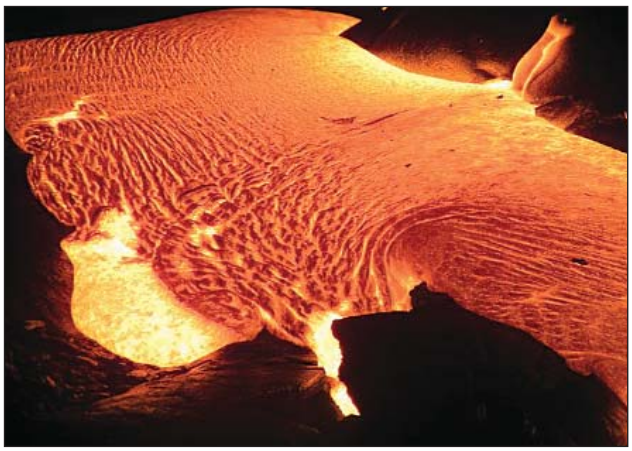


Show time. Thanks to VALVE, scientists were able to observe various facets of Kilauea's latest flare-up in a single picture.

Hurni and his colleagues are the architects of Geowarn's visualization software. His team has combined digital three-dimensional maps with the powerful data-processing tools of Geographic Information Systems used by surveyors and other field specialists to create a template that monitoring data can be fed into and displayed. Experts find the approach intriguing. The system, says Newhall, gives "an unusually good integration of different kinds of data and an ability to look at them together in space and time." Moreover, Geowarn and VALVE, both of which could be adapted to use on any volcano, promise to fundamentally alter how scientists who study volcanoes interact, says William Rose, a volcanologist at Michigan Technological University, Houghton. "We are all specialists trapped in disciplinary holes unless we … put our observations together," he says.

One caveat, of course, is that the new systems are blind to instinct. Volcanologists standing on a fuming mountain must have "a gut feeling for how the activity is going," says geophysicist Paul Segall of Stanford University—something that today's computers, at least, cannot possibly register.

Volcanologists hope that Geowarn or VALVE will help them refine their predictions of when a mountain might erupt, but they would be even more pleased if the new systems could aid in getting the message out to the public. "You could be scientifically superb at predicting something, but unless you can communicate that to the people who might be affected, it doesn't do any good," says David Hill, scientist-in-charge at the Long Valley Observatory in Menlo Park, California. Geowarn's backers say that scientists outlining hazard zones to elected officials and the public will be able to do so more effectively with three-dimensional, interactive maps. Newhall agrees: "This is absolutely the way to go." Indeed, plans are already afoot to hook up other volcanoes: VALVE at Long Valley, and Geowarn at Vesuvius.

–DANIEL BACHTOLD

NEWS

Bracing for the Big One on Montserrat

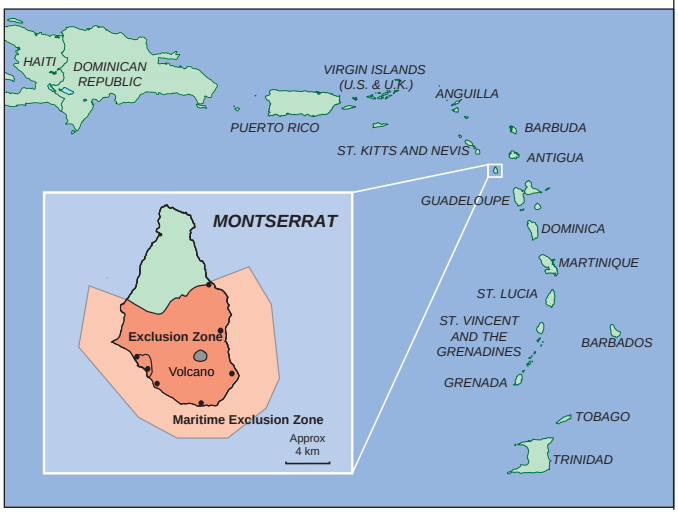
The Soufrière Hills volcano destroyed the capital and much of the rest of this island's southern half in the mid-1990s, and it may not be done yet: Its massive and still-growing lava dome has begun to threaten communities in the north, raising the stakes for the scientists who are keeping watch

MONTSERRAT—Some of the hottest pop songs of the 1980s came to life here, in a pale beige ranch-style house perched on a bluff. Elton John, Paul McCartney, and Stevie Wonder, among others, made the pilgrimage to this recording studio on the "Emerald Isle" of the Caribbean. Perhaps they drew inspiration from the shimmering turquoise waters, or maybe their muse was the mountain looming in the southeast: the Soufrière Hills volcano.

The vista is as entrancing as ever, long after the music died. AIR Studios, part of the vast Montserrat estate of Beatles producer George Martin, sits abandoned on a swath of land evacuated by authorities last October. The only sounds on a sunny afternoon last month were the sloshing of a cement mixer and the banter of volcanologist Barry Voight and his colleagues as they yanked yard after yard of plastic piping, conduit for the fresh cement, from a borehole near the studio. If a siren had blared, Voight's team members would have dropped what they were doing and hauled out of the exclusion zone as fast as they could have: The lava dome of Soufrière Hills is bigger than ever since the volcano roared back to life in the mid-1990s, and it could collapse at any time, in any direction.

Today, the volcano is calm, a taupe ash cloud drifting lazily out to sea. The researchers have just about finished installing two devices—a meter-long steel-sheathed seismometer that resembles an artillery rocket and a smaller, more cylindrical tiltmeter—near the bottom of the borehole, one of four drilled around the volcano. The sensors sit atop a strainmeter so sensitive that it can detect motions in the rock of the dimensions of an atom. The recordings from these instruments may not rival the sounds that once filled AIR Studios, but they will be music to the ears of scientists: They are expected to be the most precise readings yet of the mountain's inner stirrings.

"We're hoping to get a feel for what's happening deep in the system," says Voight, who is from Pennsylvania State University, University Park. "This volcano is a unique natural laboratory." The mountain's often enigmatic convulsions have been a boon to modelers, who are starting to put together a coherent picture of the relation between magma movements and the varying seismic signals they trigger. "The models are starting to give us some power to explain the phenomena we've seen in this eruption"—insights that can be

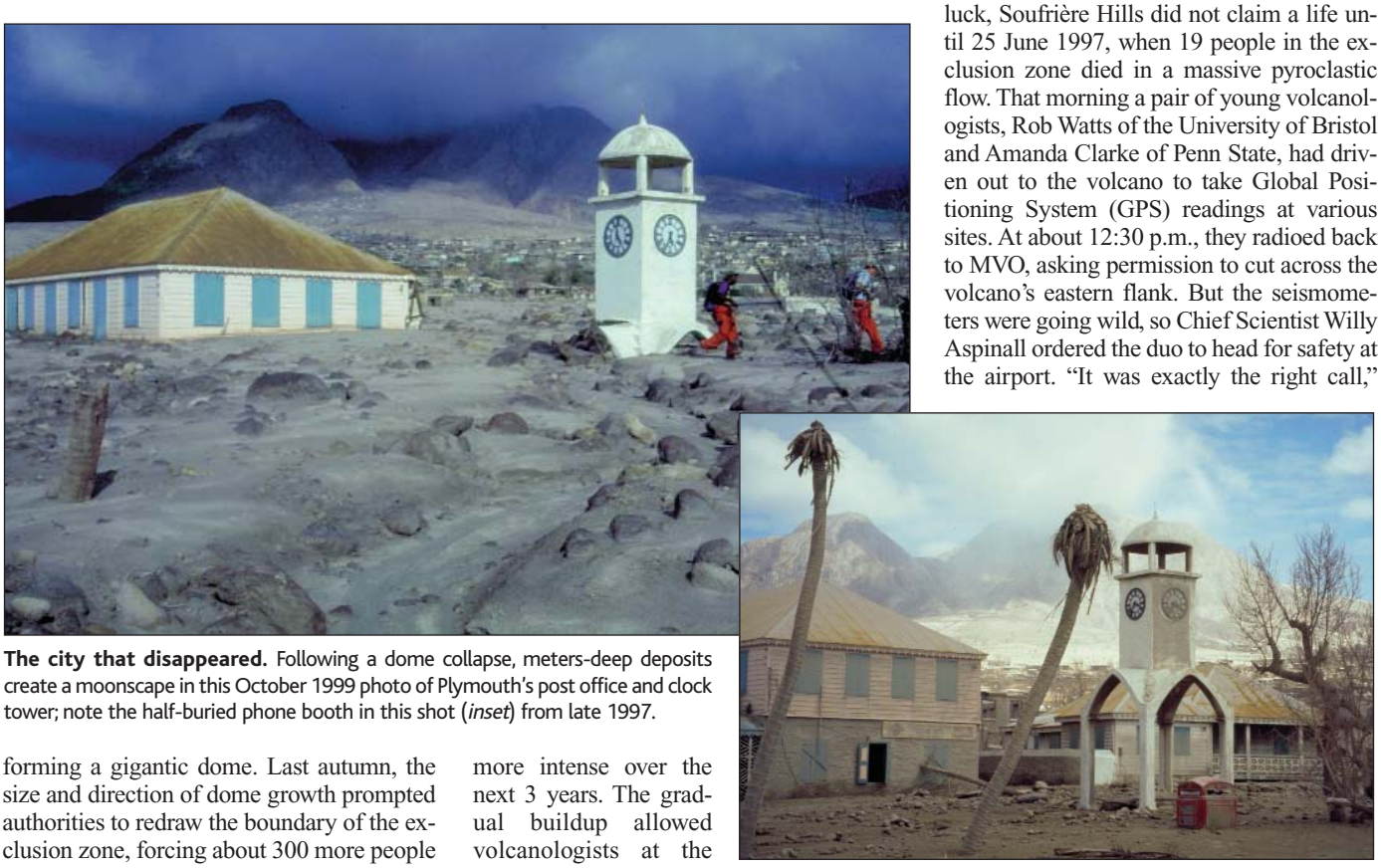


Hot zone. Growth of the lava dome toward the north forced the island's governor last October to evacuate another swath of Montserrat's dwindling inhabitable territory.

CREDIT: (TOP) USGS

applied to many volcanoes, says volcanologist Stephen Sparks of the University of Bristol, U.K., who has extensively modeled magma dynamics beneath Montserrat.

Soufrière Hills is also a gathering storm of frightening proportions. After 400 years of relative peace, the mountain erupted in 1995. In an encore 2 years later, it obliterated southern Montserrat, including the capital, Plymouth, and much of the 16-kilometer-long, mountainous island's arable land. To the credit of scientists at the Montserrat Volcano Observatory (MVO), their advice led to timely evacuations that saved all but 19 islanders, who had defied orders to leave an exclusion zone. After 20 months of relative quiet, the volcano kicked into a new phase in 1999 in which lava is piling up at the top, forming a gigantic dome. Last autumn, the size and direction of dome growth prompted authorities to redraw the boundary of the exclusion zone, forcing about 300 more people to relocate. Although some residents still grouse about the evacuation, the volcano's threat is escalating day by day. "The dome is growing, growing, growing," says MVO director Peter Dunkley, a geologist by training. "It really is quite terrifying."



The city that disappeared. Following a dome collapse, meters-deep deposits create a moonscape in this October 1999 photo of Plymouth's post office and clock tower; note the half-buried phone booth in this shot (*inset*) from late 1997.

Paradise lost

Steering a jeep over a buried bridge across a mud-drowned river, Lars Ottemöller, a seismologist at the British Geological Survey (BGS), lurches past villas smeared with wispy brown ash, every last one devoid of life, and a sign saying "Please keep our island clean." As he nears the top of St. George's Hill, fat drops of ash-laden rain begin to pelt the car, forming a gray slurry on the windshield, and a sulfurous smell in the air grows stronger. A cow matted with ash looks on forlornly as Ottemöller pulls up in front of a dilapidated concrete hut housing a transmitter for a nearby surface seismometer, one of a dozen such stations. He is here for a routine check of the equipment, but the view from St. George's Hill is anything but ordinary. A delta of volcanic mud covers Plymouth, with only a few shells and facades of taller buildings still poking through.

Fortunately, the disaster on Montserrat unfolded over months, reaching a crescendo after the southern half of the island had been safely evacuated. The first tremors of the waking volcano came in 1992 and grew more intense over the next 3 years. The gradual buildup allowed volcanologists at the Seismic Research Unit (SRU) of the University of the West Indies, in St. Augustine, Trinidad, to install better monitoring equipment at Soufrière Hills.

The volcano's first real warning shot came on 18 July 1995, when phreatic, or steam-driven, explosions sent a dense ash cloud over Plymouth. The situation "got progressively worse," says Lloyd Lynch, an SRU instrumentation specialist. A particularly severe blast on 21 August turned "day into night" in Plymouth, he recalls. "Some people were on their knees praying, thinking this was the end." Even scientists were nervous: "We didn't understand the volcano," Lynch says. In November, a lava dome began to grow, ratcheting up the level of concern. Yet, says Voight, who first came to the island in March 1996, officials and residents alike were reluctant to clear out for good, returning after two evacuations. Later that month, the first pyroclastic flows—roiling avalanches of ash, gas, and rock—prompted the third and final evacuation of much of the southern half of the island. "If the activity had built up much faster," says Voight, "there would have been a ton of deaths in Plymouth." The volcano convulsed all summer, frequently ashing the ghost town; in September an explosion sent a mortar barrage of incandescent meterwide lava blocks into a recently evacuated village, shattering half the houses and igniting fires.

Thanks to sound management and a bit of luck, Soufrière Hills did not claim a life until 25 June 1997, when 19 people in the exclusion zone died in a massive pyroclastic flow. That morning a pair of young volcanologists, Rob Watts of the University of Bristol and Amanda Clarke of Penn State, had driven out to the volcano to take Global Positioning System (GPS) readings at various sites. At about 12:30 p.m., they radioed back to MVO, asking permission to cut across the volcano's eastern flank. But the seismometers were going wild, so Chief Scientist Willy Aspinall ordered the duo to head for safety at the airport. "It was exactly the right call," says Gill Norton, a volcanologist based at BGS headquarters in Nottingham, U.K., who later ran MVO. The pyroclastic flow tore through about 10 minutes later. It was the closest any volcanologist has come to perishing on the island.

In early 1998, the mountain inexplicably went quiet. "But it didn't go back to sleep properly," shuddering and venting periodically, says MVO volcanologist Richard Herd. Nor did it resume its former lifestyle. Following abnormal seismic activity in October 1999, the lava began piling up into a new dome. Inexplicably, the volcano has per-

CREDITS: G. E. NORTON/MVO

sisted in a steady dome-building mode, punctuated by two major collapses that were triggered by heavy rains. As *Science* went to press, the dome held a whopping 200 million cubic meters of lava, about double the volume since the most recent collapse in July 2001. "There doesn't seem to be a limit to dome growth," Herd says with awe.

Paradise found

The evolving drama, observed using the latest instrumentation, has turned Montserrat into a volcanological wonderland. "It's been a phenomenal scientific opportunity," says the University of Cambridge's Clive Oppenheimer, one of more than 100 volcanologists who have worked on the island. "A huge array of techniques has been brought to bear on its surveillance," he says.

For example, at most volcanoes researchers lug bulky gas monitors out into the field for occasional readings of the amount of gas venting from a mountain. In 2001, however, scientists at Montserrat were the first to deploy miniature ultraviolet spectrometers that, during daylight, can take readings of sulfur dioxide flux every few minutes. Such accurate measurements could prove particularly handy at Soufrière Hills, where the size of eruptions, researchers believe, often seems to be linked to the speed and volume of gas escaping from the rising magma.

But so far, some of the most important findings for anticipating the next moves of Soufrière Hills have come from seismometers eavesdropping on the acoustical chatter beneath the mountain. Some of the more intriguing discordant notes are long-period (LP) events, peculiar low-frequency waves that somehow reflect the movements of gases and bubbly magma inside the conduits. Sometimes these LP waves are punctuated with high-frequency squeals of unknown origin and are called "hybrid" events. In an article in press at the *Journal of Volcanological and Geothermal Research*, Philippe Jousset and Jürgen Neuberg of the University of Leeds, U.K., have suggested that these low-frequency waves come about when the conduit resonates as magma lurches through. The frequency patterns, the researchers propose, could be explained by the amount of gas escaping from the magma to form bubbles.

These LP events are not idle chatter. On Montserrat, when LP or hybrid signals start bunching together in repetitive patterns, trouble is usually afoot: Explosions have occurred within hours after swarms, although other swarms have been linked to magma extruding into the dome.

The volcano's idiosyncrasies could also offer fundamental insights into how magma wells up from deep crustal reservoirs to the surface. A signature feature of Soufrière Hills is its cyclic activity on various time scales. It is clear that the short-term cycles, which last between 3 and 30 hours, stem from pressure buildups that result in the volcano swelling slightly before subsiding with a gaseous burp.

More mysterious are longer-period cycles. Voight and his colleagues were the first to document patterns in which tiltmeters on the crater rim register pressure buildup, after which "the seismicity turns on," Voight says:

Muckraking. Keith Rowley and Marie Edmonds sample fresh pyroclastic flow deposits in the Tar River Valley in November 1998.

CREDIT: G. E. NORTON/MVO

Swarms of LP events are unleashed. This is followed by a pulse of magma extrusion and gas release. The strength of these cycles would ebb gradually and then flare every 7 weeks or so with renewed vigor. Finally, increases in seismicity, related to the injection of fresh magma into the volcano's plumbing, have occurred roughly every 30 years at Montserrat since the late 19th century. Voight and others have proposed that these longer-term cycles are linked to changes affecting the magma reservoir more than 5 kilometers below the volcano. The mechanism remains unknown, although it probably involves periodic infusions of hot, water-rich mafic magmas into the crustal reservoir of Montserrat's more viscous, crystal-rich andesitic magma.

That is one hypothesis that the sensors near AIR Studios are supposed to help test. Last month, a team including Voight's group at Penn State, the Carnegie Institution of Washington, Duke University, and the University of Arkansas, with colleagues in Bristol and Leeds, wrapped up the installation of strainmeters, seismometers, and tiltmeters at four boreholes, each about 200 meters deep. Continuous GPS systems will straddle the holes—the first system of its kind on an andesitic volcano. Voight estimates that the new sensors should provide 100 times more resolution on tremors; besides giving a clearer picture of magma movements in the reservoir, the data will feed directly to MVO to aid in monitoring. And with their expected sensitivity, the instruments could detect changes in the volcano's plumbing in reaction to nearby earthquakes in the rough-and-tumble Lesser Antilles islands.

One current mystery concerns the lava dome: Why hasn't the monster collapsed yet? MVO's new observatory, which had its opening ceremony earlier this month, is high above the Belham Valley—high enough, scientists hope, to be out of harm's way. But as the dome just 4 kilometers away grows ever more enormous, it becomes harder to predict the volcano's likely behavior and how far the 500ºC flows and surges might travel. If the dome were to topple catastrophically in the observatory's direction, any of the 12 staff members on duty would try to ride it out in a basement corridor designed to withstand the searing heat.

Even with that remote prospect in the back of everyone's minds, it is hard *not* to become inured to the view from the operations room's picture windows of minor pyroclastic flows tumbling down the volcano's flanks. These events, which happen almost daily, sometimes a dozen or more times a day, set the pens scratching madly on a pair of seismic recording drums in the operations room and often trigger an automated alarm sent to pagers carried by the MVO scientists. Usually there is no need to worry: The flows tend to fall safely toward the northeast and peter out in tens of seconds. So far, the rarer flows to the north or northwest have ended well short of inhabited areas.

Bracing for the Big One, a major dome collapse or an enormous explosion, keeps the researchers on edge. A substantial collapse to the east would probably relieve the tension, at least temporarily removing the live bullet from the loaded chamber. A big collapse to the northwest, however, could be lethal. Based on what is known of the 300,000-year history of eruptions at Soufrière Hills and the mountain's current specifications, the odds are vanishingly low that it would erupt cataclysmically—on the scale of the eruption that destroyed most of Krakatau island in Indonesia in 1883—and render Montserrat uninhabitable. "It's like the possibility of having a hurricane the size of the Atlantic Ocean," says Bristol's Sparks. Just in case, though, authorities have a plan, "Operation Exodus," for

evacuating the entire island using ships from nearby Antigua and Guadeloupe.

"Montserrat is the wrong size," laments its governor, Anthony Longrigg. "If it were smaller, the whole island would have been evacuated. If it were bigger, we would have moved everyone farther north and we wouldn't have needed to worry so much about where we draw the exclusion zone. But Montserrat needs every bit of land we can get." And with people living right on the edge of the safe zone, that places an even heavier burden on the scientists.

Hanging in the balance

A panel of scientists including the MVO director and a handful of outside experts meets at least twice a year—or more often depending on the volcano's activity—to assess the risk to the community. They provide advice to an emergency committee including the chief minister of the locally elected Montserrat government and Longrigg, an appointee of the U.K.'s Foreign and Commonwealth Office, as the island is an overseas territory of the U.K. Ultimately, an evacuation order is Longrigg's call. It is a fine balance. In 1976, authorities on nearby Guadeloupe evacuated about 70,000 people based on uncertain scientific evidence. After a minor eruption people were allowed back onto the island, but the damage was done. "The volcano didn't kill anybody, but the economy was destroyed," says Voight.

Force majeure. A massive pyroclastic flow tears down Soufrière Hills on 7 August 1997; the volcano has coughed up twice as much magma over 7 years as that disgorged during the 1980 eruption of Mount St. Helens.

CREDIT: G. E. NORTON/MVO

When the lava dome began bulging toward the Belham Valley last September, the regular meeting of the risk assessment panel could not have come at a better time. "We felt there was a 30% chance of a pyroclastic flow coming into Belham," says Dunkley, who serves on the panel. Based on that assessment, he and his colleagues estimated that the odds that the volcano, over the course of a year, would kill an individual residing round-the-clock in Belham were about 1 in 100, classified under U.K. medical guidelines as a high risk. "It's a judgment call, but I took the view that we had to evacuate," Longrigg says. Many volcanologists, however, considered it a no-brainer. "You just can't live with that level of risk," says Herd.

In consultation with MVO, the authorities redrew the boundary of the exclusion zone, dividing a village. The 10 October evacuation order has proved deeply unpopular, particularly among some foreigners whose villas lie on the wrong side of the line. "People are bitter. It's affected their property values," says Longrigg. The bitterness may also stem from deflated hopes that the evacuation would be temporary.

The expectation was that a hurricane or sustained downpour during the rainy season last autumn would trigger a dome collapse, presumably away from Belham, which would have allowed the governor to lift the evacuation order. Despite a few serious drenchings, however, the lava dome remained intact, and according to a revised assessment in mid-January, steady dome growth has raised the risk of death to between 1 in 47 and 1 in 75 for a full-time resident in the exclusion zone, guaranteeing that Belham stays closed. Longrigg has tried to relieve the hardship by allowing workers and homeowners into the zone for 5 hours a day, six days a week. "We did that to try to keep the jobs in the zone going," he says. The most recent calculation puts the odds of death of a person spending the maximum 30 hours a week in the zone at 1 in 575; that is deemed a moderate risk. Daytrippers are expected to be out of the zone within 5 minutes if the siren sounds. The warning could save lives in the event of a minor dome collapse, says Dunkley, "but it won't help you if the big event happens."

Even as the degree of risk increases, scientists and officials are at loggerheads over the risk-assessment process. The scientists worry that they could be particularly vulnerable to litigation over their advice to Montserrat authorities. According to Voight, the U.K. agencies that have sought the advice have so far refused to assure that they would provide assistance if a scientist were sued. "It's unconscionable," he says. "They want our advice to protect the public, but up to now they have been willing to leave us holding the bag."

Discussions are under way between MVO, Montserrat authorities, and the U.K. Foreign Office over a proposal to give the risk panel status as a British scientific advisory committee. Under U.K. guidelines, committee members who have acted "honestly, reasonably, in good faith, and without negligence" would not have to pay civil damages out of their own pockets. But because only a court could determine whether a scientist was negligent, the guidelines do not provide "an absolute indemnity against liability," says Aspinall, an independent consultant who serves on the risk panel. A way forward was being sought before the panel's next meeting in May.

Montserrat's economic prospects are uncertain as well. The economy, propped up by $350 million in U.K. assistance since 1995, barely shows a pulse despite a construction boom in the north. And although the population has rebounded a bit, from a low of 2740 in late 1997 to about 4500 today—primarily due to an influx of guest workers from other Caribbean islands—it is still a pale shadow of the pre-eruption community of 12,000. "There is no town center as such, no center of the community," says BGS's Norton.

Many Montserratians displaced by the volcano have settled in England and on Antigua, and few are inclined to return: A 3-year-old U.K. program to pay the expenses of returnees has so far lured back only a few dozen people. Another brake on growth, Longrigg says, is that "you can't get insurance for investing in the north." Indeed, 35% of the workforce is employed by the government, and 80% of private sector workers are in the construction industry. The island's big hope may lie in tourism, but for now that is mostly limited to a trickle of people on day trips from Antigua. Those who have chosen to remain on Montserrat, says Herd, "have learned to live with the volcano."

With Montserratians clustered so close to the danger zone, MVO scientists and outside collaborators know they cannot let down their guard. And they could be in it for a very long haul: One andesitic volcano on Kamchatka, a peninsula in Russia's Far East, has been growing and collapsing a lava dome since 1956. "Presumably Montserrat's magma reservoir is being replenished from a deep source, and if so, then we have no constraints on volume," says Oppenheimer. The bottom line, says Dunkley, is that "this eruption is going to go on for a long time." If the past is any guide to the future of the Soufrière Hills volcano, plenty more surprises are in store. **–RICHARD STONE**