magma will fail and the volcano will erupt when exponentially accelerating seismicity or deformation approaches infinite proportions. Applied in hindsight, this method would have predicted a number of eruptions at Mount St. Helens, Redoubt, Izu Shima in Japan, Montserrat, and Galeras, Voight says.

Others have also found exponential acceleration to be a useful predictor. In the September 2002 issue of the *Journal of Volcanology and Geothermal Research*, John Murray of The Open University in Milton Keynes, U.K., and Juan-José Ramirez Ruiz of the Colima Volcano Observatory in Mexico report that swelling of Colima's upper cone began accelerating almost a year before its 20 November 1998 eruption. Applying Voight's method, successful predictions of the eruption's timing could have been made as early as 25 weeks ahead, they say.

On the other hand, the Rabaul caldera looked to have a good head of steam up when it reawakened in late 1983, says Robert Tilling of USGS Menlo Park. "You would have made a very precise forecast," he says, "but it would have been wrong." The populace was put on high alert in October 1984, but things promptly quieted down. It did not erupt until 1994. And in 1997 an intrusion beneath Long Valley drove an alarming crescendo of seismicity without reaching the surface.

Despite some encouraging developments with LP events and runaway activity, many volcanologists remain cautious on prediction. "There's no magic bullet here that will allow us to monitor volcanoes," says Tilling. "Even if monitoring data is good, it can't [always] distinguish between a large explosive event and a magma intrusion without an eruption." The rise of magma into a volcano is a complicated phenomenon, researchers say, so prediction will likely remain complicated even as observations and analyses continue to improve. Thus, although volcanologists can take pride in successful predictions that have saved tens of thousands of lives in recent decades, they cannot become complacent: The science and the technology, while impressive, have been tested on only a few volcanoes during short parts of their lives.

"There are so many unknowns," says Dan Miller. "We can't see the magma chambers or the plumbing system leading up into the volcano." And characteristics crucial to the successful ascent of magma such as gas content, viscosity, and mechanical resistance to ascent vary from volcano to volcano and even from one intrusion to the next. It makes weather forecasting look like a snap.

–RICHARD A. KERR

NEWS

# Living in the Shadow of Vesuvius

**Researchers at the oldest volcanological institute probe the inferno beneath their feet and wrestle with the politics of civil protection**

**NAPLES, ITALY**—From the snow-capped heights of Mount Vesuvius, the city looks like a densely woven blanket wrapped snugly around the volcano's slopes. From up here, with sunlight glinting off the broad crescent of the bay and far from the din of traffic, Naples and its surrounding towns look peaceful. This tranquillity makes it all the more difficult to imagine the worst-case scenario that volcanologists believe Vesuvius could inflict on Neapolitans: a repeat performance of the A.D. 79 eruption that famously destroyed the Roman towns of Pompeii and Herculaneum.

In this scenario, Vesuvius does not ooze lava and throw up a few rocks as Hawaiian volcanoes do. The pressure from below just builds and builds until it goes off like a bomb, sending a superheated column of rock, ash, and gases 20 kilometers into the sky. Within hours, this roiling mixture of gas and dust collapses back and roars down the slopes at up to 240 kilometers per hour toward the 600,000 people living around the base. These pyroclastic flows can blast through stone walls up to 3 meters thick and can flash-fry living matter. Beyond this annihilation zone, ash and volcanic rock fragments called tephra shower down over a wide area, quickly accumulating enough material—up to 500 kilograms per square meter—to collapse roofs, burying people alive.


**Ring of fire.** The urban sprawl of Naples is surrounded by the active volcanoes Vesuvius, Ischia, and the Campi Flegrei.

CREDIT: GIUSEPPE VILARDO/VESUVIUS OBSERVATORY

The good news for modern-day Naples is that, so far, there is no sign of such a head of steam building under the volcano—but just to be sure, it is being watched around the clock by the Vesuvius Observatory. Just shy of 158 years old, the observatory was the first volcanological station ever built. Its recent directors have turned it into an international center of research and a testing ground for urban volcanic risk management. Techniques and models developed by observatory scientists, often with international collaboration, are now used across the globe. But not surprisingly, says Grant Heiken, a volcanologist at Los Alamos National Laboratory in New Mexico, having responsibility for the most heavily populated volcano in the world adds real-world pressures to the science.

Over the past few years, while helping the government draw up an evacuation plan for the area, observatory scientists became involved in a bitter dispute, which split the Italian volcanology community, over how much warning Vesuvius would give of a major eruption. The academic mudslinging

has subsided, but observatory scientists are continuing to cajole colleagues in Italy and elsewhere to help them protect the millions of people living in Vesuvius's shadow.

**A volcanologist's paradise …**

Down in the city, volcanologist Giovanni Orsi chain-smokes behind mountains of paper on his desk at the observatory. "Vesuvius may be the most famous volcano, but it isn't the greatest threat to Naples," says Orsi. "People are more aware of it because it looks like a classic volcano. But the Campi Flegrei are far more dangerous," he adds, referring to the western side of the bay that is pockmarked with craters. This was the exit point of the largest eruption in Mediterranean history, 39,000 years ago, which launched at least 200 $km^3$ of magma—the equivalent of 200,000 solid-stone Empire State Buildings. That blast caused the area to collapse into the broad dish-shaped caldera that now cups the western part of Naples and the town of Pozzuoli.

The 1 million people at risk from a Campi Flegrei eruption would be far more difficult to evacuate. Add to that the volcanic island of Ischia just off the western arm of the bay, home to 50,000 and host to thousands of tourists in summer, and it becomes clear that Naples has the potential to produce a disaster on an epic scale. But for the time being, that possibility seems remote, and from a researcher's point of view, says Orsi, the area has long been "a paradise for volcanology." According to Paolo Gasparini, who was director of the observatory from 1971 to 1983, the first seismometer was invented here. Observatory scientists were also the first to record the swelling and sinking of the Campi Flegrei, now one of the main parameters in volcano surveillance. In 1999, the observatory's scientists moved from the slopes of Vesuvius into a new building downtown, and the following year the old observatory building was transformed into a volcanology museum.

The observatory's new generation of scientists would like it to be not just the oldest but the best institution of its kind. "My main objective is to increase the amount of research," says Giovanni Macedonio, the director since 2001, "in terms of the number of scientists and their productivity." Macedonio, a volcano modeler at the observatory since 1998, is promoting it as a nexus for both national and international research collaborations.

Some long-standing partnerships are already bearing fruit. Gasparini and his colleagues are putting the finishing touches on a decade-long Vesuvius project called TOMOVES that has produced the clearest picture yet of the "deep plumbing" of a volcano (*Science*, 26 November 1999, p. 1685). By using a technique called seismic tomography—setting off small explosions and analyzing the waves as they bounce back off different layers of rock—they are able to locate the limestone "floor" beneath Vesuvius, as well as the location of magma.

The same method is also being used to map the underlying structure of the Campi Flegrei in a project called SERAPIS. Researchers have now gathered the data, says project leader Aldo Zollo, a geophysicist at the University of Naples, and are beginning to analyze them. But some results are already jumping out, he says, such as the buried rim of a caldera likely formed by an eruption 12,000 years ago that encircles the entirety of the Campi Flegrei and loops right beneath the bottom of the bay.

The experiments have challenged some basic assumptions about magma systems. The classic view of a "ball of magma" beneath volcanoes is giving way to a variety of structures, including the broad sheets of magma that seem to exist beneath Vesuvius. "This model makes a lot of sense," says Jon Davidson, a volcanologist at the University of Durham, U.K. Davidson is coordinating ERUPT, an international project starting up this year that includes observatory scientists, focusing on the geochemical evolution of magma beneath Vesuvius and three other European volcanoes.

**Retired, but not forgotten.** After 155 years of vigilance on the volcano's slopes, the original Vesuvius Observatory is now a museum.

CREDIT: MAURO DI VITO/VESUVIUS OBSERVATORY

Apart from the straight geophysics, the Neapolitan area supports a better "marriage" of archaeology and volcanology than perhaps anywhere else, says observatory volcanologist Sandro de Vita. Orsi agrees: Last year, he authored a provocative paper arguing that the global impact of the Campi Flegrei eruption 39,000 years ago sparked the transition from Neandertal dominance to modern *Homo sapiens*. De Vita and his colleague Mauro Di Vito are also studying the more recent history of the area, concentrating on the coevolution of the volcanoes with the cultures of their human inhabitants. Evidence of human activities going back 6000 years remains frozen in time between layers of mud and ash from the frequent eruptions. In spite of these periodic catastrophes, the rich mud flats produced by the eruptions keep luring large groups of farming people back to the very same place.

**… And a volcanologist's purgatory**

Just west of Naples, ensconced within the dense town of Pozzuoli, lies an enormous yellow-white crater called the Solfatara. Enrica Marotta wrinkles her nose. "Yeah, it always stinks," she says. The rotten-egg smell of sulfurous gases billowing from cracks is generated by an aquifer interacting with magmatic gases several kilometers beneath the surface. Marotta, an observatory volcanologist, points out two glass bulbs connected to tubes emerging from the ground. These containers are used to measure the amount of carbon dioxide escaping from below. If the composition and rate of gas emissions change, it could presage another eruption.

Data like these, as well as from a vast array of seismometers, tiltmeters, and Global Positioning System devices arranged on and around the three Neapolitan volcanoes—and even on the bottom of the bay—all feed continuously into the observatory's surveillance system. The institution has always had two goals: monitoring the volcanoes for signs of danger while pursuing basic volcanological research. But recently, these parallel threads have been a source of discord.

The trouble began in 1994 when the national government appointed a committee of politicians together with scientists from the observatory and elsewhere to draw up an emergency plan in case Vesuvius erupts. Lucia Civetta, who was director of the observa-

tory from 1993 to 2001 and a member of the committee, says the intention was "to continually update the plan in response to new data and the movement of residents." But parts of the plan drew storms of criticism, directed at the observatory, that lasted right to the end of Civetta's directorship.

A major source of disagreement was how much warning the volcanoes can be expected to give before erupting, a key parameter for any emergency plan. Civetta and her colleagues maintain that the volcanoes are likely to give clear signals at least weeks in advance of eruption, including ground uplift, gas emissions, and characteristic seismic activity. But Giuseppe Luongo of the University of Naples, Civetta's predecessor as director of the observatory, and Flavio Dobran, an independent volcano modeler who worked with Macedonio in the early 1990s at the University of Pisa, argue that this is far from a safe bet. "[We] disagree with the Vesuvius emergency plan because it is impossible to predict an eruption 2 or 3 weeks before," asserts Luongo.

With political infighting worthy of Imperial Rome, the Italian volcanological community became polarized between the observatory and its critics. International volcanology meetings, usually friendly, laid-back events, were the scene of shouting matches and the circulation of polemical manifestos denouncing observatory scientists. Tension was increased by two nondestructive but nonetheless worrying earthquakes in the region in 1995 and 1999. Researchers outside Italy watched the struggle with chagrin. "[These conflicts] interfere with research and collaboration," says Davidson. Clive Oppenheimer of the University of Cambridge, U.K., says such disagreements are "inevitable, given the uncertainties in the Vesuvius problem."

For the past 2 years, at least in part because of Macedonio's diplomacy, the debate has cooled. In the meantime, Civetta—now at the University of Naples—Gasparini, and others have carried on, revising the Vesuvius emergency plan and incorporating measures for a Campi Flegrei eruption. The city and towns have been zoned in terms of risk from pyroclastic flows, ash, and tephra fallout, as well as mudslides and flooding. The observatory's efforts to educate the public seem to be paying off. After decades of growth, the population in Vesuvius's pyroclastic zone has begun dropping as people voluntarily move off the slopes. The objective, according to Gasparini, is to be able to evacuate these highest-risk areas in 2 to 3 days. Right now, he says, it would require at least 10 days' notice.

In spite of the acrimony, Civetta is sanguine about the Neapolitan volcanology community. "The conflict is part of the unique spirit of Naples," she says. For his part, Macedonio would like to see the *pax Neapolitana* last. He has spent a large part of his time consolidating research to cut down on overlap and melding the observatory into a national network for natural-disaster monitoring. "Now we have better data exchange and less conflicts," says Macedonio, who is tapping the U.S. Geological Survey for exchanges of data and techniques and is organizing a major symposium on Vesuvius at the old observatory in May.

The last time the skies over Naples were lit by eruptions from Vesuvius, the Campi Flegrei, and Ischia were in 1944, 1538, and 1301, respectively. Whether Naples will enjoy another century of peace, or suffer another explosive eruption, only time—and the continuing work at the observatory—will tell.

**–JOHN BOHANNON**

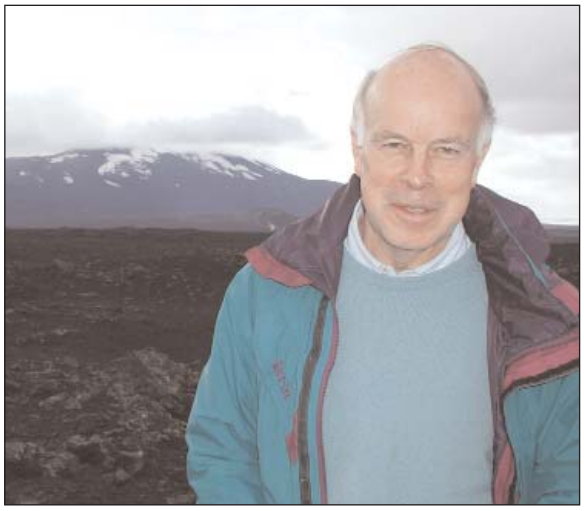
John Bohannon is a writer in Lyon, France.

NEWS

# Dr. Doom's Gruesome House Calls

**Peter Baxter's insights into the victims of volcanoes may help protect people from the bodily threat of eruptions as well as the potential long-term health effects of gases and ash**

Peter Baxter knows intimately the kind of injuries an angry volcano can inflict. On 14 January 1993, the occupational physician at the University of Cambridge, U.K., was attending a workshop in a town at the foot of Galeras, a volcano in southern Colombia. While he was visiting villages on the flanks, assessing the potential danger from avalanches of hot ash and gas, the volcano erupted. Fearful of getting caught in a pyroclastic flow—and worried about a field party that had been headed for the crater—Baxter rushed back into town. "We knew something terrible had happened," he recalls.



**Homicide detective.** Peter Baxter, here in front of Iceland's Mount Hekla, is known for his studies of how volcanoes kill.

CREDIT: CLIVE OPPENHEIMER

At the local hospital, Baxter helped treat the victims. "It was awful," he says. Galeras had claimed a friend of Baxter's, volcanologist Geoff Brown, and several colleagues. Yet, he says, "all the time I was trying to understand what was going on." That is Baxter's specialty: learning how volcanoes kill people. Most of the bodies were blown to pieces, but he was able to observe one autopsy and later interviewed the survivors. His report on the casualties, published in the *Journal of Volcanology and Geothermal Research* in 1997, offered those who work on volcanoes some seemingly obvious, but necessary, lessons. For starters: Wear hard hats and heat-resistant clothing.

"When scientists work on an active volcano, it's a very thrilling, adrenaline-pumping act. It's very easy to forget the risks you're running and to take more risks," says Steve Sparks, a volcanologist at Bristol University, U.K. Thanks in part to Baxter's work, he says, "people have a much better appreciation of just how terrible the deaths can be." In the wake of the Galeras tragedy, Sparks says, there is "a much greater awareness of risks and sensible precautions."

Baxter's pioneering work as one of the first physicians to study volcanic hazards, along with his penchant for illustrating talks with slides of corpses, has earned him the nickname "Dr. Doom" among volcanologists. His gruesome repertoire ranges from puzzling out the flesh-searing effects of pyroclastic flows to probing whether chronic ills may be linked to long-term ash exposure. The goal, he says, is to find ways to reduce loss of life during and after eruptions.

Baxter got hooked on volcanoes 2 decades ago, while he was a medical epidemiologist at the U.S. Centers for Disease Control and Prevention in Atlanta. As part of a team that investigated the health implications of disasters, he went to Mount St. Helens soon after it erupted on 18 May 1980.