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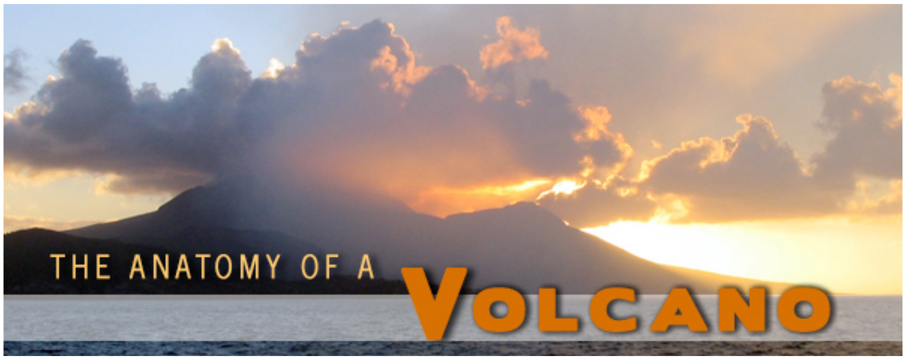


—By Charles Fergus

With remote sensing and an international army of geologists, SEA-CALIPSO takes the measure of an angry mountain.

Barry Voight first went to Montserrat, an island in the British West Indies, in March 1996. The veteran volcanologist had been invited by the island's government and by staff at the Montserrat Volcano Observatory (MVO), who were monitoring a lava dome that had been growing for four months atop the previously dormant Soufriere Hills volcano. The steep, cone-shaped volcano occupied the southern end of the 40-square-mile island, towering 3,000 feet above the capital city of Plymouth, population 7,000.

The government officials and MVO scientists wanted Voight's opinion on the potential danger from a crater-wall collapse on the volcano's western flank, which directly faced Plymouth. More than twenty-five years earlier, Voight had accurately predicted that a massive avalanche on Mt. St. Helens, in the Cascade Range in Washington, could trigger a destructive lateral blast, which took place on May 18, 1980. Since then, as a member of the U.S. Geological Survey's Volcano Hazards Response Team, Voight frequently had inspected ready-to-blow volcanoes around the world. At times, he and his fellow volcanologists gave advice leading to evacuations that saved hundreds, if not thousands, of lives.

"The Soufriere Hills volcano looked very different in 1996 than it does now," Voight recalls. "The slopes and even the crater were forested, apart from the new lava dome and some localized spots downwind where sulfur and chlorine gases had killed the vegetation. In Plymouth, ash dusted the interiors of the shops, and you noticed the gas – it affected your vision and breathing when you caught a whiff of bad air. Folks were sitting on the curbs, covering their noses with handkerchiefs and wiping their tearing eyes."

The day after he arrived, Voight caught a helicopter flight to the volcano's rim. He clambered down a notch in the crater wall and inspected the swelling lava dome and the surrounding crater walls. From his field notebook: "Yellow block and ash flows and tuff beds with altered, weathered matrix. Took block and bag samples at various elevations." Another entry: "Simon [Simon Young, a British volcanologist attached to the MVO] said he was concerned whether an old guy like me would be OK on the mountain. Someone asked him how it worked out, and Simon replied, 'I stopped worrying when I saw him bouncing down into Gages like a mountain goat.'"

Predicting Disaster

Voight felt that the crater wall on the western side of the volcano was stable. However, he judged Plymouth to be at serious risk from a pyroclastic flow, a scorching storm of fragmented lava, ash, and gas that could be released by an explosive collapse of the lava dome. The flow could surge out of the crater, race down the mountain, and overrun the town in as few as three minutes. Voight also judged that a small village on the eastern slope was at extremely high risk of destruction if an explosive eruption took place.

"The person heading the MVO at the time had little volcano crisis experience, but tightly controlled the information flow concerning the situation," Voight says. "His communications to the public officials in charge of evacuating Plymouth were way too optimistic.

"In the report I made to the governor, the chief minister, and other officials, I made sure they got my unvarnished opinion about the risk the population was facing. I had investigated a volcano disaster in Java a few months earlier, where there had been a hundred casualties from pyroclastic currents – ash hurricanes. I thought the same threat existed on Montserrat, and I used photos I'd taken of burn victims in Java to illustrate my point.

"Within a few weeks, evacuations were carried out. A few months later, the village on the eastern slope was subjected to a blitz of incandescent ballistic blocks as large as a meter in diameter, and numerous fires were set. There were no casualties, because the place had been evacuated. Over the next three years, a series of pyroclastic flows destroyed and buried Plymouth bit by bit."

During and after those eruptions, 8,000 of Montserrat's 13,000 inhabitants fled the island, half of which was turned into an ash-and-lava wasteland. The authorities built a new capital and airport at the island's north end.

Voight became a charter member of the Risk Assessment Panel formed in 1997 to advise the United Kingdom and Montserrat governments, and later was named to its successor group, the Scientific Advisory Committee, on which he currently sits. The committee gives detailed assessments of the volcano at least twice a year, and these appraisals help guide decision-making by local and UK decision-makers and the MVO. Over the same time period, Voight has carried out a series of research investigations on the island.

In 2002, Voight also helped organize a team of scientists to form the Caribbean Andesite Lava Island Precision Seismo-geodetic Observatory, or CALIPSO. “The acronym came into being after a very fine margarita imbibed in Washington, D.C.,” Voight notes, adding: “The name fits in all respects.” Seven years later, the Soufriere Hills volcano remains one of the world’s most closely studied stratovolcanoes.

Voight surveys destruction wrought by a volcano in Plymouth, the destroyed former capital of Montserrat. Credit A. Belousov

Sulfur Hills

Montserrat lies southeast of Puerto Rico in the Leeward Islands chain. George Martin, the Beatles’ former producer, has a home there (“He very kindly gave us permission to located a key borehole site on his property,” Voight says), as do many retired Canadians and Americans, who mingle with a native population of Caribbean, African, Irish, and English descent. Montserrat is a place of steam vents, sulfur deposits, bubbling mud pots, and tropical verdure, with the volcano frowning over all.

Stratovolcanoes are explosive and dangerous. They are among the most common volcanoes in the world. Many of them, including the one on Montserrat, produce magma that forms the igneous rock andesite. The word comes from the Andes mountain range on the western rim of the South American tectonic plate. Montserrat and other Caribbean islands sit above the northern rim of the South American plate, where it is subducting, or sliding, beneath the Caribbean plate. Above this zone, volcanoes erupt. A similar situation exists from Chile to California to Alaska, and from the Kurile Trench off Kamchatka to Japan, the Philippines, and Indonesia – all places where Voight has worked. This great arc of volcanism is called the Pacific Ring of Fire.

Three volcanic centers – Voight calls them “a series of dome clusters” – have developed on Montserrat. Silver Hills, at the island’s north end, is 2.6 to 1.2 million years old. The centrally located Centre Hills are 950,000 to 550,000 years old. (The Silver Hills and Centre Hills are currently inactive.) The Soufriere Hills (soufriere is French for sulfur) are younger than 200,000 years.

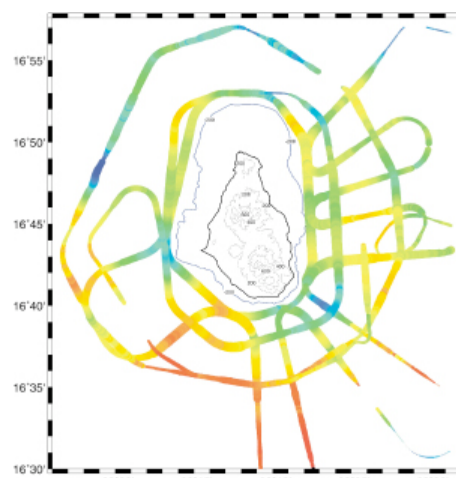
From the time the island was settled, in the early 1600s, until recently, there were no eruptions (although the geological record shows that one took place between when Christopher Columbus discovered and named Montserrat, in 1493, and its settlement by Europeans). Earthquakes caused by pulses of rising magma shook the island in the 1890s, the 1930s, and the 1960s; however, the magma lacked the energy to break through the ground surface. Then in the early 1990s the Soufriere Hills volcano began acting up again, with lava breaking out in November 1995. (Voight explains: “It’s magma when underground, lava when it gets out.”)

“With CALIPSO, we’re looking at the subduction process on a very basic level,” Voight says. “The movement of one tectonic plate beneath another causes the mantle to melt, and the molten rock, or magma, accumulates under the earth’s crust. We’re studying how the magma evolves and makes its way through the crust to the earth’s surface.”

The CALIPSO system is the first borehole monitoring array of its type to be deployed at an andesite volcano. It includes four holes, 600 feet deep and 4.5 inches in diameter. At the bottom of each are a strainmeter and a seismometer. A microbarometer and a high-precision global positioning system (GPS) sit at the surface. “The ground is a hundred times quieter 600 feet down,” Voight explains. “We can record smaller events and deeper events – such as earthquakes caused by magma moving – than would be possible at the noisier ground-surface level. And we can record earth strain to an extremely high level of precision.”

Voight and his colleagues combine data from the boreholes with information collected from GPS and seismic instruments at surface sites around Montserrat; from gas detectors on the volcano and automated camera systems facing the cone; and from ongoing visual observations.

The GPS and strain devices can measure both the up-and-down and sideways movements of numerous points on the island. “During periods when magma is building up inside the volcano,” says Voight, “the ground surface inflates like a balloon. When magma erupts from the volcano, the ground surface deflates. This happens all over the island – the ground can fall several inches while magma is being released.”



Plot developed by Eylon Shalev of Auckland University (NZ), and subsequently used as a project logo. It shows the track of the RSS James Ross during the airgun shooting. Click to enlarge.

The instruments recorded a tremendous eruption in July 2003, when a newly built dome collapsed, releasing more than 200 million cubic meters of lava. According to a journal paper Voight co-authored: “This appears to be the largest lava dome collapse in the worldwide historic record for any volcano.”

Measurements taken during this and other eruptive phases show the volume of lava released by the volcano to be much greater than what would be expected from the amount of ground subsidence taking place. To resolve this apparent contradiction, Voight and his colleagues decided to look inside the volcano. “The internal plumbing of an active volcano is a huge puzzle for earth scientists,” Voight says. “It’s almost impossible to get direct measurements. We needed to use remote sensing.”

Voight and fellow researcher Steven Sparks, a geoscientist at the University of Bristol in England, launched a research effort called SEA-CALIPSO: They would use seismic waves produced by explosions at sea to examine the volcano and the island on which it perches.

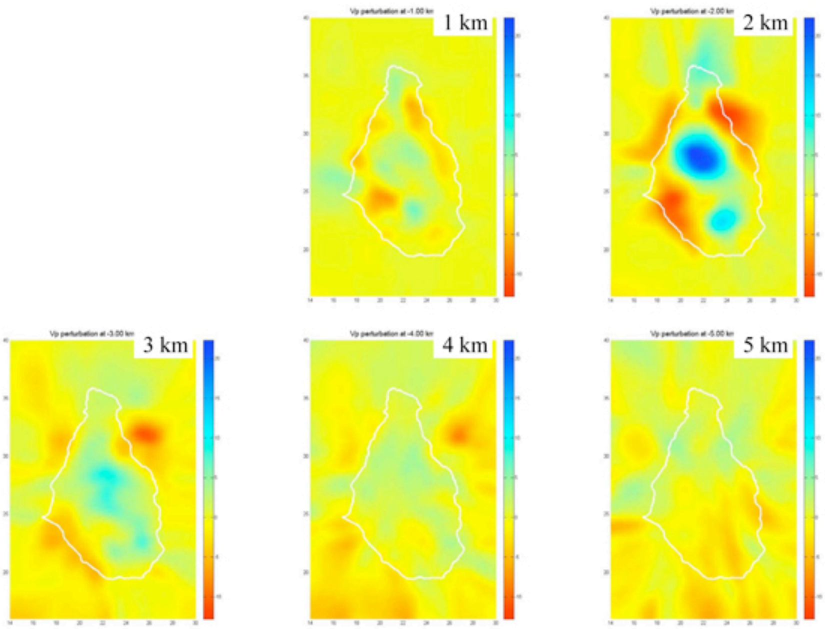
Sounding it Out

Seismic tomography, developed in the 1970s, relies on seismic waves caused by earthquakes and explosions. “You measure the velocity of the waves to compose a picture of the hidden structure,” says Voight. “Tomography literally means ‘slice-pictures,’ in which a series of high-resolution two-dimensional slices are pushed together to yield a 3-D image.” He likens the technique to a hospital CT scan (CT stands for “computerized tomography”) that employs x-rays to build a picture of organs inside the human body. In both the medical and the geological applications, advanced programs run by powerful computers solve hundreds of thousands of equations to identify subsurface details.

In preparing for SEA-CALIPSO, the researchers deployed more than 240 seismic recorders and geophones on Montserrat. Some were installed along roads, or had already been placed in monitoring stations. Others had to be carried on trails cut into the rugged rainforest interior, or landed from boats along the coast and then hauled to strategic points inland. The team also sank ten ocean-bottom seismometers deep into the sea around the island.

In December 2008, the British research vessel James Cook circled Montserrat, towing an array of air guns that fired off explosions at 60-second intervals. “Think of a hospital CT scan, with the x-ray emitter slowly circling the patient,” Voight says. More than four thousand omnidirectional explosions were set off over three days. The land-based and ocean-bottom sensors recorded the arrival times of the seismic waves produced by the detonations.

The 89.5-meter research ship also trailed a streamer of hydrophones to pick up underwater sound impulses that came bouncing back. Data from those impulses would help the researchers characterize faults on land that extended out into the sea, and different kinds of formations and volcanic deposits on the sea floor. During the experiment Voight remained on Montserrat to guide the operation and to help deploy and monitor the instruments, along with Eylon Shalev of Aukland University (NZ); the co-leader, Sparks, was onboard the ship, with oceanographer Tim Minshull advising from Southampton (UK).



A series of slices through Montserrat at different depths below sea-level. The island outline is shown by a white line. These are the basic results of the "tomography" survey, made by Eylon Shalev. The blue colors are rocks that have higher seismic velocities than the average velocity expected at a given depth. The red colors indicate regions of relatively low seismic velocities. It is clear from these results that the island is not underlain by homogeneous materials. The results can be used to better understand how the island evolved, to improve understanding of eruption dynamics and volcanic hazards, and to better locate earthquake sources.

The explosions produced 115,158 rays: paths traveled by seismic waves though geological materials whose physical properties caused the impulses to proceed at differing speeds. “Tomography yields a map of rock velocities at different locations,” Voight says. “We can convert these velocities into characteristics like stiffness, porosity, elasticity, and probable rock type.” The researchers also evaluated seismic information that CALIPSO had recorded following local and regional earthquakes. The immense quantity of data took months to crunch, to get the first look. “And we are still crunching,” says Voight. “There is plenty left to do.”

“We found that we could see down to five or six kilometers below sea level,” says Voight. “We had hoped for more depth, but most of the seismic rays were curved, and bottomed out sooner than expected. This had to do with characteristics of the local crustal rock.” The researchers detected a high-velocity crystalline core under the Soufriere Hills and the Centre Hills. They saw the glimmer of a slow-velocity region under the volcano, “possibly related to shallow magma storage,” says Voight.

Hot and Heavy

Below five kilometers, the imaging became less precise – “like a photo that’s slightly out of focus,” Voight says. SEA-CALIPSO was able to map the seismic energy bouncing off key reflecting layers farther down. Analyses guided by Penn State geoscientist Chuck Ammon located the crust-mantle boundary at a depth of about 30 kilometers, and a deeper region of slow-velocity under the south part of the island.

Things are hot and heavy down there, where the plates grind beneath Montserrat. Says Voight, “Rocks involved in the subduction slab begin to dehydrate, to lose water. The released water-rich fluid acts as a catalyst that promotes a partial melting of the mantle. Only a fraction of the mantle melts – roughly ten percent – and this molten material, of basaltic composition, begins to migrate upward.

Magma bubbles from an active volcano
Credit NASA Astronomy Picture of the Day

“The melt collects together, and when it reaches a certain size and density, it rises more rapidly, a lightweight magma balloon propelled by its buoyancy through the soft, heavy mantle rock that surrounds it. The basaltic magma ponds at the base of the crust. At this point it can, in some instances, drive a fracture – called a dike – all the way through the crust to the earth’s surface, causing an eruption.

“Under Montserrat, things are happening a bit differently. The basaltic magma begins to crystallize, creating a liquid that’s stickier and richer in silica: andesite. The andesite then rises in pulses to shallower levels, where it collects in chambers. Repeated injections of hotter basalt energize the magma, making it more mobile.”

The magma flows upward into the Soufriere Hills volcano fairly continuously and at a relatively constant rate of two cubic meters per second – “about the volume of a large refrigerator,” says Voight. “During periods between eruptions, the magma fills a series of chambers that may be stacked on top of each other. We think there’s some sort of semi-continuous transfer of magma between the chambers, and at times that transfer becomes rapid.”

Andesite magma is rich in water, carbon dioxide, and sulfur dioxide gases. Some gas is dissolved in the magma, and some sits there in bubbles. As new magma enters the system from below, it makes room for itself by compressing the resident bubbly magma. The magma also pushes against the chamber walls, which causes the surface of Montserrat to elevate.

“The chamber system acts as a huge magma sponge,” says Voight. “On top, a dome of sticky, mostly solidified lava caps the system. Pressure can build up gradually beneath the dome, and the eruption can restart.

“During an eruption, the magma that’s been squeezed inside the volcano’s reservoir is decompressed. That explains why the volume of lava produced by an eruption can be much greater than one would estimate, based simply on the amount of surface subsidence.”

The Fire Next Time

SEA-CALIPSO revealed a prominent fault trending northwest into the Caribbean on the western side of Montserrat. “This fault line has been active in the recent geological past," says Voight. "We think it influenced the location of the different areas of volcanic domes on the island, as well as the magma chambers inside the Soufriere Hills volcano.

"One of the great things about the eruption at Montserrat – mind you, this is strictly from the scientist's perspective, and not the viewpoint of somebody living on the island – is that the activity hasn't stopped. The eruption didn't build to a climax, go on for a week, then end. The volcano's relatively slow development meant we could put up instruments when and where we wanted them. So we're still learning. We've made many discoveries, and we will make others."

RSS James Cook in Port Antigua
Credit J. Hammond

According to Voight, the research at the Soufriere Hills volcano is a benchmark study that will help earth scientists understand other subduction-type stratovolcanoes. "The more we know about the system on Montserrat," he says, "the better we can forecast eruptions and anticipate other dangerous events, both here and at other andesite volcanoes around the world."

Barry Voight, Ph.D., is professor emeritus of geology and geological engineering in the College of Earth and Mineral Science, voight@ems.psu.edu. Current Penn Staters participating in the research on Montserrat include professors Charles Ammon and Derek Elsworth; post-doctoral researchers Dannie Hidayat and Christina Widiwijayanti; Ph.D. candidates Vicki Miller, Roozbeh Faroozan, Winchelle Sevilla, and Josh Taron; and many undergraduate students.

CALIPSO AND SEA-CALIPSO have drawn together scientists from Penn State, the University of Arkansas, Carnegie Institution of Washington, Cornell, Duke, Arizona State, New Mexico Tech, Bristol University (UK), Durham University (UK), University of Auckland (NZ), National Oceanographic Centre (UK), Montserrat Volcano Observatory, British Geological Survey, and Seismic Research Center (Trinidad). The PASSCAL (IRIS) Consortium and Scripps Institute of Oceanography aided SEA-CALIPSO. The National Science Foundation, Natural Environmental Research Council (UK), British Geological Survey, and Discovery Channel have helped to fund the research.

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