CALIPSO Project on Soufrière Hills Volcano, Montserrat: Prototype PBO Instrumentation Package Installed, and Operational Capture of World-Record Lava Dome Collapse during July 2003

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We present here an update to the volcano geophysics community on the status of an innovative new project designed to enhance generally our understanding of andesitic volcano eruption dynamics, and specifically, the monitoring and scientific infrastructure at the active Soufrière Hills Volcano (SHV), Montserrat. The project has been designated as the **C**aribbean **A**ndesite **L**ava **I**sland **P**recision **S**eismo-geodetic **O**bservatory, with the acronym ***CALIPSO***, and its purpose is to investigate the dynamics of the entire SHV magmatic system using an integrated array of specialized instruments in four strategically located ~200-m-deep boreholes in concert with several shallower holes and surface sites. The project is unique, as it represents the first, and only, such borehole volcano-monitoring array deployed at an andesitic stratovolcano. *CALIPSO* is a collaborative project involving PIs from Carnegie Institution of Washington (CIW), Duke University, Penn State University (PSU), University of Arkansas (UARK), working together with the Montserrat Volcano Observatory (MVO) and UK colleagues from University of Bristol and University of Leeds. *CALIPSO* is jointly funded by NSF (United States) and NERC (United Kingdom). The combined budget includes \$2.0M from NSF and \$190K from NERC, with additional *in-kind* contributions from the Government of Montserrat (GoM). Prof. B. Voight of Penn State is Project Director (Voight et al., 2003). The project has been launched with a successful and important start, with its capture of the tremendous SHV lava dome collapse of 12-13 July 2003, involving about 120 million cubic meters--the largest lava dome collapse worldwide in the historical record. 'Before and after' collapse photographs of the SHV lava dome are shown in Figure 1a & b.

The complex andesitic SHV occupies the southern third of the island of Montserrat, part of the Lesser Antilles island arc. The summit area consists of a lava dome complex that overspilled the English's Crater, a 1-km-wide crater breached widely to the east, and which before 1995 was occupied by the ~400 year old dome of Castle Peak. Non-eruptive seismic swarms occurred at ~30-year intervals in the late 19th and 20th century. The first historical (and current) eruption began in July 1995, characterized by dome collapses and sub-plinian or (more commonly) vulcanian pumiceous explosive eruptions, which have generated pyroclastic flows and surges, some of which have proved lethal to the island inhabitants. The pyroclastic flows, associated rain-torrent debris flows reworking the flow deposits, and ash health hazards forced the evacuation of the southern half of the island, and ultimately destroyed the capital of Plymouth. Almost two-thirds of the original population has left and disaster-management efforts have been challenging. Montserratians have suffered through multiple evacuations and displacements from their homes, with the last incremental evacuation carried out between October 2001 and August 2003 (Dunkley et al., 2003). The hazards that existed during this period markedly influenced the *CALIPSO* installation work.

The sensor package at each *CALIPSO* site includes: a single-component, very broad-band Sacks-Evertson dilatometer, a three-component seismometer designed by Duke/CIW (~Hz to 1 kHz), a Pinnacle Technologies series-5000 tiltmeter, and a surface Ashtech u-Z CGPS station with choke ring antenna, SCIGN mount and tall radome. The distribution of the new CALIPSO sites, along with a satellite image showing the integrated effects of the ongoing eruption are shown in Figure 2. The borehole observatory is being seamlessly integrated into the surface monitoring (seismic, geodetic, gas) networks of the MVO, and will be used to track in near real time the processes occurring in and about the magma reservoir and its associated conduit system.

The SHV system has been active and dynamic since July 1995 (Young et al., 1998 and Kokelaar, 2002), erupting ~0.5 km^3 of andesitic lava to date, culminating with the most recent and largest single eruptive event on July 12-13, 2003. The system is relatively quiet now, similar to the 20-month hiatus of little surface activity of 1998-1999 (Norton et al., 2002). With continued high levels of gas emission, however, the magmatic system remains active, and a new swarm of low frequency seismic events seismicity is being detected as this is written. It is possible that dome growth may resume at a future date. Indeed, cyclic activity at a variety of timescales has been a feature of SHV volcanism, involving seismicity, ground deformation, dome activity and gas exhalation, at the ~10 hour time scale (Voight et al., 1998, 1999). Evidence also exists for 7 and/or 14-week cycles (Voight et al., 1999; Sparks and Young, 2002), and some longer cycles (Mattioli et al., 2002, Mattioli and Herd, 2003), and the SHV eruption since 1995 is the fourth documented repetition of a 30 year cycle (Young et al, 1998). The longer time scale cycles likely originate from the deeper magmatic plumbing system giving rise to intrusions of mafic magma. The new *CALIPSO* borehole instrumentation provides much reduced noise and the ability to locate effective stations farther from the volcano than possible with surface instruments, and both features aid the sampling of seismic and deformation signals from the deep transport, storage, and recharge systems.

CALIPSO may be considered as a prototype for planned **P**late **B**oundary **O**bservatory (*PBO*) installations at several volcanic targets in the western US. Scientific objectives of the The *EarthScope* Integrated Science Plan (*ES-ISP*) relevant to magmatic systems are to investigate: 1) melt generation in the mantle; 2) melt migration from the mantle to and through the crust to the surface; 3) melt residence times at various deep reservoirs; and 4) delineation of characteristic patterns of surface deformation and seismicity, which may prove useful in eruption forecasting. The *CALIPSO* project shares most of the same scientific goals, and has moreover the benefit of a rich existing geophysical context in its deployment at SHV. Our experience during instrument design, planning, drilling and installation, systems integration, and early operation of *CALIPSO*, moreover, may prove valuable to *EarthScope* and *PBO* managers. In particular, costs associated with drilling and installation considerably exceeded the contractor's estimates, despite relative ease of drill-rig access and excellent weather during drilling operations; similarly, we under-appreciated the need for substantial software development to facilitate straightforward and complete integration of instrument package command and control on a single computing platform, remote data acquisition, and long-term data archiving.

DOSECC[1], Inc., a non-profit scientific drilling consortium, was contracted by *CALIPSO* to undertake all drilling operations on Montserrat. Drilling commenced in late November 2002 and continued through early March 2003, with all US senior staff participating in guidance and support of drill operations. A newly acquired CS-500, man-portable, diamond-coring drill rig was selected for *CALIPSO* by DOSECC. This was the first field deployment of the CS-500 (Figure 3a). Drilling was conducted generally by two-man crews on two 12-hour shifts, giving 24-hour continuous drilling except where delays were encountered, such as attempted treatments of excessively permeable or unstable fractured rock. Core of 10 cm diameter was obtained along the entire borehole length at each site and were logged by student "junior geologists" supervised by senior staff, comprising a major on-site educational effort by *CALIPSO*. All cores are housed at a MVO storage facility awaiting future detailed study. The time and costs required for drilling were considerably larger than initially estimated by DOSECC, due largely to a combination of a relatively small rig, and very permeable volcanic rock formations,

[1] Drilling, Observation, and Sampling of the Earth's Continental Crust.

which required repeated attempts at sealing using concrete grout prior to advancing down hole, thereby challenging drill-water delivery and causing major delays and expense. Four holes were completed satisfactorily to the design depth of about 200 m. The final drilling costs including all transportation, labor, materials, and rig overhead was $772/m for a total of $618K for four boreholes. The original estimated cost for drilling operations was $486K.

The dilatometer sonde was installed while the rig was on site and other instruments were added later, with one exception (Olveston site, *OLVS*) where the seismometer and a 'hot-hole' dilatometer were mechanically linked together and installed simultaneously. This was the first such installation worldwide of the newly designed Sacks-Evertson 'hot-hole' dilatometer, which because its electronics are housed at the surface, allow the sonde to be deployed at depths where downhole temperatures approach 100 °C (Figure 3b). A second such installation has been recently completed at Long Valley (Sacks et al., 2003). Each *CALIPSO* site also has a steel reinforced, poured-concrete crypt for housing and long-term protection of system electronics, data acquisition, and telemetry hardware, and in one case for top-of-borehole wellhead protection (OLVS site). A backhoe was used to excavate surface regolith to access fractured, near surface bedrock. The central, cross-braced column of the crypt functions as the monument for the CGPS antenna, which is coupled to a bedrock-grouted 1.25” steel pipe using a precision SCIGN level (Figure 3c). The crypts also contain large battery arrays for backup power, as three of the four sites have AC mains power. The sites were designed and built to be sufficiently hardened to withstand extreme meteorological events (e.g. tropical hurricanes) and only require minimum routine maintenance over an expected *CALIPSO* lifespan of more than 30 y.

The borehole sites had been selected at azimuths and distances to maximize scientific return, with some field adjustments required from preliminary plans because of changes in volcanic hazard zonation, and perceived needs to access line power and drill water (Figure 2). The sites were installed in series and data acquisition began immediately after the sensors were grouted into position at ~200 m depth, with the first completed at Trants (*TRNT*, 5.8 km from the SHV lava dome) in December 2002, then Air Studios (*AIRS*, 5.2 km), Geralds (*GRLD*, 9.4 km), and finally concluding with Olveston (OLVS, 7.0 km) in March 2003. One proximal site, a few kilometers from the dome, had to be excised from our original plans because of serious volcanic risk at the time of drilling. Analog data from the strainmeter (50 Hz sync) and seismometer (200 Hz) were initially digitized and locally archived using RefTek 72A-07 data acquisition systems on loan from the PASSCAL instrument pool. Data were periodically downloaded to a laptop after initial installation until August 2003, when the new systems were installed. Approximately 0.2 Tbytes of raw data were acquired and are currently archived at UARK for analysis.

In August 2003, the RefTek 72A-07 units were replaced with Quanterra Q330 six channel 24 bit systems equipped with PB14 digital packet balers, which can locally buffer up to 20 Gbytes of strain and seismic data in MSEED packets. All instruments are linked together via a category 5 IP LAN and data are telemetered from each remote using a single FreeWave FGR-115RE ethernet radio bridge, and where necessary by repeater, to the MVO and then to UARK by Virtual Private Network (VPN). Initial *CALIPSO* data were collected in discrete batches during 2003, and only now are we coming to the point where data streams are being transmitted routinely in near-real-time to UARK. Additional software to control and monitor every instrument at the four remote sites and 'vacuum' the data from each of the sensors is being designed to complement existing tools available through the Quanterra users group and other shareware sources. Initial coding and testing is now well underway and we anticipate that both the hardware and software components of *CALIPSO* will be fully operational and integrated with MVO surface systems by mid-2004.

The prodigious July 12-13, 2003 lava dome collapse (~120 M m^3), explosions synchronous with dome collapse, and subsequent vulcanian explosion events (Herd et al., 2003) were recorded by borehole strainmeter at 3 of the 4 sites, and by seismometer at 2 sites and these data are our immediate research focus. *This appears to be the largest lava dome collapse in the worldwide historic record for any volcano, and indeed is over twice as large as the previous record, which was the July 2001 collapse event also on Montserrat, involving 45 M* m^3. Preliminary scientific reports on this unique data set were presented at the recent Fall AGU Meeting (Linde et al., 2003; Shalev et al., 2003; Hidayat et al., 2003).

The andesitic lava dome on SHV had been growing without major collapse since the large collapse of July 2001. Several days before the latest eruption, a large number of small seismic events occurred with decreasing time interval between them, until they blended together to form a volcanic tremor (Herd et al., 2003). Pyroclastic flows from early partial dome collapses started in the morning on 12 July and grew in size throughout the day and evening, impacting the eastern parts of Montserrat. Associated buoyant ash clouds were blown toward the west, depositing thick ash accumulations around Plymouth, on the residencies of the *CALIPSO* scientists, and at several borehole sites (Figure 3c). The peak of the dome failure occurred just before midnight (AST); the dome collapses triggered several explosions, with the largest, just before midnight on July 12 (AST), coinciding approximately in time with a ~15 km ash column (Edmonds et al., 2003). Ultra-long period (ULP) signals dominate the dilatometer records at all sites (Linde et al., 2003; Shalev et al., 2003; Hidayat et al., 2003); data for the TRNT site are shown in Figure 1c. Further, smaller vulcanian explosions occurred over the next few days. The *CALIPSO* dataset is unprecedented, as no dilatometer nor deep seismometer has ever recorded such volcanic events previously, much less of such prodigious size, and the research results promise to be of major significance. MVO and *CALIPSO* scientists are examining the current data to elucidate what the volcano's newest phase will reveal in this most interesting of eruptions.

Acknowledgments

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http://www.ems.psu.edu/~elsworth/projects/calipso/
http://comp.uark.edu/~mattioli/research/CALIPSO/Intro.html

References

Dunkley, P., B. Voight, M. Edmonds, R. Herd, M. Strutt, G. Thompson, V. Bass, W.P. Aspinall, J. Neuberg, R. Sparks, G. Mattioli, D. Hidayat, D. Elsworth, and C. Widiwijayanti, 2003, The rise and fall of the Soufrière Hills Volcano lava dome, Montserrat, BWI, July 2001-July 2003: Science, hazards, and volatile public perceptions, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V51F-0342.

Edmonds, M., R. Herd, M. Strutt, and C. Mann, 2003, Deposits from the 12 July lava dome collapse and explosive activity at Soufrière Hills volcano, 12-15 July 2003, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V42B-0359.

Herd, R., M. Edmonds, M. Strutt, and L. Ottermeiler, 2003, The collapse of the lava dome at Soufrière Hills volcano, 12-13 July 2003, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V42B-0360.

Hidayat, D., B. Voight, G. Mattioli, S.R. Young, A.T. Linde, I.S. Sacks, P.E. Malin, E. Shalev, D. Elsworth, C. Widiwijayanti, R. Herd, G. Thompson, and V. Bass, 2003, Seismo-acoustics, VLP and ULP signals, and other comparisons of surface broadband and CALIPSO borehole data at Soufrière Hills volcano, Montserrat, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract U31B-0002.

Kokelaar, B.P., Setting, chronology and consequences of the eruption of Soufrière Hills volcano, Montserrat (1995-1999), in *The Eruption of Soufrière Hills Volcano, from 1995 to 1999 (T.H. Druitt and B. Kokelaar, eds.)*, *Geological Society of London, Memoirs,* **21**, 1-43.

Linde, A., I.S. Sacks, B. Voight, P.E. Malin, E. Shalev, G.S. Mattioli, and S.R. Young, 2003, Borehole strainmeters on Montserrat: the CALIPSO project and the July 2003 Eruption, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V51J-0407.

Mattioli, G., R. Herd, M. Aponte, T. Dixon, P. Jansma, and A. Smith, 2002, The dynamics of an ongoing andesitic eruption: what we have learned from surface deformation at Soufrière Hills volcano, Montserrat, BWI, Eos Trans. AGU, 83 (19), Spring Meet. Suppl., Abstract T31A-06.

Mattioli, G.S. and R. Herd, 2003, Correlation of cyclic surface deformation recorded by GPS geodesy with surface magma flux at Soufrière Hills Volcano, Montserrat, Seismological Research Letters, Vol. 74, No. 2, 230.

Norton, G.E., Watts, R.B., Voight, B., Mattioli, G., Herd, R.A., Young, S.R., Aspinall, W.P., Bonadonna, C., Baptie, B., Edmonds, M., Harford, C.L., Jolly, A.D., Loughlin, S.C., Luckett, R., and R.S.J. Sparks, 2002, Pyroclastic flow and explosive activity of the lava dome of Soufrière Hills volcano, Montserrat, during a period of virtually no magma extrusion (March 1998 to November 1999), in *The Eruption of Soufière Hills Volcano,* *from 1995 to 1999 (T.H. Druitt and B. Kokelaar, eds.)*, *Geological Society of London, Memoirs,* **21**, 467-481.

Sacks, S.I., A. Linde, P. Malin, E.A. Roeloffs, D.P. Hill, and W.L. Ellsworth, 2003, Long Valley deep hole geophysical observatory – strain instrumentation and installation, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V52B-0440.

Shalev, E., P.E. Malin, I.S. Sacks, A.T. Linde, B. Voight, G.S. Mattioli, S.R. Young, D. Elsworth, and D. Hidayat, 2003, CALIPSO borehole station observations before and during the July 2003 Montserrat Eruption, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V51J-0410.

Sparks, R.S.J., and S.R. Young, 2002, The eruption of Soufrière Hills volcano, Montserrat (1995-1999): overview of scientific results, in *The Eruption of Soufrière Hills Volcano, from 1995 to 1999 (T.H. Druitt and B. Kokelaar, eds.)*, *Geological Society of London, Memoirs,* **21**, 45-69.

Voight, B. R.P. Hoblitt, A.B. Clarke, A.B. Lockhart, A.D. Miller, L. Lynch, and J. McMahon, 1998, Remarkable cyclic ground deformation monitored in real-time on Montserrat, and its use in eruption forecasting, Geophys. Res. Lett. 25 (18), 3405-3408.

Voight, B., R.S.J. Sparks, A.D. Miller, et al., 1999, Magma flow instability and cyclic activity at Soufrière Hills volcano, Montserrat, British West Indies, *Science*, 283, 1138-1142.

Voight, B., G.S. Mattioli, S.R. Young, A.T. Linde, I.S. Sacks, P.E. Malin, E. Shalev, D. Hidayat, D. Elsworth, C. Widiwijayanti, V. Miller, R.S.J. Sparks, J. Neuberg, V. Bass, P. Dunkley, M. Edmonds, R. Herd, A. Jolly, G. Norton, and G. Thompson, 2003, CALIPSO Borehole Instrumentation Project at Soufrière Hills volcano, Montserrat, BWI: Overview and prospects, EOS Trans. AGU, 84 (46), Fall Meet. Suppl., Abstract V51J-0409.

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 the Soufrière Hills volcano, Montserrat, 18 July 1995 to December 1997, Geophys. Res. Lett. 25 (18), 3389-3392.

Figure Captions

Figure 1. a) Photo of the growing SHV lava dome taken from the automated camera system at Windy Hill in Montserrat on May 31, 2003. View to SSE. Dome apex was over 1100 m AMSL at this time and total dome volume exceeded 210 M m^3. **b)** Photo from same location taken on August 12, 2003. Approximately 120 M m^3 of the dome collapsed within a 24 hr period starting July 12, 2003. Images courtesy of the MVO. **c)** Dilatometer and vertical seismometer records from the July 12-13, 2003 dome collapse eruption as recorded at the TRNT site 5.8 km from the volcanic center. The time scale is in seconds with 0 at 12/7/03 00:44. Note the ULP (~300 s) signals observed in both records.

Figure 2. a) Montserrat map showing location of new *CALIPSO* boreholes, existing CGPS sites, and FreeWave telemetry links. Names of the sites referred to in the text are shown adjacent to the color-coded symbol. Surface broadbrand seismometers and acoustic sensors are co-located at the AIRS and HARR locations. For regional reference, a map of the northeastern Caribbean, showing nearby islands and the Lesser Antilles subduction trace is inset. **b)** ASTER image of Montserrat from April 13, 2002. Red colors correspond to healthy vegetation, while bluish-grays correspond to deposits of pyroclastic flows and surges. Note steam clouds (white) emanating from the actively growing lava dome and drifting to the SW. Image courtesy of NASA.

Figure 3. a) The DOSECC CS-500 drill rig during drilling at GRLD site in January 2003. **b)** Selwyn Sacks, Nelson McWhorter, and Brian Schleigh (from left) along with surface infrastructure at Olveston borehole site just after the first worldwide installation of the newly designed CIW “hot-hole” dilatometer. **c)** Ash deposits on top of AIRS site crypt after July 12-13 dome collapse and explosive events. Rebar reinforced concrete column surrounding bedrock-grouted steel-pipe CGPS monument with SCIGN radome, which is integrated structurally within the underground instrument crypt. The white PVC tube on right housed an acoustic sensor, which was partially buried during the eruption. 5 cm compass-ruler is shown for scale on top of upper concrete surface of the crypt. Total ash accumulation was 11.5 cm. Photo credits: B. Voight, O. Russell, and G. Mattioli.