REPORT:
The 1991 Eruptions of Mount Pinatubo, Philippines


Introduction

Recognition of the volcanic unrest at Mount Pinatubo in the Philippines began when steam explosions occurred on April 2, 1991. The unrest culminated ten weeks later in the world's largest eruption in more than half a century. Volcanologists of the Philippine Institute of Volcanology and Seismology (PHIVOLCS), joined in late April by colleagues from the U.S. Geological Survey (USGS), successfully forecast the eruptive events and their effects, enabling Philippine civil leaders to organize massive evacuations that saved thousands of lives. The forecasts also led to the evacuation of Clark Air Base (U.S. Air Force), located just east of the volcano. Nevertheless, coincidence of the climactic eruption on June 15, 1991, with a typhoon led to more than 300 deaths and extensive property damage, both caused primarily by the extraordinarily broad distribution of heavy, water-saturated tephra-fall deposits. Runoff from monsoon and typhoon rains is eroding and redistributing the voluminous pyroclastic deposits emplaced during the eruption. The resulting lahars, floods, and sedimentation have exacerbated the already severe social disruption and will be an enormous recurring problem in future years.

Mount Pinatubo is one of a chain of composite volcanoes (fig. 1 and 2) known as the Luzon volcanic arc. The arc parallels the west coast of the Island of Luzon and reflects eastward-dipping, subduction along the Manila Trench to the west. Mount Pinatubo is among the highest peaks in west-central Luzon. Its former summit (fig. 3) lay at the 1,745-m crest of a 3-km-diameter dacite dome formed during, an earlier eruptive period. The volcano's flanks, made up largely of fragmental (pyroclastic) deposits from prehistoric eruptions, were intricately dissected and sheathed in tropical vegetation (fig. 4 and 5).

Before the eruption, about 15,000 people lived in small villages on the volcano's flanks. A much larger population, about 500,000, lives in cities and villages on broad, gently sloping alluvial fans surrounding, the volcano. Clark Air Base is at the east base of the volcano, within 25 km of the summit, and Subic Bay Naval Station is about 40 km to the southwest.
Precursory Activity

During the afternoon of April 2, 1991, villagers were surprised by a series of small explosions from a 1.5-km-long line of vents high on the volcano and near the north flank of the summit dome. The explosions, which occurred over a period of several hours, formed a line of new craters (fig. 6), stripped the vegetation from several square kilometers, deposited a meter or more of poorly sorted rock debris near the vents, and dusted villages 10 km to the west-southwest with ash. By the next morning, a line of vigorous new fumaroles on the northwest flank of the summit dome (fig. 7) extended southwest from the original line of explosion craters. At the request of civil officials, about 5,000 people promptly evacuated a zone of 10-km radius around the summit of Mount Pinatubo.

Within a few days scientists from PHIVOLCS installed several portable seismographs near the northwest foot of Mount Pinatubo and began recording small earthquakes at a rate of about 40 to 140
per day. In late April, PHIVOLCS was joined by a group from the USGS, and the joint team installed a network of seven seismometers (fig. 8) with telemetry to an apartment at Clark Air Base that served as the initial home for the Pinatubo Volcano Observatory (PVO). At PVO, a network of powerful personal computers was established for gathering and processing seismic data from the new network (fig. 9).

Concurrently with establishment of seismic monitoring, the PVO team undertook a rapid geologic reconnaissance to determine the style and extent of past eruptions and to provide the basis for a volcano-hazard map (fig. 10). This reconnaissance showed that activity at Mount Pinatubo during the past few thousand years has been dominated by large explosive eruptions, each of which generated voluminous pyroclastic flows (hot, fluidized avalanches of gas-charged volcanic debris). At high speed the flows swept down the volcano's flanks and left behind thick, generally poorly consolidated pumiceous fragmental deposits. Outcrops of these pyroclastic-flow deposits (fig. 5) were found as far as approximately 20 km from the summit. Three previous radiocarbon ages plus six new ones on charcoal from these deposits indicated that the three most recent major eruptions had occurred approximately 3,000, and 4,400–5,100 years ago. In addition, debris-flow deposits along stream valleys extending far beyond the foot of the volcano indicated that erosion of pyroclastic-flow deposits on the volcano's flanks had generated lahars and sediment-laden floods that redistributed the pyroclastic debris over the lowlands surrounding Mount Pinatubo.

The PVO team used the hazard map and analysis of the volcano's unrest to acquaint civil-defense officials and military commanders with the potential hazards associated with Pinatubo's awakening. A preliminary version of a video tape depicting volcano hazards, produced by filmmaker and geologist Maurice Kraft, helped the team enormously to explain hazards that were unfamiliar in an area lacking historical eruptions. Tragically, Maurice and Katia Kraft were killed on June 3, 1991, together with others, in the eruption of Mount Unzen in Japan. Communication of information about the progress of Mount Pinatubo toward eruption was simplified by the system of hazard-alert levels shown in table 1.

Numerous small earthquakes of the type that record fracturing of brittle rock (fig. 11A) continued through May. The earthquakes were generally too small to be felt, except very locally. For 1,800 earthquakes located between May 7 and June 1, magnitudes were less than 2.5. These earthquakes were strongly clustered in a zone between 2 and 6 km deep, located about 5 km north-northwest of the volcano's summit (fig. 12). Possibly, they recorded adjustments of the earth's crust to stresses generated by growth or pressurization of a shallow body of magma.

Measurements of the rate of emission of sulfur dioxide (SO2) from the fumaroles near the volcano summit provided additional evidence that fresh magma was accumulating beneath the volcano. Successive airborne measurements showed that the sulfur-dioxide flux increased from about 500 tons/day when the first measurement was made on May 13 to more than 5,000 tons/day on May 28. When considered in combination with the sustained seismicity, these data suggested that magma beneath Pinatubo had risen to a level sufficiently shallow to promote substantial degassing of its dissolved volatile components.

About June 1, a second cluster of earthquakes began to develop between the surface and a depth of 5 km, in the vicinity of the fuming vents approximately 1 km northwest of the summit. These earthquakes may have recorded fracturing of rock as rising magma began to force open a conduit between the magma reservoir beneath the volcano and the surface. At the same time, the SO2-emission rate was declining from the peak measured on May 28; the rate was about 1,800 tons/day on May 30 and June 3, and about 260 tons/day on June 5. The latter flux was about one-twentieth of the earlier (May 28) maximum. The reduction in SO2 flux suggested that the passages through which gas escaped to the surface might have become sealed and raised concern about the possibility of rapidly increasing pressurization and an imminent explosive eruption. A likely possibility is that the sealing
agent was the degassed or freezing tip of a plug of magma rising toward the surface along the zone of fractures that supplied gas to the fumaroles.

A small explosion early on June 3 initiated an episode of increasing volcanic unrest characterized by intermittent minor emission of ash, increasing seismicity beneath the vents, and episodes of harmonic tremor (a prolonged rhythmic seismic signal believed to be related to sustained subsurface movement of magma or volatiles). In response to the growing restlessness of Mount Pinatubo, PHIVOLCS issued an alert-level 3 announcement on June 5, indicating the possibility of a major pyroclastic eruption within two weeks (table 1).

**Dome Extrusion**

An electronic tiltmeter high on Mount Pinatubo began to show a gradually increasing outward tilt early on June 6. Seismicity as well the outward tilt continued to increase until late afternoon on June 7, when an explosion generated a column of steam and ash 7 to 8 km high. After the explosion, seismicity decreased and the increase in outward tilt stopped. PHIVOLCS promptly announced an increase to alert-level 4 (eruption possible within 24 hours) and recommended additional evacuations from the volcano's flanks.

Such outward tilt and increased shallow seismicity are likely manifestations of development of a shallow conduit for delivery of magma to the surface. Indeed, establishment of a magma conduit to the surface was confirmed the following morning when observers identified a small (100-150 m diameter) lava dome close to one of the fuming vents in a canyon near the source of the Maraunot River, northwest of the summit. The emission of a persistent, low, roiling ash cloud from around the dome began at this time (fig. 13).

The period from June 8 through early June 12 was marked by continuing, weak ash emission and episodic harmonic tremor. On June 9, PHIVOLCS raised the alert level to 5 (eruption in progress). The radius of evacuation was extended to 20 km, and the number of evacuees increased to about 25,000. Generally, the ash cloud rose to the crest of the volcano, where the east wind sheared off the top of the cloud, carrying it westward. A 40-minute burst of intense seismic tremor that began at 0301 (local time) on June 12 may have been related to an increase in the vigor of ash emission. Daylight that morning showed a plume of steam and ash rising about 3 km above the volcano.

On June 10, approximately 14,000 U.S. military personnel and their dependents evacuated Clark Air Base. They traveled by motorcade to Subic Bay Naval Station, from which most eventually returned to the United States. All remaining, military aircraft except for three helicopters also left Clark that day. About 1,500 U.S. military personnel, sufficient to provide security and basic maintenance, remained behind. The PVO team of volcanologists also remained on the base. However, for an increased margin of safety, PVO moved its operations to a building near the east end of Clark Air Base, about 25 km from the volcano's summit, and continued round-the-clock monitoring there.

**Discrete Large Explosive Eruptions**

The first major explosive eruption began at 0851 on June 12, generating a column of ash and steam (fig. 14, 15) that rose to 19 km according to the weather-radar operators at Subic Bay Naval Station. Although, as noted above, a burst of seismic tremor had occurred several hours earlier, no specific seismic precursor immediately preceded this event; a high-amplitude seismic signal and the rise of the eruptive column seemed to begin simultaneously. Interpretation of the seismic records indicated that this event lasted about 35 minutes. Ash was transported southwestward past communities north of Subic Bay, and small pyroclastic flows traveled northwest and north from the vent in the headwaters of the Maraunot River. Six hundred of the remaining, 1,500 military personnel at Clark Air Base were
evacuated. The general evacuation radius was extended to 30 km, and the total number of evacuees increased to at least 58,000.

This was the first of a series of brief explosive eruptions that occurred with increasing frequency from June 12 through 15 (fig. 16, 17). As weather conditions were better on the morning of June 12 than for any of the subsequent explosive eruptions, this first event was the one best seen (visibility was also reasonably good for the eruptions of 0841 on June 13, and 1309 on June 14). Many of the later events were not directly observed at all, because of clouds, darkness, or both. Thus, many of the events were identified at the time only from the seismic signatures that accompanied them and observations of ash clouds by military weather-radar operators. Commonly, volcanologists at PVO recognized an incoming explosion signal on seismographs and contacted the radar observers for confirmation and tracking of eruption-column development.

Unlike the initial explosion at 0851 on June 12, the eruptions at 2252 on June 12 and 0841 on June 13 were preceded by 2- to 4-hour swarms of long-period earthquakes, which enabled the PVO team to issue explicit advance warnings. The pattern seemed to repeat with the resumption of frequent long-period earthquakes during the evening of June 13, and warning of another imminent explosion was given. None occurred as expected, however, as the pattern was changing to one in which long-period earthquakes continued hour after hour (fig. 11 B).

In the early morning of June 14, a brief period of clear weather gave a good view of Mount Pinatubo. In spite of the intensifying swarm (fig. 18) of long-period earthquakes, no visible ash and very little fume was being emitted. After more than 28 hours with no detectable explosive activity, however, the pace quickened during the afternoon and evening of June 14 with a series of brief large explosive eruptions that continued through the night and into the morning of June 15. Given the ongoing nature of this explosive activity, no warnings of individual explosions were given. During this series, evidence grew that the eruption clouds were issuing from two or more vents. PVO geologists north of the volcano saw two or more ash sources during the 1410 eruption, and a thermal-infrared scanner at Clark Air Force Base recorded possible multiple vents during the 2320 eruption.

Limited visibility at dawn on June 15 enabled PVO observers to see the ash cloud of the 0555 eruption. Instead of forming a tall narrow column like those seen on June 12 and 13, this eruption cloud was relatively low (radar operators reported a maximum height of 12 km) and had spread outward from the summit (fig. 19), suggesting laterally- rather than vertically-directed explosions. Concern that these developments could presage collapse of the volcano's summit and ensuing massive lateral blasts and pyroclastic flows prompted the evacuation of most of the remaining U.S. Air Force personnel from Clark Air Base.

Throughout June 14, winds had blown all the ash west to southwest from Mount Pinatubo, causing ash fall in westernmost Luzon and over the South China Sea. However, wind patterns changed early on June 15, perhaps in response to an approaching typhoon, Yunya. The view of the 0555 eruption cloud was quickly obscured by ash and rain that fell on Clark Air Base and over central Luzon throughout the day. Repeated explosions through midday were each followed 30-40 minutes later by total darkness at PVO, as winds blew ash eastward over Clark.

**Climactic Eruption**

By 1430 on June 15, all seismometers but one were not working (most were victims of pyroclastic flows), and ash with pumice fragments as large as 4 cm in diameter was falling at PVO. In retrospect it seems probable that the falling pumice and the essentially continuous fluctuation in atmospheric pressure evident in the barograph record (fig. 17) were indicators that the climactic eruption was then under way. Satellite data showed that the climactic eruption cloud rose high into the stratosphere and spread, umbrella-like, more than 200 km in all directions. Virtually blind owing to destruction of the
seismic net and near-zero visibility, the PVO staff and the few remaining Air Force personnel joined the remainder of the Clark Air Base evacuees at the Pampanga Agricultural College, about 38 km east of the summit of Mount Pinatubo on the western slopes of another volcanic cone, Mount Arayat.

The first of a series of relatively strong earthquakes (magnitudes 4.8 to 5.6) occurred at 1539, and were felt repeatedly through the night by the evacuees at the agricultural college. Volcanologists attributed the earthquakes to structural adjustment of the volcanic edifice. Unfortunately, none of the PVO seismometers functioned during the night because of the evacuation. When seismic recording was reestablished the next day, the only surviving seismometer recorded more than 150 earthquakes larger than magnitude 1.5 per hour. This rate declined rapidly (figure 18), and by the end of June earthquake counts were 10-20 per hour. For months after the eruption, high-frequency tectonic earthquakes (fig. 1-1C) dominated the seismic records, indicating continuing adjustment of the volcano and the earth's crust beneath it (fig. 12B) to the dramatic changes of mid-June.

The Effects of the 1991 Eruption

The climactic eruption destroyed the volcano's original summit. In its place is a 2-km-diameter caldera (fig. 20), the center of which is offset 1 km northward from the pre-eruption summit. The caldera probably formed from collapse of the volcano's summit on June 15 during the period of abundant large earthquakes in response to withdrawal of a large volume of magma from the reservoir beneath the volcano.

The PVO team returned to Clark Air Base early on June 16. Many centimeters of tephra (silt-, sand-, and pebble-size debris from the eruption cloud) had fallen over central and western Luzon, forming a heavy snow-like blanket (fig. 21) that had been saturated by rain. This widespread tephra blanket of June 15 has a remarkably consistent internal stratigraphy (fig. 22) - a basal gray silt-size ash deposit overlain by a coarse pumice-fall deposit that grades from pebble size at its base to sand size at its top. The basal fine-grained ash accumulated during the morning, and the overlying pumice-fall unit accumulated during the afternoon, when pumice fragments were failing at PVO.

A rapid survey of the tephra-fall deposits before the annual monsoon rains began in July showed that they range upward in thickness to more than half a meter high on the volcano (fig. 23), and that the thickest tephra deposits lie to the southwest. A preliminary estimate is that 0.8 cubic km of tephra mantles west-central Luzon, and that even more fell into the South China Sea; indeed, tephra dusted parts of Indochina more than 1,200 km away. The estimated total volume of tephra-fall deposits from the Mount Pinatubo eruption is approximately 2-4 cubic km.

Tephra-fall deposits 5 cm or more thick covered a land area of about 4,000 sq km surrounding Pinatubo. These deposits buried crops, and the weight of the rain-saturated tephra, no doubt with assistance from repeated intense seismic shaking and buffeting by wind, caused numerous roofs to collapse in the Philippine communities around the volcano and on the two large U.S. military bases (fig. 24, 25). More than 300 people died during the eruption, most of them from collapsing roofs. Without typhoon Yunya, the death toll might have been far smaller. The typhoon brought heavy rain, which saturated the accumulating tephra, and strong winds that contributed to the widespread dispersal of tephra falling from the broad stratospheric eruption cloud.

Pyroclastic flows had stripped vegetation from broad areas around Mount Pinatubo and had partly filled valleys on all sectors of the volcano with thick hot deposits of ash and coarser pumice fragments (figs. 2, 26, 27). These deposits, which extend as far as 16 km from the summit, were emplaced from rapidly moving, gas-inflated avalanches of hot volcanic ejecta. Heavier than air, these ash-rich currents sought topographic lows; thus, the deposits occur largely in the valleys. Although thin or absent on the upper slopes, the pyroclastic-flow deposits are locally as thick as 220 m and average 30-50 m thick.
over extensive valley areas. The volume of pyroclastic-flow deposits estimated from the preliminary mapping represented in figure 2 is 5-7 cubic km.

Absence of the pumice-fall deposit on the surface of the pyroclastic-flow deposits indicates that the distal and uppermost parts of the pyroclastic-flow deposits accumulated later than the mid-afternoon pumice-fall deposit. Apparently these parts of the pyroclastic-flow deposits were emplaced during the period of intense earthquakes believed to have been coincident with caldera collapse.

Pumice blocks abound in the pyroclastic-flow deposits. There are two main types, one with abundant large crystals and the other with few if any large crystals. Both types are also abundant among the pumice fragments in the tephra-fall deposits. Their abundance and freshness suggest that they are solidified samples of the erupted magma, not fragments of older volcanic rock. Interestingly, these two very different looking pumice types are nearly identical in composition (table 2); they are dacite much like the pumice erupted from Mount St. Helens on May 18, 1980. Apparently the difference in crystal content between the two Mount Pinatubo pumice types reflects differing thermal histories for different parts of the same magma reservoir.

Interestingly, tephra from the June 12 eruption contains fragments of andesite scoria as well as dacite. The andesite contains mineral grains of compositions that normally occur in basalt, not in andesite or dacite, and its chemical composition (table 2) could reflect its formation by mixing of a basalt magma with the dacite magma that erupted later in the eruption sequence. This idea raises the interesting possibility that the 1991 eruptions were triggered by the intrusion of hot basalt magma into a shallow reservoir of cooling dacite magma left over from the previous eruptive episode several centuries ago.

Partial filling of the valleys on Mount Pinatubo by the thick, loose, ash-rich pyroclastic-flow deposits thoroughly disrupted the drainage network that had become established in the 4-5 centuries since the previous eruption. Thus runoff from heavy rains associated with typhoon Yunya on June 15 sought to reestablish drainageways by flushing the accumulating hot sediment from the valleys draining the volcano's slopes. This generated disastrous lahars (volcanic mudflows) and floods while the eruption was still in progress. These lahars and floods followed the many drainages that carry runoff from Mount Pinatubo and began redistributing the new volcanic deposits in the surrounding lowlands (fig. 28). Eyewitness accounts and stratigraphic relations indicate that lahars of June 15 were generated before, during, and following the mid-afternoon pumice fall; distal lahar and flood deposits were generally emplaced after the pumice-fall episode.

The Abacan River lahars of June 15 were especially damaging; apparently burial of the low divide at the head of the Abacan River by new pyroclastic-flow deposits (figs. 2, 26) diverted the Sacobia River headwaters into the Abacan. The resulting lahars that day severely eroded the Abacan River channel through Angeles City, undercutting the banks so as to destroy homes and all of the bridges connecting the north and south parts of the city. Farther downstream they buried the major north-south highway (North Expressway) through central Luzon and caused at least ten fatalities.

The climactic eruption apparently left a wide-open vent system, for ash billowed continually (fig. 20) from vents in the caldera for about another month. It formed a column that generally rose above the volcano, and at times was as high as 15 km. Easterly to southwesterly winds caused persistent fall of very fine powdery ash in communities from west to northeast of the new summit caldera.

Episodic bursts of increased seismic tremor, apparently correlated with increased vigor of ash emission, occurred a few times per day during late June and early July. For about a week, these events were periodic at intervals of 6 to 8 hours. By early August, eruptions in the caldera had stopped, and the monsoon rains had formed a shallow caldera lake.
Beginning, in July, the annual monsoon rains generated repeated lahars and floods, which progressively buried towns and agricultural land (figs. 23, 29), destroyed homes and bridges, and frequently cut roadways. Economic devastation and social disruption from those lahars were severe. However, warnings provided by PVO based on real-time analysis of data from telemetered rain gages and flow sensors-instruments similar to seismometers that detect the high-frequency ground vibrations caused by passing lahars- have helped to minimize the loss of human life from the lahars. Generation of destructive lahars is likely to continue for years before relatively stable drainageways are reestablished. During this period, the repeated destruction of homes, farms, and infrastructure by lahars and the disruption of human activities caused by damage and traumatic evacuations will no doubt represent the eruption's greatest social impact.

Conclusions

The 1991 eruption of Mount Pinatubo was the world's largest known eruption in more than half a century. Calculations based upon the volume of erupted products indicate that about 3-5 cubic km of dense magma—approximately ten times the volume of magma involved in the 1980 eruptions of Mount St. Helens—supplied the Mount Pinatubo eruption. Although an unfortunate number of lives was lost, thousands of casualties were averted by timely warnings and evacuations. Such effective warning of a volcanic crisis is a direct consequence of experience acquired—much of it since the eruption of Mount St. Helens in 1980—in volcano monitoring and volcano-hazard assessment. This eruption has highlighted the importance of a rapid and energetic response to volcanic unrest and the significance of effective communication of hazard information to public officials.

The eruption of Mount Pinatubo exemplifies the way volcanoes can wreak sudden widespread havoc on the lives of people who live near them. However, unlike some other kinds of natural hazards, volcanoes commonly give a significant advance warning. With sufficient volcano monitoring and emergency preparation, the loss of life and property can be minimized and sometimes prevented.

Acknowledgements

This report summarizes the work of a team of volcanologists from the Philippines and the United States who joined to monitor Pinatubo's activity, document the effects of its eruptions, and provide assessment of potential hazards before, during, and after the cataclysmic eruption.

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Team members from the U.S. Geological Survey were:


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