data.

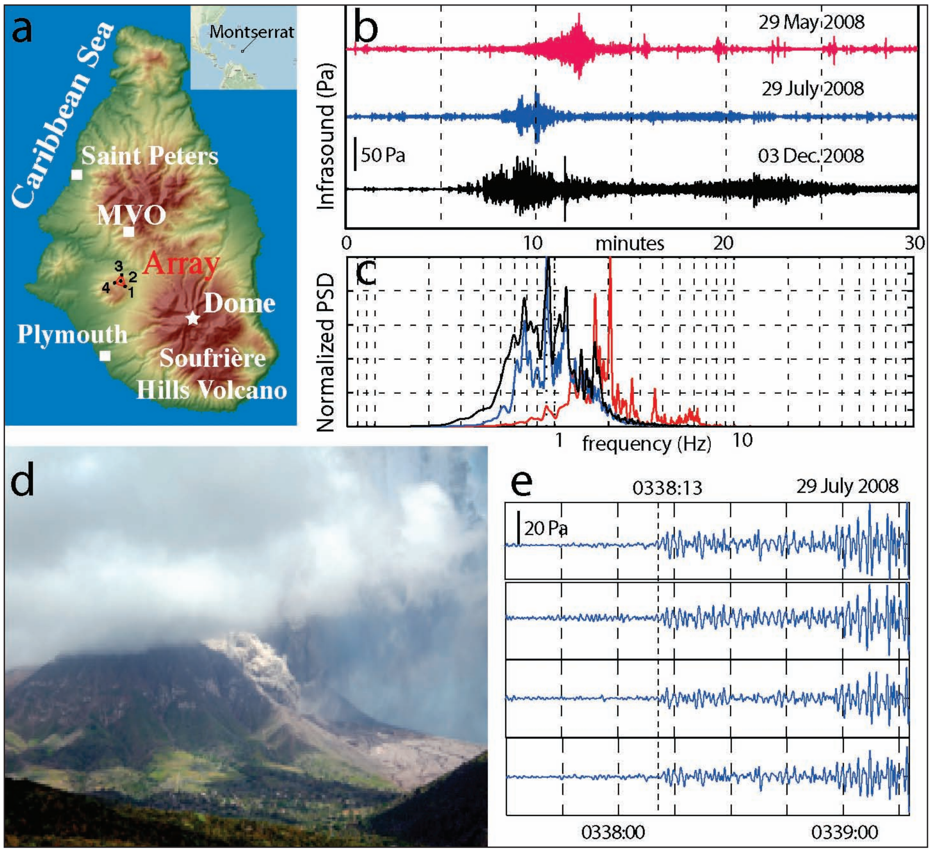
SuperMAG offers the unique opportunity to address the global spatiotemporal behavior of the large-scale ionospheric electric current system and its coupling to the magnetosphere. Studies of the variations caused by electric currents flowing in the ionosphere and magnetosphere require a subtraction of the dominant and slowly varying Earth main field. Hence, both absolute and variometer data (data with unknown baselines) are included in SuperMAG.

SuperMAG is intended to be a collaboration of all organizations operating ground-based magnetometer stations. Users must register with the SuperMAG site (http://supermag.jhuapl.edu/) to have access to a variety of data plots and products. As an added and much needed benefit, the registration system incorporates a logging system that allows the usage statistics of individual users to be tracked, providing principal investigators with the feedback needed to justify future funding from their respective supporting agencies.

Reaching Beyond Scientists

Beyond the research community, SuperMAG targets the general public, in particular, teachers and students. This puts additional requirements on the site because these groups cannot be assumed to have extensive knowledge of either the data set or the underlying physics. Consequently, the SuperMAG’s Web service is based on an intuitive interface with easily accessible tools and products.

This is in line with the eGY declaration that states, “providing ready and open access to the vast and growing collections of cross-disciplinary digital information is the key to understanding and responding to complex Earth system phenomena that influence human survival” [see *Baker et al.,* 2008]. Although humankind is likely



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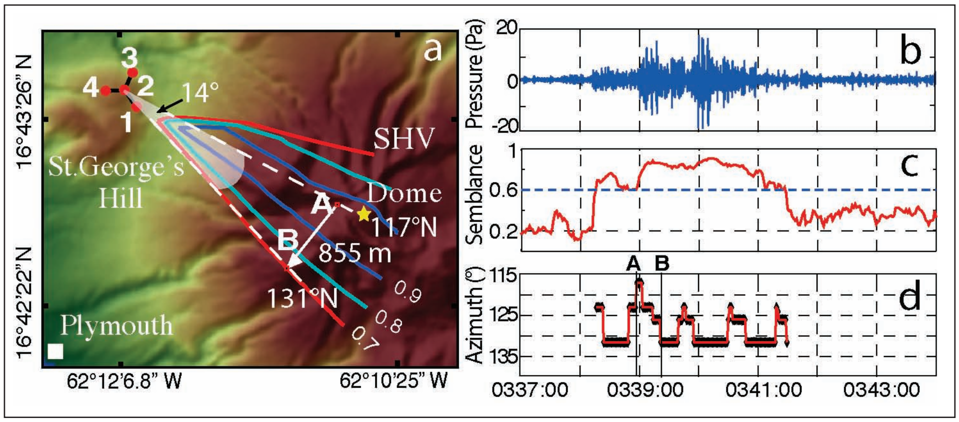

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