FIRE and MUD

Eruptions and Lahars
of Mount Pinatubo, Philippines

FIRE AND MUD: ERUPTIONS AND LAHARS OF MOUNT PINATUBO, PHILIPPINES

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A disk, prepared by the United States Geological Survey, accompanies the book. The disk contains two programs, PINAPLOT (for DOS) and VOLQUAKE (for Windows), both of which show the evolving seismicity before and after the 1991 eruptions of Pinatubo. VOLQUAKE also includes data sets for Mount St. Helens and Mount Spurr.

The book will be available on USGS and PHIVOLCS web sites.

MALACAÑAN PALACE MANILA

FOREWORD

Clear and present danger is a great unifier. When Mount Pinatubo devastated our land in 1991, it dissolved geographical, cultural, and economic barriers. Filipinos were one with each other and with the world as spontaneous aid poured into the Pinatubo region. Colleagues in the international scientific community came to help, not only to address the disaster of the moment, but also to resolve underlying scientific and technological problems of future hazards as well.

The significance of the Pinatubo experience lies not only in the successful forecasting of eruptions and lahar flows. It also highlighted many new challenges. As a circle of light increases, so does the circumference of darkness that surrounds it.

The Pinatubo event indeed shed plenty of light in volcanology. But it also highlighted many new questions: Will there be more devastating eruptions from Pinatubo? What is the volcano's eruption recurrence cycle? How do we deal with the Pinatubo lahars to minimize risk without stalling the region's development? What are the long-term impacts of volcanic deposits on the region's agricultural productivity? Which of our potentially active volcanoes will behave like Pinatubo and erupt after centuries of inactivity?

This monograph is a story of our tension, grief, insight, and relief. It also points to knowledge gaps that we must still bridge. It serves as a monument to scientific internationalism that has proven its worth. And through this monograph, we invite every reader to relive our experience at Pinatubo and to join us in taking up the new challenges ahead.

Fidel V. Ramos
President of the Philippines
MANILA
1995

PREFACE

The 1991 eruptions of Mount Pinatubo and subsequent widespread lahars are signal events both in volcanology and volcanic hazards mitigation. Accurate forecasting of the scale and date of an eruption is never easy, especially when the threatening volcano has not been monitored previously. Against considerable odds and with some critical logistical help, a small team of Philippine and U.S. scientists managed to avert a terrible disaster. Neither the eruption nor the lahars could be stopped, but, within the first 5 years of the crisis, hundreds of thousands of people have been warned and moved temporarily to safety.

The goals of this monograph are to capture a vast array of observations about the remarkable events before, during, and since the climactic eruption of Mount Pinatubo, to synthesize those observations into an understanding of Pinatubo as a dynamic, complex volcanic system (within an equally dynamic and complex social setting), and to make both observations and interpretations accessible to volcanologists around the world, especially those who must cope with similar crises in the future.

This last-mentioned goal bears special attention: Eruptions and lahars of Pinatubo's magnitude occur but a few times per century, and even less frequently in populated areas. But every geologist who studies volcanoes can identify scores of volcanoes at which such events are possible--some surrounded by even greater populations than Pinatubo. Because the options for precautionary actions are so limited around densely populated volcanoes, future forecasts must be as precise and accurate as possible. We might have only one chance to be right, for, after that, our credibility will be tenuous at best. This volume will be a vital reference for those who must make similarly difficult, high-stakes forecasts in the future. Even after such a large eruption has occurred, hazards from lahars and massive volumes of sediment will challenge the cleverest engineer, social scientist, and politician. Here, too, this volume will be a valuable reference.

We have not edited the volume specifically for student use, but instructors of volcanology will find within this monograph a selection of papers that illustrate great scholarly and practical value of viewing a volcano as a dynamic system, and, within such a dynamic system, speedy analogs of many otherwise hard-to-observe geologic processes. Advanced students will delight in seeing how their previous study in separate disciplines can be integrated and brought to bear on complex problems.

Another entire group of scientists--atmospheric scientists--also learned much from the disturbance that Pinatubo thrust into the atmosphere. Many exciting papers have resulted. These are beyond the scope of the present volume, but our last paper, by Self and others, bridges between the solid earth and atmospheric sciences and refers readers to literature of the latter.

International collaboration was notable at Mount Pinatubo--first, between Philippine and U.S. scientists, and later, spontaneously, involving scientists from at least 10 countries. An event of this magnitude would challenge any single country, and, because volcanological communities are typically small, it makes good sense for volcanologists to help each other in times of major crisis. Help given in one year is help received in the next. The Pinatubo effort epitomizes the spirit of the International Decade for Natural Disaster Reduction--international learning, from each other in a rare natural laboratory, with the ultimate goal of averting disasters wherever they might threaten.

Some of the papers in this monograph are by veterans of many volcanic crises; others are by younger scientists for whom Pinatubo was either a first eruption or for whom publication here is a first international publication. We take special pleasure in this mix, and thank both the veteran mentors and the younger scientists for their patience with each other and with the editors. Thirty-nine of the authors are or were students, including 11 first authors. Every veteran went back to school at Pinatubo, and many students are well along the way to becoming expert mentors.

Editors must make many choices on which papers and interpretations to accept. With an event like that of Pinatubo, some observations and interpretations simply cannot be confirmed or tested, either because of the extreme logistical or safety considerations or because a feature was ephemeral and is no longer the same or even present. Some data sets in this collection are regrettably sparse, but events cannot be restaged. Accordingly, as a rule of thumb, we have accepted papers that contain useful though sparse data. We have not accepted data or interpretations that are unlikely to be correct, but we have given the benefit of any remaining doubt to the author and have included some assertions that we cannot confirm.

We have worked with authors to reconcile discrepancies in observations and interpretations. Where that could be achieved, the results will be apparent as cross-references to mutually important points. Where it couldn't be achieved, we've allowed differences to stand and have noted them in the introduction to each section.

The schedule for preparation of a collection of this size, with authors around the world, poses special problems. Events like a giant eruption beg for early publication of results. However, there is also an argument for allowing the volcano enough time to show posteruption trends and allowing authors time to collect and analyze rich data sets and to communicate with each other. Some authors finished manuscripts within months; others were still in the field, struggling with ongoing monitoring responsibilities. Communication between authors will be evident in the papers; many, though perhaps not all, geographic and language barriers were overcome. Since asking for initial contributions in January 1993, we have pushed slower or busier authors hard, while begging for patience from those who were faster. Our goal was to balance timeliness with completeness.

Late in the preparation of this monograph, literally after type had been set, a budget crisis for the originally-intended publisher, the U.S. Geological Survey, forced us to choose between CD-ROM publication (only) and publication of this book by an alternate publisher. You can see that we chose the latter, and we will also make an electronic version available on the World-Wide Web. We welcome feedback from readers of both versions.

Chris Newhall, Seattle
Ray Punongbayan, Quezon City
May, 1996

ACKNOWLEDGMENTS

Many people have helped us to prepare this chronicle of Pinatubo. A simple thanks does injustice to their contributions; a more elaborate thanks, detailing each person's and group's contributions, would be a book unto itself. A Tagalog word, bayanihan, meaning an unreservedly cooperative effort to complete a big task, is an apt description for the outpouring of help that we have enjoyed.

Starting first with data collection, processing, and interpretation, we want to thank authors, with whom it has been our great pleasure and privilege to work. Your eyes and minds have captured a remarkable story. We also thank your many assistants--field assistants, lab assistants, secretaries, drafting assistants, and many more--who do not appear as authors but without whom the volume would be painfully thin. One co-author who deserves special thanks is Ma. Theresa Regalado, who served as the first editor's right hand, literally and figuratively, following an unscheduled injury.

Logistical assistance at Pinatubo required a special commitment, not only in hours, but in personal risk and sacrifice. Data sets in this collection, and successful mitigation measures that were based on those data, simply would not have been possible without sterling helicopter and fixed-wing support from the Philippine Air Force, U.S. Air Force, U.S. Navy, U.S. Marines, and the late Agustin Consunji. Drivers from USAID/Philippines, PHIVOLCS, the Philippine Mines and Geosciences Bureau, and the University of the Philippines not only kept us mobile on the ground but also doubled as field assistants, cooks, and other key support.

Critical reviews are essential for credibility. Reviewers are acknowledged in individual papers; we list them here, too, alphabetically, with our heartfelt thanks for a job well done. They were:

David Alexander, Fred Anderson, Onie Arboleda, Rich Bernknopf, Russell Blong, Marcus Bursik, Steve Carey, Mike Carroll, Tom Casadevall, Kathy Cashman, Pat Castillo, Bill Chadwick, Bernard Chouet, Toti Corpuz, John Costa, Doug Crowe, Art Daag, Mark Defant, PJ Delos Reyes, Rick

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Papers in this volume reflect work done both for immediate hazard mitigation and for research. For the first purpose, we gratefully acknowledge team funding from Office of President Fidel V. Ramos, the Philippine Department of Science and Technology, U.S. Department of Interior, the Philippine National Disaster Coordinating Council, UNESCO, USAID/OFDA, USAID/ Philippines, and the U.S. Department of Defense. For the second purpose, and for preparation of this volume, we gratefully acknowledge funds from our respective departments and a wide variety of research funding sources, including the U.S. National Science Foundation, that are acknowledged in individual papers. Most USGS funds came from its Volcano Hazards Program; we also thank its Earthquake Hazards Reduction Program, Pacific Northwest region, for valuable support during final preparation of this monograph.

The publishers of this book--PHIVOLCS and the University of Washington Press--together with the originally-intended and now-assisting publisher, the U.S. Geological Survey--are new trailmates in new terrain. Budgetary circumstances forced the USGS to seek immediate help. The USGS' Branch of Eastern Technical Reports agreed to finish camera-ready copy and PHIVOLCS, which had already contributed many papers, arranged a subsidy from the Mount Pinatubo Commission (see special acknowledgments, next page). Naomi Pascal, Pat Soden, and Veronica Seyd of the University of Washington Press responded with much-appreciated trust and flexibility, accepting the book as written and agreeing to a

concurrent World-Wide Web version. We look forward to hiking the rest of the trail together, despite the unusual circumstances under which we met!

We close this preface and acknowledgment with grateful thanks to the families of all who have worked at Pinatubo, for being supportive through initial risks and later exhaustion. We also recall, with enormous respect, wise guidance from the late Dick Janda that we use still today as Pinatubo lahars continue.

Chris Newhall and Ray Punongbayan, editors

SPECIAL ACKNOWLEDGMENTS

When a budget crisis in the U.S. Geological Survey forced us to change publishers, three organizations stepped forward with special help.

The USGS' Branch of Eastern Technical Reports (BETR), which had been preparing the monograph for USGS publication, was suddenly faced with the prospect that this report in which it had invested enormous amounts of time and skill might not get published. Two BETR employees in particular, Arlene Compher for illustrations and John Watson for text, had shaped many a gem in the rough into a polished product, with remarkable cheer and patience. Then, despite a painful reorganization and reduction-in-force, Arlene, John, Carolyn McQuaig for typesetting, Dave Murphy for final graphics work, and other BETR employees finished this huge job with great professional dedication.

The USGS also donated copies of its Mount St. Helens Professional Paper 1250, as in-kind publication support and to afford readers a chance to obtain this classic monograph together with the present Pinatubo volume.

The second group to whom we owe special thanks is the Mount Pinatubo Commission, chaired by the Hon. Salvador Enriquez (Antonio A. Fernando, Executive Director). The Mount Pinatubo Commission draws from government agencies and non-governmental organizations to manage relief and recovery from the Pinatubo eruption, including evacuation camps, resettlement areas, sediment control measures, and reconstruction of infrastructure. In recognition of the importance of Pinatubo events in volcanology and of a good understanding of volcanic events before those events can be mitigated, the Commission granted a generous subsidy that assured publication of the book.

The third source of critical support was PHIVOLCS' parent, the Department of Science and Technology (DOST) and its Secretary, Dr. William Padolina. A subsidy from DOST allowed us to print significantly more copies than would otherwise have been possible, and to offer this volume at an affordable price.

Thanks to these three organizations, many may learn the lessons of Pinatubo.

VOLCANIC DRAMA, HUMAN DRAMA

On the afternoon of June 15, 1991, Mount Pinatubo erupted between 3.7 and 5.3 km^3 of magma (8.4 to 10.4 km^3 of porous, pumiceous deposit), devastated more than 400 km^2, and blanketed most of Southeast Asia with ash (W.E. Scott and others; Paladio-Melosantos and others). For comparison, Mount St. Helens erupted only a tenth of this volume of magma but devastated and blanketed similar areas, more thinly. Within the 20th century, only the eruption of 13+-3 km^3 of magma from Novarupta (Katmai) in 1912, in a remote part of Alaska, was larger.

Even more remarkable than the volume, area of impact, and eruption rate is that this was the first event of this size to be monitored in detail (Wolfe and Hoblitt). Many startling and fascinating phenomena were observed. Some, such as the occurrence of long-period earthquakes before explosive eruptions, were previously known but magnified at Pinatubo. Others, such as early separation of a volatile phase deep within dacite reservoirs, were noticed first at Pinatubo and are now being found elsewhere (Gerlach and others). In another example, a sudden, short-lived decrease in SO_2 emission shortly before an explosion was seen first at Pinatubo (Daag, Tubianosa, and others) and is now being discovered elsewhere. Still other phenomena remain unique for the moment. For example, deep long-period earthquakes marked the intrusion of basalt into a body of crystal-rich dacitic magma (White), and mixing of the magmas triggered the eruption (Pallister and others). Both processes were previously known on geologic grounds; neither had been constrained in time and space. Similarly, interaction between the eruption column and the ground generated tremor with periods of 200 to 300 s that was recorded around the world (Zürn and Widmer), and caldera collapse did not generate earthquakes larger than magnitude 5 (Bautista and others). Geomorphic changes that a geologist might normally expect to occur within millennia have occurred within days and years (Punongbayan, Newhall, and Hoblitt).

The most remarkable fact of all is that, although Pinatubo threatened 1,000,000 people, only a few hundred perished. The eruption was accurately predicted and tens of thousands of people were evacuated to safe distances. The 1991 eruption was the first to occur at Pinatubo in about 500 years, and the lack of baseline information for an eruption of Pinatubo and for other large eruptions made forecasts highly uncertain. Local disbelief that Pinatubo was even a volcano, much less one that could erupt, posed a horrific challenge for scientists and civil defense leaders. Indeed, some of this skepticism was never overcome (Tayag and others).

Long-term accumulation of volatiles within a capped, viscous dacitic magma, and sudden intrusion of that dacite by basalt, may have contributed to a surprisingly orderly and rapid progression from first precursors to climactic eruption. Only slightly more than 2 months elapsed from the first confirmed precursors to the massive eruptions, and the most diagnostic signs occurred within just 10 days of systematic escalation of unrest in early June 1991. A hazard map and a simple 5-level alert scheme, the primary warnings to public officials, proved to be remarkably accurate. In addition, a graphic video summary of volcanic hazards, made by the late Maurice Krafft for the International Association of Volcanology and Chemistry of the Earth's Interior, grabbed even the skeptics' attention (Punongbayan, Newhall, Bautista, and others). Fast action by civil defense and local leaders led to massive evacuations and saved many lives, and, especially on U.S. military bases, much property as well. Not to be overlooked, luck also played a role: the 1991 eruption was not as large as some prehistoric eruptions, and a series of moderate-scale eruptions that preceded the climax convinced skeptics and those clinging to their land and homes that evacuation was the only prudent option.

The muddy aftermath of the eruption, in which heavy rains continue to remobilize large volumes of 1991 deposit as lahars, still batters central Luzon. More than $2x10^9$ m^3 of sediment have buried about 400 km^2 of lowland alluvial fans. Steaming hot debris flows with peak discharges of more than 1,000 m^3/s continue for hours after heavy rains and leave deposits of up to several tens of million cubic meters. Different watersheds yielded sediment at different rates, depending on factors such as slope, area versus thickness of deposit, and, later, vegetation recovery (Janda and others). Forecasts of sediment volume have been used for planning long-range mitigation projects; forecasts of imminent lahars have been used to trigger immediate evacuations. In principle, long- and short-range forecasts have been intended to help people to stay safely in their own homes and villages until they absolutely must move to higher or more distant ground; in practice, scientists, public officials, and citizens alike are still struggling to understand changing hazards and to neither underreact nor overreact. Hope runs eternal among those at risk from lahars, and people still delay their precautions until lahars are upon them (Cola). Technical accuracy in warnings is not enough to save lives; warnings must also convince those who are at risk to actually take the necessary precautions.

Dramatic changes to the face of the volcano are matched by dramatic cultural change. The minority Aeta population of about 20,000 was completely uprooted from their mountain life, wild fruits and animals, and supernatural spirits (C.B. Bautista). An even larger number of lowlanders were displaced, more physically than culturally, by the distal reaches of the eruption and by consequent lahars. Economic development of the region suffered severe short-term setbacks, and the large American military presence in the Philippines was brought to an early end.

In summary, the eruption of Mount Pinatubo in June 1991 and the subsequent lahars were the first of their magnitude to occur in a densely populated area among a people with the will and technological means to actually mitigate risks. With the benefit of good forecasts and generally constructive public responses, thousands of lives and untold amounts of property were saved. About 250 died during the eruption and a hundred more have died in subsequent lahars; without the forecasts and constructive public response, the toll would have been much greater.

Overview of the Eruptions

By Edward W. Wolfe[1] and Richard P. Hoblitt[1]

[1]U.S. Geological Survey.

Abstract

After 2 weeks of locally felt earthquakes, steam explosions announced volcanic unrest at Mount Pinatubo on April 2, 1991. The unrest culminated 10 weeks later in the world's largest eruption in more than half a century. Volcanologists of the Philippine Institute of Volcanology and Seismology were joined in late April by colleagues from the U.S. Geological Survey. Together they 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), which is located just east of the volcano. Nevertheless, the climactic eruption, coincident with a typhoon on June 15, caused 200 to 300 deaths and extensive property damage, owing to an extraordinarily broad distribution of heavy, wet tephra-fall deposits.

The volcanic unrest and eruptions, which involved intrusion of basaltic magma into a reservoir of crystal-rich, vapor-saturated dacitic magma, evolved in stages: mid-March through May--felt earthquakes in March, phreatic explosions on April 2, and persistence of numerous volcano-tectonic earthquakes; June 1-7--localization of shallow earthquakes in a narrow pipelike zone near the volcano's summit; June 7-12--lava-dome growth, accompanied by increasing ash emission and seismic-energy release, including significant episodes of volcanic tremor; June 12-14--a series of four brief vertical eruptions accompanied by a profound buildup of long-period earthquakes; June 14-15--thirteen brief surge-producing eruptions that became progressively more closely spaced; June 15--the climactic eruption, which lasted approximately 9 hours and included collapse of the volcano's summit to produce a 2.5-kilometer-diameter caldera; June 15-middle or late July--decline and termination of continuous emission of a tephra plume from vents within the caldera and steady decline of volcano-tectonic earthquakes that began during the climactic eruption (intermittent small ash eruptions continued until early September); and July-October 1992--extrusion of a lava dome within the caldera.

Runoff from monsoon and typhoon rains is eroding and redistributing the voluminous pyroclastic deposits emplaced during the eruption. Sedimentation from the resulting lahars continues to bury communities and valuable agricultural land over large areas in the lowlands surrounding the volcano.

Note to readers: Figures open in separate windows. To return to the text, close the figure's window or bring the text window to the front.

Introduction

Mount Pinatubo is one of a chain of composite volcanoes (fig. 1) that constitute the Luzon volcanic arc. The arc parallels the west coast of Luzon and reflects eastward-dipping subduction along the Manila trench to the west (Defant and others, 1989). Mount Pinatubo is among the highest peaks in west-central Luzon. Its former summit (fig. 2), at 1,745 m elevation, may have been the crest of a lava dome that formed about 500 years ago during the most recent previous major eruptive episode (Newhall and others, this volume). The volcano's lower flanks, intricately dissected and densely sheathed in tropical vegetation prior to the 1991 eruptions (fig. 3), were composed largely of pyroclastic deposits from voluminous, explosive prehistoric eruptions.

Figure 1. The location of Mount Pinatubo, within the Luzon volcanic arc.

Figure 2. Mount Pinatubo as seen from the building initially established as the Pinatubo Volcano Observatory (PVO) at Clark Air Base. Steam plume, to the right of the summit in this westward view, issued continuously from vents northwest of the summit after initial explosions on April 2, 1991. (Photograph by R.P. Hoblitt, June 6, 1991.)

Figure 3. Intricately dissected, densely vegetated upper north flank of Mount Pinatubo, which is underlain by prehistoric pyroclastic deposits. View north along the O'Donnell River from near Patal Pinto (fig. 4). (Photograph by R.P. Hoblitt, May 29, 1991.)

Figure 4. Mount Pinatubo, its major drainages, and geographic features referred to in text.

Before the eruption, more than 30,000 people lived in small villages on the volcano's flanks. A much larger population--about 500,000--continues to live in cities and villages on broad, gently sloping alluvial fans surrounding the volcano. Clark Air Base lies to the east of the volcano, within 25 km of the summit, and Subic Bay Naval Station is about 40 km to the southwest (fig. 4).

This report provides a broad view of the eruptive activity as a context for the many topical papers that follow. It draws extensively on a summary report by the Pinatubo Volcano Observatory Team (1991) and on an account of the events by Wolfe (1992); no additional citations are given for those two reports. A detailed chronology of eruptive events during June 1991 is given in table 1 of Hoblitt, Wolfe, and others (this volume), and Harlow and others (this volume) review the seismic chronology.

A sequence of developmental stages of volcanic unrest and eruptions characterized the 1991-92 activity of Mount Pinatubo. A brief review of the major stages follows:

0. The initial stage, from mid-March through May, was characterized by felt earthquakes beginning on March 15, phreatic explosions on April 2, continuing emission of steam and minor ash, essentially constant rate of seismic-energy release dominated by persistent occurrence of volcano-tectonic earthquakes, and generally increasing emission of SO_2.
. Increasing seismic-energy release in early June (fig. 4A of Harlow and others, this volume) and localization of shallow earthquake hypocenters near the volcano's summit culminated in a shallow intrusion that reached the surface on June 7 to initiate stage
0. Extrusion of a lava dome, increasing emission of a dense but low ash plume, and increasing seismic-energy release, including significant episodes of volcanic tremor, marked the interval between the first appearance of the dome on June 7 and the first large vertical eruption on June 12.
0. A series of 4 brief vertical eruptions and a profound buildup of long-period earthquakes occurred between the morning of June 12 and early afternoon of June 14. Growth of the dome may have continued through at least part of this interval.
0. A series of 13 pyroclastic-surge-producing eruptions occurred within the next 24 h. These became progressively more frequent, and seismic-energy release increased as the system evolved toward the climactic eruption.
0. An explosion at 1342 June 15 marked the beginning of the climactic eruption, which lasted approximately 9 hours and included collapse of the volcano's summit to form a 2.5-km-diameter caldera.
0. Gradually diminishing but continuous emission of tephra from vents in the

summit caldera persisted for about another month, and small intermittent ash eruptions occurred through early September. An intense swarm of volcano-tectonic earthquakes that began during the climactic eruption steadily diminished as events decreased in both number and magnitude.

0. A lava dome was extruded within the caldera from July to October 1992.

Pre-1991 Hints of an Active Magmatic System

Many observations at Mount Pinatubo before March 1991 are, in retrospect, consistent with the presence of an active magmatic system beneath the volcano. Although no historic eruptive activity was known before the 1991 events, some Aeta--the indigenous people who lived on the mountain's flanks--had reported minor explosions (Newhall and others, this volume). Hot geothermal fluids were known to be present (Delfin, 1983; 1984), and following the 1991 eruptions, a magmatic-fluid component was identified in water samples obtained before 1991 from fumaroles and drill holes (Delfin and others, 1992).

Ground fracturing and steam emission related to a landslide high on the upper northwest flank of Mount Pinatubo occurred on August 3, 1990 (Isada and Ramos, 1990; Sabit and others, this volume), 2 to 3 weeks after the occurrence of a major earthquake (magnitude 7.8) about 100 km to the northeast. Hindsight suggests that these events may have been manifestations of a magmatic or hydrothermal disturbance that marked the reawakening of the Pinatubo magmatic system. Before April 2, 1991, however, none of these phenomena caused volcanologists to suspect that an eruption might occur in the near future.

Precursory Activity and Hazard Assessment

Citizens of small communities on the lower northwest flank of Mount Pinatubo felt earthquakes beginning on March 15, 1991 (Sabit and others, this volume). Then, during the afternoon of April 2, 1991, a series of small explosions issued from a 1.5-km-long line of vents along a northeast-trending fissure on the upper north flank of the volcano (figs. 5 and 6). The explosions, which occurred over a period of several hours, stripped the vegetation from several square kilometers, deposited a meter or more of poorly sorted rock debris near the craters, and dusted villages 10 km to the west-southwest with ash. Vegetation was not charred, blocks near the vents were heterolithologic, and some were hydrothermally altered; together these observations suggest that the April 2 explosions were hydrothermal rather than magmatic in origin. Felt earthquakes and sulfur odors continued after the explosions, and a line of active steam vents extended across the volcano's upper north flank west-southwest of the fissure and explosion pits (Sabit and others, this volume). Activity soon concentrated at three main fumaroles in narrow canyons at the heads of the Maraunot and O'Donnell River valleys (figs. 6 and 7). Light ash emission occurred intermittently through early June.

Figure 5. Fissure and line of new craters formed by explosions of April 2 on upper north flank of Mount Pinatubo. View is southwestward. Prominent fumarole in distance is in the head of the O'Donnell River drainage. (Photograph courtesy of C.G. Newhall, May 1991.)

Figure 6. Major volcanic and hydrothermal features formed in the Mount Pinatubo summit region from April 2 through June 15, 1991. Preeruption topography modified from Mount Pinatubo 15-minute quadrangle (U.S. Defense Mapping Agency, Sheet 7073 II, Series S701, Edition 2-DMA). Contour interval is 100 m.

Figure 7. Three main fumaroles on north flank of Mount Pinatubo after explosions of April 2, 1991. View is approximately southward. Fumarole at left is at the head of the O'Donnell River valley; those at center and right are in headwater canyons of the Maraunot River valley (compare fig. 6). (Photograph courtesy of C.G. Newhall, May 1991.)

Concerned about the implications of the April 2 explosions and the ensuing felt earthquakes and sulfur odors, scientists from PHIVOLCS began to install portable seismographs near the northwest foot of Mount Pinatubo on April 5. The more than 200 small, high-frequency earthquakes recorded during the first 24 h of seismic monitoring led PHIVOLCS to recommend precautionary evacuation of areas within a 10-km-radius of the summit; approximately 5,000 residents evacuated. Through April and May, this network recorded between 30 and 180 high-frequency earthquakes per day (Sabit and others, this volume).

In late April, PHIVOLCS was joined by a group from the USGS, and the joint team installed a network of seven seismometers with radiotelemetry to an apartment at Clark Air Base. The apartment served as the initial home for the Pinatubo Volcano Observatory (PVO). Seismic data from the new network was gathered and processed at PVO on a DOS-based computer system (Lee, 1989). An electronic tiltmeter with radiotelemetry to PVO was also installed on the upper east flank of the volcano in late May.

Concurrently with installation of the telemetered seismic network, the PVO team undertook a rapid geologic reconnaissance to determine the style and magnitude of past eruptions as the basis for a volcano-hazard map (fig. 6 of Punongbayan and others, this volume). This reconnaissance showed that terrain as far as about 20 km from the summit of Mount Pinatubo had been repeatedly engulfed by voluminous pyroclastic flows in the recent geologic past. Lahar deposits, probably composed of debris eroded from pyroclastic-flow deposits, extended down all major drainages well beyond the pyroclastic-flow deposits. Volcanic debris transported by lahars had probably inundated large parts of the low-gradient alluvial fans that originate at Mount Pinatubo.

Hasty ^{14}C analyses of charcoal collected from pyroclastic-flow deposits during the reconnaissance yielded preliminary new emplacement ages. The new ages, when combined with three previous ages (Ebasco Services, Inc., 1977), provided an important insight into Pinatubo's behavior through time: large explosive eruptions separated by repose periods lasting millennia. The three most recent major eruptions occurred approximately 500, 3,000, and 5,500 calendar years ago. Subsequent work has refined the record (Newhall and others, this volume), but the general pattern remains the same: episodes of voluminous explosive eruptions separated by centuries to millennia of repose.

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 eruptive hazards: extensive voluminous pyroclastic flows, tephra falls, and lahars that could extend far beyond the reach of the pyroclastic flows. A preliminary version of a videotape illustrating volcano hazards, produced by filmmaker-volcanologist Maurice Krafft, enormously helped the team explain hazards foreign to people in an area lacking historic eruptions. Communication of information about Pinatubo's evolving state of unrest was simplified by a system of hazard-alert levels (fig. 4 of Punongbayan and others, this volume).

Numerous small, high-frequency earthquakes continued through May. They were generally too small to be felt, except locally. Magnitudes were less than 2.5 for all 1,800 located earthquakes between May 7 and June 1. 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 (see fig. 5 in Harlow and others, this volume); relatively few scattered earthquakes occurred beneath the summit or the nearby area of vigorous fumaroles. The location of the earthquake cluster northwest of the area of active fumaroles was puzzling. Photogeologic interpretation indicated coincidence of the earthquake cluster with a zone of young faults. Initially it was unclear whether the cluster was recording localized adjustments of the crust to stresses generated by movement, growth, or pressurization of a magma body or whether the cluster was recording tectonic activity unrelated to volcanic processes. However, the increasing rate of SO_2 emission soon strongly supported the former hypothesis.

Measurements of the rate of emission of SO_2 from the fumaroles near the volcano summit provided compelling evidence for the presence of fresh magma beneath the volcano. Successive airborne measurements showed that the SO_2 flux increased from about 500 t/d when the first measurement was made on May 13 to more than 5,000 t/d on May 28 (Daag, Tubianosa, and others, this volume). In combination with the sustained seismicity, these data suggested at the time that magma beneath Pinatubo had risen to a level sufficiently shallow to permit substantial degassing of its dissolved volatile components. Subsequent volcanic-gas emission studies related to the 1992 eruption at Mount Spurr, Alaska (Doukas and Gerlach, in press) showed that hydrolysis of SO_2 in ground water masks emission of magmatic SO_2. This conclusion, combined with the observed vigor of the fumaroles formed in early April, suggests that the increasing rate of SO_2 emission during May at Mount Pinatubo reflected progressive evaporation of the volcano's hydrothermal system. Low permeability of Pinatubo's hydrothermal system (Delfin and others, 1992) may have inhibited its capacity to recharge boiled-off water fast enough to prevent or greatly diminish preeruption SO_2 emissions (Doukas and Gerlach, in press).

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 (see fig. 7 in Harlow and others, this volume). These earthquakes apparently 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 SO_2 emission rate was declining from the peak measured on May 28; the rate was about 1,800 t/d on May 30, 1,300 t/d on June 3, and 260 t/d on June 5 (Daag, Tubianosa, and others, this volume). The latter flux was about one-twentieth of the earlier (May 28) maximum. The reduction in SO_2 flux raised concern that the passages through which gas escaped to the surface might have become sealed, perhaps by the degassed tip of an ascending column of magma, and that rapidly increasing pressurization and an imminent explosive eruption might ensue.

A small explosion at 1939 on June 3 (Ewert and others, this volume; Harlow and others, this volume) initiated an episode of increasing volcanic unrest characterized by intermittent minor emission of ash, increasing seismicity beneath the vents, episodes of harmonic tremor, and gradually increasing outward tilt at a tiltmeter high on the volcano's east flank. In response to the growing restlessness of Mount Pinatubo, PHIVOLCS issued a level-3 alert on June 5, which indicated the possibility of a major pyroclastic eruption within 2 weeks.

Dome Extrusion and Related Unrest

The electronic tiltmeter on Mount Pinatubo's upper east flank began to show accelerated outward tilt at about noon on June 6 (Ewert and others, this volume). Seismicity, as well as the outward tilt, continued to increase until late afternoon on June 7, when apparently increased emission generated a column of steam and ash 7 to 8 km high. Shortly thereafter, seismicity decreased, and the increase in outward tilt stopped. PHIVOLCS promptly announced a level-4 alert (eruption possible within 24 h) and recommended additional evacuations from the volcano's flanks.

Such outward tilt and increased shallow seismicity suggested that a shallow conduit was developing for delivery of magma to the surface. This was confirmed the following morning when observers identified a small (50- to 100-m-diameter) lava dome northwest of the summit in the upper part of the Maraunot River canyon (fig. 6). The emission of a persistent, low, roiling ash cloud from the vicinity of the dome began at this time (fig. 8).

Figure 8. Parallel plumes of steam (left, white) and ash (right, gray) that issued from June 7 to June 12 from vents in the headwaters of the Maraunot River, about 1 km northwest of the summit of Mount Pinatubo. (Photograph by R.P. Hoblitt, June 10, 1991.)

Initially the dome lay on the lower part of the northeast canyon wall and nearby part of the adjacent valley floor. Repeated aerial observations--generally under conditions of extremely poor visibility that were due to venting steam and tephra--indicated that the dome continued to grow at least until June 11. The southeastern sector of the dome was destroyed by the vertical eruptions of June 12-14. Despite the destruction, the dome margin continued to expand westward. When last seen, at about noon on June 14 (fig. 9), the dome was relatively flattopped and spanned the narrow upper Maraunot River valley. The expansion may have been due to continued extrusion or to postextrusion flowage as dome lava moved downhill under the influence of gravity.

Figure 9. Lava dome spanning the narrow upper Maraunot River canyon about 900 m northwest of the summit of Mount Pinatubo. View is southeastward. (Photograph by R.P. Hoblitt, approximately noon, June 14, 1991).

A pyroclastic-flow deposit emplaced in the upper Maraunot valley on late on June 12 or on June 13 contains abundant blocks, some of them prismatically jointed. These blocks, which were sampled after the 1991 eruptions, are believed to represent the lava dome (Hoblitt, Wolfe, and others, this volume). They consist of hybrid andesite with undercooled and quenched basalt inclusions. Major- and trace-element data strongly support genesis of the andesite by mixing of basaltic magma, represented by the inclusions, with dacitic magma, represented by juvenile pumice of the climactic eruption (Pallister and others, 1992; Pallister and others, this volume).

The period from June 8 through early June 12 was marked by increasing ash emission, swarms of shallow earthquakes largely beneath the dome, and episodic harmonic tremor. The east wind carried the ash plume westward. At times, dilute ashy density currents flowed down the upper Maraunot valley. Seen from the distance, these ashy density currents resembled the ash clouds associated with pyroclastic flows, but they neither coincided with distinct seismic explosion signals nor left recognizable flowage deposits marking their tracks. Concern raised by both the escalating degree of volcanic unrest and observation of these ashy density currents led PHIVOLCS to raise the alert level to 5 (eruption in progress) on June 9. The radius of evacuation was extended to 20 km, and the number of evacuees increased to about 25,000.

On June 10, about 14,500 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. and a comparable of number of Philippine military personnel remained behind to provide security and base maintenance. The PVO team of volcanologists also remained on the base. 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.

A burst of intense seismic tremor began at 0310 on June 12. High-amplitude tremor persisted for about 40 min, after which the amplitude gradually waned, returning to background level more than 2 h after it began. A small eruption signal with an onset time of 0341[2] was embedded in this tremor episode. Although no tephra fall was reported, the tremor burst probably coincided with an episode of increased ash emission. Daylight the next morning showed the plume of steam and ash rising about 3 km above the volcano, higher than during the previous few days, and aerial observations showed that small pyroclastic flows had coursed down the uppermost Maraunot and O'Donnell drainages and spawned small hot lahars.

[2] Times of explosive eruptions were determined from seismic-drum records, which recorded uncorrected local time.

Large Vertical Eruptions and Buildup of Long-Period Earthquakes

The first major explosive eruption began at 0851 on June 12, generating a column of ash and steam (see fig. 1A of Hoblitt, Wolfe, and others, this volume) that rose to at least 19 km, according to the weather-radar operators at Subic Bay Naval Station and Clark Air Base. At the onset, seismicity increased within a few seconds from low-amplitude tremor to a high-amplitude signal that saturated the records of all the seismic stations. The high-amplitude seismic signal and the rise of the eruptive column seemed to begin simultaneously. Interpretation of seismic records indicated that this event lasted about 38 min, although field observations suggest a duration of at least an hour (Hoblitt, Wolfe, and others, this volume). Beginning with the 0851 eruption, all seismic-station signals except from the station most distant from the volcano summit, at Clark Air Base, showed continuous seismic events and tremor until they were destroyed or their signal was otherwise lost.

Ash from the 0851 eruption was transported southwestward past communities north of Subic Bay, and a small pyroclastic flow traveled northwest from the vent in the headwaters of the Maraunot River. Six hundred of the remaining 1,500 U.S. 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 and longest of four vertical eruptions (fig. 10) from a vent on the southeast margin of the lava dome. The other three--at 2252 on June 12, 0841 on June 13, and 1309 on June 14--were progressively shorter, with durations of 14, 5, and 2 min, respectively. Weather conditions were good during the period of vertical eruptions, and all three that occurred during daylight hours were visible from PVO (fig. 1 of Hoblitt, Wolfe, and others, this volume). Good visibility for these early eruptions was really fortunate because it provided an opportunity for the PVO volcanologists and the military weather-radar observers to correlate unmistakable eruptions with their seismic and radar signatures. We quickly developed a routine that proved indispensable during periods of poor visibility: PVO volcanologists recognized an incoming explosion signal on the seismographs and contacted the radar observers for confirmation and tracking of eruption-column development.

Figure 10. Chronology of explosive eruptions of June 12-15, 1991, determined from visual observations, weather-radar observations, seismic signatures, and, on June 15, data from a recording barograph in the Clark weather station. Events of June 15 are shown in the lower diagram with an expanded time axis. Vertical spikes correspond to individual brief explosions, each of which produced a tephra plume. Time given with each spike is the time of the explosion onset determined from seismic-drum records. Solid spikes record explosions for which weather-radar observers provided realtime tephra-column heights (given in parentheses). Upper limit of radar observations was 19 km at Cubi Point Naval Air Station and 24 km at Clark Air Base. Dashed spikes record explosions for which we received no realtime radar measurements of plume height. Shading portrays known continuous tephra emission.

Ground-based observers to the west, at Poonbato, reported seeing pyroclastic flows during each of the three daytime eruptions (Sabit and others, this volume), and low tephra plumes were seen over the vent in the hours following the 0851 June 12 eruption and the June 13 eruption. Explosion plumes seen from the air along the upper 5 km of the Maraunot River valley after the 0851 June 12 eruption provided indirect evidence of new pyroclastic-flow deposits, but poor visibility prevented direct observation of the deposits themselves. Another observation flight shortly before the 1309 June 14 eruption documented new pyroclastic-flow deposits in the upper Maraunot valley. Later ground-based observations about 3.5 km downstream from the position of the 1991 dome showed deposits of only two pyroclastic flows beneath the June 15 deposits in the Maraunot valley (Hoblitt, Wolfe, and others, this volume).

Northeasterly winds prevailed during the vertical eruptions. Consequently, tephra falls extended southwestward across Subic Bay Naval Station and nearby communities to the north. No tephra fell on Clark Air Base during this period.

Unlike the initial eruption at 0851 on June 12, the eruptions at 2252 on June 12 and 0841 on June 13 were preceded by 2- to 4-h swarms of long-period earthquakes (Harlow and others, this volume), which enabled the PVO team to issue explicit advance warnings. The resumption of frequent long-period earthquakes during the evening of June 13 suggested that another eruption might be imminent, and another eruption warning was given. None occurred as expected, however, as the pattern was changing to one in which long-period earthquakes continued hour after hour.

In the early morning of June 14, clear weather gave a good view of Mount Pinatubo. In spite of the intensifying swarm (fig. 11; fig. 10B of Harlow and others, this volume) of long-period earthquakes, no visible ash and very little fume were being emitted. After 28 h with no major explosive activity, this long-period swarm culminated at 1309 (see fig. 2A of Hoblitt, Wolfe, and others, this volume) in the fourth large vertical eruption.

Figure 11. RSAM (realtime seismic-amplitude measurement; Endo and Murray, 1991) data for period of June 12-22, 1991. Vertical axis shows digital counts representing time-averaged voltage from the output of the seismic-data acquisition system. Plot shows individual explosions (compare with fig. 10) and, especially on June 14, increasing seismic-energy release related to increasing size and number of long-period earthquakes. There are no data for late June 15 and early June 16. Exponentially decreasing seismicity on and after June 16 reflects diminishing number and size of earthquakes recording structural adjustment of the volcano and the rock beneath it.

Andesite scoria, similar in composition to the andesite of the dome (Pallister and others, this volume) is the dominant component in tephra-fall deposits from the vertical eruptions. Dacite, similar to that of the climactic eruption, was a lesser component; its abundance increased from just a few volume percent in the deposits of the 0851 June 12 eruption to approximately 35 volume percent in the tephra of the June 13 eruption (Hoblitt, Wolfe, and others, this volume).

More gas-rich andesitic magma ascending behind the degassed tip that formed the dome vesiculated to drive the initial vertical eruptions that began on June 12. Transient pressure relief in the conduit from each brief preclimactic eruption led to additional vesiculation of magma and progressive replacement of the limited volume of andesitic magma in the conduit by dacitic magma, as reflected in the progressive decrease of andesitic pyroclasts and complementary increase of dacitic pyroclasts in the deposits of the vertical and surge-producing eruptions.

Surge-Producing Eruptions

A sequence of 13 explosive eruptions began shortly after the 1309 eruption on June 14 and continued for nearly 24 h. These became more closely spaced as time progressed (fig. 10), and, as discussed below, apparently reflected pyroclastic-surge production. Deteriorating weather conditions related to the approach of Typhoon Yunya obscured the view of Mount Pinatubo from Clark Air Base so that only one of these events (at 0555 June

15) was seen directly from Clark. Several were seen, however, by observers to the northwest at Poonbato and to the north at Camp O'Donnell. In addition, two night eruptions (2320 on June 14 and 0115 on June 15) were recorded by an infrared-imaging device at Clark Air Base. All views were of large pyroclastic density currents sweeping the volcano's flanks.

The first indication of a change in style to surge-producing eruptions was an observation from the north at about 1410 on June 14 of small explosions or low fountaining that sent density currents down at least the Maraunot and O'Donnell drainages. A larger eruption at 1516, seen only from the northwest, produced a large pyroclastic density current that swept northwestward about 15 km. Observation of a hot lahar in the Sacobia River valley in the late afternoon suggests that a pyroclastic density current also entered this drainage.

Three main lines of evidence, largely evaluated in hindsight, suggest the changed nature of the eruptions between the last primarily vertical eruption at 1309 on June 14 and the onset of the climactic eruption at 1342 on June 15. First, limited visual observations and infrared images were of ground-hugging pyroclastic density currents sweeping down the volcano's flanks. Second, recording barographs at Clark Air Base (fig. 2B of Hoblitt, Wolfe, and others, this volume) and Cubi Point recorded an abrupt atmospheric compression coincident with each major explosion from approximately 1516 on June 14 through 1315 on June 15 and a subsequent more protracted rarefaction; the four vertical eruptions did not produce similar atmospheric responses. Hoblitt, Wolfe, and others (this volume) speculate that the rapid atmospheric compression recorded initial collapse of the eruptive column near the onset of each of the 13 large explosive eruptions. Third, later field observations showed a sequence of multiple pyroclastic-surge deposits emplaced after the initial vertical eruptions and before the climactic eruption (Hoblitt, Wolfe, and others, this volume).

None of the surge-producing eruptions was directly visible to the PVO team at Clark Air Base before the 0555 eruption on June 15, and much of the evidence for the change on June 14 to surge production was not yet in hand. Limited visibility at dawn on June 15 enabled PVO and Clark Air Base observers to see the pyroclastic density currents of the 0555 eruption (fig. 3 of Hoblitt, Wolfe, and others, this volume). The relatively low ash fountaining (radar operators reported a maximum height of 12 km)[3] and the voluminous density-current production were in marked contrast to the high vertical tephra columns seen earlier (last previous eruption cloud seen from Clark was the vertical column of 1309 on June 14). This apparent change in eruptive style suggested that a climactic eruption, perhaps accompanied by massive pyroclastic density currents, might be imminent. Consequently, the remaining U.S. Air Force personnel and the PVO volcanologists evacuated Clark Air Base. Second thoughts led the PVO staff and a small Air Force contingent to return later that morning, but the brief evacuation caused a 3-h gap in seismic recording.

[3] Lynch and Stephens (this volume) report stratospheric eruptive plumes that persisted much longer than the eruptive events that generated them and in some cases reached much greater altitudes than indicated by the radar observations. For example, the satellite data show a plume at about 70,000 ft (21 km) for 1.5 h following the 0555 eruption. Seismic records show that this event was brief (3-5 min), and Clark Air Base weather-radar observers reported only a 40,000-ft (12-km) plume height at the time. We suspect that the satellite images record fine ash carried into the stratosphere by convection from denser eruptive columns "seen" by the radar or from hot ash clouds rising from pyroclastic density currents and that a tephra cloud maintains its identity in the stratosphere long after its parent eruption has ended.

Through June 14, winds blew virtually all of 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, probably in response to the approaching typhoon. 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 to 40 min later by total darkness at PVO, as winds blew ash eastward over Clark.

The abundance of dacite exceeds that of andesite in the pyroclastic-surge deposits, and the dominance of dacite increases upward; the stratigraphically highest surge deposits contain little or no andesite. As in the tephra-fall deposits from the vertical eruptions, fragments of these surge deposits have a broad range of density and a large proportion of dense clasts that represent relatively degassed magma (Hoblitt, Wolfe, and others, this volume).

Eruptions became progressively less vigorous and more closely spaced through the sequence of vertical and surge-producing eruptions, probably in response to increasing efficiency of the conduit system that delivered magma to the surface (Hoblitt, Wolfe, and others, this volume). By early afternoon of June 15 the supply rate had increased sufficiently to sustain the climactic eruption.

Climactic Eruption

An eruption at 1342 on June 15 initiated continuous high-amplitude tremor that saturated all operative seismic stations on Mount Pinatubo and, as we learned later, also initiated approximately 9 h of intense atmospheric-pressure variation (see barograph record, fig. 2B of Hoblitt, Wolfe, and others, this volume). By 1430, all seismometers but the one at Clark Air Base were inoperative (most were victims of pyroclastic density currents), and ash with pumice fragments as large as 4 cm in diameter was falling at PVO. The climactic eruption was clearly under way.

Virtually blind as a result of destruction of the seismic net and near-zero visibility, the PVO staff and the few remaining Air Force personnel left Clark Air Base at about 1500 to join 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. There the evacuees observed continuing ash fall and felt numerous earthquakes during the evening--small ones every minute or so, and large ones 10 to 15 min apart. The large earthquakes (M_b 4.3-5.7) were part of a series that began at 1539; the National Earthquake Information Center reported 29 events with M_b> or = 4.5 over the first 6 h (Mori, White, and others, this volume). At the time, the volcanologists speculated that the numerous felt earthquakes might record caldera formation. Indeed, subsequent views of the volcano showed that the original summit of the volcano was gone, and in its place was a new 2.5-km-diameter caldera (figs. 6, 12), the center of which is offset about 1 km northwestward from the preeruption summit. However, later analysis (B.C. Bautista and others, this volume) suggests that the largest earthquakes recorded crustal adjustments that occurred as strike-slip displacements on regional faults rather than caldera subsidence.

Satellite images showed that the climactic eruption cloud rose high into the stratosphere and expanded widely, umbrella-like. At 1540, it was 400 km in diameter, and shadow measurements against the surrounding white clouds indicate that its altitude was about 25 km at its eastern edge and 34 km at its center (Koyaguchi and Tokuno, 1993).

The Seismic Spectral Amplitude Measurement (SSAM) data (fig. 11 of Power and others, this volume) show a well-defined shift of the dominant seismic spectral peak from the 0.5- to 1.5-Hz band to the 1.5- to 3.5-Hz band approximately 3 h into the climactic eruption (at about 1630). Concurrently, the magnitude of the continuous, local, rapid atmospheric-pressure variation decreased (fig. 2B of Hoblitt, Wolfe, and others, this volume). Distant infrasonic stations also recorded approximately 3 h of intense activity correlative with the first 3 h of the climactic eruption, after which the infrasonic signal decreased in amplitude (see fig. 6 of Tahira and others, this volume).

The SSAM, barograph, and distant infrasonic data suggest collectively that the climactic phase was in full force for about 3 h and then began to wane. Structural adjustment of the volcano and the subjacent upper-crustal rocks to massive withdrawal of magma began after 2 h (1539) and accelerated an hour later (approximately 1630), as volcano-tectonic seismicity increased and long-period seismicity related to explosive volcanism declined. Unfortunately, our sole remaining seismometer failed for nearly 4 h beginning at about 2100 (fig 2A of Hoblitt, Wolfe, and others, this volume). However, the barograph record indicates that the rapid atmospheric-pressure fluctuations diminished to background level at about 2230. We interpret that time as the end of the climactic eruption.

We have no explicit evidence of the beginning and duration of caldera subsidence. It seems most likely that caldera formation occurred during the interval from 1630, when volcano-tectonic seismicity increased, to the end of the climactic eruption at 2230.

Typhoon Yunya made landfall at 0800 June 15 and decreased in intensity to Tropical Storm Yunya, which passed about 75 km northeast of Mount Pinatubo during the early vigorous hours of the climactic eruption (Oswalt and others, this volume). Owing at least in part to the atypical lower- and mid-level wind regime spawned by the passing storm, tephra was widely distributed in all directions around the erupting volcano. (Recall that prevailing winds had distributed essentially all earlier airborne tephra to the southwest.) In addition, heavy rainfall accompanied the storm. As a result, a heavy, rain-saturated, snowlike blanket (fig.13) of tephra a centimeter or more thick fell over about 7,500 km^2 of central and western Luzon, and almost all of the island received at least a trace (Paladio-Melosantos and others, this volume). The blanket has a remarkably consistent internal stratigraphy (fig. 14)--a thin, relatively fine, gray ash deposit overlain by a coarser, plinian pumice-fall deposit with conspicuous normal grading. The basal gray ash accumulated during the morning of June 15, and the overlying pumice-fall unit began accumulating during the afternoon, when pumice fragments were falling at PVO.

Figure 12. Caldera, 2.5 km in diameter, formed at crest of Mount Pinatubo on June 15, 1991. A continuous column of ash vented from the caldera floor during late June and July. Initially it filled the caldera, obscuring the caldera interior from view, but, by the time of this photograph, diminishing ash

production permitted a view into the caldera. View is southwestward. (Photograph courtesy of J. Mori, June 26, 1991.)

Figure 13. Snowlike blanket of tephra deposit of June 15, 1991, about 9 cm thick, in the eastern part of Clark Air Base, about 25 km east of Mount Pinatubo. Numerals in lower right indicate date. (Photograph by R.P. Hoblitt.)

Figure 14. Representative section of June 15, 1991, tephra deposit at a site about 36 km southeast of the summit of Mount Pinatubo near the village of Santa Catalina. The section is composed of a basal silt-size ash unit (overlying the pre-June 15 soil surface) that is 0.8 cm thick and an upper pumice-fall unit, 4.2 cm thick, which grades upward from coarse sand and granules to fine sand. (Photograph by E.W. Wolfe, June 18, 1991.)

The greatest measured thickness of the June 15 tephra-fall deposits was 33 cm, at a locality 10.5 km southwest of the vent, and deposits 10 or more centimeters thick blanketed a densely settled area of about 2,000 km^2 (Paladio-Melosantos and others, this volume). The greatest bulk accumulated west to west-southwest of the volcano's summit (see fig. 7 of Paladio-Melosantos and others, this volume). Paladio-Melosantos and others (this volume) estimate that the on-land bulk volume of tephra from the climactic eruption within the 1-cm isopach is about 0.7 km^3. Even more fell into the South China Sea; indeed, tephra dusted parts of Indochina, more than 1,200 km away. The total bulk volume of tephra-fall deposits is estimated at 3.4 to 4.4 km^3 (Paladio-Melosantos and others, this volume).

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 (figs. 15, 16). Between 200 and 300 people died during the eruption, most of them from collapsing roofs. Without Tropical Storm Yunya, the death toll would no doubt have been far less.

Figure 15. Schoolhouse in Balin Baquero River valley that collapsed from the weight of rain-saturated ash on June 15, 1991. Dark cloud in background is very fine (powdery) falling ash. (Photograph courtesy of J. Major, June 30, 1991.)

Figure 16. Aircraft hangars at Clark Air Base that collapsed under the weight of rain-saturated ash. (Photograph by E.W. Wolfe, June 29, 1991.)

Voluminous pyroclastic flows were emplaced during the climactic eruption. They extended as far as 12 to 16 km from the vent down all sectors of the volcano and impacted an area of approximately 400 km^2 (fig. 1 of W.E. Scott and others, this volume), stripping vegetation and dramatically modifying the preexisting topography. Their passage is recorded by a variety of pumiceous pyroclastic-flow deposits: massive deposits that filled preexisting valleys to depths locally as much as 200 m (fig. 2 of W.E. Scott and others, this volume); thinner, stratified deposits that veneer uplands and grade laterally into the massive valley-fill deposits; and ash-cloud deposits in distal areas that are interbedded with and adjacent to the massive deposits. Deposits of an additional lithic-rich facies cap the massive pumiceous deposits in the upper parts of several major drainages. Estimated bulk volume of the whole sequence is 5 to 6 km^3 (W.E. Scott and others, this volume).

W.E. Scott and others (this volume) review stratigraphic relations that indicate that the plinian pumice fall and the production of pyroclastic flows during the climactic eruption were at least partly concurrent, as is shown by interlayering of distal, thin pyroclastic-flow and ash-cloud deposits with the upper graded part of the plinian pumice-fall deposit. Possibly the plinian fall began first, but the two processes occurred simultaneously for at least part of the climactic eruption, and the evidence suggests that the massive valley-filling flow deposits accumulated incrementally from numerous successive flow pulses.

A coarse, clast-supported, lithic-rich facies that overlies pumiceous pyroclastic-flow deposits in the upper parts of several major drainages (fig. 1 of W.E. Scott and others, this volume) contains angular to subangular clasts, tens of centimeters to 1 m long, fragments of Mount Pinatubo's old summit. W.E. Scott and others (this volume) conclude that the lithic-rich facies formed during caldera collapse and that once collapse began, pyroclastic-flow production waned and the intense phase of the eruption ended. A supporting observation is that there is very little pumice to be found within the caldera (C.G. Newhall, written commun., June 18, 1993), although ash erupted within the caldera after the climactic eruption may have concealed deposits of climactic-eruption pumice.

The dominant juvenile component of the climactic eruption is white, phenocryst-rich pumice derived from magma that was nearly 50 volume percent crystalline. Phenocryst-poor tan pumice, identical in bulk composition to the phenocryst-rich pumice, is a subordinate component (about 10-20 volume percent, David and others, this volume). The phenocryst-poor pumice apparently originated primarily by mechanical fragmentation of phenocrysts during ascent through the conduit system in the climactic eruption (Pallister and others, this volume).

Rain produced by Tropical Storm Yunya generated lahars on June 15 in all major drainages around the volcano (Major and others, this volume; Rodolfo and others, this volume; Pierson and others, 1992). Major and others point out that the rainfall alone was insufficient to generate lahars; the additional necessary condition was altered watershed hydrology from fresh mantling pyroclastic deposits. The preclimactic and climactic eruptions satisfied this second condition by depositing a thin mantle of new pyroclastic material over the various watersheds.

On the basis of stratigraphic evidence and eyewitness accounts, Major and others found that initiation of lahars on the east side of the volcano on June 15 migrated northward during the day, apparently tracking the northwestward progression of Tropical Storm Yunya. Accordingly, peak flows from the eastern and southeastern sector--along the mountain front from the Gumain River to the Sacobia River--preceded deposition of the plinian pumice-fall deposit. Farther north, from the Sacobia River to the O'Donnell River, peak flow followed the pumice fall. Multiple flows occurred on June 15; thus, along the Sacobia-Bamban drainage as well as drainages farther south, lahars occurred both before and after the plinian pumice fall.

The June 15 lahars locally inundated arable land and homes. The most significant damage was caused by lahars along the Abacan River: dwellings upstream from Sapangbato were inundated (fig. 9 of Major and others, this volume); buildings and all bridges in Angeles City were undercut and destroyed by lateral bank erosion (figs. 10 and 12 of Major and others, this volume); and the Northern Expressway bridge downstream from Angeles was buried as the channel aggraded.

The large volumes of water responsible for the destruction along the Abacan may have been the consequence of stream capture that occurred before the climactic eruption. Before Pinatubo reawakened, a low divide separated the headwaters of the Abacan drainage from the upper reaches of the Sacobia drainage. Sometime during the night of June 14 or the morning of June 15, water from the Sacobia began to flow across the divide in the Abacan, probably because of aggradation along the Sacobia. Subsequent pyroclastic flows of the climactic eruption entered the head of the Abacan drainage by the same route (fig. 7 of Major and others, this volume).

Postclimax Phenomena

The PVO team returned to Clark Air Base and reestablished seismic recording on June 16. The one surviving seismometer initially recorded more than 150 tectonic earthquakes per hour larger than magnitude 2.0 (Mori, White, and others, this volume). The rate of seismic-energy release declined exponentially (fig. 11), and by the end of June, earthquake counts were 10 to 20 per hour. The decline continued for months, reflecting the adjustment of the volcano and the Earth's crust beneath it to the dramatic changes of mid-June. Reestablishment of a seismic network sufficient to locate earthquakes required about 2 weeks. Thereafter, earthquake locations largely defined outward-dipping trends enclosing a volume directly beneath the volcano that is relatively free of earthquakes (fig. 1 of Mori, White, and others, this volume) and may represent the reservoir that supplied the magma for the 1991 eruptions (Mori, White, and others, this volume).

The climactic eruption apparently left an open vent system, for ash billowed continually (fig. 12) from vents in the caldera for about another month. The resulting plume at times reached an altitude of 18 to 20 km. Winds caused significant fall of very fine powdery ash, especially southwest and northeast of the new summit caldera.

Episodic bursts of increased low-frequency seismic tremor, correlated with increased vigor of ash emission, occurred a few times per day during late June and most of July (Mori, White, and others, this volume). During these events, seismic amplitude increased for about 2 to 3 h and then declined to background level. From July 6 to July 11, these bursts of higher-amplitude tremor were periodic, with intervals of 7 to 10 h between events. As monsoon clouds and rain prevented direct observation of the volcano during late July, we know only that continuous ash emission had ceased by August 1; episodic ash emission continued until about September 1. By early September, the monsoon rains had formed a shallow caldera lake.

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 during the 5 centuries since the previous eruption. Runoff from heavy rains began to reestablish drainageways by eroding the new deposits. Thus, beginning in July, the annual monsoon rains repeatedly generated lahars, many of them hot from incorporation of hot pyroclastic-flow material. The lahars progressively buried towns and agricultural land, destroyed homes and bridges, frequently cut roadways, and displaced tens of thousands of residents. By the end of October 1991 (after the end of the southwest monsoon season), about 0.9 km^3 of new lahar deposits had buried 300 km^3 of lowland terrain, largely low-gradient alluvial fans formed of pyroclastic debris from previous eruptions of Mount Pinatubo (Pierson and others, this volume; Rodolfo and others, this volume). Rodolfo and others (this volume) estimate that lahars of the 1992 monsoon season delivered between 0.5 and 0.6 km^3 of new sediment to the lowlands, which accords with estimates of Pierson and others (1992) that progressively diminishing volumes of sediment are likely to be delivered to the lowland areas surrounding Mount Pinatubo for perhaps a decade. However, the 1991 and 1992 monsoon seasons were unusually mild. Sooner or later a typhoon will approach Mount Pinatubo, very likely triggering larger, more destructive lahars than have occurred so far (Rodolfo and others, this volume).

The Mount Pinatubo lahars have caused severe economic and social disruption. The dominant problem is continuing channel aggradation, which promotes lateral migration of the lahars across the low-gradient alluvial fans surrounding the volcano. Despite the resulting progressive burial of villages and valuable agricultural land, loss of life has been minimized by warning systems. Initially, warnings were provided by Philippine police and army personnel stationed at watchpoints along major river channels. Beginning in August 1991, that effort was supplemented by warnings from PVO based on realtime analysis of telemetered data from rain gauges and acoustic flow sensors (Janda and others, this volume; Marcial and others, this volume; Tuñgol and Regalado, this volume).

Numerous secondary explosions occurred during the 1991 and 1992 monsoon seasons from the interaction of water with hot pyroclastic-flow deposits. Such explosions generated tephra plumes, some as high as 18 km or more, that produced significant tephra falls and were at times mistaken by the press and some of the local populace as products of primary eruptions. Water gained access to hot pyroclastic-flow deposits by at least two different mechanisms: collapse of stream banks into streams, and invasion of ground water into hot deposits along buried stream channels. Explosions of the latter type commonly formed craters tens to hundreds of meters in diameter. Some generated secondary pyroclastic flows--hot, remobilized pyroclastic-flow deposits that traveled as far as 8 km downvalley and left prominent head scarps at their sources (Torres and others, this volume).

A lava dome formed within the new summit caldera from July through October 1992 (Daag, Dolan, and others, this volume). Its emplacement was heralded by increasing earthquakes and tremor in early July. By July 9, explosions near the center of the caldera lake had built a low pyroclastic cone that was about 70 to 100 m across and extended 5 m above the lake surface. Lava extrusion ensued; by July 14, a lava dome about 5 to 10 m high and 50 to 100 m in diameter had grown within the pyroclastic cone, which had widened to about 150 m. By July 23, the growing dome had completely buried the pyroclastic cone. Dome growth, which continued through October, was largely exogenous, marked by formation of a succession of extrusive lobes and accompanied by intermittent intense swarms of shallow earthquakes. At the end of October, the dome was 350 to 450 m in diameter and about 150 m high; its volume was about 4×10^3 m^3. A sharp decrease in seismicity on October 31 marked the apparent end of 1992 dome growth. Like the June 1991 dome, the 1992 dome consists of hybrid andesite indicative of magma mixing. Quenched basaltic andesite inclusions constitute 5 to 10 percent of the 1992 dome.

Size of the Eruption

A total bulk volume of 8.4 to 10.4 km^3 of eruption deposits is determined from a bulk volume of 5 to 6 km^3 of pyroclastic-flow deposits (W.E. Scott and others, this volume) and a bulk volume of 3.4 to 4.4 km^3 of tephra-fall deposits (Paladio-Melosantos and others, this volume). Allowing for uncertainty in the bulk density of the deposits, W.E. Scott and others estimate that the pyroclastic-flow and tephra-fall deposits together represent 3.7 to 5.3 km^3 of erupted magma (that is, dense-rock equivalent, or DRE).

The 1991 eruption of Mount Pinatubo was the world's largest in more than half a century and probably the second largest of the century. Its roughly 5 km^3 of erupted magma is an order of magnitude greater than the volume of magma erupted in 1980 from Mount St. Helens but is smaller than the 13+-3 km^3 (DRE) of ignimbrite and fall deposits from the 1912 eruption of Novarupta, Alaska (Fierstein and Hildreth, 1992). Volumes of two other large plinian eruptions that occurred early in the 20th century approximate the lower limit of estimated volume for the Mount Pinatubo eruption: the 1902 eruption of Santa María volcano, Guatemala, produced approximately 8 km^3 (uncorrected volume, equivalent to 3 to 4 km^3 DRE) of fall deposits (Fierstein and Nathenson, 1992), and the 1932 eruption of Volcán Quizapu, Chile, produced approximately 4 km^3 (DRE) of fall deposits and minor ignimbrite (Hildreth and Drake, 1992).

The climactic eruption injected approximately 17 Mt of SO_2 into the atmosphere (Gerlach and others, this volume), generating atmospheric and climatic effects that are likely to persist for several years (Hansen and others, 1992). Gerlach and others (this volume) concluded that virtually all of this SO_2 as well as Cl, CO_2, and an appreciable volume of water (approximately 96 Mt) had accumulated prior to eruption in a vapor phase in volatile-saturated magma of a crustal reservoir. A large additional volume (about 6.25 wt%) of water was in solution in the melt phase of the magma reservoir. Gerlach and others estimate that, in addition to the measured 17 Mt of SO_2, the eruption of approximately 5 km^3 of magma was accompanied by release of at least 491 to 921 Mt of H_2O, 3 to 16 Mt of Cl, and 42 to 234 Mt of CO_2.

The Magma Reservoir

Petrologic evidence suggests that the dacitic magma of the climactic eruption ascended from a reservoir that was highly crystalline (40 to 50 volume percent), relatively cool (approximately 780°C), volatile-saturated, and at an equilibrium pressure of approximately 200-220 MPa (Rutherford and Devine, this volume; Pallister and others, this volume). Using data from geothermal exploration and drilling (Delfin, 1983; Delfin and others, this volume), Pallister and others (this volume) equate 200 MPa to a depth of about 8 km beneath the pre-1991 summit of Mount Pinatubo (6 to 7 km below sea level).

Analysis of seismic results provides additional spatial evidence of the reservoir. Mori, Eberhart-Phillips, and Harlow (this volume) interpret a region of low P-wave velocity at a depth of 6 to 11 km below sea level as a magma reservoir. The low-velocity body is offset southward slightly from the summit of Mount Pinatubo. As appropriate for a body of magma, the inferred reservoir occurs in a nearly aseismic zone within the swarm of earthquake hypocenters that recorded crustal adjustments in the weeks after the climactic eruption (Mori, White, and others, this volume). The estimated volume of the low-velocity body is 40 to 90 km^3, and it is part of a still larger low-velocity body that extends as far south as Mount Negron. Mount Pinatubo's repeated eruption of virtually identical, voluminous, dacitic, pumiceous pyroclastic flows during the past 35,000 yr or more suggests that such a large, preexisting, crustal magma reservoir was repeatedly reactivated, most recently to produce the 1991-92 eruptions (Newhall and others, this volume).

The 1991 eruptions were apparently triggered by injection of basaltic magma into the dacitic reservoir (Pallister and others, 1992; Pallister and others, this volume), and the earliest erupted products, as well as the lava dome erupted in 1992, consist of hybrid andesite produced by mixing of intruded basalt with the dacitic magma of the reservoir. The occurrence of hybrid andesite, with mineralogic evidence of a basalt component in its parentage, in banded pumice fragments or as lithic clasts in the deposits of earlier eruptions of Mount Pinatubo, suggests that prehistoric eruptions were similarly triggered by intrusion of basalt into the dacitic magma reservoir (Newhall and others, this volume).

Basalt that intruded the dacitic reservoir mixed with dacite to produce a hybrid andesitic magma that ascended buoyantly (Pallister and others, this volume). The relatively degassed tip of the ascending andesite breached the surface on June 7, establishing a new eruptive conduit and supplying lava to the dome, which slowly grew during the following days.

Delicate disequilibrium textures preserved in samples of the June 1991 dome suggest that ascent and eruption of the hybrid andesite occurred within 4 days of the mixing event that formed it (Rutherford and others, 1993; Pallister and others, this volume). However, the preceding unrest--from mid-March through May--suggests that there was earlier magmatic activity. Possibly earlier intrusion of basalt into the dacitic reservoir produced deep-seated inflation that caused adjustments on faults, one of which intersected the hydrothermal system, or it produced an early hybrid magma that ascended sufficiently to penetrate the hydrothermal system but did not reach the surface.

Diminished magma volume in the reservoir caused structural adjustments including collapse of its roof. As indicated by the occurrence of lithic-rich breccia and pyroclastic-flow deposits at or near the top of the pumiceous pyroclastic-flow deposits, formation of the 2.5-km-diameter summit caldera was completed at the end of plinian eruption and production of pyroclastic flows.

Two essential conditions for the explosive 1991 eruptions were existence of vapor-saturated magma in the reservoir and intrusion of basalt into the reservoir. Eruption of hybrid andesite to form the 1992 dome implies that basalt intrusion has continued. Volatiles in the reservoir may have been sufficiently depleted by the 1991 eruptions that continued basalt intrusion has not led so far to renewal of explosive dacitic eruption (Daag, Dolan, and others, this volume).

Acknowledgments

The 1991 volcanic unrest and eruptions of Mount Pinatubo caused volcanologists of the Philippine Institute of Volcanology and Seismology (PHIVOLCS), the U.S. Geological Survey (USGS), the University of the Philippines, and the University of Illinois, Chicago, to join in an effective response to extraordinary volcanic threat and devastation. Together, these volcanologists constituted the Pinatubo Volcano Observatory Team, which made the observations on which this overview is based.

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People's Response to Eruption Warning: The Pinatubo Experience, 1991-92

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ABSTRACT

Two posteruption surveys, one in 1991 and another in 1992, assessed whether eruption warnings were received, understood, and used by citizens to take protective action. The 1991 survey showed that 71 percent of the total number of respondents (234) were forewarned; the remaining 29 percent learned of the hazard on June 12 by seeing the first large explosive events, a fact that indicates some weakness in the warning transmission.

Evacuation orders were issued by concerned Disaster Coordinating Councils or local government officials soon after danger zones were declared on April 7, June 7, and June 14-15, 1991. Eighty-six percent of the respondents received an evacuation order, but 30 percent of these people received it 2 or more days after it was issued.

Of those forewarned, 82 percent took protective action, including 46 percent who evacuated. However, within the group that evacuated, some waited two or more days after receipt of an evacuation order before moving, and some merely evacuated their women, children, and elderly or evacuated but returned. Some who did not evacuate as advised thought the eruption would not be strong enough to affect their places; others were reluctant to leave behind their houses and household effects, livestock, and crops, especially at harvest time; still others had no ready means of transport and could not walk long distances, or they believed that their God, Apo Namalyari, would not let them come to harm. Eventually, all but 5 of 234 respondents evacuated, either before or during the eruptions.

Communities in which LAKAS, an organization of the indigenous Aetas, was active showed the most exemplary operation of the system:transmission was total and response was consistently appropriate. These communities were reached by an information drive that featured the Maurice Krafft videotape on volcanic hazards, which he made for the International

Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI).

When Pinatubo threatened again to erupt in 1992, more than 90 percent of the respondents were forewarned and responded appropriately, indicating a marked improvement in the system. However, some overreaction was observed as an evacuation order was received by respondents who lived outside the danger zone. The errant evacuation order was traced to two sources: (1) some local government officials, who interpreted the Alert Level 5 released by the Philippine Institute of Volcanology and Seismology on July 14, 1992, to mean an eruption similar to that of June 12, 1991, and, hence, evacuation of the 20-kilometer-radius danger zone and (2) a popular radio announcer who broadcast that an eruption was imminent within 72 hours. The discrepancy between the warning message released by the source and that which was actually received appears to be a simple transmission problem. But other factors, including some features of the alert levels, may have inspired overexpectations and overreactions.

Note to readers: Figures open in separate windows. To return to the text, close the figure's window or bring the text window to the front.

INTRODUCTION

If timely warning can be given of an impending disaster-causing event, the severity of the resulting disaster or adverse consequences can be reduced. The Mount Pinatubo 1991 eruption provides an excellent example of how accurate forecasting and timely warning saved lives from the destructive agents unleashed by a violent eruption. The number of casualties at the height of the June 1991 eruptions was small (only 200 to 300) despite the violence of the explosions and the vastness of the area affected. Early, perceptible signs from the volcano and prompt warning and mobilization of disaster-response officials minimized the human losses. It is precisely on account of its success that the Pinatubo warning system makes an interesting object of review. Its strengths, as well as its imperfections, provide insights on how other volcano-eruption warning systems could be developed or improved.

The degree to which the severity of the disaster can be reduced by warning depends on the interplay of the major components of a warning system, namely (1) the source and timing of the warning, (2) the warning message, (3) the warning transmission, and (4) the recipients' response (modified from UNDRO, 1986).

A team from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) assessed all four aspects of the Pinatubo warning system to identify areas of success and those which needed improvement. The review involved two sampling surveys among the affected households: the first conducted within a month after the June 1991 major eruptions and the second during the month following the declaration of Alert Level 5 in July 1992.

METHODOLOGY

The 1991 survey was by stratified random sampling of respondents who had lived in the danger zones or zones recommended for evacuation. Respondents were selected from barangays that lay within 10 km, 10 to 20 km, and 20 to 40 km of the volcano's preeruption summit, radii that formally defined danger zones (fig. 1). 1990 census figures indicate that the barangays within the 10-km and 10- to 20-km danger zones had 7,653 households, or 41,100 residents; the 20- to 40-km danger zone, which included 106 barangays in 17 towns, had 58,696 households and more than 331,000 inhabitants (National Statistics Office, 1990).

Figure 1. Map of the Mount Pinatubo area showing recommended evacuation zones ("danger zones") of various radii, and barangays cited in the text.

The only recommendation for evacuation in 1992 was for the danger zone within <10 km of the summit. Very few people were affected, because most former residents of this zone had remained in evacuation camps or resettlement areas since 1991. Our survey was conducted among the next nearest population, from the 10- to 20-km danger zone. On the eastern side of the volcano, most barangays within the 10- to 20-km danger zone that were sampled in 1992 had only about half of their original pre-1991 eruption populations. The other residents had either relocated or were still in evacuation centers. On the western side, most of the former residents of the sample barangays in this zone were living (officially) in the relocation sites, but many were also spending days, weeks, or even months on their preeruption land planting and gathering food, whenever they felt it safe enough to do so. Some looked on the relocation site as a kind of "bakasyunan" or vacation home.

In both surveys, sampling size was determined by using a normal variable (z) value of 1.96 (see appendix 1 for the formula and computation). The survey covered only the survivors and is biased in favor of those who took precautions. However, those who died constituted a very small percentage of the population at risk, so the resulting bias is deemed insignificant. The respondents were of two types: households (with the household head or an adult household member as respondent) and key informants from among barangay and municipal officials. Household respondents were randomly selected from lists of household heads provided by barangay leaders, with substitutions when the original respondents were either unavailable or unwilling. Interviews were conducted by PHIVOLCS staff and volunteers (local school teachers) with the aid of interview schedules (appendix 2) and, as needed, interpreters.

WARNINGS AND RESULTS

THE SOURCE AND TIMING OF WARNING

Normally, the source of eruption warning should be the entity tasked to study and monitor active volcanoes. In the case of the Philippines, this entity is PHIVOLCS. But when Mount Pinatubo started showing signs of restiveness in April 1991, PHIVOLCS had no monitoring at the volcano and, hence, no warning system for the area.

Consequently, it was not PHIVOLCS that recognized the first signs of volcanic unrest but, rather, indigenous Aetas who lived on the slopes of the volcano. Some of these Aetas, members of Lubos na Alyansa ng mga Katutubong Ayta sa Sambales (LAKAS) (Negrito People's Alliance of Zambales), reported their observations to PHIVOLCS through Sister Emma, a sister of the Franciscan Missionaries of Mary (FMM) who was doing missionary work among the Aetas.

Upon receipt of the LAKAS report, PHIVOLCS immediately began to monitor Pinatubo and, thenceforth, became the principal source of warnings. Details of the monitoring activities and chronology of preeruption events are given by Sabit and others (this volume) and Wolfe and Hoblitt (this volume); details of preeruption warnings are given by Punongbayan and others (this volume). Those warnings provided enough lead time for the beleaguered inhabitants to pack up and run away from the volcano.

The Warning Message

The warning message consisted of hazard zonation maps, alert levels, and "danger zones," which were zones of recommended evacuation, simplified from the hazard maps. Preliminary hazard zonation maps were disseminated by PHIVOLCS on and after May 23, 1991. These maps delineated the areas likely to be affected by the destructive agents, namely, pyroclastic flows, ash fall, and lahars. These maps illustrated the probable extent of the most probable hazards and served as guides for evacuation of endangered communities. Since the major eruption of June 15, 1991, the lahar hazard part of these maps has been updated several times.

Alert levels were designed to describe various levels of eruptive activity and danger. These provided information on the condition of the volcano, including whether its activities would likely culminate in an eruption. The alert levels were based on instrumentally derived data and daily visual observations. The original scheme of alert levels that was released on May 13, 1991, is shown in table 1.

Table 1. Alert levels for Mount Pinatubo, May 13, 1991.

Table 2. Alert levels and danger zones issued on Mount Pinatubo, 1991-92 (PHIVOLCS, variously dated).

Daily volcano bulletins and special advisories on the volcano's condition always indicated the alert level and an associated danger zone that should be avoided and evacuated. PHIVOLCS' recommendations for evacuation were translated and transmitted by the concerned Disaster Coordinating Councils (DCCs) or local government officials as evacuation orders. A chronology of alert levels and danger zones declared in connection with Pinatubo's activity in 1991-92 is presented in table 2.

When the temporary seismic station installed near the volcano recorded high seismic activity on the first 3 days of operation, April 5-7, PHIVOLCS declared a danger zone of 10 km radius that was centered on the volcano's summit and advised evacuation of the residents from the area. Initially, volcanologists considered employing an alert level terminology used at other Philippine volcanoes but opted to design a new one for Pinatubo (table 1). The 10-km danger zone was reiterated when the alert level scheme shown in table 1 was officially adopted on May 13, 1991, and Alert Level 2 was raised. It was maintained even when Alert Level 3 was raised on June 5. When Alert Level 4 was declared on June 7, the danger zone's radius was increased to 20 km. On June 14, this was further expanded to the 30-km radius. During the June 15 explosions, the danger zone was expanded to a 40-km radius to allow for the possibility of devastating, large-scale pyroclastic flows of a caldera-forming eruption. The danger zone was shrunk back to a 20-km radius on June 18, though Alert Level 5 remained. On September 4, the alert level was lowered to 3, and the danger zone was shrunk back to a 10-km radius. The alert level was further lowered to 2 on December 4. Alert Level 2 remained in effect until the volcano started manifesting a resurgence of activity in July 1992.

In 1992, renewed seismicity prompted PHIVOLCS to raise the Alert Level to 3 on July 9 and then to 5 on July 14, when viscous lava reached the surface and began to form a dome. The 10-km danger zone, in effect since September 1991, was maintained throughout the 1992 unrest.

The volcano's 1992 activities were entirely different from its 1991 eruptions. These were characterized by quiet effusion of lava and dome building punctuated by minor explosions and hence were not as explosive and hazardous as the 1991 events. Realizing the need to reflect these differences in the alert level scheme, PHIVOLCS revised the definitions of alert levels toward the end of the year. The first three alert levels were retained with only a slight revision of Alert Level 3 interpretation, but Alert Levels 4 and 5 were substantially modified (table 3).

Table 3. Revised alert levels for Mount Pinatubo (revised December 1992).

Alert Level 4 will be used only for impending hazardous explosive eruptions or for ongoing eruptive activity that involves only small explosions or lava dome extrusions. Alert Level 5 will be used only for large explosive eruptions in progress. Definitive time windows for the occurrence of an eruption, such as "eruption possible within 2 weeks" for Alert Level 3 and "eruption possible within 24 hours" for Alert Level 4, were modified to "within days to weeks" and "within hours to days," respectively.

Transmission of Warning

At the five most active volcanoes being monitored by PHIVOLCS--Mayon, Bulusan, Taal, Hibok-Hibok, and Canlaon--eruption warnings are usually passed through the appropriate DCC. When one of these volcanoes manifests abnormal behavior, PHIVOLCS interprets its changing behavior and decides whether or not to send warnings and, if so, when. As soon as PHIVOLCS decides to issue a warning, it notifies the Office of the President and the national and local DCCs, through Volcano Bulletins and advisories that explain the condition of the volcano and recommended actions. The DCCs, in turn, transmit the warning to those at risk and respond in various other ways. Although transmission of warnings is officially the responsibility of the DCCs, PHIVOLCS observatory personnel help deliver warnings to nearby inhabitants. Later, PHIVOLCS' main office might release information to the media to clarify and explain the volcano's condition.

This warning procedure was modified in the case of Pinatubo. Warning messages were formulated at PHIVOLCS' main office and transmitted simultaneously through the DCC hierarchy, major national and local newspapers, radio and television stations, nongovernmental organizations (NGOs), and directly to the endangered inhabitants.

Multipath warning transmission has been found to create confusion, duplication, and administrative problems in some situations. This is why, at other monitored Philippine volcanoes, warnings and evacuation advice are passed, as much as possible, through the concerned DCCs. The effectiveness of the modified transmission procedure adopted at Pinatubo was assessed by use of two indicators: (1) consistency between the warning message released by the source (PHIVOLCS) and the message received by the recipients and (2) the time gap between issuance from the source and receipt by the target public.

Respondents were asked if they received any eruption warning and (or) evacuation order, and, if so, when. The 1991 survey showed that 71 percent of the 234 respondents knew of the impending eruption before June 9, 1991, the date on which Alert Level 5 was issued, either through their own observation (9 percent) or through their own observation and forewarning from PHIVOLCS, media, local officials, or other people (62 percent). Before June 12, the date of the first large explosive events, 82 percent of the respondents knew of the danger. Subtracting the 9 percent (roughly) who knew only through their own observation, it appears that about one-fourth of the respondents were not reached by warnings before explosive eruptions began. By June 14, 99 percent of the respondents knew of impending danger, from continued warnings and, especially, from observing the preparoxysmal eruptions (Wolfe and Hoblitt, this volume).

Danger zones that were delineated by PHIVOLCS served as basis for the DCC's issuance of evacuation orders. Evacuation orders were transmitted soon after the danger zones were declared by PHIVOLCS, on April 7, June 7, and June 14-15. Those within the 10-km danger zone should have received their order as early as April 7; those within the 10- to 20-km danger zone, on June 7; and those within the 20- to 40-km danger zone, on June 14-15.

Two hundred and two (86 percent) of the 234 respondents received an evacuation order while 14 percent did not. Of the 32 respondents who did not receive an evacuation order, all except two (one from the <10 km danger zone and one from the 10- to 20-km danger zone) were from the more distant, 20- to 40-km radius danger zone (table 4). Most received their evacuation orders on the day or 1 day after the danger zone was declared by PHIVOLCS; others received the evacuation order 2 or more days later, reflecting some delay in the transmission. Delays in transmission were reported in all the danger zones.

Table 4. Receipt of eruption warning and evacuation order by date. [Household survey, 1991; number of respondents was 234; EW, eruption warning; EO, evacuation order; cum%, cumulative percentage of the 234 respondents]

Table 5. Respondents who received preeruption warning and (or) false evacuation order. [Household survey, 1992; number of respondents was 130; all respondents for the 1992 survey were from the 10- to 20-km danger zone]

In 1992, 94 percent of the respondents learned of the impending eruption on or before July 14, the day PHIVOLCS issued Alert Level 5 (table 5). Almost all the respondents received the warning from multiple sources, with PHIVOLCS, the media, and military officials as the most common transmitters.

Throughout the 1992 activity, PHIVOLCS merely reiterated the continued enforcement of the 10-km danger zone. Therefore, evacuation was recommended only for those who had returned to the <10-km danger zone despite advice against reoccupation of the area. Because the 1992 survey was confined to the 10- to 20-km danger zone, no respondent was expected to have received an evacuation order. Surprisingly, 8 percent of the respondents (all from Pampanga) reported that they received an evacuation order either from municipal or barangay officials or through the media.

One Municipal Disaster Coordinating Council (MDCC) official admitted that the council decided to order evacuation of barangays beyond the 10-km but within the 20-km radius (including one community that was already living in a relocation center) on the night of July 15. The council even provided vehicles to bring the evacuees to the evacuation centers. According to the town official interviewed, they wanted to play it safe. If the anticipated eruption would be similar to the June 12, 1991 eruption, then the 10- to 20-km danger zone would be affected, so why should they wait?

Respondents from the villages Sapangbato and Margot of Angeles City reported that sometime before July 14, 1992, a popular radio announcer, citing PHIVOLCS as his source, broadcast that Mount Pinatubo would erupt within 72 h. It is interesting to note that the PHIVOLCS alert levels do not include one that indicates that the volcano may erupt within 72 h. The signal with the closest time reference is Alert Level 4, which means that eruption is possible within 24 h. But Alert Level 4 was not used in 1992, as the Alert Level jumped from 3 to 5.

The People's Response to Warnings Issued

The final test of a warning system's effectiveness is the receipt of and appropriate response to the warning by the target recipients. The warning, no matter how timely, accurate, and precise, will not be of any value unless the recipient of the warning takes appropriate defensive action.

Response to 1991 Warnings and Evacuation Orders

One hundred sixty-seven respondents, representing 71 percent of the total number of respondents (234), had forewarning of the eruption and were asked what they did when they learned that the volcano was going to erupt. About 81 percent of those who received forewarning took appropriate action, by evacuating immediately (the response that was called for in the case of those living within the 10-km radius as early as April and those living within the 10- to 20-km radius starting June 7) or by taking some other defensive action (such as preparing for evacuation, convening a meeting, disseminating the warning, seeking further information or confirmation, or observing for further signs, responses that were appropriate at radii of 10 to 20 km from April to June 7 and at radii of 20 to 40 km until June 15). Eight respondents from the <10-km danger zone who should have evacuated immediately merely took other precautionary actions like preparing for evacuation, seeking additional information, or watching out for further developments. Another 13 respondents (from the 20- to 40-km danger zone) overreacted by evacuating before they were ordered to do so.

In contrast, 13 percent of those who were forewarned either waited for the eruption or ignored the warning; and 5 percent ran without definite destination, prayed, or cried without taking any defensive action (table 6).

Table 6. Response to preeruption warning in each of the danger zones.[Household survey, 1991; number of respondents was 167]

Table 7. Response to evacuation order, 1991. [Number of respondents was 234]

Table 8. Reasons for not evacuating immediately as when advised.[Household survey, 1991; number of respondents was 69]

The responses to evacuation orders (a step beyond warnings) indicate that all the respondents except five (2 percent) eventually evacuated (table 7). Fifty-eight percent of all respondents evacuated when and as advised, and an additional 11 percent evacuated even without or before receiving evacuation order. But 23 percent delayed evacuation and 6 percent evacuated selectively. Households that evacuated selectively either (1) sent their women, children, sick and elderly to safety while the able-bodied adult males stayed behind or (2) evacuated all together but then allowed some member(s) of the household to return home (usually during daytime).

Table 8 lists some of the reasons given by those who dallied or evacuated selectively. Some thought that the eruption would not be strong enough to affect their place; some were reluctant to leave behind their property and livelihood, especially as it was harvest time; some had no ready means of transport and could not walk long distances; and some believed that their God, Apo Namalyari, would not let them come to harm. One respondent did not want to leave immediately because it was fiesta time.

Responses to 1992 Warnings

In 1992, PHIVOLCS advised the inhabitants of the 10- to 20-km danger zone to avoid the 10-km danger zone (where some residents would otherwise hunt or gather food or tend farm plots), be alert to possible deterioration in the volcano's condition, and prepare for this possibility. About 8 percent of the respondents received an evacuation order (table 5), some from their local officials, others through radio. Two percent of the respondents evacuated their entire households and another 3 percent evacuated selectively (table 9). The latter were from one community that was ordered by the municipal DCC to evacuate but, instead of complying fully, sent only its women, children, elderly, and sickly to the evacuation centers, where they stayed for about 3 months. Another community, about 15 km from the volcano, was ordered to evacuate and was even provided with vehicles for evacuation, but it refused to comply because residents believed that Apo Namalyari would protect them.

Table 9. Response to preeruption warning and false evacuation order.[Household survey, 1992; number of respondents was 130; all from the 10- to 20-km radius danger zone]

Had there been a real need for evacuation, the noncompliance of the recipients would have exposed them to danger. But, because the evacuation order was an overreaction on the part of the concerned officials and misinformation on the part of the radio announcer who broadcast "warning" of an imminent eruption within 72 h, their noncompliance led to no harm. Nevertheless, the more appropriate response on the part of the recipients of the evacuation order should have been to seek further information or verification of the order, instead of not to comply.

Among those who took other defensive action (table 9), some overreacted by suspending their normal activities, such as going to school or going to work, for 1 to several days. This overreaction occurred principally while waiting for the "imminent eruption within 72 hours" that was broadcast by the irresponsible radio announcer sometime before July 14, 1992.

DISCUSSION AND CONCLUSIONS

The fact that most respondents took appropriate defensive actions and evacuated as advised indicates that the warning system worked well enough in 1991. It performed even better in 1992. Nevertheless, some aspects could still be improved. For improvement, the following findings are particularly important:

1. The failure, in 1991, of 18 percent of those who were forewarned to take any defensive action and the delayed or selective evacuation of 34 percent of those who received evacuation orders indicate some failure to stimulate protective action.

Inhabitants who received warnings and evacuation orders but did not take defensive action obviously lacked appreciation of the magnitude of the dangers posed by the volcano. Even those who delayed evacuation or evacuated selectively showed lack of understanding of the gravity of the threat. Either the information drive launched by PHIVOLCS and other disaster response organizations before the eruption did not reach these respondents or the information campaign failed to drive home to them the magnitude of the threat and the urgency as well as the possibility of avoiding the volcano's fury.

It is worth pointing out that all of the respondents contacted by the LAKAS organization showed the exemplary appropriate response. All (except one old man who chose to die rather than leave his home) prepared and evacuated promptly. These respondents recounted that, before the eruptions, the eruption threat and the hazards posed by the volcano had been explained to them by PHIVOLCS and other officials. They had also been shown the videotape on volcanic hazards produced by the late Maurice Krafft for IAVCEI (Punongbayan and others, this volume).

Some other Aetas did not fare as well. According to one informant (a Protestant pastor), a group of Aetas was about to evacuate (on the 15th of June) along with the others who were fetched by chartered buses. But these people changed their minds when they could not read sign boards on the buses that indicated which should be boarded by Villar residents, by Moraza residents, and so on. After boarding at random and being twice informed that they were in the wrong bus, they were so embarrassed that they decided to return to the mountain and seek refuge in the so-called caves, saying that Apo Namalyari would protect them.

Two other informants said half of the residents of sitio Lomboy were very reluctant to evacuate. Most of them did not want to leave their belongings, crops, and livestock and believed that Apo Namalyari would not let them come to harm. Many of them did not believe that the eruption would be strong enough to affect their places. Some feared lowlanders would burn their crops and homes. A Korean pastor was finally able to convince them to leave, but they put off their departure until the next morning and spent the night in some kind of natural shelter that they called caves. That night, pyroclastic flows buried the caves and killed those inside.

The findings of the survey corroborated news reports about the reluctance or refusal of some endangered inhabitants to leave the danger zones. In April, Aeta tribesmen who refused to move out reportedly said "they were afraid to leave their 'precious belongings&'" (Alcayde, 1991) or reasoned that they could not leave because their camote crops were due for harvesting. The latter group promised to leave as soon as the harvest was done (Gob, 1991). One Aeta leader who stayed behind was quoted to have said "Mahina lang siguro ang pagsabog dahil hindi naman ito narinig dito sa Belbel" ("The eruption was probably weak because it wasn't heard here at Belbel"), referring to the April 2 explosion (Empeno, 1991).

By June 9, Mayor Richard Gordon of Olongapo City was reported to have dispatched trucks to "clear" barangays within the 20-km danger zone where "there were still some Negritoes who chose to stay where they were, because of their livestock and other properties" (Villanueva and Dizon, 1991). One of the holdouts compromised by sending his family not to an evacuation center but to a place a bit farther away from the volcano, saying "Hindi naman daw kami aabutan ng pagputok ng bundok" ("We heard that the eruption will not reach us") (Cortes, 1991).

Hours after intensified ash emission on June 9, evacuees who earlier refused to leave were reported to have finally climbed into trucks brought by rescuers. Hundreds of Aetas with their belongings and work animals lined the roads, waiting for trucks to bring them down to evacuation centers. But there were still others who refused to be evacuated (Velarde and Bartolome, 1991). The mayor of San Marcelino reported that during rescue operations on June 9, 10 Aeta families opted to stay, believing that the eruption was nothing serious--"para lang daw malakas na bagyo'yan" ("it is just like a strong typhoon") (De Villa, 1991).

As late as June 11, Zambales Governor Deloso reported that some 200 tribesmen still refused to leave their settlements in Barangays Moraza, Nacolcol and Maguisguis. He added that the men may have wanted to stay to harvest their palay and camote crops so they could repay their loans to the Land Bank of the Philippines (anonymous, 1991a). An Aeta in Moraza who defied the evacuation order and stayed on to keep an eye on his home, farm, and carabao (water buffalo) was quoted to have said "We fear the volcano, but if we left our carabaos, we'll die" (Morella, 1991). In another barangay, Belbel, the barangay captain reported that some 252 tribesmen also refused to leave their homes (Anonymous, 1991b).

The anecdotes from the survey informants, and these news reports, highlight some of the communication and cultural problems with which the warning system had to contend. These problems indicate a need for hazard-awareness promotion that is more intensive and broader in outreach than was possible during the 2-month period from the time the volcano started showing signs of restiveness up to the time of the major explosions.

2. In 1991, the failure of 18 percent of the respondents to receive preeruption warning before June 12, the failure of 14 percent of the respondents to receive an evacuation order at any time (even after the June 15 eruption), and delay in the receipt of evacuation order by 26 percent of the respondents all indicate some deficiencies in the transmission system. In the <10- and 10- to 20-km danger zones, it is possible that the transmission network did not reach the most remote areas or the communities that were on the move.

Again, it is worth noting that in the case of the communities with a grassroots organization like LAKAS, warning transmission was total despite difficulties of transportation and terrain. The organization ensured that everyone received the warning and evacuation order.

The official warning system was unable to reach all residents of the large, 20- to 40-km danger zone during the short, hectic time that that zone was in effect (June 15-18). Communities in this zone are easily accessible but too numerous to reach in such a short time. Broadcast radio served as the principal channel for warning communities in this area. The warning communication system was improved in 1992 by the distribution of two-way radios to barangay leaders.

3. In 1992, the receipt of a false evacuation order by 8 percent of the respondents is a clear case of discrepancy between the warning message released by the source and the message transmitted to the concerned

inhabitants. Issuance of this evacuation order for communities outside the official danger zone may have been a simple case of caution or overreaction on the part of the local officials. However, incentives for evacuation such as the availability of relief and emergency resources and the usual outpouring of sympathy might also have inspired the move.

The overreaction may also be traced, at least in part, to the warning messages released by PHIVOLCS. The United Nations Disaster Relief Office (UNDRO, 1986, 1987) advised, among other things, that warnings should be consistent in content and as specific as practicable in their information concerning the magnitude of the event, the place at which it is expected, and the time when it will occur. The 1991 alerts were indeed specific--in terms of expected magnitude, areas likely to be affected, and time of occurrence--but they were specific to the 1991 eruptive activities. The application of these same alerts to the less explosive and less hazardous 1992 events may have given rise to undue concern and inspired exaggerated media reporting.

After the 1992 experience, revision of the alert levels was in order. The revision removed the implication that eruptions could be predicted to the nearest hour or day, especially at volcanic systems in which the vent was already open. The original alert levels focused mainly on the imminence or occurrence of a large explosive eruption. The revised alert levels allow for differentiation of large and small eruptions. Missing still are the recommended actions for each of the alert levels and each of the danger zones. How to incorporate these without making the scheme of alert levels inflexible and too specific remains to be studied.

One specific aspect of the PHIVOLCS warning messages that went against UNDRO advice was the inconsistency in the danger zones associated with the various alert levels. In 1991, Alert Level 4 was associated with a 20-km danger zone, and Alert Level 5 was associated with both a 20-km and a 40-km danger zone. A 40-km danger zone was declared because there was concern about pyroclastic flows from a big eruption and the possibility that a caldera might form. The alert level-danger zone association, though not intentionally established, lingered, so that when Alert Levels 4 and 5 were released in 1992, an understandable reaction was to react as in 1991 and evacuate the 10- to -20-km danger zone.

There are at least two options for rectifying this source of potential misunderstanding. One is to explore the possibility of striking some correspondence between alert levels and danger zones. The assumption is that it is possible to determine the areas likely to be endangered by each type and magnitude of activity referred to in each alert level. However, eruptions vary in style and intensity, so such a correspondence may not be feasible.

The alternative is to consciously dissociate the alert levels from danger zones, define a permanent danger zone, and keep other danger zones open-ended and adjustable.

Another possible improvement in the alert level scheme would be to reword the "Interpretations" and specifically the phrase "eruption is possible within 2 weeks [or 24 hours]." That phrase was variously interpreted to mean "eruption will occur 2 weeks [or 24 h] hence" or that "an eruption *would* occur within 2 weeks [or 24 h]." Ironically, the wording was actually chosen to avoid making specific predictions. Rather, it was meant to define a window in which an eruption was *possible* and to indicate disappearing margins of safety. Thus, at Alert Level 2, an eruption within the next 2 weeks was judged unlikely, but at Alert Level 3, this was no longer true. At Alert Level 3, an eruption was unlikely within less than 24 h, but at Alert Level 4 all reassurances of safety was gone--an eruption could occur at anytime (C.G. Newhall, written commun., 1994). The Pilipino translation of the phrase "eruption is possible within. . ."--"maaaring mangyari ang pagputok sa loob ng" would have conveyed the message that the authors meant to convey. A Pilipino version of the alert level scheme could be pilot tested the next time one of our volcanoes becomes restive.

The broadcast of a warning that an eruption was imminent within 72 h, falsely attributed to PHIVOLCS, triggered discussions on the wisdom of the modified warning transmission procedure adopted at Pinatubo. Critics of the multipath transmission procedure claimed that had PHIVOLCS stuck to the DCC channel instead of directly dealing with the media, reporters would not have been able to cite it as their source for their false or sensationalized reports. The traditional DCC channel would certainly minimize the warning source's need to deal with the media and make it easier to pinpoint responsibility for erroneous reporting. But it would also limit the area that could be reached, given a short lead time for warning dissemination. The institution of an emergency broadcast system might provide a mechanism for effectively involving media in warning transmission. The concept is not new, and there have been attempts to establish such a system. The idea is worth reviving. An emergency broadcast network could be identified, with media representatives officially identified and properly trained to handle warning and emergency response operations. This move might not eliminate exaggerated or fabricated reports but could minimize the effect of such reports if people listen to and believe only the official transmitters.

4. The fact that 94 percent of the respondents in 1992 knew of the impending eruption before Alert Level 5 was released and that 92 percent responded appropriately indicates improvement in warning transmission as well as in inducing optimal response. However, because no evacuation was required,

the improvement in the percentage of appropriate response may be more apparent than real. The question remains, would this percentage be as large should there be a call for evacuation of areas beyond the 10-km radius?

Mount Pinatubo's continuing activity provides an excellent opportunity to continue the development of the eruption warning system. We hope the experience in evolving a suitable warning system for Pinatubo will yield some valuable lessons for issuing warnings at other active volcanoes.

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APPENDIXES

Appendix 1. Computation of sampling size, household survey, 1991-92.

Appendix 2. Distribution of respondents, 1991 and 1992

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Appendix 3. Interview schedule.

Assessment and Response to Lahar Hazard around Mount Pinatubo, 1991 to 1993

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ABSTRACT

Lahar hazard at Pinatubo is a function of prodigious sediment yield from Pinatubo's upper and middle slopes and the sediment storage capacity in the adjoining lowlands. Both are diminishing but at mismatched rates. Sediment yields set world records during the first three posteruption years, and yields in the Balin Baquero-Bucao and Marella watersheds may do so for several years more. In general, sediment yields peaked early and are decreasing rapidly in east-side watersheds, where the volume of 1991 pyroclastic-flow deposit is relatively low, deposits and streams are confined in a few steep-walled valleys, thin ash fall from secondary explosions is common, and vegetation recovery is fast. Sediment yields peaked later and are decreasing slowly in west-side watersheds, where pyroclastic-flow deposits are more voluminous, numerous small streams drain a broad, gently-sloping, unconfined pyroclastic apron, and vegetation recovery was initially slow.

We anticipate that slightly more than 3 cubic kilometers of sediment will move from the volcano's slopes into surrounding lowlands. By late 1993, almost two-thirds of this amount had already arrived in the lowlands; most of the remaining third will be from the Balin Baquero-Bucao and Marella watersheds. Sediment yield from the Gumain watershed virtually stopped in 1992, and that in the Abacan stopped because its 1991 headwaters were recaptured by the Sacobia in April 1992; 1991-93 yield in the Sacobia-Abacan-Pasig system was about three-fourths of the expected total.

Optimism that the worst is past, especially for the east side of Pinatubo, should be tempered by three factors. First, channels in the middle reaches of

alluvial fans are filled, so the threat of lahars to several populated areas remains high. On unconfined alluvial fans of the Pasig-Potrero, Marella-Santo Tomas, and, perhaps, the Sacobia Rivers, sediment must continue to spread beyond present river channels, into catch basins, if the overall problem is to diminish. Towns on these fans that are beyond the reach of the most sediment-laden flows (debris flows) could be protected from more dilute hyperconcentrated flows and floods by relatively low ring dikes if flows are allowed to spread onto surrounding agricultural land, but that solution has not, to date, been politically acceptable. Second, unusually heavy rainfall, if sustained for several days or more, would temporarily reverse the declining sediment yield and cause serious overbank lahars. Third, erosion and incorporation of sediment predating the 1991 eruptions into current lahars will add an as-yet-uncertain volume to deposits, and reworking of lahar deposits themselves will move sediment problems downstream and fill some distal reaches of channels that have not heretofore been filled.

Throughout the first 3 years of the Pinatubo crisis, assessments and warnings of lahar hazard, followed by mitigating actions, saved many lives and some property. Long-range warnings, including hazard maps and briefings, identified communities at high risk and led some residents to move transportable belongings--sometimes even houses--to safe, high ground. Immediate warnings from manned watchpoints, supplemented by rain gauges and flow sensors, alerted remaining people to flee villages when their lives were at risk. Information about the nature and magnitude of lahar hazard was also an important basis for planning projects, both sociopolitical and engineering, to help residents through this difficult time.

Despite some notable successes, not all warnings were perfect, nor were all warnings heeded. An early excess of false alarms made residents of some areas doubt all alerts; in other areas, dikes and other sediment-control structures offered a false sense of security that delayed evacuations. Some costly but futile efforts at lahar mitigation could have been avoided. In some of these instances, better scientific information and better presentation of that information could have reduced unnecessary losses; in other instances, competing political, economic, and social factors limited the acceptance of scientific information.

Note to readers: Figures open in separate windows. To return to the text, close the figure's window or bring the text window to the front.

INTRODUCTION

Lahars from Mount Pinatubo have been flowing into densely populated areas of central Luzon since the major eruption of June 1991, taking a small toll of lives but causing enormous property losses and social disruption (fig. 1) (Mercado and others, this volume; C.B. Bautista, this volume). Bank erosion and thick lahar deposits have left more than 50,000 persons homeless, and flooding and isolation have affected more than 1,350,000 people in 39 towns and 4 large cities. More than 1,000 km^2 of prime agricultural land is affected by or at risk from lahars, flooding, and siltation. The lahar problem also delays economic recovery, as some potential investors wait until the lahar problem subsides.

Figure 1. A, Damage from lahars in Barangay Lourdes, Bamban, as seen looking upstream on January 29, 1992. Damage occurred in August 1991, when breakout of a newly impounded lake just upstream breached the dike that had earlier protected Lourdes. In the background, mounds of sediment have been bulldozed from the river channel in an attempt to fill the breach. B, Areas that were severely affected by lahars, 1991-93.

Loss of life, property losses, and low investor confidence can be minimized by accurate and timely assessment of the lahar threat and corresponding prudent actions by those at risk. In this paper we examine approaches to the lahar hazard used in the 3 years following the 1991 eruption, with the goal to understand what was done well and what might yet be improved. We describe the evolution of our scientific understanding of the lahar hazard at Pinatubo, note specific warnings that were issued, and describe how those warnings were (and can still be) used to mitigate risks from Pinatubo lahars.

LAHAR HAZARD ASSESSMENT TEAMS

Preeruption and syneruption assessments of lahar hazard at Pinatubo involved scientists from the Philippine Institute of Volcanology and Seismology (PHIVOLCS), the University of Illinois at Chicago, and the U.S. Geological Survey (USGS). The Pinatubo Lahar Hazards Taskforce (PLHT) was formed under the leadership of K.S. Rodolfo to assess and warn of lahar hazards, principally on the west side of Pinatubo. Members of the team were drawn from the University of Illinois at Chicago, PHIVOLCS, the Philippine Mines and Geosciences Bureau (MGB), and the University of the Philippines' National Institute of Geological Sciences (UP-NIGS). In 1992, the PLHT became the Zambales Lahar Scientific Monitoring Group (ZLSMG). Lahar hazard assessment on the east side of Pinatubo, from 1991 to the present, was handled principally by PHIVOLCS with assistance from USGS scientists. This division of responsibility between the two groups and the two sides of the volcano began as a matter of logistical necessity and organizational autonomy; over time, the two teams may be merged into one.

Within days after the climactic eruption, PLHT organized systematic observations of lahars from a watchpoint at Dalanaoan, San Marcelino (15 km southwest of Pinatubo, along the Marella River; fig. 1B), and, while road conditions still permitted, from a watchpoint at Malumboy, Botolan (27 km northwest of Pinatubo, along the Bucao River). At the same time, topical but less systematic observations of lahars were begun on the east side of Pinatubo by PHIVOLCS and USGS scientists, who were often interrupted by the continuing eruptions. By 1992, both teams were making systematic observations and meeting to exchange insights as often as possible.

Both PHIVOLCS and PLHT have assessed lahar hazards and advised government officials on proposed mitigation measures. Their analyses have been similar, though PLHT and its successor, ZLSMG, have been more outspoken on proposed engineering countermeasures. At times, relatively minor scientific differences have arisen between the two groups, and media attention has focused more on the messengers than on constructive portrayal of the scientific differences.

Other organizations have made independent lahar hazard assessments, including the Philippine Bureau of Soils and Water Management and the U.S. Army Corps of Engineers, as noted below.

Warnings by PHIVOLCS and others are provided to the Office of the President, the National Disaster Coordinating Council (NDCC), the Regional Disaster Coordinating Council for Region III (RDCC-III), the Department of Public Works and Highways (DPWH), the Department of Social Welfare and Development (DSWD), and to Provincial, Municipal, and Barangay Disaster Coordinating Committees (PDCC's, MDCC's, and BDCC's) (fig. 2).

Figure 2. Communication paths for lahar warnings at Mount Pinatubo. A, Short-range warnings. B, Long-range warnings (principally by briefings, transmittal of written reports, maps, and press releases). Abbreviations: ATO, Air Transport Office, Manila; PHIVOLCS, Philippine Institute of Volcanology and Seismology; PNP-AFP, Philippine National Police-Armed Forces of the Philippines; PLHT/ZLSMG, Pinatubo Lahar Hazard Taskforce/Zambales Lahar Scientific Monitoring Group; PAGASA, Philippine Atmospheric, Geophysical, and Astronomical Administration; WPC/RDCC III, Watch Point Center/Regional Disaster Coordinating Council of Region III (operating agency=Office of Civil Defense, Region III); NDCC, National Disaster Coordinating Council (operating agency=Office of Civil Defense); PDCC, Provincial Disaster Coordinating Council; MDCC, Municipal Disaster Coordinating Council; BDCC, Barangay Disaster Coordinating Council; DPWH, Department of Public

Works and Highways; DSWD, Department of Social Welfare and Development.

DEFINING THE THREAT

A lahar is a rapidly flowing mixture of volcanic rock debris and water, typically with 40-90 percent sediment by weight, and thus having a consistency ranging from muddy water to a dense slurry. We recognize two types of lahars at Pinatubo, defined in greater detail by Pierson and others (this volume). The first, **debris flow,** has high viscosity, notable yield strength, and sediment concentrations typically greater than 60 percent by volume. The second, **hyperconcentrated flow,** has moderate viscosity, low yield strength, and sediment concentrations of 20 to 60 percent by volume.

All lahars from Pinatubo are caused, directly or indirectly, by heavy, seasonal monsoon rainfall that is enhanced by rain from tropical cyclones. The rainy season can begin as early as May and continue through November; monsoonal rains normally coincide with the typhoon season and are heaviest during June through September, but early- or late-season tropical cyclones can extend the lahar season. The June 1991 eruption provided the missing ingredients for lahars: a severely disturbed landscape in which runoff would be high and an abundant supply of loose, easily erodible sediment. Most lahars of Pinatubo begin as surface runoff of rainfall; a few begin by the sudden release of standing water that has ponded on or against the margins of other deposits. The flowing water rapidly entrains loose sediment from channel beds and banks and is transformed into a sediment-rich flow with the sediment concentrations noted above.

These generalizations, based mainly on climatic data for the Pinatubo region and on experience at Mayon and at other volcanoes around the world, were understood at the time of the June 1991 eruption. In addition, we needed to learn:

What was the approximate range of velocities, discharge, sediment content, temperature, and flow behavior to be expected for the Pinatubo lahars?

How would lahars vary from one watershed to the next?

What critical amounts of rainfall would be needed to trigger lahars of various sizes?

Preliminary data about the character of Pinatubo lahars came quickly. The flows of June 15, though not observed by our scientific team, were soon reconstructed (Major and others, this volume), and additional flows were soon observed (Pierson and others, this volume; Rodolfo and others, this volume; K.M. Scott and others, this volume). A working hypothesis was sketched out for three types of Pinatubo watersheds, based on their average slopes and intensity of eruption impact (see K.M. Scott and others, this volume). Other workers used oblique aerial photographs and preeruption topographic maps to estimate the volume of new pyroclastic deposits (then estimated to be 5-7 km^3, now judged to be 5.5+-0.5 km^3, W.E. Scott and others, this volume), and Pierson and others (1992) estimated that between 40 and 50 percent of this debris would be transformed into lahars over the next decade. Clearly, the lahar problem would be massive and persistent.

Semiquantitative details about individual lahars were filled in during the first lahar season, comprising the period from June through November 1991. Table 1 summarizes observations of lahars in the Sacobia River; elsewhere around Pinatubo, lahars have roughly similar characteristics, scaled upward or downward according to the size of the watershed and the volume of sediment that can be entrained.

Information concerning the critical rainfall necessary to trigger lahars of various sizes came more slowly, as we had to install a network of rain gauges and observe enough flows to draw valid conclusions. During 1991 and 1992, about 6 mm of rainfall over 30 min (0.2 mm of rain per minute) was sufficient to trigger lahars in the Marella and Sacobia watersheds, and rain at double that rate triggered medium to large lahars, especially if that rainfall was sustained for several hours or if there had been other rain in the preceding days. Figure 5 of Tuñgol and Regalado (this volume) illustrates lahar-triggering thresholds for various intensities and durations of rainfall.

Total rainfall of about 2,000 mm (station MSAC) during 1992 resulted in production of about 1×10^8 m^3 of lahar (water+sediment) (M.T.M. Regalado, unpub. data, 1994; Tuñgol and Regalado, this volume). For amounts of rainfall experienced in 1991 and 1992, the total volume of a lahar appeared to increase linearly with rainfall during the event (Regalado and Tan, 1992; Tuñgol and Regalado, this volume). In the Sacobia-Pasig watershed during 1992, lahar yield (V, sediment+water) was about 1×10^3 m^3 /mm of rainfall/km^2 of upland watershed. The same relation held for individual storms and for the lahar season as a whole. Lahar yields per millimeter of rainfall per square kilometer were generally lower in other watersheds; details of lahar yields will be discussed in the section "Long-Term Warnings: Hazards Assessment and Hazards Maps."

By 1992 and 1993, we began to detect several **changes** that could be projected as trends--in total sediment yield, sediment yield normalized for watershed area and rainfall, channel filling, upstream and downstream migration of the principal reaches of deposition, and other parameters. Most of these are noted and discussed later in this chapter; perhaps the most notable of these changes are the decreasing sediment yields normalized for rainfall and watershed area. Experience elsewhere suggests that this decrease will probably be exponential (Pierson and others, 1992), though perhaps not all the way back to preeruption levels (Pierson and Costa, 1994). Figure 3 contains computer-fit, manually adjusted curves for that decrease, projected back to preeruption yields of roughly 10^5 $m^3/km^3/yr$, still high in comparison to stable watersheds.

Figure 3. General decreases in sediment accumulation from 1991 to 1993. A, Volume of sediment accumulation (approximates sediment yield), per year. Symbols and lines for lahar years 1-3, measured values; dashed lines, projections, discussed in text. Shaded area, projection of Pierson and others (1992) for Pinatubo as a whole. B, Rates of sediment accumulation normalized for watershed area. C, Rates of sediment accumulation normalized for watershed area and rainfall. Lastly, we checked to see if our perception of the threat was consistent with what the geological record told us about the lahars from past eruptions of Mount Pinatubo, and it was. The general topography of gently sloping alluvial fans around Mount Pinatubo, soils maps of central Luzon, and inspection of exposures all suggest that much of the central valley of Luzon and all of the Santo Tomas plain owe their fertile soils and sediment to lahars and related floods of Pinatubo.

PUBLIC EDUCATION AND WARNINGS

PHIVOLCS and PLHT began to provide general public education about lahars, long-range warnings about what might be expected in coming months and years, and short-range warnings about lahars expected within minutes to days.

Education about the Threat

Before June 15, 1991, residents and local leaders of the Pinatubo area had only slight familiarity with lahars that had occurred at Mayon Volcano in 1984 and at Nevado del Ruiz, Colombia, in 1985. Fortunately, a videotape that was made by the late Maurice Krafft for the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), largely in response to the lahar tragedy in 1985 at Nevado del Ruiz, showed graphic, frightening, but realistic images of lahars and their effects on people. We showed this video to many decisionmakers and citizens, and the result was a noticeable increase in awareness and concern.

As described by Major and others (this volume), the first lahars formed from rainfall on preclimactic eruption deposits on the afternoon of June 14, almost 24 h before the climactic eruption. Much larger lahars occurred during that eruption, triggered by rain from passing Tropical Storm Yunya. On and shortly after June 15, people learned firsthand that lahars were raging torrents that destroyed bridges, eroded river banks, and flooded fields where riverbanks were overtopped. But most people still had little idea of the magnitude or persistence of the hazard that would be with them for years to come and had no concept of the insidious sediment buildup in channels that would soon lead to many more overbank lahars and floods.

Use of the term "lahar" was vigorously promoted on June 15, 1991, and in subsequent days by two of us (K.S. Rodolfo and J.V. Umbal), who were concerned that the previously introduced term "volcanic mudflow" misrepresented the material transported (mostly sand and coarse debris rather than mud), and, for that reason, gave people a dangerously understated sense of the threat (a similar concern was raised by Voight, 1988, 1990). Another purpose of introducing the term "lahar" was pedagogical: a catchy, unfamiliar term might (and did) get special attention. Indeed, the term lahar has now received so much attention that it has become a metaphor for practically any disaster in the Philippines.

Scientists targeted three groups for special education: news reporters, public officials (including civil defense officials and engineers), and police and army personnel assigned to lahar watchposts on the slopes of Mount Pinatubo. Instruction of the news media was provided in the course of day-to-day interviews and field trips, as reporters struggled to understand lahars. Educational posters were prepared, as were, later, several videos and a primer booklet on Pinatubo lahars.

Formal press conferences on lahars were rare (perhaps, too rare); one-on-one and informal group interviews with scientists were common, as was press coverage of scientists giving briefings to emergency meetings of public officials. Most press contacts were at PHIVOLCS' Main Office in Quezon City; in Zambales with the Pinatubo Lahar Hazards Taskforce; and in San Fernando, the site of many emergency meetings for public officials. Most interviews were with the chiefs of PHIVOLCS and PLHT, though a number of PHIVOLCS and PLHT staff served as spokespersons when needed.

Concern among both volcanologists and public officials was high.

Throughout late June and July 1991, one of us (R.S. Punongbayan) briefed government officials, including then-President Corazon Aquino, about both the eruption and lahars. In mid-July, another of us (K.S. Rodolfo) met with officials of the Department of Public Works and Highways (DPWH) and stressed that past eruptions at Pinatubo and similar volcanoes had been followed by such large lahars and volumes of deposited sediment that equally or more serious hazards lay ahead. A week later, another of us (R.J. Janda) met with the same group, outlined how sediment would move from the steep slopes of each watershed and fill lowland channels, and indicated how monitoring of erosion and channel filling in each watershed could provide information critical to the mitigation of the sediment problem. DPWH officials requested a ranking of barangays (villages) at risk and an estimation of the volumes of sediment that could be expected. On August 30, two of us (T.C. Pierson and K.S. Rodolfo) met with DPWH Secretary Jose P. de Jesus and his staff to further explain the lahar threat and to offer to work with design engineers on proposed engineering countermeasures.

For barangay leaders and the general public, illustrated flyers, posters, and leaflets were prepared and distributed by PHIVOLCS, the RDCC, the Philippine Information Agency, and others. One poster, "Mga Dapat Gawin Upang Maiwasan ang Pagiging Biktima ng Mudflow" ("How to Avoid Becoming a Victim of a Mudflow"), offered suggestions for what residents should do before, and when, they are warned of lahars (fig. 4). Paraphrased, the poster said:

0. Stay away from potential mudflow channels when it is raining at Mount Pinatubo and nearby hills;
0. If you live in a lowlying place, move immediately to high ground, keeping in mind that mudflows go to areas that are usually flooded during the rainy season. Keep in mind that some rivers and streams are already shallow from materials from Mount Pinatubo's eruption, so it is possible that these rivers will overflow;
0. Make your own "hill" at least 4 m high and widen the top to serve as an evacuation center;
0. Make barriers, if possible, but be aware that mudflows can be fast and strong;
0. Each group of houses should have a watchperson on a nearby hill to sound mudflow alarms;
0. Be ready with flashlights and a radio;
0. Listen for warnings and pay attention to the authorities;
0. Stay calm and don't be fooled by false news or rumors. WE WON'T HAVE TO WORRY IF WE STAY ALERT AND STAY TOGETHER.

Figure 4. Mga Dapat Gawin Upang Maiwasan ang Pagiging Biktima ng

Mudflow ("What you should do to avoid becoming a victim of a mudflow"), a poster issued by the RDCC Region III, Philippine Information Agency, and Philippine Institute of Volcanology and Seismology in 1992. English translation is in the text.

In the absence of suitable coarse riprap to protect against erosion by lahars, the advice to "build your own high ground" was later concluded to be unwise, and the advice was withdrawn before any manmade hills were actually built.

During the second lahar season (May-November 1992), PHIVOLCS released four new educational tools. The first was a pamphlet, "A Technical Primer on Pinatubo Lahars," written to explain the general behavior of lahars to public officials, the news media, and other interested groups (Punongbayan and others, 1992a). Perhaps the most useful feature of this primer was a distinction between "malapot" (sediment-rich, viscous) and "malabnaw" (relatively dilute, less viscous) lahars, corresponding roughly to debris flows and hyperconcentrated flows, respectively. The distinction made it clear that lahars were fundamentally different from normal streamflow and much harder to control than normal floods. Another useful concept introduced in the primer was attenuation of flows, so that people would understand that warnings of "2-m-deep flow" past manned watchpoints upstream from populated areas might only be "0.5-m-deep flow" or less in distal areas.

A second educational tool, requested by participants in the May 1992 International Scientific Symposium on Mount Pinatubo, was a set of impact scenarios for three representative storms (Punongbayan and others, 1992b). In order of increasing severity, the storms were (1) normal afternoon rainshowers, (2) prolonged monsoonal rainfall ("siyam-siyam," literally, 9+9 days), and (3) intense typhoon rains. Scenarios of future lahars and their impacts were chosen from the most likely actual events, such as burial of Barangay Tabun of Mabalacat town. For example, starting on Day 5 of a "siyam-siyam," the scenario said:

In Mabalacat, sediment now fills to within m of the flat surface on which Tabun and Dolores are built . . . . [Day 6] Rain continues . . . more lahars, all rivers. Bgy. Tabun is now "Natabunan" (covered) with m of sediment. Before taking a shortcut through Tabun, lahars washed out the Bamban Bridge . . . . [Day 7] Unexpectedly great erosion of the banks of the Pasig-Potrero below Mancatian, coupled with rapid buildup of sediment in the channel just downstream, now threatens Santa Rita, Pampanga . . . . [Day 9] The Pasig-Potrero breaks out, but to the east, into Potrero, rather than into Santa Rita . . . .

The only event in this scenario that did not actually occur in 1992 was breakout on the east bank of the Pasig-Potrero; rather, flow broke over the southwest bank and buried Barangay Mitla of Porac and Barangay Balas of Bacolor (near Santa Rita). Many other events in the scenarios occurred in

1992 or 1993. Ironically, because these scenarios were so accurate, we later wondered whether we should have presented them as forecasts rather than as hypothetical scenarios. Our data were too sparse to have predicted these events with customary scientific certainty, but were we certain enough by laymen's standards? Would "forecasts" rather than "scenarios" have had a stronger, more constructive effect in preparing communities for lahars? The answer to all three questions is, in retrospect, "yes."

A third educational tool was a booklet in Tagalog titled "Ang Lahar" (The Lahar), designed principally for barangay leaders (Philippine Institute of Volcanology and Seismology, 1992b). The booklet contained nontechnical information about lahars, hazard zones, and the RDCC-PHIVOLCS lahar-warning system (the last is discussed under Short-Range Warnings).

The fourth and perhaps the most important tool was a video companion to the booklet, also titled "Ang Lahar," that provided basic information about lahars and showed graphic examples of 1991-92 damage to towns around Mount Pinatubo. Separate documentaries by Manila TV stations showed similar footage, with an emphasis on social impacts, and two new scientific videos ("Lahars of Pinatubo," by K.S. Rodolfo and H. Schaal, University of Illinois at Chicago; and "Pinatubo Volcano: Lahars and Other Volcanic Hazards," by M.T. Dolan, Michigan Technological University) were released in 1994. All of these videos have been wonderfully effective in conveying concepts that, for nonscientists, words and maps cannot convey.

Long-Range Warnings: Hazards Assessments and Hazards Maps

Information about topography, previous lahars, watershed and channel characteristics, volumes of erodible sediment, trends in current activity, and probable patterns of rainfall have been translated into long-range warnings about areas that will be at the greatest risk over coming months to years. This information has been presented in the form of hazard maps, tables of estimated sediment yield, or general statements of changing hazard, such as channel capture or upstream migration of avulsion points. Long-range warnings have influenced some decisions about relocation of towns, possible engineering countermeasures, and general emergency planning. They have also given residents a chance to move portable property--machinery, furniture, appliances, personal belongings, harvestable crops, farm animals, and even dismantled structures--out of the expected paths of future lahars. Some examples of this information are given in the following section.

Lahar Season 1, June through November 1991

On May 23, 1991, PHIVOLCS distributed a page-size map of volcanic hazards to civil defense and political leaders. Lahars (called "volcanic mudflows" on the map) were represented as hachures and later as bold lines along each of the major river valleys. Areas of potential overbank flow were not indicated because we lacked the fine-scale topographic maps needed to forecast likely points of overflow and paths of such flows across the alluvial fans. Clearly, the main preeruption channels were the most likely paths for lahars; we could not forecast whether and where lahars might fill channels and avulse.

Immediately after the June 1991 eruptions, questions about the long-term outlook for lahars at Pinatubo included:

How big is the lahar problem?

How long will the problem last?

What areas will be at greatest risk?

Over the next several years, will lahar deposits cover entire alluvial fans of Pinatubo, including all towns thereon, or just selected parts of those fans?

Between August and October 1991, PHIVOLCS and PLHT prepared the first of what was to become a series of mudflow (lahar) hazard maps. Two from PHIVOLCS were on a 1:100,000-scale base provided by the National Mapping and Resource Information Authority (NAMRIA) (Punongbayan and others, 1991a,b). The first, released in August, showed a zone judged to be "subject to mudflows" as of July 30. The second, released in October, showed lahars that had occurred as of September 15 and a significantly larger zone "subject to mudflows." The October hazard assessment was based on the lahars that had occurred to date, topography, and a subjective judgment about how widely lahars might spread during the next 1 to 5 years in the absence of engineering countermeasures. A simplified version of the October map is included as data layer A on figure 5. The October map was the first of the lahar hazard maps to be printed and widely distributed and, as such, was very influential even though the evolving crisis required later expansion of its hazard zones. Many of the evacuation sites, relocation sites, and other elements of recovery were based on that map and its subsequent revisions.

Figure 5. Comparison of four Pinatubo lahar hazard maps, 1991-92. Only the zone of highest lahar hazard from each map is shown. Differences in intended periods of applicability, in data sets, and in assumptions lead to different maps and, in some instances, confusion among users of these maps.

Data layers are discussed in the text.

Also in August and September 1991, detailed lahar hazard maps (at a scale of 1:36,400) were issued by PLHT for the Santo Tomas and Bucao Rivers (Pinatubo Lahar Hazards Taskforce, 1991a,b). These maps were based on lahars to date, topography, a qualitative approximation of future lahar volumes, and projected channel avulsions. The map for the Santo Tomas River (dated August 23, 1991) showed lahars as of that date and four hazard zones, as follows: (a) areas subject to lahars and moderate to heavy flooding; (b) areas subject to overbank lahars and moderate to heavy flooding; (c) areas prone to minor or moderate flooding; and (d) areas subject to lahars escaping from filled irrigation canals. A September 5, 1991, map for the Bucao River used a similar zonation. In effect, these zonal categories ranked lahar hazard from highest to lowest. The relatively large map scale enabled officials and residents to judge whether their barangays, town streets, and secondary roads were in relatively high or relatively low danger.

Starting in September 1991 and continuing through the first half of 1992, the USGS, PLHT, and PHIVOLCS made semiquantitative estimates of probable volumes of lahars for the coming decade (Pierson and others, 1992). By then, it was apparent that sediment was being shed into surrounding lowlands at approximately 0.5 to 1.0 x 10^9 m^3/yr from a total upland source area of about 540 km^2, or at about 10^6 m^3/km^2 of upland watershed area per year, one order of magnitude faster than at Mount St. Helens and at the previous historical recordholder, Sakurajima Volcano, Japan (Janda and others, 1984). By analogy from Mounts Galunggung and Kelut in Indonesia, Pierson and others (1992) estimated that 40 percent of primary pyroclastic deposits on the east side of Pinatubo and 50 percent of the larger volume of primary deposits on the west side would be eroded and redeposited by lahars within roughly 10 years after the 1991 eruptions. Total sediment yield was projected to be approximately 2.5 to 3.6 km^3 of the estimated 4.8 to 7.0 km^3 of primary source material. Pierson and others (1992) also used aerial oblique photographs to estimate that 10 to 15 percent of most 1991 pyroclastic flow deposits had been eroded by September 10, 1991, and then used that volume of sediment as the first-year value on a sediment-delivery-rate decay curve, constructed from Mount Galunggung and Mount St. Helens data. Integration under that curve projected 1.2 to 2.5 km^3 of sediment yield during the first posteruption decade (fig. 3A).

Using the additional assumption that lahars would spread in fans and deposit to an average thickness of about 2 m, the projected 2.5 km^3 of sediment was translated into areas that could be covered by lahars during the coming decade (Pierson and others, 1992; also shown as data layer B on fig. 5). Potential hazards from future lahars (or from related backflooding and siltation) were mapped as being high or moderate, in relative rather than absolute terms. Whether lahars would actually impact this broad an area will depend in part on the actual advent and paths of typhoons, which deliver the most intense rains of lahar-generating duration. Preliminary copies of this 1:250,000-scale long-range hazards map were given to the Secretaries of National Defense and Public Works and Highways in mid-September 1991. In October 1991, the Bureau of Soils and Water Management issued a GIS-based map of "Mudflow and Siltation Risk," showing a "high-risk area" subject to "moderate to severe mudflows and/or siltation" (data layer C on fig. 5), a "low risk area" subject to "low siltation," and a non-risk area (high ground) (Bureau of Soils and Water Management, 1991). The "high risk" zone of this map is much larger than that of any of the preceding maps, because it is a map of the distribution of sandy soils around Pinatubo. This map serves a useful purpose of reminding us that Pinatubo has, indeed, been the source of the fertile sandy loams throughout much of central Luzon, but it neglects to note that this sediment has been supplied by many eruptions over geologic time (>35,000 years, Newhall and others, this volume). Thus, risk appears to be exaggerated on this map. Given the relatively modest scale of the 1991 eruption in comparison to previous eruptions of Pinatubo, we do not expect the "high risk" zone of this map to be fully covered during the next decade.

One awkward role for PHIVOLCS geologists began during late 1991--responding to requests to "certify" that specific parcels of land were safe from lahars before new construction, loans, or other uses could proceed. Hazard maps were the primary guide for geologists, but, as has been indicated, several maps had been issued at various scales, and they were not understood by all applicants, not detailed enough for all purposes, and not legal documents. It was entirely appropriate for PHIVOLCS to examine sites of proposed evacuation camps and other major public projects, including one unsuitable resettlement site (Rabanes, San Marcelino) on which infrastructure was built, despite rejection of that site by PHIVOLCS, and which was destroyed by lahars in 1993. However, the task of checking hundreds of parcels has been burdensome, especially for parcels that are neither obviously safe nor obviously doomed. Risk is rarely "black or white," but present procedures in certification demand that it be considered so.

At the end of the first lahar season, PHIVOLCS and PLHT combined data from aerial photographs and field measurements and estimated 8×10^8 m^3 of deposited 1991 lahar sediment. This corroborated the estimate by Pierson and others (made in 1991, published in 1992) that between 5 and 10×10^8 m^3 of sediment would be moved into lowland areas in 1991. The estimated volumes of 1991 lahar deposits, categorized by river system, were provided to the Department of Public Works and Highways on March 24, 1992, for the purposes of design and decisions on engineering countermeasures.

On April 4, 1992, lahar hazards along the Abacan and Sacobia Rivers changed dramatically. A secondary explosion and pyroclastic flow from valley-filling 1991 deposits allowed the Sacobia River to capture drainage that had been entering the Abacan River (Martinez and others, this volume;

Torres and others, this volume). Thus, the hazard along the Abacan decreased sharply, while that along the Sacobia increased. Some residents of villages along the Sacobia voiced suspicions that residents of Angeles City (along the Abacan) had caused the change, but the capture had been wholly natural, and it returned drainage to its preeruption pattern.

Lahar Season 2, May through November 1992

During 1992, lahars did not reach as far as they had in 1991, and the loci of deposition migrated up most of the alluvial fans. The reasons for these two changes are still under study; factors may include faster and greater runoff in 1991 than in 1992, channel filling and thus an increasing number of channel avulsions, and distal decreases in stream gradient. The effect of this migration was that towns like Concepcion and Bacolor (figs. 1B, 5), hard hit during 1991, were spared in 1992, while upstream barangays of the towns of Mabalacat and Porac were hard hit in 1992 and 1993.

In July 1992, in response to ever-changing conditions and a request for more specific, barangay-by-barangay assessments of lahar hazard, PHIVOLCS released a revised lahar hazard map on a large-scale (1:50,000) ozalid base that showed many, though not all, barangays at risk (Philippine Institute of Volcanology and Seismology, 1992a) (data layer D in fig. 5). On this map, hazards zones for the next 1 to 2 years were estimated on the basis of lowland topography (in which contours were a relatively coarse 20 m, with some intermediate 10-m contours), proximity to nearly filled river channels, volume of sediments to be expected, and a subjective estimation of how far and how widely overbank flows might spread. Two hundred and sixty nine barangays that fell within these newly defined hazard zones were listed, in an effort to help those unaccustomed to reading maps. At least one breathless radio announcer told listeners that all 269 barangays were at dire risk during the next rainstorm, and many people have found it difficult to understand that a hazard map with the words "subject to" is not an absolute prediction that all of the high hazard zone will get buried, but, rather, a geologist's graphic shorthand to indicate that actual flows over a period of years could but not necessarily *would* go anywhere within that zone.

Also on this map, hazard zones for the O'Donnell-Tarlac, Sacobia-Bamban, and Pasig-Potrero Rivers were larger than indicated in the October 1991 assessment, on the basis that 1992 lahars could have an equivalent volume to those of 1991 (8×10^8 m^3). Hazard zones for the Abacan and Gumain Rivers were reduced, reflecting the April 1992 capture of the upper Abacan by the Sacobia River and nearly complete erosion in 1991 of source materials in the Gumain drainage. Hazard zones for the Santo Tomas and the Bucao drainages were roughly the same as those in the August and September 1991 maps of PLHT (1991a,b). Page-size versions of these hazard maps were distributed with a corrected list of barangays at risk.

In late August 1992, the National Economic Development Authority (NEDA) and PHIVOLCS published a set of GIS-based maps of lahar hazard (Philippine Institute of Volcanology and Seismology and the National Economic Development Authority (PHIVOLCS-NEDA), 1992a). Hazard zones were modified only slightly from those of PHIVOLCS' July 1992 map (PHIVOLCS, 1992a), but the base map was substantially improved by including barangay and town boundaries. Important advantages of the GIS-based maps are that they can be revised quickly if conditions at and around the volcano change and that information about lahar hazard can be overlain by "data layers" for population, infrastructure, land use, evacuation routes, and myriad other parameters. An update of this PHIVOLCS-NEDA map, at a scale of 1:200,000, was issued on December 7, 1992 (PHIVOLCS-NEDA, 1992b).

The period after the 1992 lahar season was a time for scientists to analyze data they had gathered during 1991 and 1992 and to consider some new questions, including:

Was rainfall experienced during 1991 and 1992 below, near, or above the long-term average rainfall for these areas?

Had sediment yield at Pinatubo passed its peak and already begun to decline? (Sediment yield appeared to decline from 1991 to 1992, and we were asking whether we were past the period of peak sediment yields or just seeing an aberration due to unusually light rain.)

Unfortunately, discontinuation of rainfall monitoring at Clark Air Base in November 1991 and problems with telemetered rain gauges high on the west side of Pinatubo in 1992 prevent a direct comparison of rainfall for these 2 years. If we use rainfall at Dagupan as a proxy for that at Clark (table 2), we might conclude that rainfall on the east side during 1991 and 1992 was close to the long-term average, as was that on the west side (at Cubi Point). Rainfall high on the west slopes (fig. 8, stations BUG and QAD) was even higher than that of Cubi Point during 1991; we do not have comparable data for 1992, nor do we have any long-term average for BUG and QAD to tell whether the high rainfall in 1991 was above or below that average. Thus, we can say only that rainfall in 1991 and 1992 was not **demonstrably** different from long-term averages.

Field measurements during late 1992 suggest that, on the east side of

Pinatubo, the volume of 1992 lahar deposits was about 40 percent that of 1991 (table 3). However, similar measurements on the west side suggest 1992 sediment volumes that were nearly equal to those of 1991. Thus, even though sediment yield on the east side appeared to have peaked and to have begun to decrease, we could not say the same for Pinatubo as a whole.

Was the difference between east and west related to rainfall? Again using Dagupan as a proxy for Clark and using Cubi Point to represent the west side, the ratio of $Rainfall_{1992}/Rainfall_{1991}$ was about 1.3 on the east and 1.0 on the west. This small, insignificant difference suggests that differences in rainfall did not account for the different sediment behavior from east to west during 1991 and 1992. Rather, we think that differences in watersheds, including differences in volume of 1991 pyroclastic debris, slopes and stream channels, and vegetation recovery, were responsible for different patterns of sediment yield. Declining yields on the east side appeared to be the start of the anticipated exponential decline in sediment yield (Pierson and others, 1992).

Lahar Season 3, May through November 1993

Among the questions we asked in 1993 was:

Did erosion of pre-1991 source materials, now apparent in some river valleys, add significantly to the volume of deposits to be anticipated?

Along some stream valleys, erosion had already cut through 1991 pyroclastic-flow deposits and into older deposits. Did sediment that was eroded from deposits predating 1991 add significantly to the volume of lahar deposits in 1992, above that anticipated in early studies? In the Sacobia-Abacan watershed, the volume of 1991-92 lahar deposits ($270x10^6$ m^3, table 3) exceeded the volume of 1991-92 erosion of the June 1991 pyroclastic fan (about $138x10^6$ m^3, table 3). Could the difference represent the volume of debris predating 1991? An even greater contrast arose in the Pasig-Potrero watershed, where only $23x10^6$ m^3 was estimated to have been eroded from the 1991 pyroclastic-flow fan, although about $90x10^6$ m^3 of sediment was deposited downstream (table 3). If these values are extrapolated through 1993 and into the future, the ultimate volume of lahar deposits might be substantially greater than originally estimated. However, similar comparisons in the Balin Baquero-Bucao watershed show the opposite relation; that is, the volume of deposits is **less** than the volume eroded from 1991 pyroclastic-flow deposits (table 3). Either the uncertainties in estimating volumes are so great that these differences are within normal estimation error or differences between watersheds on the east and the west sides of the volcano have led to earlier and faster erosion of pre-1991 materials on the east than on the west.

Clearly, uncertainties in estimating volumes are large, but we think that advanced erosion in east-side watersheds has also cut significantly into underlying, pre-1991 deposits. Should deposits that predate 1991 on the west side of Pinatubo ultimately be eroded to the same extent, the lahar problem in west-side watersheds might be 50 percent larger than originally estimated.

Another question we asked in 1993 was:

Was the rate of sediment deposition in 1993, by watershed and total, declining from rates in 1991 and 1992?

The volume of lahar sediment deposited on the east side of Pinatubo during 1993 was approximately 130×10^6 m^3, about 85 percent of that deposited in 1992 and one-third of that deposited in 1991 (table 3). The Pasig-Potrero sediment accumulation was anomalously high in comparison to other east-side yields, probably because the watershed's "clock" was reset by the large secondary pyroclastic flow of 1992 and because a large secondary explosion on October 6, 1993, captured a significant amount of drainage from the upper Sacobia. The volume of sediment deposited on the west side of Pinatubo during 1993 was approximately 375×10^6 m^3, about 85 percent of that in both 1991 and 1992 (table 3). Thus, sediment yields declined noticeably on the east but slowly on the west. Similar trends appear when sediment yield is normalized for watershed area (fig. 3B).

Sediment yields per unit of rainfall (table 4) also show declining trends. Despite the fact that sediment yield per millimeter of rainfall (per square kilometer of watershed area) varied considerably from one drainage to the next (some of the apparent variability is surely the result of poorly constrained volume estimates), the **average** sediment yield of Pinatubo clearly decreased from 1991 to 1993 (from 1.5×10^6 $m^3_{deposit}/km^2_{watershed}$ and ~460 $m^3_{deposit}/mm_{rain}/km^2_{watershed}$ in 1991, to 0.9×10^6 $m^3_{deposit}/km^2_{watershed}$ and ~300 $m^3_{deposit}/mm_{rain}/km^2_{watershed}$ in 1993 (table 4, figs. 3B,C).

This general trend toward decreasing sediment yield at Pinatubo has two important corollaries: that both the numbers and sizes of individual lahars, and the annual accumulations of sediment, will continue to decrease noticeably over the next several years. The precise rates at which they diminish will depend on storm events and annual rainfall, on channel captures such as that in 1993 which shifted some flow from the Sacobia watershed into the Pasig-Potrero, and on broad differences in watershed response. As regards differences in watershed response, three watersheds illustrate the range of possible behavior. The Gumain River, with a relatively small amount of 1991 pyroclastic flow-material in a generally steep watershed, was reamed out in 1991 and has produced very little sediment since 1991 (table 3, fig. 3A). Subsequent rapid recovery of vegetation in the Gumain watershed had little effect on sediment yield because source material was already exhausted. The Sacobia-Pasig watershed, with an intermediate amount of 1991 pyroclastic-flow material, large channels in a steep-walled valley, frequent secondary ashfall, and intermediate degrees of vegetation recovery, produced its peak sediment yield in 1991 and now shows a well-defined trend of decreasing sediment yield: from 1610 $m^3_{deposit}/mm_{rain}/km^2_{watershed}$ in 1991 to 608 $m^3_{deposit}/mm_{rain}/km^2_{watershed}$ in 1993. In contrast, sediment yield in the relatively gentle-terrain, pyroclastic-flow-rich, slowly revegetated Balin Baquero-Bucao watershed may or may not have peaked as of the end of 1993. Its future decline, though ultimately certain to occur, cannot yet be quantified. In the absence of any data to constrain its rate of decline, we assume that sediment yield will have declined to $1x10^6$ m^3/yr (and to 10 $m^3_{deposit}/mm_{rain}/km^2_{watershed}$) after 20 years (dashed lines for Balin Baquero-Bucao, figs. 3A,C).

By using the computer-selected rates of declining sediment yield for the Sacobia-Pasig and O'Donnell Rivers, by choosing a rate of decline for the Marella that is intermediate between those of the Sacobia-Pasig and Balin Baquero-Bucao, and by assuming that further sediment yield from the Balin Baquero-Bucao watershed will decrease at the rates shown in figures 3A and 3C, we can make forecasts of eventual sediment yield for each watershed and for the volcano as a whole (last column of table 3). Though some assumptions are still required, these new forecasts are based increasingly on actual data, rather than on an assumed rate of decay that was adopted from volcanoes with much smaller eruptions than that of Pinatubo. Uncertainties are high in a forecast based upon only three annual measurements, but we think the forecasts are, nonetheless, an improvement over our original projections. The estimates are also consistent with observed differences in sediment yields from one watershed to the next. The new forecasts can serve for 1994 and will be revised as needed in subsequent years.

Interestingly, these new forecasts that are based on actual Pinatubo data are very similar to earlier forecasts that were based on an analogy with other volcanoes (Pierson and others, 1992). The only significant differences are in east-side watersheds where, apparently, incorporation of a significant volume of pre-1991 material is suggested by the abovementioned discrepancy between volume of erosion on the pyroclastic fan and volume of lahar deposits. Whether erosion of pre-1991 material on the west side will be as extensive as that on the east remains to be seen. If it is as extensive, the ultimate volume of sediment will be higher than that forecast here.

A third question we asked in 1993 was:

Was the upstream migration of sedimentation, noted in 1992, continuing?

Upstream migration of deposition continued in the Pasig-Potrero and Sacobia valleys through 1993, and avulsions above Mancatian on the Pasig-Potrero River brought lahars into that village for the first time. In contrast, some deposition in the Santo Tomas valley shifted downstream and toward the low southern margin of the Santo Tomas lahar field, largely as spillover from continuing deposition in the Marella valley. On July 1, 1993, ZLSMG released a revised, 1:50,000-scale lahar hazard map for the western Pinatubo area that identified points where lahars were likely to overtop and breach the dike that was being constructed along the south bank of the Santo Tomas River. This map accurately anticipated the site of an August 19 breach at the Western Luzon Agricultural College (WLAC). The map was modified after that breach and was modified again after lahars of October 4-7 breached the repaired dike at WLAC once again, as well as at other correctly predicted points at its eastern and western ends (Zambales Lahar Scientific Monitoring Group, 1993). Construction of dikes along the Santo Tomas River has resulted in faster, areally restricted deposition between Dalanaoan and San Marcelino proper than would have otherwise occurred, and, when breakouts have occurred, the artificially high origin points of the breakouts may have contributed to the distance traveled by breakout lahars.

All of the preceding long-range assessments of Pinatubo lahars were based on measured 1991-93 change at Pinatubo, supplemented by experience elsewhere. As a cross-check, we also asked:

Is the long-range assessment shown in the abovementioned hazard maps, based on events of just 3 posteruption years, consistent with what the geologic record tells us about entire periods of lahars following previous eruptions of Mount Pinatubo?

Pumiceous and sandy deposits in the lowlands of central Luzon are derived from lahars and related streamflow and overbank flooding. The sediment fans that surround Mount Pinatubo consist of layer upon layer of lahar and other stream deposits. Pinatubo sediments can be recognized beneath most cities and towns of Tarlac and Pangasinan Provinces, all the way northward to the Lingayen Gulf; beneath most cities and towns of Pampanga, all the way southward to Manila Bay; and beneath all towns of the Santo Tomas plain (Castillejos, San Marcelino, San Antonio, San Narciso, San Felipe) and Bucao plain (Botolan), in Zambales. Smaller parts of other provinces--Bataan, Bulacan, and Nueva Ecija--are also underlain by Pinatubo-derived sediment.

Prehistoric terraces throughout the Pinatubo area represent previous "high-stands" of sediment-rich flows. Examples include the terrace upon which Clark Air Base is built, one or more terraces immediately south of the town of Porac, several terraces along the Marella-Santo Tomas Rivers including those upon which the Aglao and the Palan evacuation camps are built, terraces along the Bucao River including that upon which San Juan and the main part of Botolan town are built, and terraces along the O'Donnell River upon which the old Crow Valley bombing targets were built (now, mostly buried) and on which Patling and Santa Lucia, Capas, are constructed.

Does this wide reach of Pinatubo sediments, areally and vertically, mean that all of these areas will be covered by lahar or flooding before the current crisis ends? We do not believe this is likely, and to draw finer distinctions, we asked:

What areas were covered after single previous eruptions of Pinatubo comparable in size to that of 1991 (specifically, after the penultimate "Buag" eruptions of 500 years ago)?

What are the ages of sediments in terraces that are still unburied, at various heights above present levels of fill, and were those sediments deposited only after much larger eruptions than that of 1991?

Which of these areas were covered by lahars, and which were covered by less lethal, but still troubling, floodwaters?

Radiocarbon ages for 25 lahar and related flood deposits (Newhall and others, this volume) help to distinguish between areas that were buried after the 500-yr B.P. Buag eruptions and areas that remained untouched after those eruptions. In general, in a clockwise direction from Tarlac Province around to Zambales Province, low-lying areas of Bamban and Capas were flooded and (or) buried by lahar and fluvial sediment of the Buag eruptive period, while slightly higher land around Mapalacsiao (Hacienda Luisita) and Clark Air Base was not covered by sediment of that period. The youngest **known** lahars to cross Hacienda Luisita occurred during the Crow Valley age eruptions, 5,000 to 6,000 years ago, while the youngest **known** lahars to cover the **whole** of Clark Air Base occurred during the Maraunot eruptive period, about 2,700 years ago. Some lahars did cover the Friendship area, and perhaps part of Clark Air Base, during the Buag eruptive period. Information for lahar deposits of the Pasig-Potrero River, on either side of Porac, is less well defined, but we are sure that the entire Porac area was covered by Maraunot lahars (3,000-2,500 years ago), and we also suspect that some of the famed sand- and gravel-mining of Porac might have been of Buag deposits. Terraces of the Floridablanca area, including that upon which Basa Air Base is built, are even less well known, but it appears from pyroclastic-flow deposits high in the Gumain watershed that the latest voluminous fill of the Gumain valley (and hence the most likely age of the terraces, below) was during the Pasbul eruptive period, about 9,000 years ago. However, some of the terrace deposits of Floridablanca could have been derived by flow in the Porac River, which in the recent geologic past has captured flow from the Pasig-Potrero; therefore, we would not be surprised if the youngest terraces of the Floridablanca area are the same age as those near Porac, 3,000-2500 years or younger.

Along the Santo Tomas plain, only the highest prehistoric lahar terraces remain unburied as of this writing, including a narrow terrace near Sitio Palan, and one or more broad terraces above Aglao and below Kakilingan. Between the present channel of the Santo Tomas River and Castillejos, deposits of 3,000- to 2,900-year-old lahars are just a meter above the level of 1993 fill. Upslope from Kakilingan, in Sitio Buag, it appears that Buag-age lahars filled or nearly filled some canyons but did not bury relatively high terraces. On one of these high terraces, a pre-Hispanic settlement (Dr. E. Dizon, Philippine National Museum, written commun., 1992) was buried lightly by ashfall from Buag eruptions but was not inundated by Buag lahars.

In the valley of the Bucao River, Poonbato was built on two or three prominent terraces, and downstream barangays were built on terraces overlooking the active channel of the Bucao. The main part of Poonbato and its new church, built on deposits of the Crow Valley eruptive period (6,000-5,000 yr old), were buried in 1992. A Buag deposit that formed the south bank of the Bucao River just downstream from Malumboy was buried in 1993. There is no reassurance from the geologic past for the safety of Botolan town; without dredging or other intervention, Botolan will probably be buried.

Why are some parts of Pinatubo's lahar fans relatively high and apparently safer than others? The main factor is probably the scale of the eruptions that supplied sediment for the lahars. The volume of erupted products has been generally declining in Pinatubo eruptions, from 35,000 yr ago to the present (Newhall and others, this volume). The 1991 eruption and the Buag eruptions were about one-half or one-third the size of Maraunot and Crow Valley eruptions, and about one-fifth or less of the size of the >35,000-year-old Inararo eruptions. In general, the highest terraces around Pinatubo formed after the large Maraunot and Crow Valley eruptions, when the level of sediment fill rose to those relatively high levels. However, not every terrace of those older periods can be considered safe: Poonbato is now buried and several of the highest terraces of the Santo Tomas plain are dangerously close to being overtopped. Also, we found no lahar deposit or sediment terraces of Inararo age, associated with Pinatubo's largest eruptions;

some might have been completely eroded, but most are probably buried beneath younger sediment.

In summary, lahar hazard maps that have been published in the 3 years since the 1991 eruption are broadly consistent with the geologic record. Lahars in the balance of the present crisis will not cover all areas around Pinatubo that have previously been covered by lahars, but they will threaten some areas that have not yet been buried, especially in the Santo Tomas, Bucao, and Pasig-Potrero watersheds. The areas threatened will depend partly on which areas are made more, or less, vulnerable by stream captures and by human intervention. Engineered dikes and other construction works have undoubtedly decreased risk to some areas but have probably increased risks elsewhere.

Short-Range Warnings

Information about approaching typhoons, rainfall on the volcano slopes, or lahars passing upper observations points was translated into **short-range warnings** of lahars expected within minutes to days. Some people chose to keep living in hazardous areas because they didn't believe the warnings, had no reasonable alternative, or simply chose to rely on short-range warnings for their safety (Cola, this volume). Those who chose to rely on short-range warnings took calculated risks that warnings would be issued early enough for them to escape. In return, they were able to remain in their own homes and on their own land for as long as possible and clung to the hope that their places would not be overrun by lahars.

Lahar Season 1, June through November 1991

The first short-range warnings were issued during the urgent, last-minute preparations for a possible eruption (Punongbayan and others, this volume). Lahars had previously been discussed as a possible adjunct to that eruption, on June 13, 1991, when weather forecasters recognized that Typhoon Diding (international name, Yunya) was heading toward central Luzon, and volcanologists realized that the storm would probably generate lahars from the fresh deposits of eruptions then in progress. New warnings about lahar hazard were issued to civil defense, local officials, and military commanders on June 13 and 14 and appeared as headlines, together with the "mudflow" part of the May 23 hazard map, in the Manila Bulletin (fig. 6), the Philippine Daily Enquirer, and other Manila papers on June 14.

Figure 6. Headlines of the Manila Bulletin, June 14, 1991, warning of impending mudflows and showing the rivers along which they would likely

pass.

The center of Typhoon Diding, downgraded to a tropical storm after it began crossing Luzon, passed within 100 km of Pinatubo's summit at about 1100 on June 15. Rain from Diding generated lahars from already-emplaced deposits and continued to generate lahars from fresh deposits of the climactic eruption that afternoon. Additional warnings of these lahars were issued on radio stations just before and throughout the climactic eruption, especially when reports arrived that bridges in Angeles City and in Barangay San Rafael, San Marcelino, had been destroyed by lahars. Some of these warnings originated from PHIVOLCS and the Office of Civil Defense; others were based on reports from citizens or reporters.

By the end of July 1991, the Regional Disaster Coordinating Council (RDCC Region III) deployed police and army units to ten primary (upslope) lahar watchpoints, one each on the O'Donnell, Bangut, Sacobia, Abacan, Pasig-Potrero, Porac, Gumain, Marella-Santo Tomas, Maloma, and Bucao Rivers. Initially, lahar watchers were housed in tents and made relatively crude "eyeball" estimates of the height of lahars passing their watchpoints. Information was relayed to central points at Camp Olivas, San Fernando, Pampanga, and the Zambales Provincial Disaster Coordinating Council in Iba, Zambales. Those centers raised simple alerts: Lahar Alert 1 (rain is falling on Pinatubo; get ready); Lahar Alert 2 (rain is continuing and a lahar could form; get set); and Lahar Alert 3 (a lahar has been confirmed; go to high ground).

Lahar watchers were drawn from the large personnel pools of the Philippine National Police (PNP) and Armed Forces of the Philippines (AFP) and served for about 2 weeks before being relieved by new watchers. Each group received a small amount of training before deployment, but frequent rotation limited the expertise that could be developed. During the first part of the 1991 lahar season, RDCC III in Camp Olivas tended to declare Alert 3 for all lahar-threatened areas whenever a lahar hit a single channel in Tarlac or Pampanga. This was before it became clear to everyone that the lahar-triggering rains in July 1991 were being delivered to the east side of Pinatubo by the trade winds, whereas the western slopes remained dry and lahar free (Rodolfo, 1991). An unfortunate consequence was that people in Zambales, roused too often by an Alert 3 without a corresponding lahar, became distrustful of the warnings and were largely ignoring them when the southwest monsoon finally arrived and brought lahars to Zambales. Lahar warnings on a channel-by-channel basis were started by late September 1991 after several meetings with RDCC and PDCC officials. However, people remained skeptical of warnings aired over the radio. Another difficulty with the PNP-AFP watchpoints was that many were located so far above the lahar channels that, in inclement weather, they would be shrouded by clouds and mist. Furthermore, those on hilltops were subject to lightning strikes; on one occasion, two watchers were killed by lightning drawn to their radio antenna. (For the 1992 rainy season, primary watchpoints along the Porac, Gumain, and Maloma Rivers were abandoned, and all-weather buildings were constructed at the other watchpoints.)

Secondary watchpoints were established at each major bridge or river crossing, all in populated areas. These were manned by police, generally without special training about lahars but equipped with two-way radios to learn of lahars coming their way and to relay information about those lahars as they passed each secondary watchpoint. Information flowed to and from Camp Olivas (for all of Pampanga, Tarlac, and Zambales) and the Zambales Provincial Disaster Coordinating Council at the capital in Iba (for Zambales).

PHIVOLCS and PLHT staff coordinated closely with weather forecasters at Clark Air Base and Cubi Point Naval Air Station, particularly as typhoons approached. Although the primary responsibility for typhoon warnings remained with the Philippine Atmospheric, Geophysical, and Astronomical Service Administration (PAGASA), PLHT and PHIVOLCS staff were able to give extra verbal and graphical warnings to communities threatened by lahars, on the basis of detailed weather information.

USGS, PHIVOLCS, and PLHT scientists also provided warnings of lakes impounded by pyroclastic flows or lahars that might fail catastrophically. One such warning was issued by PHIVOLCS to the RDCC on July 25, 1991, about a lake impounded in the upper Pasig-Potrero watershed. Regrettably, the warning on July 25 could not be specific and was the last official mention of this lake before it broke out on September 7, 1991, and killed several people downstream. More specific warnings were issued by PLHT about the largest such impoundment, where the Mapanuepe River was impounded by lahar deposits from the Marella River (fig. 7). On August 25, 1991, at 1700, PLHT warned PNP watchers at Dalanaoan of an impending lake breakout from Mapanuepe within the next few hours. The warning, however, was not disseminated to town officials until 2200 because the watchers' radio ran out of power. When the warning was finally disseminated, the municipal officials of San Marcelino and San Narciso were very reluctant to act on it because of previous false Alert 3 signals and because most of the people were already asleep. Fortunately, the San Marcelino police did awaken people of Barangay San Rafael before the breakout actually occurred at 0400 the next day and destroyed 8 houses (Umbal and others, 1991; Rodolfo and Umbal, 1992; Umbal and Rodolfo, this volume). The only casualty was a person who suffered a heart attack.

Figure 7. Mapanuepe Lake (left), impounded when lahars of the Marella River (lower right) blocked a tributary, the Mapanuepe River (left). Breakouts of this lake in 1991 prompted engineers to cut a channel through the ridge that lies south of (behind) the channel through which Mapanuepe Lake was still draining at the time of this photo. View is to the southwest, down the Santo Tomas River, which is the combined flow of the Marella and Mapanuepe Rivers. Much of the alluvial fan in the background (upper right) was buried by lahars in 1993.

In August 1991, after an emergency deployment of radio-telemetered rain gauges and acoustic lahar flow sensors (fig. 8) (LaHusen, 1994; Hadley and LaHusen, 1995; Marcial and others, this volume), a period of initial testing, and some initial difficulties with telephone and two-way radio links to civil defense officials, PHIVOLCS began to relay realtime instrument-based warnings to the Watch Point Center (WPC) of the RDCC at Camp Olivas, San Fernando, Pampanga. Instrumental records of flows were not yet calibrated by direct observations of those flows, nor did we know how much rain was needed to generate lahars, so warnings were limited to statements about rainfall and the occurrence of a strong signal on the instrumental flow monitors. Quiescence on the flow sensors was used to control frequent rumors of lahars. In general, WPC used PHIVOLCS' advice of lahar signals only to query the manned watchpoints; to our knowledge, WPC did not issue any lahar alert in 1991 solely on the basis of instrumental data from PHIVOLCS. One of the engineers who worked at WPC later told us that, because they didn't see the data themselves, they preferred to rely on reports from human observers.

An alternate lahar warning network, consisting of tripwires and rain gauges (Iwakiri, 1992), was installed by DPWH and operated by staff of the WPC. Tripwires and rain gauges were installed at two sites, Barangay Dolores (Mabalacat) and Barangay Sapangbato (Angeles City), and rain gauges were installed at those sites and at Barangay Dalanaoan (San Marcelino); Sitio Ugik (Botolan); Sitio Pasbul (Camias, Porac); and at the PNP Delta 5 manned watchpoint (Porac) (fig. 8), between February 1992 and April 1992. Unfortunately, the large size of these units (principally, of the 10- to 15-m-high concrete and steel mast) limited their installation to sites that were accessible by road--usually at lower elevations and far from the lahar source area. The tripwires were located so close to the towns at risk, and were broken so frequently by lahars and also by people, and were later buried so deeply by lahars, that they have been of little use. The rain gauges have been more useful, though correlation between rainfall and lahars is always questionable for rain gauges that are far from the lahar source area. Data are telemetered in realtime to RDCC-III in Camp Olivas and to the PDCC in Iba, Zambales, where they are interpreted by engineers and relayed by radio operators to manned watchpoints for confirmation. During the height of the 1992 monsoon season, however, the rain gauges at Dalanaoan and Ugik stopped transmitting data, owing to power problems that were not remedied until after the lahar season was over.

Figure 8. Sites of instruments and manned watchpoints for providing short-range warnings of lahar hazard around Pinatubo.

Lahar Season 2, May through November 1992

In 1992, to improve the technical accuracy of short-range warnings, we needed to answer the following questions:

What volumes of lahar discharge result from various amount of rainfall?

Can rainfall records and records from acoustic flow monitors (AFM's) serve as proxies, or even improvements, on direct observations from manned observation posts?

What levels of discharge are occurring, how and where is deposition occurring, and what channels are precariously full?

Is 1992 lahar activity changing relative to that of 1991, especially in any systematic way that can be of predictive value?

In June 1992, PHIVOLCS began systematic field monitoring of lahars in east-side channels, initially in the O'Donnell, Sacobia, Abacan, Pasig-Potrero, and Gumain channels and later reduced to the Sacobia and Pasig-Potrero. Staff reported peak discharges by radio, prepared simple hydrographs, recorded changes in the character of flows from start to finish, measured lahar temperatures, and took samples when practical (Arboleda and Martinez, this volume; Martinez and others, this volume). This activity was patterned after PLHT observations made on the Marella River in 1991; activity continued there and at the Bucao River in 1992 (Rodolfo and others, this volume; Umbal and Rodolfo, this volume).

Special effort was made to calibrate individual flow sensor records with observed discharge so that flow sensor data might be used as a substitute for manned observations. The first attempt at calibration, after lahar season no. 1, was for flows in the Marella watershed (Regalado and Tan, 1992). Similar work was done in the Sacobia watershed during lahar season no. 2 (Tuñgol and Regalado, this volume) and continued during lahar season no. 3 (Regalado and others, 1994). Though quantitative calibration of flow sensors in rivers other than the Sacobia is still ongoing, we can already use AFM records from all of these to distinguish the order of magnitude of discharge (for example, $10 m^3/s$, $100 m^3/s$, $1,000 m^3/s$, corresponding to small, medium, and large lahars). Qualitative information about the size of lahars is now included in PHIVOLCS' warnings to WPC/RDCC. In one early instrumental distinction of lahar size (August 1992), PHIVOLCS' advice of unusually strong lahar signals in the Sacobia was not used immediately by WPC/RDCC to order an evacuation, and 8 people downstream were killed by a major lahar. Since that time, somewhat greater credence has been given to instrumental indications of lahar size, but, even in the 1994 lahar season, people still find it much easier to visualize, and thus trust, a manned watchpoint's report of lahar depth (in feet) than either a quantitative or qualitative report of discharge. Few among those receiving warnings seem to be bothered that flow depth depends strongly on the channel width.

Records of flow sensors and observed discharge were also correlated with rainfall in the Sacobia watershed during 1992 and 1993. The results have allowed us to give an even earlier alert to WPC/RDCC, even before flow is detected. The thresholds for lahar generation, measured during the 1992 lahar season and described under the section "Defining the Threat," are our present (1994) basis for issuing warnings to WPC/RDCC. Because these thresholds will rise as sediment yield (normalized to rainfall) decreases, we will need to revise thresholds for warning in future years.

Also during the 1992 lahar season, we briefly explored the possibility of computer modeling of lahars to improve our understanding of flow processes and to help forecast traveltimes and downstream discharges. However, the simplest model available to us (DAMBRK, PC version) had no rigorous way of adding or subtracting sediment, and we knew from field observations that these were important processes. We could force the model to replicate some aspects of observed flows, but we concluded that, at Pinatubo, the model had no predictive value (R. Dinicola, USGS, oral commun., 1992).

A special concern arose in July 1992 when Pinatubo threatened to erupt anew. Mindful of past disasters at Kelut Volcano in Indonesia, where a crater lake was repeatedly ejected by eruptions until engineers lowered the lake level through a series of tunnels, we made rough estimates of the volume of water in the caldera lake and how much of that water might be converted to lahars were the lake to be ejected suddenly. Estimates of lake volume ranged from $5x10^6 m^3$ to $8x10^6 m^3$ (November 1991 air photographs), depending mainly on assumptions about the lake's average depth. However, as a lava dome grew, our concern decreased, because the lake appeared shallow, perhaps as shallow as a few meters. The eastern half of the lake gradually disappeared during this period, from alluvial filling aided in small measure by uplift of the lake floor. (Note, at the time of this writing, July 1994, the lake is several tens of meters deeper and has a substantially greater volume than it did in November 1991.)

Late 1992 and early 1993 was also a time to reestablish a battered lahar warning system. PHIVOLCS-USGS rain gauges and flow sensors required cleaning, repair, and replacement, and several needed to be moved to higher elevations in the lahar source regions to obtain more direct information about events in the source regions, longer lead times in warnings, and reduced risk of vandalism. This work was completed just before the 1993 lahar season.

Lahar Season 3, May through November 1993

The upgraded network of rain gauges and flow sensors operated successfully through the 1993 lahar season, with minimal periods of instrument failure. As expected, the threshold for lahar generation did rise slightly (Regalado and others, 1994), but not enough to change procedures for issuance of alerts. Alerts from PHIVOLCS to RDCC typically started with an alert that strong rain was falling on the upper slopes, followed by qualitative updates on the size of a resulting lahar ("small," "moderate," or "large," on the basis of the amplitude and duration of the AFM signal). Manned watchpoints provided similar information about the size of lahars, expressed as depth of the lahar (in feet). The latter reports were widely monitored by other watchpoints and local officials. Lahar watchers quickly realized that flows spread and peaks attenuate as they move downslope, so that by the time most flows reach downstream areas, reported "10-foot" lahars might be only a foot or two deep.

Some of the forward (higher elevation) manned watchpoints were discontinued in 1993, and more were discontinued in 1994, placing greater demands on PHIVOLCS instruments for initial warnings and on secondary (lower elevation) watchpoints for reports on arrival times and depths of lahars. As of this time of writing (July 1994), the formal lahar alert scheme from RDCC still retains the original 3 levels, with essentially the original meanings noted earlier. No formal distinction is made to indicate the size of an advancing lahar; rather, the depth of flow (in feet) and intensity of steaming are reported, with or without size information from PHIVOLCS, through a radio network of local observers at secondary watchpoints.

RESPONSE TO WARNINGS

The public's first and most effective response to lahar warnings was to move out of the way of the lahars. On June 14, 1991, PHIVOLCS' recommendation for general evacuation (principally for the eruption but also for lahars) was extended from 20 to 30 km in radius from Pinatubo's summit, and on June 15 it was extended again, to 40 km in radius (Punongbayan and others, this volume). During, and for weeks after, the climactic eruption, between 150,000 and 200,000 persons filled more than 300 evacuation camps (United Nations Disaster Relief Organization, UNDRO, unpub. data, 1991). Not everyone within 40 km of Pinatubo could or did evacuate; our impression, based only on anecdotal evidence, is that most of those who evacuated did so from fear of the eruption and associated earthquakes and lightning and not from the threat of lahars. But by so doing, some people also protected themselves from lahars.

After the eruption, evacuations were ordered every time Lahar Alert 3 (confirmed lahar--go to safe ground) was raised. Initially, evacuation recommendations were for all low-lying areas around the volcano; later, they were made on a river-by-river basis. Estimating the number of evacuees is complicated by having different barangays and families evacuating at different times, in some cases several times. The population of a reduced number of lahar-safe evacuation camps (~160) fluctuated seasonally, depending on rainfall. During periods of little rain and relatively low risk, the evacuee population dropped below 25,000 persons; during periods of heavy rain and strong lahars, the evacuee population swelled to more than 150,000 persons (UNDRO, unpub. data, 1992; Mercado and others, this volume). By the end of 1992, more than 50,000 persons had lost their homes entirely and another 150,000 had suffered some flooding or lahar damage (C.B. Bautista, this volume), and most of those people had been helped in evacuation centers.

As soon as the persistent character of the crisis became apparent, semipermanent and permanent resettlement sites were proposed as an alternative to evacuation camps. At about 10 previously undeveloped sites, the government built marketplaces, schools, health clinics, and buildings to attract and house manufacturing and other industry. Paved roads and utilities were, in many instances, of even higher standard than that in communities from which evacuees had come. Would-be settlers were offered low-interest loans to buy residential lots and to build houses. However, jobless, homeless families are reluctant to take on loans that they cannot repay, and for this and a variety of other reasons, displaced families have been slow to move into resettlement areas (C.B. Bautista, this volume). Virtually all of those who have moved from evacuation camps to more permanent resettlement areas have been replaced in the evacuation camps by families that are newly displaced by ongoing lahars.

Concurrently with operation of evacuation camps and development of resettlement areas, engineers from the Philippines, the United States, Switzerland, New Zealand, and Japan considered engineering measures to control the hazard itself. Politicians' reluctance to sacrifice any areas and engineers' training led them to try conventional channel maintenance measures--including construction of small "sabo dams" to trap sediment and stabilize base level, dredging of channels, and raising of dikes. The initial goal, more hopeful than realistic, was to contain the sediment within existing channels and other relatively small areas. Numerous small sabo dams were built but were promptly overrun (fig. 9). The dams were so hopelessly undersized that most scientists, and many engineers, recognized that they were little more than an employment program for local residents displaced by the eruption and visible evidence that the government was doing something rather than nothing.

Figure 9. Overtopped and breached sediment dam ("sabo dam"), in the Sacobia River just northwest of Clark Air Base. A, Aerial view, looking downstream. Small hut and person can be seen for scale. B, View from the right bank of the downstream face of the dam.

Not surprisingly, the worst problems of lahar incursions into populated areas were on unconfined alluvial fans of the Pasig-Potrero, Sacobia-Bamban, and Marella-Santo Tomas Rivers rather than in the deeper Bucao and O'Donnell valleys. Shallow channels on the alluvial fans filled quickly, and much overbank flow occurred. The dilemma for engineers quickly became apparent: the alluvial fans were not conducive to sediment storage, whereas the deeper valleys in which sediment could be trapped had relatively few people at risk.

When larger dikes were proposed to trap sediment on the fans of the Sacobia-Bamban, Pasig-Potrero, and Marella-Santo Tomas Rivers, we argued that the volumes of sediment would be so great that the only practical solution would be to let that sediment spread over relatively large "catch basins" outside current channels and in locations where sediment would naturally deposit. Most of the potential catch basins were in cultivation. In June 1992, PHIVOLCS and DPWH proposed catch basins to residents of Bacolor and Santa Rita, Pampanga (fig. 10), but the proposal was angrily rejected. No one was prepared to allow his own land to be buried.

Figure 10. Newspaper headlines describing government efforts to convince local residents of need for sediment catch basins (Manila Star, June 21, 1992).

Neither an engineer nor nature waits for debate, and, from 1991 to this time of writing, dikes on all sides of Pinatubo have been built, and all have been breached at their weakest points or points with the lowest freeboard during actual lahars. Failure at any point along a dike renders downstream portions of that dike useless (Rodolfo and others, 1993). Most failures of dikes to date have stemmed from the simple geometric difficulty of containing very large volumes of sediment within narrow confines, a faulty assumption that sediment would be deposited evenly along the full length of a diked channel (it will not), or an underestimate of the erosive power of lahars on dikes.

After the 1993 lahar seasons, new, larger and stronger dikes were constructed along the outer perimeter of many areas that had been buried by lahar. In effect, catch basins were created, though they were not called by this name. These larger, widely spaced dikes are surely more realistic measures than their predecessors, but they will still be tested by remaining lahars, especially in their upper reaches where sediment fill is the fastest.

One successful engineering measure was excavation of a spillway to stabilize the level of Mapanuepe Lake, newly impounded behind lahar deposits of the Marella River, and thus to prevent overflows and potentially catastrophic breakout floods. Meetings between PLHT, DPWH engineers and consultants, Dizon Mines management and engineers, and local officials led to an engineering solution in which a permanent spillway was excavated into bedrock at the southern margin of the lake, roughly 300 m away from the present edge of the lahar dam. Excavation started on October 23, 1992, and the spillway first opened on November 20, 1992, fixing lake level at or below 121 m in altitude.

In July 1992, PHIVOLCS had preliminary discussions with DPWH and Gov. M. Cojuangco of Tarlac Province to discuss a creative, promising combination of sociopolitical and engineering measures. In that combination, the government would temporarily lease land to be used as catch basins, until the new sediment fill could be returned to agricultural production. Towns around the margins of the catch basin would be protected by dikes. The scheme recognized that it would be much easier to protect the town of Bamban if sediment were allowed to spread around it; otherwise, efforts to confine sediment within dikes of the Bamban River were likely to assure burial of Bamban. Money to lease the land and to provide other incentives for relocation would come in part from money intended for engineering works. Regrettably, decisions were made to keep building narrow, undersized sediment-containment dikes along the Bamban and other rivers. At the same time, with strong ties to family land, no strong incentives for relocation, and seemingly high and substantial new dikes in their backyards, most residents stayed in their villages, even in high-risk areas, and left only when or just before their communities were overrun by lahars. In 1992, lahars buried parts of the proposed leases in Tarlac Province before any formal leasing action was taken, and then the main path of lahars from the Sacobia shifted to the Pampanga side of the river, where government leasing of land had not been seriously considered. Thus, on both sides of the river, residents lost their life savings and livelihood **and** lost any opportunity that the government would lease or buy their land.

Debate continued in late 1992 about the most effective long-term measures for mitigating lahar risk. Our impression is that debate became more polarized, between those who advocated engineering structures and those who advocated that available funds be spent for resettlement and other social measures. In an ongoing saga of trial and error, each side could now point to serious problems with the other--for example, failed dikes and unpopular, half-vacant resettlement areas. In defense, each side could point to its own successes. In some instances, media coverage misrepresented positions, setting up "pro-dike" and "anti-dike" sides when, in fact, principal points were that (1) dikes might, in some instances, be viable engineering options, and (2) dikes ought to be built only if they would be large enough and strong enough to actually work as intended and not inadvertently introduce a false sense of security or an unduly long-term maintenance problem (for example, Rodolfo, 1992). These are different statements of the same conclusion, but some media groups saw them as different conclusions.

Many of the practical, philosophical, and emotional issues that arose bore a marked similarity to issues raised by dike construction that keeps the lower Mississippi River from being captured by the Atchafalaya River (McPhee, 1989). In general, dike construction made more sense to those at risk than to disinterested observers.

In August and October of 1993, as in 1992, policymakers of the Mount Pinatubo Commission were forced by serious lahars to reexamine their long-range mitigation plans. Dredging and dike construction during the 1992-93 dry season was no match for the volume of 1993 lahars, so channels on the alluvial fans soon became choked with sediment, some of the dikes were overtopped, and several towns were badly damaged. Early lahars of the 1994 rainy season have already overtopped some dikes that were constructed or raised during the 1993-94 dry season, and greatly reduced freeboard at others. In a long-term view, undersized dikes have had little effect on where lahar sediment has been deposited, and most might just as well have not been built. They have postponed inevitable burial for some communities, and they might ultimately save a few communities right at the edge of where sediment would have naturally spread. But they have been built at great cost--roughly half of the monies available for coping with this disaster, plus loss of opportunities to use the same monies for nonstructural or even better structural measures, and losses attributable to a false sense of security until lahars were at hand.

Among the questions raised anew were:

What engineering solutions ***can*** *be technically viable? In order to be viable, what design specifications would they need?*

If an engineering solution saves a town for a year, or so, is it worth the associated costs? The direct cost of the dike is simple to calculate; indirect costs, and the value of saving a town for a year, are more subjective.

Are some engineering solutions actually aggravating lahar problems, for example, by initially helping lahars to reach far downstream, and now by causing avulsions to move upstream and thus damage towns on the edges of alluvial fans?

Politically, economically, and scientifically, what are the most practical options for catch basins, that is, land that can be used for sediment storage until the lahar crisis has passed?

We are neither engineers nor policymakers so we will not presume to answer these latter questions. Rather, we mention them to illustrate the continuing dilemma faced by all who seek to mitigate the lahar hazards of Mount Pinatubo: how to help people stay in their communities wherever possible and yet not waste resources where communities cannot be defended against lahar without spending an inordinate amount of money and (or) running a high risk that lahar defenses will ultimately fail. Scale and topography are major parts of the dilemma: solutions that might have worked where lahars are smaller, governments are wealthier, and valleys are deeper, are not readily transferable to Pinatubo. Denial of the hazard and difficulties in reaching political consensus are also important factors. Rather than asking that sediment be kept from all populated and cultivated areas, citizens and their leaders would do better to decide which areas must be protected and which can be temporarily sacrificed and to ensure that both hazard and compensation are fairly distributed.

SUGGESTIONS FOR FUTURE WARNINGS

Can lahar warnings at Pinatubo be improved? Yes, without question. Some improvements relate to incomplete data and uncertainties about process, and others relate to when and how warnings are conveyed. For technical improvements of long-range forecasts, we need to keep tracking:

0. Sediment budgets, including how much sediment that predates 1991 is being incorporated into current lahars, how much sediment is flushing straight through the river systems, and, especially, how rapidly the annual sediment yields are declining.
0. Details of topographic change in lowlands, with a contour interval of 5 m or less. Excellent maps have been made for limited areas, for a few flight dates, but to our knowledge there are no plans to make repeated, high-precision photogrammetric surveys of topographic change around the entire volcano.
0. Reaches of lahar deposition, because those reaches will be the sites of the next channel avulsions and overbank lahar damage. This effort requires

frequent remeasurements of cross sections of each major river draining Pinatubo.

Increasingly, GIS technology can be used to analyze, display, and disseminate current information about watershed response and risk. All long-range planning for lahar mitigation must anticipate and be adaptable to continued, rapid, major changes in the hydrologic system, such as stream captures. For example, captures of Abacan drainage by the Sacobia, and part of the Sacobia drainage by the Pasig-Potrero, are unlikely to be the last such events, and GIS-based hazard maps can be changed accordingly.

For technical improvements in short-range forecasts, we still need:

0. Timely transmission of typhoon tracks and detailed evaluations of southwest monsoon air masses, from PAGASA to scientists and RDCC-III personnel at Pinatubo.
0. Continued operation of rain gauges and flow sensors on the upper and middle slopes of Pinatubo, with commensurate technical support for those instruments and calibration of flow sensors to actual discharges.
0. Better realtime communication with WPC/RDCC, perhaps aided by a duplicate data-receiving station at WPC to serve as a backup and to counteract skepticism that we encountered in 1991-1992. A more ambitious extension of this would be to link all lahar watchers--police, military, scientists, and others--by a robust radio communications network, supplemented where possible by voice telephone and facsimile machines.

Equally or even more important than technical refinements in forecasts, we need to strengthen the channels by which our scientific results are actually used in lahar mitigation measures. Four specific improvements in our presentation would be:

0. Additional, highly visual presentations of hazard, such as videotapes and working models that are prepared in cooperation with those who are experienced in shaping public opinion and public policy.
0. Warnings that speak clearly and firmly despite inescapable uncertainties in the outcome of such complex events as lahars. A graphic illustration of this need came during raging lahars in early September 1992, when several villages were being overrun by lahars and when the chief of RDCC Region III (Gen. Pantaleon Dumlao) said to one of us, "Yes, you warned us, but you didn't shout loudly enough." Scientists are trained to be conservative in their warnings, but there are times when we must make our best guesses loudly and clearly, even without a full set of data.
0. Better use of scientific consensus in public statements. Differences of opinion among scientists are inevitable and have occurred. Some have

concerned purely scientific matters; others have concerned recommendations for mitigation. Unfortunately, these differences have been played out in the newspapers rather than in private discussions among scientists, and we have therefore lost some credibility, as a group, in the eyes of decisionmakers. Development of written scientific consensus before public statements would help all parties.

0. Equal attention to decreasing lahar hazard as to increasing hazard, partly to avoid undue alarm, partly to retain our credibility for those times when urgent warnings are needed, and partly to help people return to their land where such return is reasonably safe.

FUTURE LAHAR HAZARD

The nature of Pinatubo lahar threat was discussed in earlier sections. Here, we call special attention to three anticipated **changes** in hazard: extreme rainfall; diminution of annual sediment yield; and continued, even increasing, distal sedimentation.

Extreme Rainfall

Rainfall in the Pinatubo area is highly variable from one year and one month to the next, depending on typhoons and on sustained "siyam-siyam" southwest monsoon rainfall. Rainfall during 1991 and 1992 was close to the long-term mean (table 2). In contrast, that at Cubi Point in 1993 (7,165 mm, with 3,102 mm in August alone) was far above the mean and set new records for that station. Rainfall in excess of 2,500 mm/yr in Manila and Clark Air Base occurs, on average, about once every 10 yr, most recently in 1972 (>3,000 mm in the July-August period) and 1986 (>2,000 mm in August alone); none of our east-side stations approached these high levels yet, but, clearly, such levels can be reached.

Daily rainfall can also be heavier than has occurred since the eruption. We do not know the maximum daily rainfall during 1991 to 1993 at Clark Air Base or that at Cubi Point during 1993; during 1991 and 1992, the 24-h maximum at Cubi Point was 280 mm (J.S. Oswalt, oral commun., 1991). We have recorded higher amounts at many of our stations on Pinatubo itself (highest=744 mm in 24 h, from 0600 July 25 to 0600 July 26, 1994 at QAD), but we do not have a long-term average against which that could be compared.

Thus, in terms of the heavy rainfall that can generate severe lahars, rainfall in

1991 to 1992 was well below historical maxima, and within 1 standard deviation of average values. 1993 rainfall at Cubi Point was an historical maximum, while that at other west-side stations was probably normal. We expect that the next decade will include at least one additional year with heavy rainfall, >2,500 mm/yr on the east side and >5,000 to 6,000 mm/yr on the west side.

Diminution of Annual Sediment Yield

Lahars and rapid sediment accumulation will diminish and eventually stop. In terms of sediment volume, we are at the time of this writing (July 1994) about two-thirds through the crisis (fig. 3; table 3); we are farther along in some east-side watersheds and not as far along on the west. Both the geographic scope and the timescale of further mitigation options, including resettlement and engineering measures, should recognize that sediment yields are diminishing rapidly and will soon become more manageable, perhaps without need to undertake massive measures.

Continued Distal Sedimentation

As vegetation recovers and as other aspects of the 1991 watershed disturbance heal, runoff, like sediment yield, will diminish. However, high rates of runoff may linger a few years longer than high rates of sediment yield. If so, two phenomena will result. First, bank erosion in downstream channels will be high, so maintenance of remaining dikes will remain a major task. Second, some of that erosion will be of lahar deposits themselves, and the remobilized sediment will be washed farther downstream. One can think of Pinatubo sediment as moving into distal lowlands in two steps--first as lahars that are deposited on alluvial fans around Pinatubo and second as gradual but persistent movement of that sediment into more distant channels, for years or even decades after lahars have ended. Low-gradient river channels, even far from Pinatubo, will experience gradual siltation and diminution of channel capacity. As that capacity diminishes, normal rains will produce overbank flooding. Dredging will be required as a long-term flood-control measure in those areas, and the need for distal dredging may soon outstrip the need for dikes and other structures nearer to Mount Pinatubo.

CONCLUSIONS

Erosion and lahars in posteruption Pinatubo watersheds have filled lowland channels at rates that are unprecedented in the history of volcano hazards mitigation or sediment control. Almost all of the sediment transport occurs as lahars, which are episodic events dependent on heavy rain. Sediment yields at Pinatubo, on the order of 10^6 $m^3/km^2/yr$ during 1991-93, were an order of magnitude larger than at Sakurajima and at Mount St. Helens immediately after eruptions.

Rates of change in the lahar hazard are as remarkable as the initial magnitude of that hazard. Sediment yields are declining, on average by 20-30 percent per year and in some drainages by half or more each year. Sediment yields have decreased most sharply in east-side watersheds, where volumes of 1991 pyroclastic-flow deposits are small to moderate, slopes are relatively steep, and vegetation recovery is relatively rapid. In the Sacobia-Pasig watershed, three-fourths of the expected sediment has already arrived in the lowlands. Even on the west side, more than half of the expected sediment has arrived in the lowlands. Rates of sediment yield in 1993, normalized for watershed area and rainfall, ranged from one-third of 1991 values (in the Sacobia-Pasig system) to 100 percent (or more?) of 1991 values (in the Balin Baquero-Bucao) (table 4).

Despite long-range decline of sediment yield, days or weeks of extreme rainfall can still generate bank-full or overbank flow of several thousand cubic meters per second of dense lahar slurry. As channels are filled to capacity, each new storm and rainy season, and especially extreme rainfall, will cause new avulsions and shift flows wildly from one side of an alluvial fan to the other. One day or one season a community might be relatively safe; the next, it might be buried in lahar deposits. Then, as quickly as it was buried, that area might be isolated from future hazard.

Scenarios of lahar hazard offered by PHIVOLCS and PLHT/ZLSMG--long-range and immediate--have been dire yet generally accurate. Undersecretary of Public Works and Highways T. Encarnacion said to us, in 1992, "You were right . . . unfortunately." Some of our warnings have been based on hard data, others on general experience and intuition. We have walked a fine line between issuing timely warnings (some were backed only by sparse data) and reliable warnings (backed by ample data). Most citizens and most public officials have responded constructively, being willing to make precautionary evacuations, even after a few false alarms. Mutual understanding, courage to risk being wrong, and tolerance in case of false alarms are essential.

Hazard maps, booklets, and videos have correctly identified the most hazardous areas; immediate warnings from rain gauges, flow sensors, and manned watchpoints alerted people who remained in these communities to move to high, safe ground at particularly critical times. Of the three sources of immediate warnings, rain gauges and manned watchpoints were immediately useful, while flow sensors are gradually gaining acceptance. Civil defense has tried with reasonable success to fine-tune evacuations so that they are neither too large nor too small. After serious problems with false alarms in 1991, warnings are now reliable enough that most people are choosing to evacuate when warned, albeit at the last minute.

Of the more than 50,000 people who lost their homes to lahars, an unknown but substantial percent would have been killed had there been no warnings. Actual deaths from lahars, in contrast, are approximately 100--many times fewer than might have been killed without warnings. Jeepneys (local public minivans) and dump trucks full of property--furniture, household goods, farm animals, and harvested crops--accompany the exodus of evacuees, so we judge that much portable property has also been saved, though poignant scenes of people digging through fresh mudflow deposits to salvage belongings indicate that much has also been lost.

Hazard maps and estimates of long-term sediment yield have been important input to some decisions on long-term lahar mitigation. Major relocation sites have been sited (or, in the case of Rabanes, canceled) on the basis of such maps. Year-to-year emergency plans have been made on the basis of such maps. But only some decisions about engineering control of lahars have utilized available scientific information. Many small dams and small and large dikes have been built in the face of scientific judgment that they are too small or in places where any structure will be overrun. Information about expectable volumes of sediment is only one and sometimes a relatively minor factor in mitigation decisions, in competition with differences in perception of both risk and solutions (table 5), peoples' reluctance to leave and "sacrifice" their land, a lack of attractive alternatives for those at risk, political competition, and cost of mitigation measures.

Table 5. Differences in perception and approach between various parties in Pinatubo lahar mitigation.

Geoscientists:

0. approach natural hazards as forces to be understood and, when necessary,

avoided, rather than as forces to be controlled.

0. think over a wide range of spatial and time scales, from cubic centimeters to cubic kilometers and from minutes to millennia.
0. think of natural hazards as complex, ongoing, ever-changing processes that need to be studied continuously. Frequent changes in facts and interpretations seem perfectly natural, indeed, good.
0. must often be the bearers of bad news and must therefore be prepared for hostile receptions.

Engineers:

0. are trained to control or otherwise design against natural hazards (floods, landslides, and others). To not do so is professionally awkward, just as it is for a doctor to "give up" on a patient.
0. think principally on the scale of their structures and the design life of those structures.
0. are trained to design with available or quickly obtainable data and to add a factor of safety for future change. Opportunities to change design after construction are limited.

Residents:

0. view natural hazards as God's will, largely beyond their control but possibly preventable by prayer and engineering works.
0. must deal with harsh reality of finding food and shelter, which before a lahar is certainly easiest on their own land.
0. have emotional as well as economic attachment to the places in which they were born and raised.

Politicians and other policymakers:

0. view natural hazards as political and policy problems.
0. need to make decisions on technical issues even when technical advice is conflicting or uncertain, and even when the natural situation is sure to change.
0. are caught in a quandary between being sympathetic to public pressure for quick fixes, yet knowing that resources for coping with the lahar hazard are limited and must be used to everyone's advantage.
0. are sensitive to issues of reelection and duration of their own responsibility.

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We acknowledge the seminal contributions of our late colleague, Dick Janda, and honor his memory with senior authorship. While most of us were still preoccupied with day to day events, Dick was already thinking in terms of watershed processes and how an understanding of those processes would lead to better forecasts.

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The Mount Pinatubo Disaster and the People of Central Luzon

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ABSTRACT

The eruption of Mount Pinatubo and subsequent widespread and persistent lahars and flooding have taken a serious toll on the people of central Luzon. The most serious toll has been the displacement of more than 10,000 families (more than 50,000 persons) whose houses were destroyed and whose farmland or other source of livelihood was buried. Initially, the indigenous Ayta people were hardest hit, and many remain displaced from their livelihood and their cultural roots. Since the eruption, many lowlanders have also become evacuees, driven from their homes and land by lahars and floods.

Evacuations and damage from the volcano have undermined preeruption social standing and community leadership. Psychological stress is high. Decisions about how to mitigate lahar hazard have provoked suspicions between neighboring communities. Decisions about how to organize resettlement areas have engendered lively debate and, among some, concern that well-intended humanitarian relief is becoming a substitute for self-sufficiency. Viable resettlement options are badly needed, in which provisions for livelihood and social stability are given even more attention than matters of housing and visible public infrastructure.

Note to readers: Figures open in separate windows. To return to the text, close the figure's window or bring the text window to the front.

INTRODUCTION

Since its major eruptions of June 12-15, 1991, Mount Pinatubo has changed the landscape of central Luzon, uprooted thousands of residents from their homes and means of livelihood, and affected the agenda not only of the local, regional, and national governments but also of nongovernment organizations. This paper aims to provide an overview of the social and psychological impact of the volcanic eruption and some of the issues and problems of resettlement.

METHODS

The discussion is based on several sources: documents of the now-defunct Mount Pinatubo Task Force and the Mount Pinatubo Resettlement and Development Commission, which was created by law in September 1992 to replace the task force; unpublished reports of the regional government agencies, specifically the National Economic Development Authority, the Department of Public Works and Highways, the Department of Agriculture, the Department of Agrarian Reform, and the Department of Social Welfare and Development; relevant clippings of all major newspapers from June 1, 1991, to December 31, 1992; papers read in scientific conferences and various forums; findings of ongoing studies; and other published materials on the Mount Pinatubo disaster.

Apart from written documents, the paper relies heavily on interviews with key informants in government and nongovernment institutions and discussions with victims in evacuation centers and resettlement sites. Some of the points in this overview first arose in a field-based multidisciplinary study of one municipality, Concepcion, Tarlac, which is located in the direct path of lahars (fig. 1) (C.B. Bautista, 1993). Our team of social scientists lived in the area for 3 months, from October to December 1991. The team's findings were later validated or qualified by key informants in other areas of central Luzon. In February 1992, a workshop involving researchers and key resource persons in the municipality was organized. A month later, some of the research findings were disseminated in a town assembly held on March 27, 1992.

Figure 1. Locations of barangays, towns, cities, and provinces cited in this report. All of the barangays and smaller sitios that are shown in parentheses, except Poonbato, were destroyed by the eruption. Poonbato was destroyed by subsequent lahars.

Some of the team members went to Concepcion at regular intervals thereafter--twice a month from April to July 1992, about once a week from August to September, and biweekly in October and November to follow up developments there. While data were updated in Concepcion, another small research project was organized from October to December 1992 to gather information on the disaster in central Luzon. Devastated villages, resettlement sites, and evacuation centers were visited. Interviews with respondents in government agencies and discussions with victims and their care-givers were conducted within this time period.

SOCIAL AND PSYCHOLOGICAL ASPECTS OF THE MOUNT PINATUBO DISASTER

The 1991 eruption of Mount Pinatubo and its muddy aftermath have affected hundreds of thousands of central Luzon's residents in varying degrees, depending upon the specific hazard and their physical vulnerability to it. For purposes of accuracy in assessing the social and psychological impact of Mount Pinatubo on the population, the effects of the volcanic eruption are discussed separately from the effects of lahars and floods.

Victims of the 1991 Eruption

Ash fall from Mount Pinatubo's eruptions in June 1991 affected about a million people, half of whom were from the province of Pampanga (table 1) (Pardo de Tavera, 1992). A quarter of a million people remained displaced 1 week after the first major blasts, of whom about 3 percent were in formally organized evacuation camps (Department of Social Welfare and Development, unpub. disaster monitoring report, September 28, 1991). Tens of thousands of central Luzon residents fled to Metro Manila, and about 30,000 of these took refuge in the Amoranto Stadium in Quezon City. Though generally harmless in areas far from Mount Pinatubo, wet ash fall from 5 to 50 cm deep caused 189 deaths in areas near the volcano when roofs collapsed under its weight (Magboo and others, 1992; Spence and others, this volume). Ash fall also damaged public structures that housed social services. Ninety-eight hospitals and health centers, 18 public markets, 13 municipal buildings, and 70 other government buildings were destroyed (Department of Public Works and Highways, 1992a).

Table 1. The distribution of families and persons affected by ash fall (Pardo de Tavera, 1992)

Province/City	Families	Percent of total	Persons	Percent of total
Bataan	7,551	3.5	31,322	3.1

Pampanga	113,640	52.6	529,578	51.9
Angeles City	15,688	7.3	62,770	6.2
Tarlac	11,371	5.2	61,633	6.0
Zambales	49,827	23.0	245,582	24.1
Olongapo City	17,815	8.2	88,935	8.7
Nueva Ecija	79	0.2	373	.0
Total	215,971	100.0	1,020,193	100.0

Of all persons affected, the hardest hit were the Aytas, an indigenous tribe (Shimizu, 1989). Around 7,800 Ayta families, or 35,000 persons, were forced to flee their homes (Task Force Pinatubo, 1992). The Ayta's economic and cultural life before the eruption was rooted in Mount Pinatubo. They lived by the volcano's rhythm, timing the planting and harvesting of their crops by the volume of steam rising continuously from a natural vent on the upper slope. A relatively dense steam meant a good harvest; a thin one augured a sparse yield (Lubos na Alyansa ng mga Katutubong Ayta ng Sambales (Negrito People's Alliance of Zambales, LAKAS), 1991, p. 32). They hunted in the volcano's wooded slopes and fished in the rivers that drained it. The volcano was not only the source of the Ayta's livelihood but also the abode of Apo Namalyari, their God, and home to the spirits of their ancestors. For these reasons, the Ayta's evacuation from the volcano was especially disruptive and heart-rending. A vivid chronicle of their life and exodus is given in Eruption and Exodus (LAKAS, 1991).

From that book's account, earth tremors and heavy steam from the volcano summit at 1600 on April 2, l991, caused panic-stricken Aytas from villages along the Zambales mountain slopes to flee their homes and converge in a village 12 km from the volcano's base. Those who ignored the first ominous signs on April 2 fled in waves within the next 2 weeks. By the third week of April, the number of evacuees in Poonbato, Botolan, Zambales, reached about 4,000.

Even Poonbato was not the last stop of the Aytas documented in the book. They changed sites with each extension of the danger zone from a 10- to 20-km radius of the volcano, from 20 to 30 km, and finally from 30 to 40 km. Some groups moved 9 times in 1991 before they found semipermanent relocation sites.

Fortunately for the Poonbato Aytas, whose experience was documented, the group was kept intact throughout the exodus. As organized constituents of the Lubos na Alyansa ng mga Katutubong Ayta ng Sambales (LAKAS), they were also in a better position to maintain their cultural and tribal bonds and to critically assess the options opened to them. The acronym of the federation, LAKAS, means power.

This was not the case, however, among the Aytas living on other parts of the volcano. Mount Pinatubo's eruption scattered them to various evacuation centers and disrupted their political and administrative structure. New leaders and factions began to emerge as the tribes separated (Tadem and Bautista, 1993).

Anticipating the need for Aytas to vacate the slopes of Mount Pinatubo, the government set evacuation procedures in place before the major eruptions in June 1991. Conditions in the evacuation sites, however, were extremely difficult for Aytas. The tents provided only minimal shelter from the elements. Evacuees suffered from extremely hot days and cold and damp nights in these tents. There was no basic sanitation. As a consequence, respiratory and gastro-intestinal ailments were common. In early August, the Department of Social Welfare and Development reported that 156 Ayta children had died in evacuation centers in Tarlac and Zambales from various diseases such as measles, bronchopneumonia, and diarrhea.

Cultural differences accounted for the spread of some of these diseases. The measles outbreak is a case in point. A study conducted by the Department of Health reveals that its immunization campaign did not reach all vulnerable children in the camps. The cultural gap between the Aytas and health workers prevented the latter from reaching Ayta children (Magpantay and others, 1992; Surmieda and others, 1992). Some health workers believed that the Aytas eschewed Western medicine in favor of their own. However, the Sisters of the Franciscan Missionaries of Mary, who pioneered the literacy campaign among Aytas in Poonbato, claim that Aytas generally know when to ask for Western medical help. What was missing, at least initially, was rapport between health workers and Ayta evacuees that was based on an understanding of the Ayta culture. Malnutrition also contributed to high mortality among Ayta children (Surmieda and others, 1992).

Aside from getting more sick than their lowland counterparts in evacuation centers, Aytas were also disoriented by the surroundings far from their upland homes. They were unaccustomed to the sight of flatlands and plains, and they longed to roam the mountains and hills again in communion with nature and their God (LAKAS, 1991).

Thus, the Aytas were the prime victims of the volcanic eruption itself, before secondary effects like lahars and floods were taken into account. They were evacuated earlier than any other group, and throughout the ordeal of moving from one evacuation site to another, they were totally uprooted from their way of life. Even their resettlement sites, with high population density and town plaza complexes, were alien to their preeruption existence.

Victims of Lahars and Floods

Areas Most Damaged

The major eruptions and the plight of the Aytas in evacuation centers dominated newspaper headlines in June 1991. Since that time, lahars and floods have devastated many more villages and towns. Because preeruption river channels have been clogged by lahars, subsequent rainfall cannot drain away through those channels, so it floods adjoining lowlands.

By October 1992, most parts of 29 barangays (villages) had been buried by lahars to depths of several meters (table 2). Eleven of these were in only one municipality--Botolan, Zambales. Six were in Tarlac and 12 in the densely populated province of Pampanga. Half of Pampanga's abandoned barangays were in the municipality of Bacolor. The 29 severely affected barangays were home to almost 10,000 families, or about 53,000 people (1990 National Statistical Office population estimates for these 29 barangays, as stored in the National Economic Development Authority Region III Geographic Information System data base). Even this high number is surely an underestimate, because it counts only those in barangays within which most sitios (hamlets) were buried. Families from devastated sitios of relatively less affected barangays are not counted.

Most of these families once lived in the densely populated barangays of Pampanga, the province that bore the brunt of lahars in the first 2 years. Porac, one of the most severely affected of central Luzon's once bustling towns, symbolizes Pampanga's travails. Many of its residents have left.

Floods caused by silted waterways have added to the misery of central Luzon's lowland victims. Compared to 1991, 1992 was the year of floods. Siltation of river channels (much by lahars) caused subsequent floods that submerged barangays in at least 18 municipalities (table 3). As of October 1, water from the September monsoon rains had not yet subsided in low-lying parts of these municipalities, and additional barangays (especially in Zambales) were also isolated by floods at this time. In the province of

Bataan, adjoining the Pinatubo area, the municipalities of Dinalupihan, Hermosa, and Orani experienced persistent floods in 1992. Newspaper accounts on the week of August 20, 1992, cite the evacuation of residents of Hermosa from floodwaters of up to 5 to 7 feet (Philippine Daily Inquirer, August 20, 1992).

Table 2. Lahar-devastated barangays that were virtually abandoned in October 1992, listed by municipality and province.

[List of barangays is based on interviews with key informants in the municipalities, corroborated by newspaper accounts and field observations. The number of affected families and persons are taken from the 1990 National Statistics Office figures as stored in the data base of the National Economic Development Authority, Region III GIS Project]

Province	**Municipality**	**Barangay**	**Families**	**Population**
Pampanga			6,084	33,213
	Bacolor	Balas	308	1,771
		Duat	300	1,840
		Parulog	321	1,970
		Potrero	786	4,624
		San Antonio	887	5,718
		Santa Barbara	507	2,991
	Mabalacat	Cacutud	268	1,101
		Dolores	1,471	6,310
		Tabun	430	2,191
	Porac	Mitla	287	1,785

		San Jose Mitla	217	1,297
	Santa Rita	San Juan	302	1,615
Tarlac			1,832	10,634
	Bamban	Malonzo	128	811
		San Pedro	385	2,039
		Bangcu	35	216
	Concepcion	Malupa	230	1,463
		San Martin	178	1,220
		Santa Rita	876	4,885
Zambales			1,913	9,388
	Botolan	Villar	230	1,121
		Poonbato	483	2,553
		Moraza	112	569
		Belbel	124	534
		Burgos	145	669
		Cabatuan	77	330
		Malomboy	208	1,097
		Owaog-Nebloc	34	168
		Palis	79	328
		Nacolcol	143	693

	Maquisquis	278	1,326
Total		9,829	53,435

Comparative Effects of Lahars and Floods, 1991 and 1992

Owing perhaps to the previous year's experience with lahars, there were very few deaths due to lahars and floods in 1992. Whereas 100 of the 932 disaster-related deaths in 1991 were due to lahars, fewer than 10 died from lahars during 1992 (1991 figures are from the Special Transition Report of Task Force Pinatubo, May 1992, and include deaths from illness in evacuation camps; 1992 data are from the Department of Social Welfare and Development Region III Disaster Monitoring Report, September 28, 1992). Sixteen deaths, however, were due to floods in 1992, as opposed to none in 1991.

Although the number of casualties decreased, significantly more people were affected by lahars and floods in 1992 than in 1991. A total of 33,400 families, or 159,939 persons, suffered the effects of lahars or floods in the first year (Department of Social Welfare and Development, 1992). In contrast, five times more families (164,191) and persons (802,742) were victimized by the end of August in the second year (Department of Social Welfare and Development, unpub. Disaster Monitoring data, September 28, 1992). The marked increase in the number of people affected was due primarily to massive lahar-induced floods in 1992. Viewing the data by type of hazard reveals that 144,259 families experienced floods in 1992, while 19,932 families were affected by lahars (table 4).

Table 3. Municipalities that were flooded, or isolated by flooding, as of late August 1992 (shown by asterisk) or October 1, 1992.

[All these municipalities were (and will continue to be) affected by clogging of river channels by lahars]

Province	**Municipality**
Pampanga	Minalin

	Guagua
	City of San Fernando
	Santo Tomas
	Macabebe
	Floridablanca
	Mexico
	Bacolor
	San Simon (*)
	Sasmuan (*)
	Porac (*)
Zambales	Cabangan
	San Marcelino
Bataan	Hermosa (*)
	Dinalupihan (*)
	Orani (*)
Tarlac	Bamban
	Concepcion

Table 4. Distribution of affected families, listed by province and type of disaster.

[The 1991 figures were taken from DSWD (1992a). The 1992 data were taken from DSWD (1992b). Data are current up through the lahars and floods which occurred around August 15, 1992]

Province	Percent of Families Affected			
	Lahar, 1992	Floods, 1992	Lahar and flood combined	
			1992	1991
Bataan	-	17	15	5
Bulacan	-	2	2	
Nueva Ecija	-	<1	-	<1
Pampanga	27	52	49	62
Tarlac	40	5	9	13
Zambales	33	24	25	20
Total	100	100	100	100
Number	19,932	144,259	164,191	33,400

At least 3,140 houses were completely destroyed and 3,072 were seriously damaged in 1992. Of the former category, 54 percent were demolished by lahar and the rest by floods. These data are principally for Pampanga; additional houses were destroyed in Tarlac and Zambales.

A discussion of the effects of lahars and floods on people is not complete without mentioning damage to infrastructure and agricultural lands--damage that has profoundly affected livelihood and quality of life. Lahars inundated 15 km of roads, damaged 13 major bridges throughout the 1991-92 period, and threaten to affect another 10 bridges in the coming years (Department of Public Works and Highways, 1992b; Environment Management Bureau, 1992). Mudflows also breached 58 km of river dikes, half of which were along the Pasig-Potrero River.

Lahars and floods affected as much as 42 percent of the total cropland of Pampanga, Tarlac, and Zambales. By province, Tarlac had the highest percentage of its cropland damaged (52 percent of 841 km^2), followed by

Pampanga (41 percent of 618 km^2) and Zambales (13 percent of 236 km^2) (Department of Agriculture Region III, unpub. data, 1992).

In 1991, almost 9 out of 10 lahar-affected agricultural areas were planted to rice (Task Force Pinatubo, 1992). In 1992, that ratio remained practically the same; only a slight shift occurred toward sugarcane (Department of Agriculture Region III, unpub. data, September 28, 1992 Summary of Damage Report).

This observation also holds for agricultural lands inundated by floods. They were overwhelmingly rice based. Because floods induced by lahar deposition in river channels usually left a layer of mud in their wake, farmers in affected rice-producing areas had to rehabilitate their lands.

Beyond their direct effects on agricultural lands, lahars and floods affected 5 national and 176 communal irrigation systems that serviced 483 km^2 of farmlands and 25,476 farmers (Task Force Pinatubo, 1992). The latter figure includes many whose lands were spared from either lahars or floods.

In terms of the people associated with the land, a total of 11,540 farmers in Pampanga, Tarlac, and Zambales were affected by lahars in 1991. During this year, 85 percent of them were almost equally distributed between Pampanga and Tarlac. In 1992, however, the number of lahar-affected farmers declined by half, a finding consistent with the drop in the area of croplands newly affected by lahars.

Farmers in those areas covered with 7 to 15 cm of lahar were better off than their counterparts in places with more than 15 cm but less than 30 cm of mud. The land of farmers with 15 cm or less of lahar just needed to be plowed, while the land of those with thicker lahar had to be scraped. Still other land was either buried beyond rehabilitation by lahar or sunk in emergent lakes, and those who farmed such land must look for alternate land or leave farming.

Most of the affected farmers, especially in Pampanga and Tarlac, were land reform beneficiaries. Some are leaseholders, others amortizing owners, and still others are new owners who have fulfilled the state's requirement of land transfer. The loss of land owned through land reform, albeit temporary in a geologic sense, was a special blow to beneficiaries who have painstakingly paid in full and obtained legal ownership of their parcel of rice- or corn-producing lands. Among amortizing owners, those who have paid a significant amount of the cost of the land stood to feel the loss more than those who have defaulted on their payments.

Some Social Effects of Lahars and Floods

For the former residents of barangays devastated by lahars, the disaster mitigated an internal process of social differentiation. Prior to the calamity, the population in these villages was divided into those with access to agricultural assets or opportunities for overseas employment and those without. Lahars buried agricultural lands, equipment, and houses in these communities regardless of the wealth of the owner. In some instances, residents who were relatively well-off lost so much that they found themselves in positions similar to those who were once their social inferiors. It is in this sense that ordinary folks have referred to Mount Pinatubo as the "Leveller" or the "Equalizer."

On the whole, however, class distinctions have not been eradicated, because many of those with financial resources managed to find new homes elsewhere. Residents who could not afford to go anywhere else were able to dig up housing materials, appliances, and furniture, thus preserving at least some of their position in the village's social hierarchy.

Although the basic social hierarchy has been maintained in those communities whose residents have remained intact in relocation sites, some new organizations of community life have emerged in relocation sites populated by residents hailing from different barangays. In addition, the social distance among groups in places that have not yet been severely affected by the disaster has been bridged by a significant increase in communal activities that have cut across classes. Religious rituals such as prayer sessions and processions around villages and along the river channels have been the most visible activities in different parts of central Luzon. The rituals have been conducted all year round, although they are practiced most frequently during the rainy season.

Apart from religious rituals, participation in activities to protect barangays from lahars (such as sandbagging) or to protest government decisions designating particular areas as catch basins have been documented. The explorations of the Disaster Coordinating Council to use the Candaba swamp as a catch basin for lahar was met by strong opposition from residents living in several municipalities in Pampanga.

In the summer of 1992, the Department of Public Works and Highways planned to make a sediment-trapping "sabo" dam in Maskup along the Sacobia River to contain lahars that were expected to flow into some parts of Mabalacat, Pampanga. Residents of this municipality resisted the plan, fearing that it would divert lahars to other parts of the town. Some of those interviewed claim that a few residents threatened the contractors who were beginning to survey the area. As a consequence, the plan was shelved.

The national government was not the only target of protests from angry residents who perceived efforts to protect some localities to threaten their own. Municipalities were pitted against each other as attempts to protect one political territory were deemed to be at the expense of a neighbor. The sandbagging operation along the boundary of San Fernando and Bacolor, Pampanga, is a case in point. The latter's folks rejected the fortification efforts of the former because it will trap lahars in Bacolor (Daily Globe, September 16, 1992, verified by the author from key informants).

San Fernando's local officials were also caught in a dispute with those from Santa Rita, Pampanga. San Fernando officials were alleged to have asked the local court to stop residents of Santa Rita from putting up a sandbag dike, lest the dike divert lahars and floods into San Fernando, Pampanga's capital (Philippine Star, September 25, 1992; Philippine Daily Inquirer, September 25, 1992). The provincial governor's mediation apparently led to the withdrawal of the suit on the same day.

The politics of lahar defenses also resulted in tension between neighboring communities. Sometimes, rumors were an outlet for the growing suspicion among neighboring barangays. Key informants in one municipality, for instance, cited ill will aroused by the differential impact of lahars on two sides of the river within that municipality. Those on the side that was spared were suspected of having breached the dike on the affected side. While such an operation would have been impossible to achieve without the affected area knowing about it, the impression held sway.

The fact that dike construction raised ill will reflects the extent to which lahar defense has become a highly politicized issue. A political culture in which the powerful are able to get away with practically anything, especially in rural areas, accounts for much of the cynicism and suspicion with which efforts to defend human settlements are viewed.

Some Psychological Effects of Lahar and Floods

A cursory review of the graffiti on walls of abandoned homes reveals the angry and plaintive expressions of victims who, despite early warnings from the Philippine Institute of Volcanology and Seismology (PHIVOLCS), were caught off guard. Nothing in their individual and collective past prepared them for the disaster. As such, many of the victims suffered from psychological problems even long after their initial evacuation.

A study of victims and service providers in Tarlac (Jimenez, 1993) vividly described the evacuation process, which traumatized adults and children:

But whether it came by day or night, the sound and sight of the lahar was enough to frighten the people into immediate escape. The lahar was terrifyingly high and steaming hot, they reported. It swept along with it tree trunks and rocks so huge and heavy that it took five men to move them later on. Many believed it to be the end of the world and all thought they would die then. All thought of immediate escape. There were those who only had time to scoop in their infant children and run off, all the while shouting to their older children to run ahead. (Few) had enough time and presence of mind to scoop up ... belongings.

There was pandemonium as they ran, they recalled. People were screaming and crying as they ran, calling on their God for help and deliverance. Everyone was terrified and shouting for help. In their haste, they tripped or ran into each other, fell, picked themselves up and begun to run blindly again...there was a mad rush to get on the trucks. The women and children came off badly in this scramble, as they were pushed aside or thrown unceremoniously on.

Those who were caught in their houses only had enough time to rush up to their roofs. There, families huddled together in fear and for comfort--awaiting their certain death. All spent the night terrified, crying, and praying to God for help and mercy ...."

Jimenez (1993) also reported several symptoms of stress among the victims who evacuated to the centers. Upon arrival in the evacuation sites, they trembled from cold and fear continuously. Some went into hysterical laughter. Even days later, victims found it difficult to sleep and did not have much appetite for food. Some of Jimenez's respondents judged that the Mount Pinatubo disaster affected males and females differently. Males tended to become more quiet and withdrawn than did the women, and spent time in all-male drinking sessions.

More than a year after their lives were uprooted, service providers in a relatively well-established resettlement site for farmers in Zambales cited sudden bouts of crying, irritability, and constant headaches among the resettlers, which could only be traced to the trauma of Mount Pinatubo. Symptoms of stress were not confined to those who left their homes. For those living along the potential corridors of lahars and floods, the monsoon season heralded sleepless nights, with families anxiously awaiting the warning to flee their homes. So intense was the stress that when the warning signals--church bells or successive gunshots--were raised, key informants reported incidents of residents who suffered from heart attacks.

Many of the psychological problems confronted by those who took flight from the perils of lahars and those who continue to live in natural catch basins could be attenuated by mass resettlement to areas that are not vulnerable to the disaster. Unfortunately, snags in the resettlement process and attachment to their original lands and homes have discouraged many would-be settlers from moving to resettlement areas. To the dismay of scientists who warn against remaining in danger zones, many of the potential victims have chosen to remain in high-risk areas because they have no viable alternatives.

ISSUES OF RESETTLEMENT

As noted earlier, the Mount Pinatubo disaster has displaced tens of thousands of people in Tarlac, Pampanga, and Zambales. A conservative estimate based only on the population of 29 most thoroughly buried barangays in 1992 is around 53,000 people, a figure that is bound to increase in 1993.

The U.S. Army Corps of Engineers Recovery Action Plan team projected in a briefing for the Mount Pinatubo Commission that about 1,900 km^2 of land in the three provinces may be buried beneath 2 m of lahar debris. The study, which basically supports the PHIVOLCS projections, prompted the commission to estimate that about 74,000 residents in the high risk areas could no longer be defended against lahar and might have to be evacuated by force (Mount Pinatubo Commission, 1993). These people, who were not victims during the 1991 and 1992 rainy seasons will add to the 53,000 dislocated victims.

Because of the scale of human displacement, the state poured massive financial resources into the development of various resettlement projects. Total expenditures during 1991 and 1992 were at least P2.5 billion (US $93 million) for evacuation and resettlement sites (Mercado and others, this volume). In addition, various civic groups, private relief agencies, and development-oriented nongovernmental organizations in some of the state's resettlement sites also infused private resources into these efforts. The Loob Bunga Resettlement Site in Zambales, for instance, stands out in terms of its private resources. At least 11 organizations extended food assistance, provided health and nutrition services, and promoted livelihood projects, as well as literacy and spring-water development projects.

Technocratic Top-Down Planning or Bottom-Up Participatory Approaches

An ongoing controversy over the state's resettlement efforts boils down to differences in the basic approach to the problem of resettlement. From the perspective of a technocrat, resettlement requires technical planning based on the principles of scale and efficiency. The logic underlying the technocratic perspective of the now-defunct Mount Pinatubo Task Force can be described as follows. The infrastructure and settlement patterns of some modern cities in the world were planned at critical junctures in their history. The present Tokyo, for example, developed from the ruins of the Great Kanto earthquake of 1923 and from the Second World War. While these calamities resulted in untold human misery, they also provided the occasion to plan the modern Tokyo.

Because the Pinatubo disaster dislocated tens of thousands of victims, the technocrats hope to address victims' needs while maximizing the rare opportunity to use planning principles. Their idea is to put up settlements bigger than the usual barangays in order to economize on basic services like schools, public markets, and hospitals. The concept for the physical layout of the envisioned towns drew from the sprouting subdivisions in Metro Manila and its suburbs, the plaza complex found in most towns, and ideas about the practicality of grid road networks versus the current linear pattern in rural areas.

In addition, because government will be building new towns anyway, the Mount Pinatubo Task Force's logic dictates that they might as well fit into the Regional Spatial Development Strategy of central Luzon. This strategy conceives Region III to be the transit lane between the resource-rich provinces of northern Luzon and the densely populated industrialized areas of Metro Manila. As such, central Luzon will "serve as a catchment area for population and industry spill-over from the metropolis, while maintaining its comparative advantage in agriculture in some places." The plans also project the region in the role of "providing the requirements of the Northern Luzon provinces in terms of processing and manufacturing of goods and their eventual shipment to areas of destination" (Mount Pinatubo Task Force, 1991).

The overall technocratic vision explains why new resettlement areas have gridded street systems, modern public buildings clustered around a plaza, productivity centers (large buildings intended for use as factories), and uniform houses made of either hollow concrete blocks or nipa (a palm).

However, these complexes have attracted much negative attention. Some critics are silent on the basic approach but object to aspects of the content or implementation of the program; other critics question the basic philosophy and the implementation of the plans. The first group of critics accepts the technocratic planning process but assails the state for its insensitivity to the plight of central Luzon's dislocated residents. Site development has been deemed too slow in the face of victims who have languished in evacuation centers for more than a year. In the case of O'Donnell, Capas, Tarlac, the most developed of the sites, millions of pesos had to be advanced by a cooperative headed by a private citizen to hasten the pace of its development.

Apart from the speed, the phasing of the project has also been questioned. Cemented roads and public buildings were put up before houses. To make matters worse, livelihood development efforts were relegated to the background, so some who moved into the resettlement areas decided to leave and others hesitated to move in. On the whole, these criticisms do not question the plaza complex or even the construction of public buildings as long as these are done after housing and livelihood needs are met.

The second group of critics questions not only the content of the plans but also the spirit and process of planning imbedded in them. Drawing from the principles of participatory development, these critics stress the importance of planning **with** and not **for** the affected people. In this approach, victims should participate actively in all stages of planning.

The participation of would-be resettlers is crucial for practical and psychological reasons. Victims will make sure that projects will meet their needs, and they will feel a pride of ownership. The resulting houses and emergent communities may not conform aesthetically to the technocratic vision, but they will be houses and a community in (and for) which the displaced families will work hard and succeed. Psychologically, the process of participation is as important as the visible outcomes of collective decisionmaking, because it enhances the self confidence of individual victims and the community's collective confidence in being able to rebuild its life in the new site.

The criticisms emanating from proponents of participatory development have two implications for resettlement. There can be no uniform design or blueprint for resettlement sites. This means some of the basic parameters in terms of sites can be set at the national or regional level, but the conceptualization of plans will have to be decentralized to the level of the communities involved. The second implication is that community organizational efforts must be an integral part of the resettlement process. It is easy enough to give lip service to community organizing, but it is hard to find capable people who have internalized the spirit of participatory development. Case studies of resettlement sites by the nongovernmental organization (NGO) Philippine Business for Social Progress, for instance, reveal that some NGO's that are committed in principle to participatory development encounter problems of finding enough good organizers.

Coordination

Meaningful and effective decentralized planning requires coordination with local and regional government agencies and NGO's. For all the criticisms hurled against the state in the last 2 years, it is the only institution that can mobilize all of the basic resources needed in resettlement work. Only the state is in a position to officially allocate land from the public domain and negotiate with private owners. Infrastructural works such as roads, power, sanitation, and schools are also better left with government.

Coordination with and among government agencies is necessary to speed up the process of resettlement. This is easier said than done. Even under a centralized scheme, conferences on relief and rehabilitation have been haunted by a recurring complaint--that government agencies continue to function within their own turfs. As such, the disaster-related programs have been far from integrated (Bonifacio, 1992). NGO's also have problems of duplicated effort and lack of communication. Key informants claim that very little is done to coordinate services rendered. Furthermore, when collaborative decisions are reached, there are no mechanisms for carrying them out.

In their book based on the lessons learned from disasters in different parts of the world, Anderson and Woodrow (1989) cautioned against too much stress on NGO coordination. Although they argue for coordination of services, they raise basic questions. Who is in charge of coordination? Whose purpose does it serve? Is it intended to ease the work of NGO's and make logistical requirements run smoothly or is it to ensure the highest possible involvement of the victims in decisionmaking and planning?

Long-Term Development versus Dependency

Underlying the abovementioned questions is an argument for integrating disaster-related work with long-term development goals. If enhancing the capacities of victims and reducing their vulnerabilities is not kept in mind by development workers at every point of the rehabilitation and resettlement process, then well-intentioned attempts to improve coordination will merely add to a host of other emergency efforts that defer long-term development to the future.

In debates over models for development, all agree that the creation of economic and social structures, while necessary, is not a sufficient gauge of development. Over the long run, external agents cannot ensure a people's well being; only the people themselves can do that, by increasing their capacities and reducing their vulnerabilities.

Given the demands of ministering to the daily requirements of rehabilitation or resettlement, even the more development-oriented NGO's and committed government agents may fail to see how their humanitarian work can stifle the capacity of the victims to rise from the ashes. As their short-term emergency assignment becomes institutionalized in the field, they may be insensitive to the incipient dependence developed in the victims who are unwittingly made to rely on external agents for their needs.

Many of those involved with redevelopment around Pinatubo realize the dependence they have inadvertently created in the course of their work. NGO's operating in the Loob Bunga Resettlement site are themselves alarmed by the perpetuation of a culture of dependence and mendicancy among resettlers (Mondragon, 1992). While they all agree that food for work programs will have to end, they are prevented from focusing on rehabilitation by a lack of opportunities to sustain livelihood projects in the site.

The original concept of the new resettlement towns assumed industrial development in the central Luzon region. The planners hoped that multinational and domestic investors would see the prospect of employing resettlers in the newly built productivity centers. However, the uncertainty over the landscape of central Luzon in the next few years and the sluggish nature of overall Philippine economy has, to date, prevented investors from risking their fortunes in these centers. Naturally, concerns about livelihood have slowed acceptance of resettlement. Respondents to a survey by the Philippine Business for Social Progress (PBSP, 1993) revealed that most respondents gave livelihood a higher priority than housing. The relative absence of income sources in the resettlement sites accounts for the refusal of would-be settlers to move to the new sites. It also explains why some of those who moved in earlier have already left the sites.

The fact that some displaced victims have returned to their old homes has led the NGO's in Zambales to seriously consider internal repatriation.

Supporters of repatriation point out that some of the victims who decided to stay put in their barangays at the height of the evacuations seem to have rebuilt their lives faster than anyone in the resettlement sites. It may be possible for some to return to their old homes during the dry season and to go to the resettlement sites when the rains begin. It may also be possible for some victims to evacuate to sites near their original barangays rather than to the resettlement areas.

CONCLUSIONS

The eruptions of 1991 and their muddy aftermath have taken an enormous toll on the people of central Luzon. Fewer than 1,000 lives have been lost, but more than 200,000 families and more than a million people have suffered some loss or dislocation as a result of ash fall, lahars, or flooding. Of these, barangays that were home to 9,800 families (53,000 people) were so severely buried or otherwise damaged that they have been virtually abandoned. Large areas of agricultural land have been covered, some beyond immediate rehabilitation, and additional areas have lost their supply of irrigation water.

Current victims of the Pinatubo disaster have not yet seen the end, and many others are still potential victims. The next several years will continue to bring untold misery to central Luzon. Those who are presently dislocated, and those who will be dislocated in the next several years, need resettlement options that provide livelihood and that facilitate psychosocial adjustments to the trauma of being uprooted. The task is urgent, because people in high-risk areas will agree to move away only if there are viable alternatives.

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OBSERVATIONS AND RECONSTRUCTIONS: THE 1991-92 ERUPTIONS

Several fortuitous circumstances led to a wide variety of observations of the 1991 eruptions. Pinatubo gave observers ample advance warning--eruption precursors and, if those were not enough, the publicized drama of evacuations (Punongbayan, Newhall, Bautista, and others) and a series of preclimactic eruptions (Hoblitt, Wolfe, and others). Observers were ready on the ground both east and west of Mount Pinatubo, and, until the climactic eruption, in helicopters as well (west-side story by Sabit and others; east-side story by Hoblitt, Wolfe, and others; summary by Wolfe and Hoblitt). Others made ground-based and satellite-based weather observations. Oswalt and others describe observations by C-band weather radar at Clark Air Base and Cubi Point Naval Air Station, an infrared telescope at Clark, and rawinsondes and pilot balloons for upper level air temperature, humidity, pressure, and wind speed and direction, until nearly the climax of the eruption. Microbarographs at Cubi and Clark and a temperature recorder and rain gage at Cubi recorded throughout the eruption. Geostationary (GMS) and polar-orbiting (AVHRR) satellites captured most of the eruption (Koyaguchi; Lynch and Stephens; Oswalt and others). Tahira and others describe infrasonic and acoustic gravity waves as recorded in Japan, and Zürn and Widmer report very long-period oscillations recorded by a worldwide network of broadband seismographs.

The general chronology of events is given by Wolfe and Hoblitt in the introductory section. The present section includes an interesting observation by Hoblitt, Wolfe, and others that preclimactic eruptions changed from vertically directed explosions (June 12, 13, early 14) to smaller, more frequent, less energetic eruptions with greater components of pyroclastic surge. The authors present a model in which the rate of pressurization of the tip of the magma column is controlled by competing rates of influx of magma, degassing during repose periods, and eruptions themselves.

Plinian fall deposits from the climactic June 15 eruption are relatively thin and inconspicuous (Paladio-Melosantos and others), partly because Typhoon Yunya, which passed near Pinatubo during the eruption, spread ash in all directions over a broad area. Near-source tephra deposits were also scoured by pyroclastic flows, and tephra along the main lobe was blown into the South China Sea. Regrettably, we had almost no information about offshore ash fall while most papers of this collection were being written. Fortunately, sea-bottom samples that were brought to the surface in 1994 (Wiesner and Wang) provide an important, late-breaking constraint on the volume of tephra fall and of the eruption as a whole.

Pumiceous pyroclastic-flow deposits from the climactic eruption--thick valley fill and thin ridge veneers--formed throughout the period of plinian fall, quite unlike models in which pyroclastic flows follow plinian tephra fall. W.E. Scott and others infer either quasicontinuous low-level collapse of portions of a sustained plinian column or repeated collapse of the entire column. Relatively late-stage, lithic-rich pyroclastic flows probably reflect entrainment of old edifice material as the caldera formed.

Significant, as-yet-unresolved discrepancies exist between estimates of column height from weather radar and those from satellites (the latter, 10 km higher during the 0555 eruption of June 15) (see Hoblitt, Wolfe, and others; Lynch and Stephens). Originally, the discrepancy was explained as a result of temperature disequilibrium and adiabatic cooling within the rising eruption column, but the discrepancy remains even if the temperatures are derived from clouds that were some distance away from the eruption column and drifting with similar vectors to that of the ash cloud (Lynch and Stephens). Eruption columns of June 14 and early June 15, as seen from satellites, were different from those seen from the ground. One explanation is that visible and multispectral weather images can show ash in lower concentrations than can weather radar.

Volcanologists routinely correlate deposits with observed eruptions, but most reconstructions of the largest historic and prehistoric eruptions are based on extrapolation of inferences from smaller eruptions. Pinatubo allowed direct correlation of an unusually large and quantified eruption column with features of deposits. Koyaguchi used the rate of expansion of the umbrella cloud, plus grain-size data, to estimate volumetric flow rate of cloud, mass discharge rate, and thence dense-rock-equivalent (DRE) volume of plinian fall deposits. His estimates can be compared to those of Paladio-Melosantos and others as a test of the theoretical approach, or, if one prefers the theoretical approach to sparse field data, his estimates can place upper and lower bounds on the actual volume of tephra. Koyaguchi's estimate for the volume of plinian fall deposit is 2 to 10 km^3 DRE, whereas that of Paladio-Melosantos and others is 1.6 to 2.0 km^3 DRE. Some of the difference between these two estimates might be explained by W.E. Scott and others' observation that pyroclastic flows (not included in these estimates) were occurring at the same time and could easily have complicated the dynamics of the eruption column.

Also included are two important contributions from far-field, global data. Tahira and others report on-scale, high-resolution infrasonic and acoustic gravity waves in Japan that provide more detail about the intensity of the climactic eruption than was obtained from monitoring near Mount Pinatubo. The infrasonic records show that the strongest phase of the eruption began at 1342, lasted only about 3.5 h, and weakened further after about 10 h. Microbarograph records of acoustic gravity waves recorded in Japan show oscillations at 4.4 mHz, one of two frequencies of Rayleigh wave oscillation noted by the other contributors of global data, Zürn and Widmer. Apparently, the same atmospheric oscillation that was recorded directly by microbarographs as acoustic gravity waves became coupled to the solid earth and was also recorded as long-period seismic waves.

When the dust finally settled, literally and figuratively, a new caldera was 2.5 km in diameter and more than 650 m deep. Low-resolution digital topography for the preeruption and posteruption periods (Jones and Newhall) shows the new caldera and valley-filling pyroclastic-flow deposits relative to the old summit. Major northeast- and southeast-trending conjugate faults that intersect at Pinatubo, and the origins of the Sacobia, Abacan, and Pasig-Potrero Rivers in a single pyroclastic fan, are clearer in this low-resolution digital topography than in previously published 1:50,000-scale topographic maps.

An important observation in the aftermath of the eruption was that still-fluidized or re-fluidized pyroclastic-flow deposits can move farther downslope as secondary pyroclastic flows (Torres and others). Suspected from previous geologic studies but never before observed, these remobilized pyroclastic flows produce deposits that are nearly indistinguishable from those of the primary pyroclastic flows, except that the former are emplaced at slightly lower temperature and are slightly fines-depleted relative to the parent material.

Beginning in July 1992, another intrusion of basaltic magma into the large dacitic reservoir beneath Pinatubo threatened to replicate events of 1991. Magma mixing and ascent of hybrid andesite occurred as in 1991, but this time they did not trigger a large explosive eruption (Daag, Dolan, and others). The residual dacitic magma was probably depleted in volatiles, but an alternate explanation of the different outcomes was that the 1992 intrusion was too slow or too small to serve as a trigger. As of this writing, Mount Pinatubo remains intermittently restless.

SELECTED IMPACTS

When Pinatubo was threatening to erupt, reports of effects and recovery strategies from eruptions elsewhere in the world were a useful starting point for contingency planning; after the eruption, the demand for such reports rose sharply. A full account of the effects of the Pinatubo eruption is beyond the scope of this volume but would be valuable for future workers.

For now, an overview of impacts, with special emphasis on people, is told compellingly by C.B. Bautista in the introductory section. Starting in 1991, the Pinatubo story has been a saga of massive evacuations (at times, reaching more than 200,000 persons), massive multiyear dislocations (as of 1993, more than 50,000 persons), and extensive damage to towns, infrastructure, and farms. Initially, the indigenous Aeta population was hit hardest; later, they were joined by an even greater number of lowlanders, routed from their homes and land by lahars. Substantial social changes are underway--some temporary, some irreversible and permanent.

Impacts on buildings, described by Spence and others, were unusually serious because the ash was wet (from typhoon rains) and therefore heavier than it would have otherwise been. Impacts of ash on industries, health, and agriculture are topics for future discussion by others.

Economic impacts of the eruption and lahars are described by Mercado and others, who see a serious but temporary interruption in the economy. Immediate impacts such as loss of income from agriculture and from the U.S. bases are expected to diminish as crops recover and new industry fills the former military bases. Investor confidence and regional infrastructure are also expected to recover.

Socioeconomic Impacts of the Mount Pinatubo Eruption

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ABSTRACT

The Mount Pinatubo eruptions and their aftereffects, particularly lahars during rainy seasons, not only have taken the lives of many but also have wrought havoc to the infrastructure and to economic activities of Central Luzon. Damage to crops, infrastructure, and personal property totaled at least 10.1 billion pesos ($US 374 million) in 1991, and an additional 1.9 billion pesos ($US 69 million) in 1992. In addition, an estimated 454 million pesos ($US 17 million) of business was foregone in 1991, as was an additional 37 million pesos ($US 1.4 million) of business in 1992. Lahars continue to threaten lives and property in many towns in the provinces of Tarlac, Pampanga, and Zambales.

The actual destruction, coupled with the continuing threat of lahars and ash fall, has disrupted the otherwise flourishing economy of Central Luzon, slowing the region's growth momentum and altering key development activities and priorities. Major resources have been diverted to relief, recovery, and prevention of further damage.

The costs of caring for evacuees (including construction of evacuation camps and relocation centers) was at least 2.5 billion pesos ($US 93 million) in 1991-92, and an additional 4.2 billion pesos ($US 154 million) was spent during the same period on dikes and dams to control lahars.

The longevity and impact of the calamity is so great that the public and private response must go beyond traditional relief and recovery. Return to preeruption conditions is impossible. Instead, responses must create an attractive climate for new investments, provide new livelihood and employment alternatives, promote growth in areas that are safe from future lahars and flooding, and provide an infrastructure that is tough enough to survive future natural disasters.

INTRODUCTION

The eruptions of Mount Pinatubo and their continuing aftereffects have disrupted the flourishing socioeconomic environment in Central Luzon. Economic growth, which had been spreading to the region from Manila and which was slated for an extra boost from conversion of former U.S. military bases, has been weakened by the eruption. The auspicious development picture for the region has been replaced by uncertainty and delays. For the short and medium term, rehabilitation and reconstruction dominate socioeconomic planning; for the long term, planning needs to take advantage of new opportunities that are presented by massive rebuilding of the socioeconomic infrastructure.

This paper presents actual and projected damage arising from the Mount Pinatubo eruptions, their implications for Central Luzon's development, and broad directions that could be taken to respond to the calamity. This report is neither comprehensive nor complete, as the calamity is still ongoing.

NATURE OF THE DISASTER

During the June 15, 1991, eruption, heavy damage was caused by ash fall, which buried large tracts of land and collapsed roofs of buildings near the volcano. Although ash fell in varying amounts across the whole of Luzon, the most heavily affected provinces were those adjacent to Mount Pinatubo--Pampanga, Tarlac, and Zambales.

Continuing effects are now brought by lahars--rain-induced torrents of loose volcanic debris that flow down the major river systems around the volcano and out into densely populated, adjoining lowlands. Lahars destroy and bury everything along their path: people and animals, farm and forest lands, public infrastructure, natural waterways, houses, and other facilities. Infilling of stream channels has caused overbank flows, drowning of areas behind natural impoundments, and other forms of flooding in low-lying areas.

Secondary explosions also continue--explosions that occur when heavy rain and runoff come in contact with still-hot pyroclastic deposits on the volcano's slopes. These explosions produce fine, powdery ash fall that continues to impact, among other things, the former Clark Air Base.

REPORT ON DAMAGE

In the 2-year period since June 1991, the damage from eruptions and their aftereffects has been staggering and debilitating. Worse, it is expected to continue for at least several years more, until lahars no longer occur.

Damage is reported in different ways for different sectors. That for public infrastructure, natural resources, and military facilities is the estimated cost to repair or replace damaged assets. Estimates of damage to trade and industry include the cost to repair or replace facilities and projected income from foregone sales and service. Estimated damage in agriculture is the expected value of yield multiplied by the area damaged.

Except for the basic data on monthly foregone income per industry type (see table 8), which was provided by the National Statistics Office (NSO), all reports on damage provided below came from government agencies and departments involved in rescue, relief, reconstruction, and rehabilitation and were consolidated through the National Disaster Coordinating Council (NDCC). The NDCC used this information to recommend to the President of the Philippines which areas should be declared to be under a state of calamity.

The other legal body that facilitated information gathering on damage was the Presidential Task Force on the Rehabilitation of Areas Affected by the Eruption of Mt. Pinatubo and its Effects, popularly known as Task Force Mt. Pinatubo. Created by President Corazon C. Aquino on June 26, 1991, by Memorandum Order No. 369, Task Force Mt. Pinatubo was mandated to guide all rehabilitation efforts of the government and to coordinate these with the private sector and, whenever necessary, with the international community. In December 1992, the work of Task Force Mt. Pinatubo was taken over by the Mount Pinatubo Assistance, Resettlement and Development Commission (MPC) created under Republic Act No. 7637.

AREAS AND POPULATION AFFECTED

From June 1991 to November 1992, means of livelihood, houses, or both were partially or wholly lost in 364 barangays (villages) (table 1). About 329,000 families (2.1 million people), about one-third of the region's population, lived in these 364 barangays at the time of the 1990 census. In 1991, 4,979 houses were totally destroyed and 70,257 houses were partially damaged. The number decreased in 1992, when 3,281 houses were wholly destroyed and 3,137 units were partially damaged (table 2).

Of the 329,000 families (2.1 million persons) affected, 7,840 families (35,120 persons) were of the Aeta cultural minority (Office for Northern Cultural Communities, unpub. data, August 14, 1991). Although constituting less than 2 percent of the total affected population, these cultural minorities have received significant attention.

Table 1. Total number of barangays affected as of November 17, 1992 (National Disaster Coordinating Council, 1992).

["Affected" refers to a situation where means of livelihood, houses, or both are lost or partially or completely destroyed]

Province	Affected barangays	Number of families
Zambales	96	30,115
Pampanga	173	239,131
Tarlac	88	44,367
Angeles City	5	14,197
Nueva Ecija	2	1,331
Total	364	329,141

Table 2. Total number of houses damaged (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; Department of Social Welfare and Development, unpub. data, 1992).

[Partial damage refers to any degree of physical destruction attributed to the disaster. Total destruction is the condition when the house is no longer livable]

Extent of damage	1991	1992	Total
Totally destroyed	4,979	3,281	8,260
Partially	70,2	3,1	73,3

damaged	57	37	94
Total	75,236	6,418	81,654

Table 3. Total cost of damage to infrastructure as of August 23, 1991 (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; Department of Public Works and Highways, Region III, unpub. data, 1991).

[The prevailing foreign exchange rate during this period was $1 = 27.07 pesos]

Infrastructure subsector/Facility	**Damage Cost (in thousand pesos)**
Transportation	1,149,908
Communication	13,215
Power and electrification	54,918
Water resources	1,568,642
Social infrastructure	1,045,708
Total	3,832,391

Table 4. Damage to Contract Reforestation and Integrated Social Forestry projects, 1991 (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; Department of Environment and Natural Resources, Region III, unpub. data, 1991).

[This damage was caused by ash fall and ash flow. Contract Reforestation--Regular DENR project involving a 3-year plantation and maintenance of forest trees through family-based, community-based, and corporate-based modes of contracting. Integrated Social Forestry (ISF)--community-based/family-based planting of 20% forest trees and 80% agricultural-based crops. Contractors are given a 25-year security of tenure through the certificate of stewardship contract (CSC)]

Province	Contract Reforestation		Integrated Social Foresty	
	Area (hectares)	Value/Amount lost (pesos)	Area(hectares)	Value/Amount lost (pesos)
Zambales	2,108.0	33,576,690.8	799.7	6,136,419.5
Pampanga	2,116.1	19,137,420.8	1,789.8	1,749,500.0
Tarlac	4,842.0	54,440,562.8	1,719.1	760,563.8
Bataan	529.0	8,133,902.2	236.5	1,507,500.0
Total	9,595.1	115,288,576.6	4,545.1	10,153,983.3

Table 5. Major river systems affected (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; PHIVOLCS/NEDA, 1992).

[Total lahar hazard areas include those prone to lahar deposition, siltation and flooding, and bank erosion]

River system	Areas actually affected as of August 1992 (hectares)	T
Abacan	2,930	4,060
Bucao-Balin Baquero	5,380	8,600
Maloma	1,820	1,700
O'Donnell-Bangut	3,350	11,54(
Pasig-Potrero	4,370	10,00(

Porac-Gumain	3,140	3,370
Sacobia-Bamban	10,310	25,09(
Santo Tomas	4,640	12,59(
Total	35,940	76,95(

Table 6. Actual damage to agricultural area by commodity as of July 1991 (Department of Agriculture, Region III, unpub. data, 1991; National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992).

Commodity	**Area or number damaged**	**Value (Philippine pesos)**
Rice (hectares)	81,895	350,855,594
Vegetables (hectares)	2,486	163,548,456
Rootcrops (hectares)	2,070	182,791,365
Assorted fruit trees (number)	2,646	290,061,075
Fisheries (hectares)	7,129	284,098,228
Livestock and poultry (heads)	778,714	203,191,200
Total		1,474,545,918

DAMAGE BY SECTOR

PUBLIC INFRASTRUCTURE

In its damage assessment report as of August 23, 1991, the Department of Public Works and Highways (DPWH) Regional Office III estimated damage to public infrastructure amounting to 3.8 billion pesos (table 3). The gravest destruction was on irrigation and flood control systems, roads and bridges, and school buildings. Additional damage of at least 1 billion pesos was done to roads and bridges by lahars of 1992 (National Disaster Coordinating Council, 1992).

NATURAL RESOURCES

The Mount Pinatubo eruptions buried some 18,000 ha of forest lands in ash fall of about 25 cm (Paladio-Melosantos and others, this volume). The heaviest concentration of ash fall was in the mountains of Botolan and San Marcelino in Zambales, in Porac and Floridablanca in Pampanga, and in Bamban and Capas, Tarlac.

Reforestation activities have been seriously set back. Approximately 14,140 ha of newly established plantations were destroyed and some 125 million pesos worth of seedlings were lost (table 4). About 43,800 ha of natural forest cover and old plantations were damaged.

Heavy rains that came after the eruptions caused ash deposits from the mountain slopes to wash down to low-lying areas in the form of lahars. At least eight major river systems have been clogged by lahars (table 5; see also Arboleda and Martinez, this volume; Martinez and others, this volume; Pierson and others, this volume; Rodolfo and others, this volume; K.M. Scott and others, this volume; Umbal and Rodolfo, this volume).

AGRICULTURE

About 96,200 ha of agricultural land was seriously affected by ash fall. Damage to crops, livestock, and fisheries was about 1.4 billion pesos (table 6).

Damage from lahars, flooding, and siltation, as of November 17, 1992, was reported to be 778 million pesos (table 7). Of this, crops suffered the biggest damage (547 million pesos), followed by fisheries (165 million pesos), sugarcane (57 million pesos), and livestock (10 million pesos). The estimate of 778 million was later raised to 1,422 million (see table 10).

TRADE AND INDUSTRY

The manufacturing subsector, and consequently the exporting subsector, was heavily damaged. Lost assets for 559 firms totaled 851 million pesos. Foregone production losses for 1991 were reported to be about 45 percent of the potential sales for the year 1991, or 454 million pesos, and 424 million pesos of capital investment was destroyed at 306 surveyed firms. The furniture industry was hardest hit, with damage of 156.5 million in 108 firms. The processed food sector suffered 97 million pesos of loss in 18 firms, and the gifts, toys, and housewares sector lost 60 million pesos in 92 firms.

In 1992, foregone income in the manufacturing subsector was 1.5 million pesos per month, followed by the wholesale and retail subsector with foregone income of 846,000 pesos per month. Foregone income for the financial, real estate, and business services subsector was about 635,000 pesos per month, and that of the transportation, storage, and communication subsector was estimated to be 65 million pesos per month.

Total foregone income during 1992, in all sectors, was 3.1 million pesos. By province, industries in Pampanga and Tarlac had the greatest share of foregone sales, of 1.7 million and 0.6 million pesos per month, respectively (table 8).

SOCIAL SERVICES SECTOR

Health.--An increase in morbidity and mortality rates occurred mainly in evacuation centers. The leading diseases were acute respiratory infections (ARI), diarrhea, and measles (Department of Health, unpub. data, 1991). The death rate (Aetas and lowlanders combined) was 7 per 10,000 per week during 1991; that for Aetas in 1991 reached as high as 26 per 10,000 per week, and averaged 16 per 10,000 per week (Department of Health, 1992), and was especially high among Aeta children.

Social welfare.--The continuing threat of lahars has required that relief--food, clothing, shelter, and other help--be provided far beyond the period that is normal for typhoons and other calamities. As of October 28, 1993, approximately 1,309,000 people were being served outside evacuation centers. As of the same date, 159 evacuation centers were being maintained by the Department of Social Welfare and Development (DSWD) throughout Region III, housing some 11,455 families or 54,880 persons and providing them with food-for-work or cash-for-work assistance.

Education.--Destruction of about 700 school buildings with 4,700 classrooms displaced an estimated 236,700 pupils and 7,009 teachers. Damage to school buildings was estimated to be 747 million pesos as of August 1991 (table 9), an amount that is growing with continuing lahar activity. (Note: This value is also included within the category of social infrastructure in table 3.) Disruption of schooling is compounded by use of undamaged school buildings as evacuation centers, which forces delays in the opening of classes and causes other disruptions of the school calendar.

Initial damage to instructional materials, furniture, equipment, and other school supplies was estimated at 93 million pesos (Department of Education, Culture, and Sports, unpub. data, 1991).

MILITARY FACILITIES

Damage to military facilities was considerable, but estimates of that damage are difficult to obtain or make. For the purposes of this report, we use an estimate of 3.8 billion pesos of damage in 1991 and no additional damage in 1992 (table 10). This estimate does not include heavy damage to former U.S. military facilities.

ALL SECTORS

In sum, damage and production losses resulting from the eruption and subsequent lahars were about 10.5 billion pesos in 1991 and 1.9 billion pesos in 1992 (table 10). These values include only damage and losses that are readily quantifiable. Additional losses, not included in these estimates, include human life, social fabric of communities, children's schooling, and a host of other, mostly social, items that are discussed in C.B. Bautista (this volume).

Table 7. Existing damage to agricultural commodities (in million pesos; Department of Agriculture, Region III, unpub. data, 1991; National Disaster Coordinating Council, 1992).

[Damage cost = total area damaged x expected yield per hectare. Expected yield is computed by referring to precalamity yield. Postcalamity yield is derived by referring to precalamity yield and subjecting the damaged crops to recovery chances/percentages. The value of the crops with negative chances/percentages is derived by multiplying them by the prevailing market prices of the crops. This value then becomes the damage cost.]

Commodity	1991	1992	Total
Crops (hectares)	987.2	546.8	1,534.0
Livestock (heads)	203.2	9.8	213.0

Fisheries (hectares)	284.1	164.9	449.0
Sugarcane (hectares)		56.9	56.9
Total	1,474.5	778.4	2,252.9

Table 8. Monthly foregone gross income per industry type per affected province for 1992 (National Statistics Office, Region III, unpub. data, 1992)

[The estimated loss to industry was based on the proportion of the affected households and their average expenditure on each type of industry. Does not include construction (52,689 pesos). No provincial breakdown available]

Province	**Manufacturing**	**Wholesale/ Retail**	**Transport/ Storage/ Communication**
Bataan	45,000	23,000	25,000
Bulacan[1]	23,000	5,100	590
Nueva Ecija	23,000	12,000	2,100
Pampanga[2]	1,100,000	540,000	22,000
Tarlac	230,000	190,000	8,900
Zambales	103,000	76,000	6,100
Total	1,524,000	846,100	64,690

[1]Municipality of Calumpit only.

[2]Includes Angeles City.

Table 9. Estimated cost of damage to school buildings by province or city as

of August 12, 1991 (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; Department of Education, Culture, and Sports, Region III, unpub. data, 1991).

[Ash fall is the major cause for this type of damage]

Province/City	Cost (in thousand pesos)
Zambales	410,000
Bataan	34,000
Olongapo City	140,000
Pampanga	130,000
Tarlac	13,000
Angeles City	12,000
Bulacan	5,050
Nueva Ecija	3,200
Total	747,250

Table 10. Existing sectoral damage and production losses, 1991-92 (in millions of pesos) (National Disaster Coordinating Council, 1992; Presidential Task Force on Mount Pinatubo, 1992; National Economic Development Authority, unpub. data, 1991, 1992).

Sector	1991	1992	Total 1991-92
Public infrastructure	3,830	454	4,284

Agriculture	1,474	1,422	2896
Military facilities	3,842	0	3,842
Trade and industry	851	0	851
Natural resources	125	0	125
Foregone income (trade and industry).	454	37	491
Total	10,576	1,913	12,489

Table 11. Gross Regional Domestic Product by industrial origin from 1987 to 1992 at constant prices, Region III, Central Luzon (in thousand pesos; Economic and Social Statistics Office, National Statistical Coordination Board, unpub. data, July 1993).

Industrial origin	1987	1988	1989	1990	1[illegible]
Gross Regional Domestic Product	57,456,387	61,712,579	64,419,389	68,814,787	67,[illegible]84
Agriculture and forestry	12,943,820	13,241,781	14,462,739	15,849,415	16,[illegible]16
Agriculture	12,928,545	13,230,282	14,450,556	15,833,694	16,[illegible]51
Forestry	15,275	11,499	12,183	15,721	9,9[illegible]
Industry	23,567,988	26,618,118	26,751,658	29,187,703	27,[illegible]07
Mining and quarrying	1,324,296	1,435,041	1,519,655	1,297,769	1,1[illegible]3

Manufacturing	17,237,722	19,960,049	19,802,819	22,691,941	21,[illegible]47
Construction	3,264,967	3,296,771	3,368,449	3,248,637	3,8[illegible]4
Electricity, gas, and water	1,741,003	1,926,257	2,060,835	1,949,356	1,6[illegible]3
Services	20,944,579	21,862,680	23,204,992	23,777,669	23,[illegible]61
Transportation	3,444,086	3,600,625	3,766,868	3,781,629	3,7[illegible]0
Trade	8,766,074	9,034,766	9,592,306	9,772,620	9,6[illegible]6
Finance and housing	769,154	826,842	911,405	978,366	964[illegible]
Real estate	3,389,119	3,586,285	3,848,135	3,962,822	3,9[illegible]3
Private services	3,188,222	3,326,732	3,534,305	3,643,687	3,4[illegible]6
Government services	1,387,924	1,477,430	1,551,973	1,638,545	1,6[illegible]0

COSTS OF EVACUATIONS AND OTHER RISK MITIGATION

It is beyond the scope of this paper to discuss evacuations and other risk mitigation measures in detail. However, for comparison to estimates of damage, at least 2.5 billion pesos was spent in construction and operation of evacuation sites (Department of Budget and Management, Region III, unpub. data). About 4.2 billion pesos was spent in 1991-92 for dredging of river channels and for construction of dikes and dams to control lahars (Department of Public Works and Highways, 1992).

IMPACT ON THE REGIONAL ECONOMY

The 1991 Gross Regional Domestic Product (GRDP) of Region III accounted for about 9.4 percent of the Gross Domestic Product (GDP) (Economic and Social Statistics Office, National Statistical Coordination Board, ESSO-NSCB, unpub. data, July 1993). (The GDP is Gross National Product (GNP) less net factor income from the rest of the world.) The average growth of the region's GRDP from 1987 to 1991 was 5 percent per year (NEDA, Agricultural Staff, 1993). The largest contributor from 1987 to 1991 was industry (42 percent), followed by services (35 percent) and agriculture (23 percent) (table 11).

Because of the eruption, the GRDP in 1991 amounted to only 67.2 billion pesos, compared to the 1990 GRDP of 68.8 billion pesos (table 11). This represents a 1.6 billion pesos (2.3 percent) reduction in output. All sectors of the economy were affected by the eruption. Hardest hit were manufacturing, mining and quarrying, agriculture, and private services.

In 1992, GRDP amounted to 72.2 billion pesos, a 7 percent increase from 1991. Industry and services exhibited positive growth rates (Economic and Social Statistics Office, National Statistical Coordination Board, ESSO-NSCB, unpub. data, July 1993). However, agricultural productivity was still below the 1991 level because lahars took additional agricultural lands out of production in 1992.

RECOMMENDATIONS

The overall impact of the Mount Pinatubo eruptions is the slowing down of the region's growth momentum and alteration of key development activities and priorities. The calamity can, however, be taken as an opportunity, in which rehabilitation and reconstruction can aid in regional development. Specifically, rehabilitation and reconstruction should:

1. Mitigate further destruction, mainly from lahars and flash floods.

2. Normalize and accelerate economic recovery including the creation of an attractive investment climate.

3. Provide adequate livelihood and employment alternatives, especially for displaced farmers and workers (including those from Clark Air Base and the former Subic Bay Naval Station).

4. Promote growth and development in resettlement and new settlement areas that can serve as alternatives to heavily devastated or high risk areas.

5. Ensure the continuous flow of goods and services, especially during relief operations following future calamities.

6. Strengthen public awareness and institutional mechanisms for disaster preparedness.

7. Reduce the infrastructure's susceptibility to damage from lahars and other natural disasters.

8. Prevent future degradation of the environment and rehabilitate damaged ecosystems.

The complexity of these challenges and the expectation of more lahars to come demand no less than a well-coordinated, integrated response from the government sector, non-governmental organizations, and the victims themselves. With unity, selflessness, and honesty of those who serve and are being served, economic growth in the disaster-stricken areas of Central Luzon will become a reality.

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