PERSPECTIVES: PINATUBO ERUPTION

"To Make Grow"

C. G. Newhall, J. A. Power, R. S. Punongbayan

Mount Pinatubo's enormous eruption on 15 June 1991 and its muddy aftermath made the volcano's name—"to make grow"—seem singularly inappropriate. But 10 years after the eruption (*1*), growth has again overtaken destruction. New towns and industries are replacing those that were buried, and plants and animals are filling old and new ecological niches.

Volcanology has also grown. For the first time, modern instruments captured the signatures of a sulfur-rich, explosive, caldera-forming eruption before, during, and after the eruption (see the first figure). Some concepts were affirmed; others were shredded and swept away. Some puzzles were solved; others remain.

Short-term coupling between regional earthquakes and volcanism is enigmatic and often dismissed. Yet, after sleeping for 500 years, Pinatubo awoke just hours after a magnitude 7.8 earthquake along the Philippine fault, 100 km northeast of the volcano, in July 1990. During the interval between the earthquake and Pinatubo's 1991 eruption, data are too sparse to determine the exact relation between the two. The detection of long-period earthquakes 35 km beneath Pinatubo before the eruption and the nature of early-erupted rocks suggest fresh basaltic magma from Earth's mantle (*2*, *3*). Fault slip subjected the crust beneath Pinatubo to static compression of 1 bar and could have squeezed preexisting magma upward (*4*).

Pinatubo produced between 15 and 20 megatons of SO_2, about 20 times more than could have been dissolved in the volume of the erupted magma (see the second figure) (*5*). It thus confirmed an earlier inference from El Chichón's eruption in 1982 that CO_2, H_2O, SO_2, and other volatiles could accumulate in magma far in excess of saturation, forming a discrete bubble phase at least 5 to 10 km beneath Earth's surface, not just in the top few kilometers of the crust (*6*–*8*). At Pinatubo, 200 to 1000 megatons of these supercritical volatile bubbles accumulated in the uppermost part of a large (~100 km^3), long-lived, SiO_2-rich dacitic magma reservoir. Work since the Pinatubo eruption suggests that many, perhaps all, large explosive eruptions are of magma that contains a substantial bubble phase at depth.

C. G. Newhall is with the U.S. Geological Survey (USGS), University of Washington, Seattle, WA 98195, USA. E-mail: cnewhall@usgs.gov J. A. Power is at the USGS, Alaska Volcano Observatory, Anchorage, AK 99508, USA. E-mail: jpower@usgs.gov R. S. Punongbayan leads the Philippine Institute of Volcanology and Seismology (PHIVOLCS), Quezon City 1101, Philippines. E-mail: rsp@philonline.com.ph

CREDIT: (TOP) R. P. HOBLITT; (BOTTOM) T. J. CASADEVALL

Before and after. **(Top)** Pre-eruption Mount Pinatubo on 9 June 1991, viewed from the northeast. The ridge in the foreground may have been the wall of a prehistoric caldera that was only slightly larger than that which formed in 1991. **(Bottom)** Summit caldera on 1 August 1991, viewed from the northeast. The caldera formed by collapse during the 15 June 1991 eruption. The ash cloud in the image stems from a small explosion that had just occurred. From (*2*).

In theory, basaltic and dacitic magma should not mix because of their different viscosities: Basaltic magma is fluid, whereas dacitic magma is highly viscous. But Pinatubo confirmed such mixing on a time scale of days to weeks (*9*, *10*). A relatively small plume of basaltic magma rose into the large, crystal-rich dacitic magma reservoir that had resided for thousands of years about 5 to 15 km beneath Pinatubo. Cooling and crystal growth in the basalt and heating and volatile exsolution in the dacite brought viscosities close enough for the magmas to mix in a ratio of 1 part basalt to 2 parts dacite.

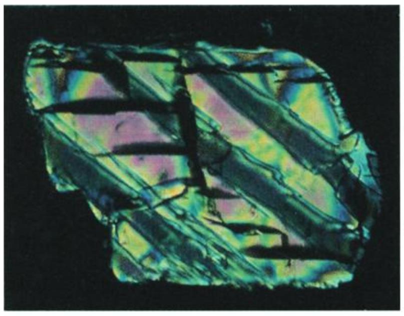
By 7 June 1991, the buoyant, mixed magma had punched its way up through the large dacitic reservoir and overlying crust and begun to form a small lava dome. This vanguard magma lost so much of its gas as it worked its way to the surface that it oozed sluggishly onto the surface. But once the pathway was cleared, magma could rise faster and thereby approach the surface with its full measure of gas and explosive potential. All residents of the area were evacuated. On 12 June, gas-charged magma reached the surface and produced a 20-km-high mushroom-shaped cloud.

The geologic record of previous eruptions warned that an even larger eruption was likely. We were anxious to learn what geophysical or geochemical unrest might be diagnostic of such a large eruption. Yet from 12 to 14 June, successive eruptions became smaller (*11*). Pinatubo's unrest differed from that of many smaller eruptions only in a sharp increase in the number and magnitude of shallow, long-period earthquakes on 14 June, just 1 day before the dramatic eruption of 15 June (*12*). The precursor data from Pinatubo, and a power-law relation of magnitude and frequency among other eruptions (*13*), suggest that big eruptions begin as small ones, just as with earthquakes, sand pile avalanches, and many other natural phenomena (*14*, *15*).

The volume of magma erupted on 15 June 1991 was the second largest of the 20th century, after that of Katmai/Novarupta in Alaska in 1912. Within the conduit, 10 to 20% of the magma was subjected to such intense shear that feldspar and other crystals were shredded even in their liquid host, so finely that they can be identified only in an electron microscope (*9*, *16*).

The eruption formed a mushroom-shaped cloud with a diameter of 500 km; at its crown, the cloud was 35 to 40 km above sea level. In little more than 3 hours, Pinatubo erupted about 5 km^3 of magma. Slightly more than half the magma formed pyroclastic flows (fast-moving avalanches of hot rock fragments and volcanic gases), and the remainder fell in a continent-scale blanket of ash and coarser particles.

Contrary to early models of plinian eruptions—explosive events that form enormous dark columns of tephra and gas high into the stratosphere—pyroclastic flows and fall occurred more or less simultaneously from different parts of the eruption column, fall from the top and flow from the base (*17–19*). The thickest and most voluminous pyroclastic flow deposits were produced by relatively low-energy fountains and spill-over from a widening crater; thinner, more widespread pyroclastic surge deposits were produced by collapse of the high eruption column. Ash began its journey in the tall eruption column and in clouds winnowed from the pyroclastic flows; it fell to Earth from Luzon to India.



Signs of sulfur. This anhydrite crystal in the pumice is indicative of a very sulfur-rich magma.

CREDIT: J. S. PALLISTER

Pinatubo nearly exhausted itself on 15 June 1991, vented gently for a few months thereafter, and ended its eruption with a lava dome in July to October 1992. Another batch of basalt had arrived from depth and mixed with dacite, but without the long-term accumulation of volatiles in the dacite, the result was a sluggish last grunt.

As subsurface activity waned, that on the surface remained extremely rapid. Torrential tropical rains washed ~60% of the 1991 deposit off the volcano and set a new world record for annual sediment yield per square kilometer of watershed (*20–22*). Fine ash on steep valley walls was the first to disappear. Rivers then cut deep channels, fed from thousands of tributary rills. Water and erosion triggered explosions, avalanches, and renewed flow of hot pyroclastic debris (*19*). Valleys filled in 1991 with 200 m of fresh deposit were soon deeper than before the eruption (*23*). In a single typhoon, rapid runoff and erosion might deepen and widen the upper reaches of channels by tens of meters and dump tens of millions of cubic meters of hot debris flow on downstream communities. The economic losses and human displacements resulting from these posteruption hydrologic events exceeded those of the 1991 eruption.

While tracking erosion and deposition for hazard assessments, geologists also addressed more fundamental questions. Pinatubo's rivers provide an exceptional natural experiment on river response to sediment loading. High sediment loading led to efficient bedload transport, as in arid regions (*22*). Rocks rolling in flow shallower than their diameters are a geomorphic extreme that points to sediment supply as the main variable in whether stream beds move grain-by-larger-grain or all at once (*24*).

As sediment-laden flash floods (lahars) waned in the late 1990s, the new caldera lake was still changing rapidly. Beginning as a hot puddle in 1991 that could barely survive evaporation and sediment influx, the lake firmly established itself in 1992. By the time a spillway was dug in 2001, the lake was 110 m deep and showing dramatic changes in thermal structure and chemistry that will be fascinating to watch in coming years.

Pinatubo's eruption helped volcanology to grow. It also demonstrated that relatively small investments in pre-eruption monitoring can yield big dividends in scientific insights and life-saving warnings.

References and Notes

1. Ten years of science from the 1991 Mount Pinatubo volcano eruption, American Geophysical Union Fall Meeting, San Francisco, CA, 10 to 14 December 2001.
2. C. G. Newhall, R. S. Punongbayan, Eds., *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines* (PHIVOLCS, Quezon City, and Univ. of Washington Press, Seattle, WA, 1996). The full text of the book is available online at http://pubs.usgs.gov/pinatubo.
3. R. A. White, in (*2*), pp. 307–327.
4. B. C. Bautista *et al.*, in (*2*), pp. 351–370.
5. G. J. S. Bluth *et al.*, *Geophys. Res. Lett.* **19**, 151 (1992).
6. J. F. Luhr *et al.*, *J. Volcanol. Geotherm. Res.* **23**, 69 (1984).
7. T. M. Gerlach *et al.*, in (*2*), pp. 415–433.
8. P. J. Wallace, *J. Volcanol. Geotherm. Res.* **108**, 85 (2001).
9. J. S. Pallister *et al.*, in (*2*), pp. 687–731.
10. M. J. Rutherford, J. D. Devine, in (*2*), pp. 751–766.
11. R. P. Hoblitt *et al.*, in (*2*), pp. 457–511.
12. D. H. Harlow *et al.*, in (*2*), pp. 285–305.
13. T. Simkin, L. Siebert, *Volcanoes of the World* (Geoscience Press, Tucson, AZ, 1994).
14. P. Bak, *How Nature Works* (Oxford Univ. Press, Oxford, 1996).
15. M. Buchanan, *Ubiquity* (Crown Publications, New York, 2000).
16. M. Polacci *et al.*, *Bull. Volcanol.* **63**, 83 (2001).
17. W. E. Scott *et al.*, in (*2*), pp. 545–570.
18. M. Rosi *et al.*, *Bull. Volcanol.* **62**, 549 (2001).
19. R. C. Torres, thesis, University of Hawaii (2001).
20. R. J. Janda *et al.*, in (*2*), pp. 107–139.
21. J. V. Umbal, *J. Geol. Soc. Philippines* **52**, 1 (1997).
22. S. K. Hayes, D. R. Montgomery, C. G. Newhall., *Geomorphology*, in press.
23. R. S. Punongbayan *et al.*, in (*2*), pp. 21–66.
24. D. R. Montgomery *et al.*, *Geology* **27**, 271 (1999).

25. USGS work with PHIVOLCS is made possible by the Volcano Disaster Assistance Program of the Office of Foreign Disaster Assistance at the United States Agency for International Development (USAID).

PERSPECTIVES: PINATUBO ERUPTION

The Climatic Aftermath

Alan Robock

The eruption of Mount Pinatubo on Luzon Island, Philippines (15.1°N, 120.4°E), on 15 June 1991 produced the largest stratospheric volcanic aerosol cloud of the 20th century (*1*). In just a few days, about 20 megatons of SO_2 was injected into the stratosphere (*1*). The effect of the eruption on global climate could be felt for years. Surface air temperatures over Northern Hemisphere (NH) continents were cooler than normal by up to 2°C in the summer of 1992 and warmer than normal by up to 3°C in the winters of 1991–92 (see the figure) and 1992–93.

A recent conference (*2*) highlighted the intense research activity in the 10 years since the eruption. From ozone destruction to global changes in atmospheric circulation, the impacts of explosive volcanic eruptions on weather and climate have been elucidated (*3*). Insights into the effects of volcanic eruptions on surface temperatures have helped attribute the warming of the past century to anthropogenic greenhouse gas emissions. Better seasonal forecasts should be possible after the next major eruption.

In the 2 years after the Pinatubo eruption, data from the Total Ozone Mapping Spectrometer (TOMS) and other sources showed unusual O_3 decreases at mid-latitudes and NH high latitudes (*4–7*). Column O_3 was reduced by about 5% in mid-latitudes (*4–6*). The ozone was destroyed by the same mechanism that causes the ozone hole over Antarctica in October each year. Sulfate aerosols produced by Pinatubo and injected into the lower stratosphere provided surfaces for hetero-

The author is in the Center for Environmental Prediction, Department of Environmental Sciences, Cook College, Rutgers University, New Brunswick, NJ 08901, USA. E-mail: robock@envsci.rutgers.edu