This document is downloaded from DR-NTU (https://dr.ntu.edu.sg)
Nanyang Technological University, Singapore.

Active source seismic experiment peers under Soufrière hills volcano

Mattioli, Glen.; Voight, Barry.; Sparks, R. S. J.; Shalev, E.; Malin, P.; Kenedi, C.; Minshull, T. A.; Paulatto, M.; Hammond, J.; Hidayat, Dannie.; Widiwijayanti, Christina.

2010

Voight, B., Sparks, R. S. J., Shalev, E., Malin, P., Kenedi, C., Minshull, T. A., et al. (2010). Active source seismic experiment peers under Soufrière Hills Volcano. Eos, Transactions American Geophysical Union, 91(28), 245-247.

https://hdl.handle.net/10356/94953

https://doi.org/10.1029/2010EO280002

© 2010 American Geophysical Union (AGU). This paper was published in Eos, Transactions American Geophysical Union and is made available as an electronic reprint (preprint) with permission of (AGU). The paper can be found at the following official DOI: [http://dx.doi.org/10.1029/2010EO280002]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 27 Nov 2020 06:13:49 SGT

Active Source Seismic Experiment Peers Under Soufrière Hills Volcano

PAGES 245–247

Characterizing internal structures of active volcanoes remains an enigmatic issue in geosciences. Yet studies of such structures can greatly improve hazard assessments, helping scientists to better monitor seismic signatures, geodetic deformation, and gas emissions, data that can be used to improve models and forecasts of future eruptions.

Several passive seismic tomography experiments—which use travel times of seismic waves from natural earthquakes to image underground structures—have been conducted at active volcanoes (Hawaii's Kilauea, Washington's Mount St. Helens, Italy's Etna, and Japan's Unzen), but an inhomogeneous distribution of earthquakes compromises resolution. Further, if volcanic earthquakes are dominantly shallow at a given location, passive methods are limited to studying only shallow features. Thus, active source experiments—where seismic waves from the explosion of deliberately set charges are used to image below the surface—hold great potential to illuminate structures not readily seen through passive measures.

On the West Indies island of Montserrat, volcanic earthquakes are typically shallower than 4 kilometers deep. To get the deeper data needed to three-dimensionally (3-D) image the volcano's plumbing system, an active source seismic experiment, called the Seismic Experiment with Air-gun source of the Caribbean Andesitic Lava Island Precision Seismo-geodetic Observatory (SEA-CALIPSO) [see *Mattioli et al.*, 2004], was carried out in December 2007 (see Figure 1).

Before this experiment, knowledge of the deep structure of Montserrat and its signature volcanic center, the Soufrière Hills volcano, was limited, with proposed models based on restricted geophysical, geological, and petrological data. Now analysis of data from SEA-CALIPSO has generated high-resolution images of Montserrat's structure, volcanic edifices, and adjacent crust. These images will advance scientists' understanding of crustal evolution in arc systems, magma storage and transport systems, and volcanic processes.

Montserrat's Volcanic Complexes

Three centers of volcanism have been previously identified on Montserrat, with nonoverlapping volcanic activity: Silver Hills (active around 2600–1200 thousand years ago), Centre Hills (active around 950–550 thousand years ago), and Soufrière Hills–South Soufrière Hills (active for the past 170 thousand years). Each complex is about 6 kilometers south of its neighbor, suggesting migration rates of 5–9 kilometers every million years.

The Soufrière Hills volcano is the only currently active volcanic center on Montserrat. Noneruptive volcano-seismic swarms at Soufrière Hills occurred about every 30 years in the late nineteenth and the twentieth centuries, but with the exception of a minor seventeenth-century lava effusion, no historical eruptions were recorded on Montserrat prior to the 1990s.

In 1995, small to moderate steam and ash eruptions began in July and were followed by lava dome growth and sporadic pumiceous explosions. By 1997, pyroclastic flows had forced the evacuation of the southern two thirds of Montserrat and had decisively destroyed the capital city of Plymouth, the seaport, and the airport, causing collapse of the island's economy. Plymouth currently is buried and abandoned.

Since 1995, one cubic kilometer of lava has erupted. Twenty-one people and innumerable animals have been killed, and more than 60% of the population has left. The eruption remains dangerous: A lava dome collapse in February 2010 of 40–50 million cubic meters produced large pyroclastic flows and added a square kilometer of new land to the eastern coastline.

The current eruption has been studied in detail [*Druitt and Kokelaar*, 2002], but knowledge of deep structure is scarce and elements of the magmatic system under Soufrière Hills are imprecisely determined. For example, the magma reservoir top has been estimated at about 5 kilometers deep on the basis of mineral assemblages, melt inclusion data, and deepest earthquakes near the conduit. However, recent data from global positioning systems suggest that a much deeper reservoir is exerting pressure, causing the surface to deform [*Mattioli et al.*, 2010].

The rock erupting at Soufrière Hills is a crystal-rich andesite, typically derived from intrusion and fractional crystallization of basaltic magma deep in the crust. Because the chemical composition of the crust changes when andesite is added, a record of altered crust should exist under the volcanic centers with properties different from adjacent basaltic crust and detectable by seismic tomography.

The SEA-CALIPSO Active Source Experiment

The SEA-CALIPSO experiment involved installing a land array consisting of 28 three-component seismometers (Reftek model RT130) and 209 one-component "Texan" seismometers (Reftek model RT125A), and an array of 10 ocean bottom seismometers (OBSs), which together recorded continuously at 250 or 100 samples per second. Montserrat Volcano Observatory seismometers (nine units) were also used. Signals were generated by an eight-air-gun array towed at a depth of 10 meters by the RRS *James Cook*. A total of 4413 shots were fired at a pressure of 2000 pounds per square inch every 60 seconds (roughly every 140 meters) along circular and radial ship tracks (Figure 1). Shots were also recorded on a 600-meter, 48-channel digital streamer.

First-arrival tomographic inversions over the 47- × 54-kilometer target area used subsets of 58–66 stations with approximately even spacing. Data from as many as 180,000 raypaths were used in damped smoothed inversions to produce 2-D and 3-D images of the *P* wave seismic velocity [*Paulatto et al.*, 2010a, 2010b; *Shalev et al.*, 2010]. A preliminary 2-D inversion of a subset of data using first arrivals and wide-angle reflections reveals a heterogeneous high-velocity body underneath the island (Figure 1b), representing the cores of volcanoes and subjacent intrusions. An interface at about 2 kilometers in depth is interpreted as the paleoseafloor, depressed under the island from volcanic loading.

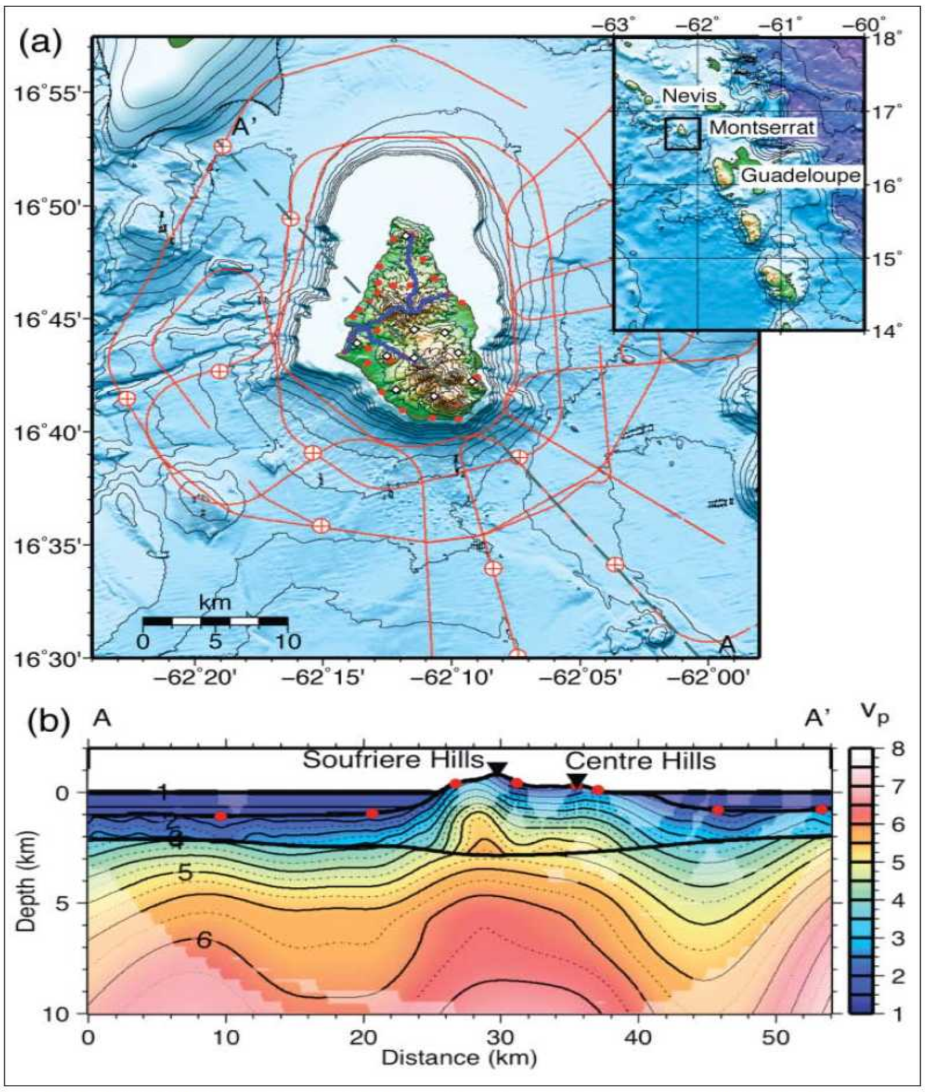

Fig. 1. (a) SEA-CALIPSO ship tracks (red curves) and ocean bottom seismometer locations (red quartered circles) near Montserrat. RefTek RT130 seismometers (red dots), RefTek RT125A seismometers (blue dots), and Montserrat Volcano Observatory seismometers (white diamonds) are also shown. From the data collected through SEA-CALIPSO, a tomographic section was constructed from A-A'. Regional setting is seen in the inset. (b) The two-dimensional P *wave velocity cross section from A-A'* [Paulatto et al., *2010a], measured in kilometers per second. Red dots are the stations used in the inversion. Triangles mark summits of volcanic centers. The pale region not covered by raypaths was calculated through a final inversion calculation.*

Better constrained 3-D inversions show that high-velocity cores, interpreted as crystallized intrusions, underlie the two extinct volcanic centers to depths of at least 8 kilometers but extend only to about 5 kilometers under Soufrière Hills. A low-velocity zone underlies Soufrière Hills at depths between about 5 and 10 kilometers and is interpreted as a reservoir of partly crystallized magma that feeds the current eruption. Two shallow areas of low velocity in the northeast and southwest flanks of the island reflect volcaniclastic deposits and hydrothermal alteration.

The inversions based on active source data were extended to 25 kilometers in depth with lesser precision using teleseismic data. Receiver function studies define the Mohorovičić discontinuity (the boundary between the crust and the mantle) at about 30 kilometers in depth at this location [*Sevilla et al.*, 2010]. Offshore reflection profile lines reveal deep wedges of volcaniclastic debris and important tectonic details that illuminate the intimate connection between tectonics, volcanism, and sedimentation in volcanic arcs.

From Deep Structures to Deeper Insight

The SEA-CALIPSO study is a rare active source tomographic experiment of a hazardous andesitic island stratovolcano, and the first to present a detailed image of an island arc volcano in the Lesser Antilles. Initial and future results will help scientists understand volcanism at Montserrat and provide insights on how regions of intermediate composition are developed within primarily basaltic crust at interoceanic arcs. This research enables comparisons of the Lesser Antilles arc with the Marianas, Izu-Bonin, and Aleutian arcs and provides constraints for dynamic models of magma flow and explosive volcanism that can apply to subduction arc volcanoes worldwide.

A new special section of *Geophysical Research Letters,* titled "SEA-CALIPSO Arc

Volcano Imaging on Montserrat," focuses on this project, its setting in the West Indies, and the ongoing eruption of Soufrière Hills volcano (see http://www.agu.org/journals/gl/special_sections.shtml?collectionCode=CALIPSO2&journalCode=GL).

Acknowledgments

Funding was provided by U.S. National Science Foundation (NSF), National Environmental Research Council (NERC), Discovery TV, British Geological Survey, and British Foreign and Commonwealth Office. We thank R. Reichlin, L. Johnson, R. Kelz, S. Esperanca, and A. Shor at NSF; H. Beadman at NERC; Marine Services staff under C. Day; the RRS *James Cook* crew under P. Gauld; the GeoPro air gun team; the Scripps team; J. Fowler, B. Beaudoin, and M. Fort at Incorporated Research Institutions for Seismology PASSCAL Instrument Center; V. Hards and M. Strutt at Montserrat Volcano Observatory; our research colleagues C. Ammon, L. Brown, A. Clarke, D. Elsworth, A. Linde, S. Sacks, and C. McClintock; and the many people who worked hard on land and aboard ship to collect data during December 2007.

References

Druitt, T., and B. Kokelaar (Eds.) (2002), *The Eruption of Soufrière Hills Volcano, Montserrat, From 1995 to 1999*, *Geol. Soc. Mem.*, vol. 21, 645 pp., Geol. Soc., London.

Mattioli, G., et al. (2004), Prototype PBO instrumentation of CALIPSO project captures world-record lava dome collapse on Montserrat, *Eos Trans. AGU, 85*(34), 317, doi:10.1029/2004EO340001.

Mattioli, G., R. A. Herd, M. H. Strutt, G. Ryan, C. Widiwijayanti, and B. Voight (2010), Long-term surface deformation of Soufrière Hills volcano, Montserrat from GPS geodesy: Inferences from simple elastic inverse models, *Geophys. Res. Lett.*, *37*, L00E13, doi:10.1029/2009GL042268.

Paulatto, M., et al. (2010a), Upper crustal structure of an active volcano from refraction/reflection tomography, Montserrat, Lesser Antilles, *Geophys. J. Int.*, *180*, 685–696, doi:10.1111/j.1365-246X.2009.04445.x.

Paulatto, M., et al. (2010b), Probing the interior of an active volcano: 3D seismic tomography at Montserrat, paper presented at New Advances in Geophysics Meeting 2010: Magma Emplacement and Storage in the Earth's Crust, Br. Geophys. Assoc., London.

Sevilla, W. I., C. J. Ammon, B. Voight, and S. De Angelis (2010), Crustal structure beneath the Montserrat region of the Lesser Antilles island arc, *Geochem. Geophys. Geosyst.*, *11*, Q06013, doi:10.1029/2010GC003048.

Shalev, E., et al. (2010), Three-dimensional seismic velocity tomography at Montserrat from the SEA-CALIPSO offshore/onshore experiment, *Geophys. Res. Lett., 37,* L00E17, doi:10.1029/2010GL042498.

—BARRY VOIGHT, Pennsylvania State University, University Park; E-mail: voight@ems.psu.edu; R. S. J. SPARKS and J. HAMMOND, University of Bristol, Bristol, UK; E. SHALEV, P. MALIN, and C. KENEDI, Institute of Earth Science and Engineering, University of Auckland, Auckland, New Zealand; T. A. MINSHULL and M. PAULATTO, University of Southampton, Southampton, UK; G. MATTIOLI, University of Arkansas, Fayetteville; and D. HIDAYAT and C. WIDIWIJAYANTI, Earth Observatory of Singapore, Singapore