VOLCANIC HAZARDS AND THEIR MITIGATION: PROGRESS AND PROBLEMS

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> *"Natural calamity strikes at about the time when one forgets its terror."*
> Japanese proverb [see *Shimozuru*, 1981]

Abstract. At the beginning of the twentieth century, volcanology began to emerge as a modern science as a result of increased interest in eruptive phenomena following some of the worst volcanic disasters in recorded history: Krakatau (Indonesia) in 1883 and Mont Pelée (Martinique), Soufrière (St. Vincent), and Santa María (Guatemala) in 1902. Volcanology is again experiencing a period of heightened public awareness and scientific growth in the 1980s, the worst period since 1902 in terms of volcanic disasters and crises. A review of hazards mitigation approaches and techniques indicates that significant advances have been made in hazards assessment, volcano monitoring, and eruption forecasting. For example, the remarkable accuracy of the predictions of dome-building events at Mount St. Helens since June 1980 is unprecedented. Yet a predictive capability for more voluminous and explosive eruptions still has not been achieved. Studies of magma-induced seismicity and ground deformation continue to provide the most systematic and reliable data for early detection of precursors to eruptions and shallow intrusions. In addition, some other geophysical monitoring techniques and geochemical methods have been refined and are being more widely applied and tested. Comparison of the four major volcanic disasters of the 1980s (Mount St. Helens, U.S.A. (1980), El Chichón, Mexico (1982); Galunggung, Indonesia (1982); and Nevado del Ruíz, Colombia (1985)) illustrates the importance of predisaster geoscience studies, volcanic hazards assessments, volcano monitoring, contingency planning, and effective communications between scientists and authorities. The death toll (>22,000) from the Ruíz catastrophe probably could have been greatly reduced; the reasons for the tragically ineffective implementation of evacuation measures are still unclear and puzzling in view of the fact that sufficient warnings were given. The most pressing problem in the mitigation of volcanic and associated hazards on a global scale is that most of the world's dangerous volcanoes are in densely populated countries that lack the economic and scientific resources or the political will to adequately study and monitor them. This problem afflicts both developed and developing countries, but it is especially acute for the latter. The greatest advances in volcanic hazards mitigation in the near future are most likely to be achieved by wider application of existing technology to poorly understood and studied volcanoes, rather than by refinements or new discoveries in technology alone.

INTRODUCTION AND HISTORICAL PERSPECTIVE

Most of the Earth's crust is of magmatic origin, attesting to the enormous role that volcanic and related magmatic processes have played in forming the outermost solid rind of our planet. In addition, the distribution of volcanoes, past and present, can be closely linked to the dynamics of the crust and mantle within a plate tectonics context. Some foreign rock fragments (called "xenoliths") contained in eruptive products represent the deepest samples of the Earth's interior that have been recovered to date from any drill hole. Thus it is hardly surprising that many geoscientists work in terranes or on research topics directly or indirectly associated with volcanic rocks. Yet within the geoscience community, relatively few specialize in volcanology, the study of the transport and eruption of magma [*Sigurdsson*, 1987], with emphasis on active or potentially active volcanoes [*Tilling*, 1987*a*].

Of the more than 1300 volcanoes known to have erupted in Holocene time, about half are classified as active (i.e., those that have erupted in recorded history). On average, about 50 of these volcanoes erupt each year, an eruption frequency that appears to be obtained for all historical time [*Simkin et al.*, 1981]. Individual volcanoes, however, may remain in repose for many centuries or even millennia and thus may be classified as dormant (i.e., could become active again) or extinct (i.e., not expected to erupt again). The shortcomings of pigeonhole classification are evident; in a general way, the longer the period of intereruption repose, the more energetic the next eruption. Some of the

Published in 1989 by the American Geophysical Union.

Reviews of Geophysics, 27, 2 / *May 1989*
pages 237–269
Paper number 89RG00436

worst volcanic catastrophes in history have occurred at volcanoes believed to be "extinct," for example, the A.D. 79 eruption of Vesuvius that destroyed Pompeii and Herculaneum [*Sigurdsson et al.*, 1985] and the 1951 eruption of Mount Lamington, Papua New Guinea [*Taylor*, 1958].

Volcanic Disasters and the Emergence of Volcanology

Historically, the study of eruptive phenomena has been spurred by volcanic catastrophes. Indeed, the earliest accurate description of an eruption is contained in letters from Pliny the Younger to the Roman historian Tacitus, describing the asphyxiation of his uncle, the famous scholar Pliny the Elder, who was observing the A.D. 79 eruption of Vesuvius as it destroyed Pompeii. The 1815 eruption of Tambora (Sumbawa Island, Indonesia), considered the largest eruption in recorded history, caused more than 90,000 human deaths and global climatic impact [*Self et al.*, 1984; *Stothers*, 1984; *Stommel and Stommel*, 1983]. Yet because of the volcano's remoteness, poor global communications, and the immature status of the natural sciences at the time, this huge eruption attracted little attention beyond the affected part of the Indonesian archipelago. The first scientific expedition to study this cataclysmic event was not sent until 1847 [*Zollinger*, 1855]. That same year, a small primitive volcano observatory was established on the flank of Vesuvius.

In contrast to the feeble, belated scientific response to the Tambora eruption, the 1883 eruption of Krakatau (Sunda Strait, between Java and Sumatra, Indonesia) prompted the first well-organized scientific investigation of a volcanic catastrophe and its aftermath [*Verbeek*, 1885; *Symons*, 1888] (see also *Simkin and Fiske* [1983]). Scientific expeditions were quickly dispatched, and comprehensive studies were made and published by scientists from the Netherlands and other countries within a few years of the eruption. As emphasized by *Simkin and Fiske* [1984], who aptly termed Krakatau 1883 "a classic geophysical event," these studies greatly advanced not only volcanology, but also meteorology, oceanography, and biology. From the 1883 Krakatau eruption "the world quickly learned that the impacts of large geophysical events are global, and that they demonstrate the interdependence of land, sea, and air" [*Simkin and Fiske*, 1984, p. 48].

The study of the effects of the 1883 Krakatau catastrophe provided new insights into the processes and hazards associated with a violently explosive eruption, but little was learned about how a volcano behaves before an eruption. Early in the twentieth century, volcanology began to evolve from an expeditionary, after-the-fact endeavor into the modern, multidisciplinary science that it is today. In the 6-month period May–October 1902, three eruptions in Central America and the Caribbean (Soufrière, St. Vincent; Mont Pelée, Martinique; Santa María, Guatemala) killed more than 36,000 people. T. A. Jaggar, Jr., a 31-year-old assistant professor in geology at Harvard University at the time, was one of the geologists sent to study the effects of the Mont Pelée and Soufrière eruptions. This experience and that gained later from studies of volcanoes and earthquakes in Alaska, Italy, Japan, and Costa Rica convinced Jaggar that the expeditionary method of study was inadequate and that to fully understand volcanoes, it is necessary to observe and measure their eruptive and associated seismic activity on a continuous basis before, during, and after eruptions. The devastation Jaggar witnessed at Martinque also convinced him that a better understanding of the processes that could kill "thousands of persons by subterranean machinery totally unknown to geologists and then unexplainable was worthy of a life work" [*Jaggar*, 1956, p. 62].

Jaggar was a scientific visionary who recognized that a true understanding of eruptive phenomena would require the establishment of permanent observatories to study active volcanoes [*Macdonald*, 1953]. His vision and research goals were shared enthusiastically by the noted Japanese seismologist, F. Omori, of the Imperial Earthquake Investigation Committee. In 1910, Omori designed and deployed a seismometer ("tromometer") to detect earthquakes beneath Usu Volcano (Hokkaido), marking the first instrumental monitoring of a volcano [*Shimozuru*, 1981]. In 1911, Omori founded an observatory at Asama Volcano (Honshu). Meanwhile, Jaggar obtained several Omori-type seismometers and designed equipment to measure the temperature of an active lava lake in Halemaumau Crater within Kilauea Volcano's summit caldera [*Jaggar*, 1956]. A "technology station" was set up at the edge of Halemaumau lava lake in July 1911, and, after many difficulties, F. A. Perret and E. S. Shepherd (Geophysical Laboratory of the Carnegie Institution, Washington, D. C.) succeeded in obtaining the first thermocouple measurement of the temperature (1000 ± 25°C) of liquid basaltic lava (see *Shepherd* [1912], cited in the work of *Bevens et al.*, [1988], and *Apple* [1987]).

The Hawaiian Volcano Observatory (HVO) was founded "officially" in January 1912, upon Jaggar's arrival to assume the directorship. Following the founding of the observatories in Japan and Hawaii the young science of volcanology has continued to mature through the establishment of, and studies conducted at, additional volcano observatories elsewhere in the world. Jaggar's visionary objective of a global network of observatories has only been partially achieved, because many of the world's active and potentially active volcanoes still are little studied and poorly understood. Very few are being adequately monitored.

Scope and Purpose of This Paper

Many useful books and review papers treating various aspects of volcanology appeared in the 1970s [e.g., *UNESCO*, 1972; *Macdonald*, 1972; *Civetta et al.*, 1974; *Bullard*, 1976; *Williams and McBirney*, 1979; *Sheets and Grayson*, 1979]; a new international journal (*Journal of Volcanology and Geothermal Research*) was launched in 1976. Scientific and public interest in volcanoes and volcanology increased dramatically in the 1980s, following the well-documented reawakening and catastrophic eruption of Mount St. Helens in the spring of 1980 [*Lipman and Mullineaux*, 1981; *Manson et al.*, 1987]. It is beyond the scope of this paper to consider recent advances in mineralogy, igneous petrology, and geochemistry that have contributed to an improved understanding of magmatic processes operative in volcanic systems. The interested reader is referred to pertinent review papers [*Carlson*, 1987; *McCallum*, 1987; *Marsh*, 1987; *Ghiorso*, 1987] and the references cited therein and in the report for 1983–1986 compiled by *Longhi* [1987].

This paper primarily focuses on some geophysical aspects of volcanology, and its purpose is threefold: (1) to review the progress in volcano-monitoring and hazards mitigation studies made since the early 1970s, (2) to compare some volcanic disasters and crises in the 1980s within a context of hazards mitigation, and (3) to highlight problems and challenges that confront volcanologists and government officials who work to reduce volcanic risk.

TABLE 1. Some Notable Volcanic Disasters Since the Year A.D. 1000 Involving 300 or More Fatalities

			Primary Cause of Death				
Volcano	*Country*	*Year*	*Pyroclastic Flow*	*Debris Flow*	*Lava Flow*	*Posteruption Starvation*	*Tsunami*
Merapi	Indonesia	1006	1,000*				
Kelut	Indonesia	1586		10,000			
Vesuvius	Italy	1631			18,000†		
Etna	Italy	1669			10,000†		
Merapi	Indonesia	1672	300*				
Awu	Indonesia	1711		3,200			
Oshima	Japan	1741					1,480
Cotopaxi	Ecuador	1741		1,000			
Makian	Indonesia	1760					
Papadajan	Indonesia	1772	2,960				
Lakagigar	Iceland	1783				9,340	
Asama	Japan	1783	1,150				
Unzen	Japan	1792					15,190
Mayon	Philippines	1814	1,200				
Tambora	Indonesia	1815	12,000			80,000	
Galunggung	Indonesia	1822		4,000			
Nevado del Ruíz	Colombia	1845		1,000			
Awu	Indonesia	1856		3,000			
Cotopaxi	Ecuador	1877		1,000			
Krakatau	Indonesia	1883					36,420
Awu	Indonesia	1892		1,530			
Soufrière	St. Vincent	1902	1,560				
Mont Pelée	Martinique	1902	29,000				
Santa María	Guatemala	1902	6,000				
Taal	Philippines	1911	1,330				
Kelut	Indonesia	1919		5,110			
Merapi	Indonesia	1951	1,300				
Lamington	Papua New Guinea	1951	2,940				
Hibok-Hibok	Philippines	1951	500				
Agung	Indonesia	1963	1,900				
Mount St. Helens	U.S.A.	1980	60‡				
El Chichón	Mexico	1982	>2,000				
Nevado del Ruíz	Colombia	1985		>22,000			
		Total	65,140	53,900	28,000	89,340	53,090

An exception is made for the May 1980 eruption of Mount St. Helens, which caused the worst volcanic disaster in the history of the United States [from *Tilling*, 1989, Table 1.2]. Values are rounded off to the nearest ten.

*Includes deaths from associated mudflows; however, the validity of the 1006 eruption has been questioned [*Djumarma et al.*, 1986].

†Includes deaths from associated explosions and/or mudflow activity; estimates are unreliable and probably too high.

‡Principal causes of deaths were a laterally directed blast and asphyxiation.

TABLE 2. Principal Types of Volcanic Hazards and Selected Examples

Type	*Example*	*Reference*
	DIRECT HAZARDS	
Fall processes		
Tephra falls	Vesuvius, 1906	*Lacroix* [1906]
Ballistic projectiles	Soufrière (St. Vincent), 1812	*Anderson and Flett* [1903]
Flowage processes		
Pyroclastic flows, surges	Mount Pelée, 1902	*Fisher et al.* [1980]
Laterally directed blasts	Bezymianny, 1956	*Gorshkov* [1959]
Debris avalanches	Mount St. Helens, 1980	*Voight et al.* [1981]
Primary debris flows (eruption triggered)	Nevado del Ruíz, 1985	*Herd and the Comité de Estudios Vulcanológicos* [1986]
Floods (jökulhlaups)	Katla, 1918	*Thorarinsson* [1957]
Lava flows	Kilauea, 1960	*Macdonald* [1962]
Other processes		
Phreatic explosions	Soufrière (Guadeloupe), 1976	*Feuillard et al.* [1983]
Volcanic gases and acid rains	Dieng Plateau (Indonesia), 1979	*Le Guern et al.* [1982]
	INDIRECT HAZARDS	
Earthquakes and ground movements	Sakurajima, 1914	*Shimozuru* [1972]
Tsunami (seismic seawave)	Krakatau, 1883	*Simkin and Fiske* [1983]
Secondary debris flows	Semeru, 1976	*Volcanological Society of Japan* [1978]
Posteruption erosion and sedimentation problems	Irazú, 1963–1964	*Waldron* [1967]
Atmospheric effects	Mayon, 1814	*Commission on Volcanology* [1975]
Posteruption famine and disease	Lakagigar (Laki), 1783	*Thorarinsson* [1979]

Principal data sources: *Blong* [1984] and *Crandell et al.* [1984].

VOLCANIC AND RELATED HAZARDS

Comparison With Other Hazards

On a global basis and relative to most other hazards, natural or man-made, volcanic and related hazards occur infrequently and affect few people [*Wijkman and Timberlake*, 1984, Figures 1 and 5]. Average annual economic loss and human casualty from volcanic hazards are correspondingly low if considered globally, but volcanic disasters, like earthquakes, can have significant short-term human and economic impact. In the United States, for example, the annual economic loss from volcanic eruptions is at least an order of magnitude less than the loss (0.6 billion dollars) caused by earthquakes, which in turn is nearly an order of magnitude less than the loss associated with floods and ground failures [*Hays and Shearer*, 1981]. The deadliest eruption in history (Tambora, Indonesia, 1815) killed 92,000 people (Table 1), compared with 500,000 killed in the worst hurricane (Ganges Delta, Bangladesh, 1970). Perhaps the deadliest natural disaster was the Huahsien earthquake (Shensi, China) in 1556, which killed more than 820,000 people [*DeNevi*, 1977]. More recently, the 7.8-magnitude Tangshan (China) earthquake in July 1976, according to Chinese government figures, killed about 240,000 people [*Shi Diguang*, 1987], but some outside observers have claimed that the fatalities may have exceeded 800,000.

Estimates suggest that the average U.S. citizen is much more likely to die from coronary arrest while shoveling snow or from a lightning strike than from either an earthquake or a volcanic eruption [*White and Haas*, 1975, Figures 3 and 4]. Nonetheless, since the year 1000, more than 300,000 people have been killed directly or indirectly by volcanic eruptions (Table 1), and at present, about 360 million people (about 10% of the world's population) live on or near potentially dangerous volcanoes [*Peterson*, 1986, Table 15.1]. The circum-Pacific region, because it contains most of the world's active volcanoes and densely populated countries, has faced, and still faces, a disproportionately high risk, in terms of economic loss and human deaths, posed by volcanic and related hazards [*Simkin and Siebert*, 1984; *Blong*, 1984].

Direct and Indirect Hazards

The types and nature of volcanic and associated hazards have been well described [e.g., *Macdonald*, 1975; *Blong*, 1984; *Crandell et al.*, 1984; *Office of the United Nations Disaster Relief Co-Ordinator (UNDRO)/UNESCO*, 1985]. A list of the principal hazards (Table 2) is presented here; all examples of hazards given involved human fatalities and/or destruction of property. It should be emphasized that an eruption commonly produces multiple hazards. For example, the May 18, 1980, eruption of Mount St. Helens included a debris avalanche, a laterally directed blast, mudflows, pyroclastic flows and surges, steam blast ("phreatic") explosions, and tephra fall [*Christiansen and Peterson*, 1981]. Of these, the avalanche, directed blast, and mudflows caused most of the deaths and devastation.

Some terms in this paper may be unfamiliar to some readers. "Pyroclastic" ("fire-broken" in Greek) describes fragmented molten lava and/or solid rock expelled during explosive eruptions. Highly explosive eruptions are called "plinian," after Pliny the Elder, who was killed during the A.D. 79 eruption of Vesuvius. "Tephra" refers to airborne fragmental volcanic ejecta of any size; "ash" is tephra with grain size less than 2 mm. "Lahar," an Indonesian term, describes volcanic debris flows (including "mudflows"), which are slurries of volcanic debris and water that can vary widely in proportion. A debris flow is considered "primary" if it is triggered by eruptive activity, most commonly by melting of snow and/or ice by hot volcanic materials, and "secondary" if caused by noneruptive processes, most commonly by heavy sustained rainfall in terrain underlain by unconsolidated volcanic deposits. "Jökulhlaups" (an Icelandic term), also called "glacier bursts," are periodic high-discharge floods of subglacial water, caused most commonly by volcanic or geothermal activity but sometimes by purely glaciological processes.

Of the direct hazards, lava flows are typically associated with nonexplosive to mildly explosive outpourings of fluid lavas (e.g., basaltic to basaltic andesite), such as those produced at Kilauea and Mauna Loa (Hawaii), Etna (Sicily), and Piton de la Fournaise (Reunion Island, Indian Ocean). Most other direct hazards are linked with explosive eruptions of steep-sided composite volcanoes. Excellent descriptions of pyroclastic processes and products characteristic of explosive eruptions are given by *Fisher and Schmincke* [1984]. Of the indirect hazards, secondary mudflows, atmospheric effects (shock waves and electrical discharges), and magma-induced earthquakes and ground dislocations are common but the least severe. In terms of human fatalities, the indirect hazards of tsunami and eruption-caused famine are as significant as the direct hazards of pyroclastic flows and primary mudflows (Table 1).

Hazards, Risks, Disasters, and Crises

The distinction between the terms "hazards" and "risks" and the terms "disasters" and "crises" is commonly blurred; in particular, hazards and risks are sometimes used synonymously. In this paper an attempt will be made to use these terms consistently with the following definitions, adapted in part from *Fournier d'Albe* [1979] and *Newhall* [1982]:

1. Hazard is the volcanic phenomenon that poses a potential threat to persons or property in a given area within a given period of time; if sufficient data exist, a probablility should be assigned to a potential hazard.
2. Risk is the probability of a loss (such as life, property, productive capacity, etc.) within an area subject to volcanic hazards. Assessment of risk involves the consideration of the relation risk = (value) × (vulnerability) × (hazard), where value may include the number of lives threatened, the economic worth of property, civil works, and productive capacity, and vulnerability is a measure of the percentage (0 to 100%) of the value likely to be lost in a given hazardous event.
3. Disaster is an event that is marked by the significant loss of value (as defined above) resulting from volcanic and related hazards.
4. Crisis is a situation during which a volcano shows signs of instability or unrest, interpreted to augur impending eruptive activity and associated hazards. A crisis may or may not culminate in a dangerous eruption, but it always causes anxiety and/or socioeconomic disruption among the populace affected.

MITIGATION OF VOLCANIC RISK

As emphasized by *Tilling and Bailey* [1985], the effective mitigation of volcanic risk builds from a foundation of long-term basic research on volcanoes, inactive as well as active (Figure 1). An improved knowledge of "how volcanoes work," the focus of a recent international symposium [*Tilling*, 1987*b*, 1988*a*, *b*], is the common point of departure for all volcanic hazards studies. Specifically, five elements are essential to mitigate the risk from volcanic and related hazards: (1) identification of high-risk volcanoes; (2) hazard identification, assessment, and zonation; (3) volcano monitoring and eruption forecasting; (4) engineering-oriented measures; and (5) volcanic emergency management.

Identification of High-Risk Volcanoes

Of the some 600 active volcanoes known in the world, only a small fraction of them have been, or are being, studied in detail. Economically and scientifically developed countries lack sufficient resolve to study and monitor all of the active or potentially active volcanoes within their borders; the situation is even more acute for the developing countries, which contain most of the world's explosive volcanoes, many in densely populated regions. Nonetheless, identification of high-risk volcanoes is required to determine which ones should receive the most attention by scientists and public safety officials, within the limitations of whatever resources may be available.

Attempts have been made to compile lists of high-risk volcanoes [e.g., *Shimozuru*, 1975; *Matahelumual*, 1982; *Lowenstein and Talai*, 1984; *Yokoyama et al.*, 1984]. All

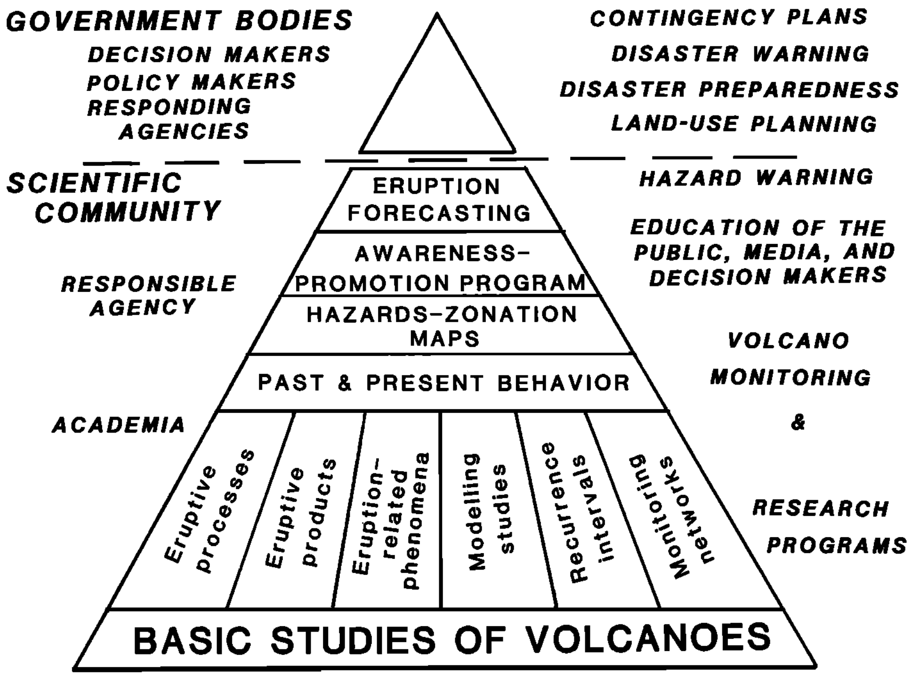

Figure 1. Diagram showing that an effective program of volcanic hazards mitigation must be built on a strong foundation of basic studies, followed by successively more specialized investigations to prepare hazards zonation maps and to predict the future behavior of the volcano. The apex is separated from rest of the triangle to indicate the division of primary responsibility between the scientists and civil authorities, who must consider socioeconomic and political factors in addition to scientific information in making decisions (modified from *Tilling and Bailey* [1985, Figure 1]).

such lists utilize rating criteria involving some or all of the following factors: (1) frequency, sites, and nature of recorded historical eruptions; (2) information on recent prehistoric eruptions as inferred from mapping and dating studies; (3) known ground deformation and/or seismic events ("earthquake swarms"); (4) nature of eruptive products as possible indicators of explosive potential; and (5) various demographic determinants, such as population density, property at risk, and fatalities and/or evacuations resulting from historical volcanic disasters or crises.

In 1983, participants in three UNESCO-sponsored workshops identified 89 high-risk volcanoes: 42 in southeast Asia and the western Pacific, 40 in the Americas and the Caribbean, and seven in Europe and Africa [*Yokoyama et al.*, 1984]. However, this compilation is hardly definitive, because geologic and geophysical data are inadequate for sound evaluation of many volcanoes. For example, had scientists, using the criteria adopted at the 1983 UNESCO workshops, rated the El Chichón Volcano (Mexico) before its violent eruption in 1982 [*Luhr and Varekamp*, 1984], it would not have been scored as being high risk. Ironically, the Nevado del Ruíz Volcano (Colombia) was not identified as being high-risk by the 1983 workshop participants. Its eruption 2 years later caused more than 22,000 deaths, perhaps as many as 27,000 [*Podesta and Olson*, 1988]. However, scientists are quite aware of the deficiencies in the available data used to identify high-risk volcanoes. *Yokoyama et al.* [1984, p. 21] cautioned that the "low . . . ratings for certain volcanoes, hence not identified as 'high risk' by the criteria used, may simply reflect incomplete and/or incorrect information, not necessarily low risk. In fact, the volcanoes *not listed* (authors' italics) . . . should be the focus of increased scientific investigations to establish their actual potential for eruptions and related hazards."

Hazard Identification, Assessment, and Zonation

Identification and assessment of volcanic and related hazards were not prime subjects of scientific inquiry until the 1960s [e.g., *Markhinin et al.*, 1962; *Searle*, 1964; *Crandell and Mullineaux*, 1967]. However, the 1919 eruption of Kelut (Java), which killed about 5000 people, motivated the Dutch scientific community to establish a "Volcano Watch" at the "most deadly East Indies volcanoes." This "watch," which included a network of six observatories at their "most dangerous" volcanoes (all in Java), was the forerunner of the present Volcanological Survey of Indonesia (VSI). In addition to initiating the systematic observation of some volcanoes, another important result of the Volcano Watch was the first systematic attempt, beginning in the 1920s, to classify the Indonesian volcanoes in terms of their hazards, including the preparation of hazards zonation maps. On the basis of only topographic considerations and records of historical eruptions, these rudimentary maps delimited zones of "danger" to population and "regions that may be destroyed" [*Neumann van Padang*, 1960].

As detailed by *Crandell et al.* [1984], the essential data to make useful volcanic hazards assessments include those utilized in the identification of high-risk volcanoes. In addition, further attention is paid to the geologic (especially stratigraphic), petrologic, and geochemical information on the nature, distribution, and volume of the eruptive products. From such data it is possible to reconstruct a volcano's past events and eruptive behavior, which in turn provides the basis for assessing potential hazards from future eruptions.

Hazards assessments are generally predicated on the assumption that the same general areas on a volcano will most likely be affected by the same kinds of eruptive events at about the same average frequency in the future as in the past. Obviously, this assumption may not always be complete. The eruptive behavior, vent locations, and topography of a volcano all may change with time. Moreover, for many volcanoes the period for which the eruptive record and behavior is known may be too short to "capture" infrequent but potentially high magnitude events. The longer the period spanned by the data base used to reconstruct past eruptive behavior, the more useful and reliable the hazards assessment is, if the volcano has not changed its "style."

Hazards zonation maps at appropriate scales should be an integral part of a hazards assessment, because they portray the pertinent information in a summary fashion readily understood by land use planners and decision makers as well as by scientists. This cartographic representation of hazards zonation can vary widely, depending on the specific hazards in question, and is discussed in detail by *Crandell et al.* [1984]. Figure 2 shows the hazards zonation map that was prepared a month

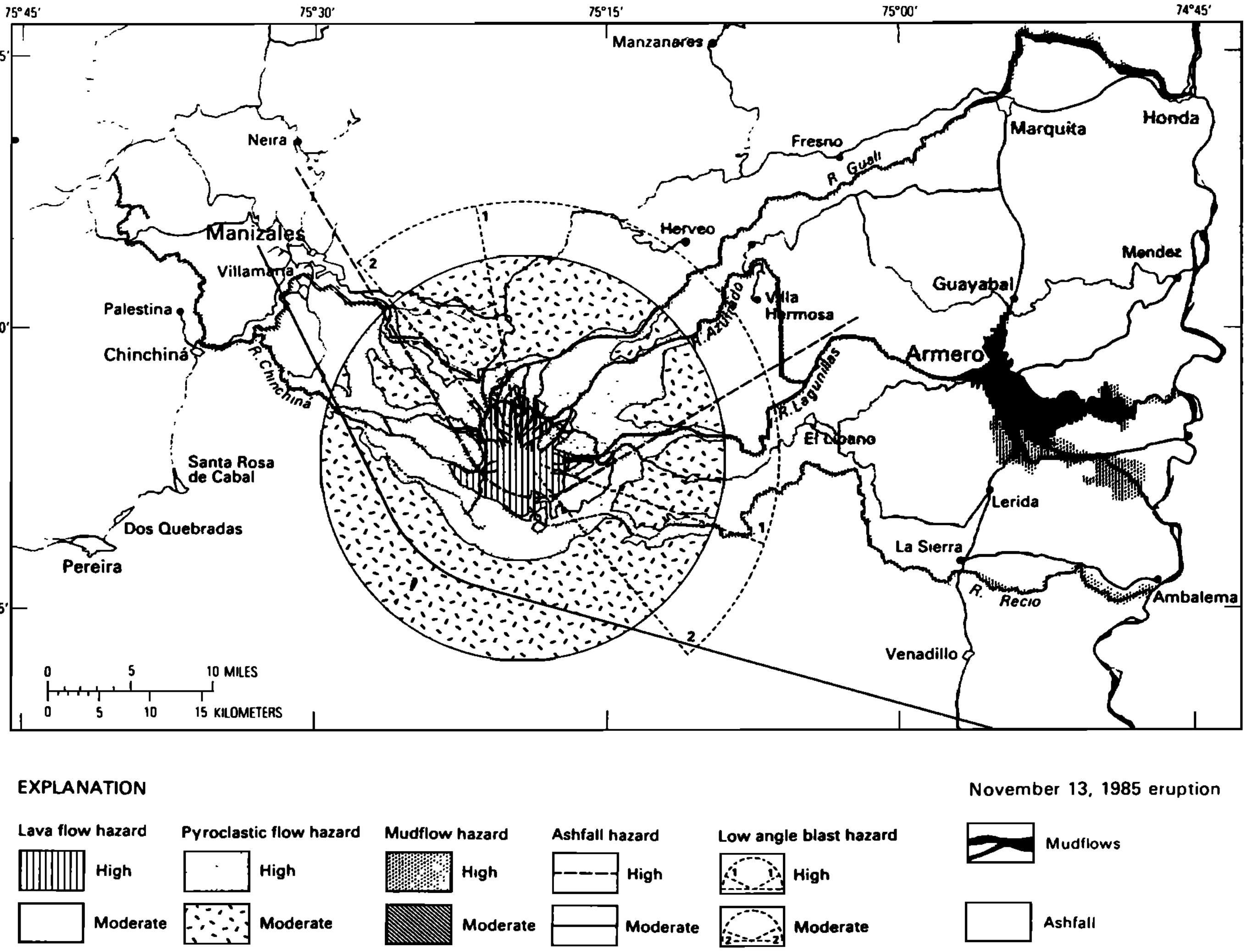

Figure 2. The hazards zonation map for Nevado del Ruíz Volcano, Colombia (reprinted by *Herd and the Comité de Estudios Vulcanológicos* [1986, Figure 4]). Although this map accurately anticipated the nature and areal extent of potential volcanic hazards and was available more than a month before the catastrophic eruption on November 13, 1985, its usefulness was negated by ineffective emergency management during the disaster (see text).

before the Ruíz volcanic disaster; this map anticipated accurately the areal extent of the mudflows and ashfalls from the November 13, 1985, eruption.

Volcanic hazards assessments and/or hazards zonation maps are now available for a number of the world's high-risk volcanoes or volcanic regions (see, for example, the compilation of *Scott* [1989, Table 3.5]). However, hazards assessments are not available, or even forthcoming, at present for many potentially dangerous volcanoes (e.g., El Chichón (Mexico) and El Misti (Peru)).

Volcano Monitoring and Eruption Forecasting

Systematic surveillance of volcanoes began early this century. Experience gained at well-monitored volcanoes indicates that most, and perhaps all, eruptions are preceded and accompanied by measurable geophysical and/or geochemical changes. Appropriately, volcano monitoring provides the primary data for short-term forecasts (hours to months) of eruptions; longer-term forecasts (1 year or longer) generally are premised on other data, most commonly the long-term eruptive record of the volcano.

The rationale and techniques of volcano monitoring and eruption forecasting have been summarized in several review volumes and articles [e.g., *UNESCO*, 1972; *Civetta et al.*, 1974; *Decker*, 1986; *Newhall*, 1984*b*]. Of these summaries the compilations of the 1970s still remain the best and most comprehensive presentations of the basic monitoring techniques, while the subsequent works emphasize refinements in, and applications of, volcano monitoring in the 1980s. In addition to these review papers, many studies specific to a volcano or region also have been conducted: Mount St. Helens [*Lipman and Mullineaux*, 1981], Mount Etna [*Barberi and Villari*, 1984], Campi Flegrei (Phlegraean Fields) [*Barberi et al.*, 1984*a*], and Hawaii [*Decker et al.*, 1987].

Most monitoring techniques are designed to measure changes in the physical or chemical state induced by the movement of magma into or within a volcanic system. In building toward an eruption or intrusion, magma influx into an upper crustal magma reservoir commonly results in the swelling (or inflation) of a volcano; such inflation can be measured and tracked by seismic and geodetic studies. With the onset of an eruption or intrusion, pressure on the reservoir is relieved, and the volcano typically undergoes rapid shrinking (or deflation). An intrusion involves the subsurface movement/injection of magma without culmination in a surface outbreak. For many volcanoes, eruptive or intrusive events are preceded and/or accompanied by harmonic or volcanic tremor, which is characterized by nearly continuous narrow-band seismic vibration, predominantly of a single frequency, believed to be associated with motion of magma or of volcanically heated fluids [e.g., *Aki et al.*, 1977; *Chouet et al.*, 1987; *Koyanagi et al.*, 1987; *Leet*, 1988].

To date, seismic and ground deformation techniques have been the most widely and routinely applied in volcano monitoring [e.g., *Shimozuru*, 1972; *Decker and Kinoshita*, 1972; *Kinoshita et al.*, 1974]. Several other geophysical monitoring methods show promise but at the moment must still be considered experimental: microgravity [e.g., *Jachens et al.*, 1981; *Rymer and Brown*, 1987], geomagnetic [e.g., *Davis et al.*, 1984; *Zlotnicki*, 1986], geoelectrical [e.g., *Zablocki*, 1975, 1978; *Jackson and Kauahikaua*, 1987], remote sensing [e.g., *Malingreau*, 1984; *Francis et al.*, 1988], and thermal radiation [e.g., *Moxham*, 1972; *Kieffer et al.*, 1981] methods. Another promising but also still experimental approach is the application of geochemical methods to monitor the emission and temporal variation of volcanic gases: general methodology and total analysis [e.g., *Le Guern*, 1983; *Greenland*, 1987], sulfur dioxide [e.g., *Stoiber et al.*, 1983; *Krueger*, 1983], carbon dioxide [e.g., *Harris et al.*, 1981; *Casadevall et al.*, 1987], hydrogen [e.g., *Sato and McGee*, 1981; *McGee et al.*, 1987], radon and/or mercury [e.g., *Chirkov*, 1975; *Williams*, 1985], and helium [*Friedman and Reimer*, 1987; *Williams et al.*, 1987].

Short-term eruption forecasts are still most reliably made largely on the basis of seismicity and/or ground deformation alone. Experience worldwide, however, shows that optimum volcano monitoring is best achieved by integrating a combination of approaches, rather than relying on any single method or precursory indicator.

Engineering-Oriented Countermeasures

Volcanic eruptions cannot be controlled, but some hazardous phenomena can be tempered by engineering measures or structures to lessen impact or extent. To date, most of the engineering countermeasures have addressed hazards associated with flow processes (lava flows, debris flows, and floods) and, to a lesser extent, tephra loading and effects on buildings. Of these, lava diversion perhaps has attracted much coverage by the news media because of the dramatic human interest slant ("man fights nature"). Attempts to mitigate hazards by diverting a lava flow from potentially destructive paths have been summarized by *Macdonald* [1972, p. 419]. The diversion methods involve the disruption of active vent areas or flow channels or the erection of barriers or deflectors. The earliest known lava diversion effort was during the 1669 eruption at Etna; it was not successful. Rock diversion barriers were constructed by bulldozers during the 1955 and 1960 eruptions of Kilauea Volcano, Hawaii, and attempts were made to disrupt a lava flow channel by aerial bombing during the 1935 and 1942 eruptions of Mauna Loa. All of these attempts in Hawaii were largely ad hoc and ultimately proved to be unsuccessful. However, more recent studies and efforts in lava diversion have been more systematic and perhaps more successful (see the section on progress in engineering-oriented countermeasures).

The mitigation of the damage caused by debris flows and floods commonly involves one or more of the following countermeasures [*Sudradjat and Tilling*, 1984; *Japan Sabo Association* (*JSA*), 1988]: (1) dikes and channel works along river banks to divert flow courses; (2) check and steel-slit dams to retard or prevent the downstream movement of large blocks and boulders; and (3) sand pockets to trap loose, finer-sized materials. These structures, together with seeding and soil stabilization projects on steep volcanic slopes, collectively are known as "sabo" in Japan and "saborem" in Indonesia, the two countries that have been the most active in the development and construction of such systems. In addition to the physical structures to contain or deflect debris flows, some "sabo works" also include various event detection devices (seismic and thermoelectric devices, "trip wires," etc.) installed higher on the volcano flank to register the passage of pyroclastic and/or debris flow to give warning of potential danger to the communities downstream [e.g., *Sumaryono and Kondo*, 1985; *Volcanic Sabo Technical Centre* (*VSTC*), 1986].

Other engineering-oriented countermeasures include the lowering of the water level of reservoirs in the path of potential debris flows or mudflows in order to accommodate the debris volume and to prevent/minimize overtopping. This measure was specifically recommended by *Crandell and Mullineaux* [1978] in their volcanic hazards assessment of Mount St. Helens and implemented in 1980, weeks before the May 18 eruption [*Miller et al.*, 1981]. Following the 1919 eruption of Kelut (Java, Indonesia), during which more than 5000 people were killed by lahars, a system of tunnels was constructed to drain and lower the level of water in Kelut's crater lake. The drainage tunnel system proved its effectiveness in greatly reducing the lahar hazards during Kelut's next eruption in 1951 [*Neumann Van Padang*, 1960].

Engineering-oriented methods to minimize tephra hazards are not considered in this paper, because they mainly require nongeoscience approaches, such as improvements in the design of structures and stricter enforcement of building codes in the affected volcanic regions. *Blong* [1981] provides a good review of the impact of tephra falls and volcanic bombs on buildings.

Volcanic Emergency Management

Emergency management plays a pivotal, if not the most critical, role in coping with a volcanic disaster or crisis. Yet this important element in reducing volcanic risk draws little attention from scientists and decision makers alike, even in the developed countries with active or potentially active volcanoes. This situation is lamentable but perhaps understandable, in view of the fact that volcanic hazards occur infrequently relative to the human life span and compared to most other types of hazards, let alone relative to the day-to-day demands of an increasingly complex society. The Japanese proverb quoted at the beginning of this paper [*Shimozuru*, 1981] is especially apt for volcanic hazards.

That more effort in natural hazards studies should be placed in emergency management and related societal impacts has been emphasized in several recent works [e.g., *White and Haas*, 1975; *Sheets and Grayson*, 1979; *UNDRO/UNESCO*, 1985; *Peterson*, 1986, 1988], all of which also attest to the complex interaction among the scientists, officials, land managers, news media, and the general public (see, for example, *Peterson* [1988, Figure 1]). The development of more effective emergency management of volcanic and other natural hazards transcends scientific issues per se and must, in the final analysis, be addressed by decision makers within a framework of other societal concerns (Figure 1). However, geoscientists could and must do much more in working toward improved volcanic emergency management.

PROGRESS IN HAZARDS MITIGATION STUDIES

During recent years, considerable progress has been made in understanding how volcanoes work, such as magma supply and delivery systems, eruption frequency and dynamics, and eruptive processes and products [*Self and Francis*, 1987]. This improved understanding has in turn strengthened the basic underpinnings for more specialized hazards mitigation studies. While no major breakthroughs in approach or methodology in hazard mitigation can be claimed during the past decade or so, improvements in instrumentation, data collection and transmission, and data analysis and interpretation have led to correspondingly more refined techniques of volcano monitoring and eruption forecasting. Below I highlight some geophysical examples of such advances.

Volcano Monitoring

Progress has been greatest in the general area of geophysical methods of volcano monitoring. Reflecting the advances in electronics and computerized data collection, seismic monitoring can now quickly and precisely determine the hypocentral locations (the maximum error is ≤ 2 km, but the average is ≤ 1 km) of magma-induced events [e.g., *Klein*, 1978; *Fremont and Malone*, 1987]. The larger seismic events can be located automatically by "real-time processing" (RTP) systems [e.g., *Hill*, 1984]. The greatly enhanced accuracy and precision in analyzing seismic data have made possible detailed three-dimensional models of volcanic seismicity [*Klein et al.*, 1987], which, together with ground deformation data, provide the primary basis for determining the configuration of crustal volcanic plumbing systems in a variety of plate tectonic settings: convergent plate (subduction) boundary (e.g., Mount St. Helens [*Scandone* *and Malone*, 1985]), divergent plate boundary (e.g., Krafla (Iceland) [*Tryggvason*, 1986]), and intraplate (e.g., Kilauea [*Ryan*, 1988]).

Ground deformation monitoring methods also have been refined with improvements in computerized data collection and analysis, especially in connection with use of telemetered, continuously recording tiltmeters [e.g., *Westphal et al.*, 1983; *Wyatt et al.*, 1984; *Agnew*, 1986]. The newest generations of electronic distance measurement (EDM) instruments used to monitor horizontal ground deformation are lighter weight, easier to use, and have self-contained microprocessors for rapid computation of line distances in the field. The two-color geodimeter [*Slater and Huggett*, 1976; *Langbein et al.*, 1982], which eliminates the need for atmospheric corrections, has been used with good results in monitoring the ground deformation at Long Valley caldera [*Hill*, 1984; *Linker et al.*, 1986].

Some promising results have been obtained from recent geoelectrical monitoring studies. For example, measurements of the Earth's weak natural electrical current, called "self-potential" (SP), near an eruptive fissure about 60 hours after the onset of the September 1977 eruption at Kilauea volcano indicated local increases as great as 70 mV [*Dzurisin et al.*, 1980]. A controlled-source electromagnetic (CSEM) technique for monitoring resistivity has been employed at Kilauea since 1979, and correlations were observed between variations in resistivity and some magma intrusions. Particularly significant was the finding that "some aseismic magma movements that are not detected by seismic or geodetic techniques may be easily detected by CSEM monitors" [*Jackson et al.*, 1985, p. 12,555]. *Yukutake et al.* [1987] also observed significant magma-related temporal variations in electrical resistivity at Oshima Volcano, Japan. A combination of geoelectrical techniques (SP, CSEM, and very low frequency (VLF)) is being used to monitor the 1983–present Pu'u 'O'o eruption at Kilauea, the longest-lived rift eruption in Hawaii in historical time [*Jackson*, 1988].

Recent advances in geodetic applications of satellite positioning and other forms of space geodesy, especially the Global Positioning System (GPS) being tested in Hawaii and elsewhere, hold increasing promise that the few-parts-per-million resolution needed for volcano monitoring may be soon attained [e.g., *Prescott and Svarc*, 1986; *Schutz*, 1987]. The GPS, once it is fully tested and shown to be routinely precise and accurate, can augment and/or supplant conventional geodetic volcano monitoring.

Not all recent progress in volcano monitoring has been "high tech" and expensive. For example, the manual measurement of distances between benchmarks by means of a steel tape monitors movement across small thrust faults at the base of the growing lava dome at Mount St. Helens and has provided a remarkably simple but highly reliable method (Figure 3) to predict dome-building eruptions [*Swanson et al.*, 1983]. This simple, inexpensive monitoring technique should encourage scientists to devise and test other "low-tech" monitoring techniques, including repeated careful field observations to detect any visible changes in the state of the volcano with time.

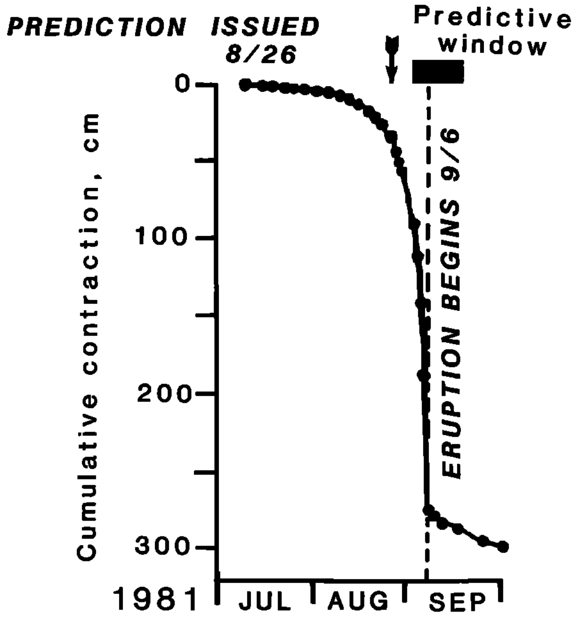

Figure 3. An example of a useful and inexpensive "low-tech" monitoring technique used to successfully predict dome-forming eruptions at Mount St. Helens. The plot shows the cumulative contraction of the distance (measured by steel tape between two benchmarks) across the toe of a thrust fault at base of the growing lava dome. The arrow marks the issuance date of the eruption prediction, the black rectangle shows the period during which the eruption was predicted to occur ("predictive window"), and the dashed vertical line indicates the eruption onset. Such simple measurements are in good accord with data obtained with more sophisticated but more expensive monitoring methods (see Figure 4) [from *Swanson et al.*, 1983, Figure 3].

Eruption Forecasting and Prediction

Progress in volcano monitoring has not been matched by commensurate advances in eruption forecasting. Generally speaking, changes in the rate and amplitude of monitored parameters provide insufficient information for precise forecasts of the place, time, and character of the anticipated activity. Nevertheless, according to *Decker* [1986, p. 269], precursory seismicity has guided observers to arrive "within a few hundred meters of the outbreak locations" before the onset of "all the eruptions of Kilauea Volcano since 1979."

Strictly speaking, however, the successful anticipation of the likely sites of eruptive activity at Kilauea does not constitute a true "forecast" or "prediction," because the specific time of the outbreak cannot be determined in advance. The remarkable record of successful forecasts and predictions at Mount St. Helens since June 1980 [*Swanson et al.*, 1983] provides a context for useful distinctions between the terms "factual statement," "forecast," and "prediction" as defined by *Swanson et al.* [1985, p. 397]:

> A *factual statement* describes current conditions but does not anticipate future events. A *forecast* is a comparatively imprecise statement of the time, place, and ideally, the nature and size of impending activity. A prediction usually covers a shorter time period than a forecast and is generally based dominantly on interpretations and measurements of ongoing processes and secondarily on a projection of past history.

A classic example of a successful long-term forecast is that of *Crandell et al.* [1975, p. 441], who wrote that Mount St. Helens will "erupt again, perhaps before the end of this century." The volcano erupted 5 years later. An example of one of the many successful predictions at Mount St. Helens and associated factual statements is illustrated in Figure 4 and Table 3. About 10 hours after the updated prediction at 0900 local time (LT) on March 19, 1982, eruption began with an explosion, preceded by about 2 hours of intense seismicity. Extrusion of new lava began about 1 day later and continued until April 12 [*Swanson et al.*, 1985]. In my opinion the near-perfect record of predictions of dome-building eruptions at Mount St. Helens is one of the most significant advances in hazards mitigation since the emergence of volcanology as a modern science. It must be remembered, however, that these eruptions are relatively small events, hazardous only to those working within the summit crater. The successful predictive methods used at Mount St. Helens need to be tested for more voluminous and explosive eruptions there and at other volcanoes.

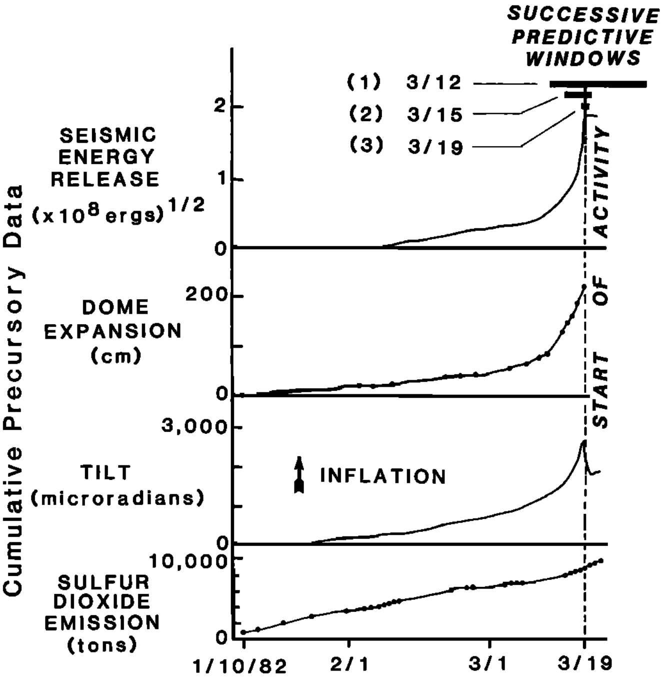

Figure 4. The acceleration of precursory activity before the onset of the March–April 1982 eruptive activity at Mount St. Helens (modified from *Swanson et al.* [1985, Figure 3]). Dome expansion is measured by electronic distance measurements of horizontal displacement, tilt change by electronic tiltmeter, and sulfur dioxide emission by correlation spectrometer (COSPEC). Excerpts from predictions 1, 2, and 3, issued on March 12, 15, and 19, respectively, are given in Table 3; solid bars indicate the successively narrowing predictive windows.

TABLE 3. Examples of Factual Statements and Predictions of the Onset of the March–April 1982 Eruptive Episode at Mount St. Helens

Time, LT	*Date*	*Factual Statement or Prediction Issued**
0900	**March 5**	Factual statement: "Seismicity ... increased around 21 February and has remained at a level somewhat above background since that time. ... Measurements made last week (27 February) show only slow ground deformation ... and no significant increase in gas emissions." (Measurements after 0900 on March 5 show increased rates of deformation.)
0800	**March 12**	Factual statement and prediction 1: "Seismicity ... continues at elevated levels. ... Rates of ground deformation in the crater have increased during the last two weeks. ... Based on rates of deformation, an eruption is likely within the next 3 weeks. Deformation is confined to the crater area, suggesting that renewed dome growth will occur." (Measurements on March 15 showed greatly accelerated deformation.)
1900	**March 15**	Prediction 2, updated: "An eruption, most likely of the dome-building type, will probably begin within 1 to 5 days." (Rates of deformation and seismic energy release continued to increase rapidly.)
0900	**March 19**	Prediction 3, updated: "An eruption will begin soon, probably within 24 hours. The character of both the seismicity and deformation in the crater area indicates that the most likely type of activity is dome growth."
1927	**March 19**	Eruption begins (see text).

Modified from *Swanson et al.* [1985]. *Quoted from *Swanson et al.* [1985, pp. 415–416].

Voight [1988*a*], drawing on data for dome-building eruptions at Mount St. Helens and Bezymianny (Kamchatka) in 1960, proposes a method of prediction based on a mathematical analogy between the terminal stages of materials failure and precursory volcanic behavior. A novel feature of his prediction method is the use of inverse rate-time plots of monitoring data (ground deformation, seismic energy release, etc.), and Voight claims that his approach could improve predictions by recognition of predictive windows sooner than other methods and by narrowing of their widths. However, the general utility of Voight's prediction method remains to be tested against explosive eruptive styles and a variety of volcano types [*Tilling*, 1988*c*]. To date, only a few explosive eruptions have been successfully predicted: Tolbachik, Kamchatka, [*Tokarev*, 1978]; Mount St. Helens [*Swanson et al.*, 1985]; and Sakurajima [*Ishihara*, 1988].

Hazards Assessment and Zonation

The reliability of a volcanic hazards assessment depends on the quality and abundance of basic geologic data and the time span encompassed by the data base used in the assessment. Progress in hazards assessments in recent decades is measured largely by the fact that they are now becoming increasingly available for volcanoes in the United States and other countries [see *Scott*, 1989, Table 3.5]. However, these hazards assessments vary widely in scale and in the breadth and depth of data used to prepare them.

Most assessments focus on potential volcanic and associated hazards, commonly ranked in terms of relative severity, but very few attempt to quantify the probabilities of each type and magnitude of hazard. *Crandell et al.* [1984] briefly review the few attempts made in the quantification of hazards, including the semiquantitative probabilistic assessment of intermediate- (weeks to months) and long-term (years to millennia) volcanic hazards and risks at Mount St. Helens as proposed by *Newhall* [1982]. Subsequently, *Newhall* [1984*a*] extended his method to consider the probabilities of the following five short-term (week-to-week or shorter) volcanic states: quiet, slight unrest, severe unrest, dominantly nonexplosive dome growth, and explosive eruption. Newhall cautions that uncertainties in the estimates of probabilities are at least an order of magnitude. More recently, *Hoblitt et al.* [1987], in a preliminary statistical evaluation of tephra hazards for the entire Cascade Range, give calculated minimum annual probabilities of areas receiving 1, 10, and 100 cm of tephra during future eruptions. Most of the uncertainty in their calculations derives from the large uncertainty in the annual eruption probability; too few postglacial eruptions have been documented for most Cascade volcanoes.

Engineering-Oriented Countermeasures

The massive debris avalanche from the May 18, 1980, eruption of Mount St. Helens blocked parts of the preexisting drainage of the north fork of the Toutle River to form natural dams, behind which lakes were formed or enlarged with rainfall and runoff [*Meyer et al.*, 1986]. It was recognized that the failure of these "landslide" dams, which are composed of unconsolidated, easily erodible volcanic debris, could cause catastrophic mudflows and floods, especially during the winter, when rainfall and snowpack are maximum. As an interim emergency measure, the U.S. Army Corps of Engineers, in the fall of 1982, began to control the rise of the level of water behind the largest of these debris dams (Spirit Lake) by barge-based pumping and discharge into outlet channels. The water level of and discharge from Spirit Lake are now regulated by a permanent system of pipe and tunnel outlets [*Sager and Chambers*, 1986].

The diversion of lava flows to minimize volcanic hazards has received more attention from the geoscience community than other engineering-oriented measures. Although lava diversion probably will never be a major means of hazards mitigation because of its high costs and enormous legal implications [*Decker*, 1986], it may be a viable option under special circumstances [*Lockwood*, 1988]. Perhaps the greatest effort by man to control lava flows occurred in 1973 at Heimaey, Iceland; massive volumes of seawater were sprayed to cool the advancing flow front, and diversion barriers were constructed in an attempt to protect a vital fishing harbor [*Williams and Moore*, 1983]. Icelandic scientists generally believe that the diversion effort was successful in the sense that the harbor likely would have been destroyed if no efforts at diversion had been carried out. During the 1983 eruption of Etna, explosives and earthen barriers were used in attempts to divert major flows [*Abersten*, 1984; *Lockwood and Romano*, 1985]. This lava diversion effort generated considerable controversy among Italian scientists, largely because of its high costs (3 million dollars), but most conceded that the efforts, especially the use of barriers, were successful.

The reawakening of Mauna Loa in 1975, after 25 years of quiet [*Lockwood et al.*, 1987*a*], generated a flurry of official interest in lava diversion plans to protect the city of Hilo from possible future Mauna Loa flows [e.g., *State of Hawaii*, 1977; *Commander-in-Chief, Pacific (CINCPAC)*, 1978; *United States Army Corps of Engineers*, 1980]. Some of the emergency planning included experiments on bomb-cratering tests [*Torgerson and Bevins*, 1976; *Lockwood and Torgerson*, 1980] should aerial bombing be exercised as an option in lava diversion; bombing had been tried previously on Mauna Loa flows in 1935 and 1942 with little planning or success. As it turned out, no lava diversion efforts were necessary during the 1984 Mauna Loa eruption, because flows advancing toward Hilo "self-diverted" by natural branching [*Lockwood et al.*, 1985]. In 1986 a lava diversion barrier was constructed to protect the Mauna Loa Observatory, an atmospheric research facility (operated by the National Center for Atmospheric Research) situated at 3425 m elevation on the north flank of the volcano [*Lockwood et al.*, 1987*b*]. The effectiveness of this barrier is yet to be tested.

In recent decades, Japan has made significant advances in the general area of engineering-oriented countermeasures to mitigate the hazards from debris flows and from tephra. A vigorous long-term national program operates to upgrade existing "sabo works" and to construct new ones, as well as to maintain and improve the country's system of tephra fallout shelters, dugouts and open spaces for heliports, and other refuge facilities [*Disaster Prevention Bureau* (*DPB*), 1988*a*]. As a specific example of such improvements, some sabo works include a warning system that automatically shuts down road traffic, in a manner analogous to that at railway crossings, when the event detection sensor high on the volcano's flank registers the occurrence of a pyroclastic flow or lahar.

THE 1980s: DECADE OF VOLCANIC DISASTERS AND CRISES

The catastrophic eruption of Mount St. Helens on May 18, 1980, ushered in the most disastrous period of volcanic hazards since the year 1902, when more than 36,000 people lost their lives as a result of volcanic activity (Table 1). It thus seems useful to briefly review the volcanic disasters and crises in the 1980s [*Tilling*, 1986] within the context of hazards mitigation studies and then to consider the lessons learned, or not learned, and the measures that should be taken to reduce losses from future eruptions.

Major Volcanic Disasters

Mount St. Helens, U.S.A., 1980 Before 1980, Mount St. Helens had been dormant since 1857, and people living in the region did not think of the mountain as an active volcano. Following a week of intense precursory seismicity, phreatic explosions began on March 27, 1980. During the ensuing intermittent phreatic activity through May 17, volcano monitoring was greatly expanded and confirmed visual observations that the volcano, especially the north flank, was deforming at a high rate because of magma intrusion into the volcanic cone [*Endo et al.*, 1981; *Lipman et al.*, 1981]. Triggered by a magnitude 5.1 earthquake on the morning of May 18, the paroxysmal eruption of Mount St. Helens marked the worst volcanic disaster in the history of the United States, causing the loss of 57 lives, scores of injuries, and more than 1 billion dollars' worth of damage. The first minute of the May 18 eruption produced a 2.7-km^3 debris avalanche, a powerful laterally directed blast, and the start of a 9-hour-long plinian eruption that ejected more than 1.1 km^3 of uncompacted tephra (Figure 5). Shortly thereafter, small pyroclastic flows also began to occur, and the hot volcanic materials melted snow and glacial ice, causing destructive mudflows and floods. With the exceptions of a few smaller explosive episodes, the post–May 1980 eruptive activity of Mount St. Helens has mainly involved the endogenous and exogenous growth of a composite lava dome (Figure 6) within the crater formed on May 18 [*Swanson et al.*, 1987; *Chadwick et al.*, 1988].

Because the eruption of Mount St. Helens was thoroughly documented and received copious media coverage worldwide, public and scientific awareness of volcanic phenomena and hazards increased dramatically. Almost overnight, "Mount St. Helens" became household words synonymous with volcanic catastrophe. The disaster catalyzed, and provided compelling budgetary justification for, an expanded program of volcanic hazards studies in the United States [*Tilling and Bailey*, 1985]. Before 1980, programs repeatedly proposed by the U.S. Geological Survey (USGS) to increase research on and monitoring of U.S. volcanoes in addition to those in Hawaii failed to receive funding from Congress. After May 1980, however, increased funding permitted the USGS to establish a permanent facility at Vancouver, Washington, to monitor the continuing eruptive activity at Mount St. Helens and to acquire baseline data for other Cascade volcanoes. On May 18, 1982, this facility was formally designated the David A. Johnston Cascades Volcano Observatory (CVO) in memory of the USGS volcanologist killed 2 years earlier at Mount St. Helens. More recently, under a cooperative program between the USGS and the state of Alaska, an Alaska Volcano Observatory, considerably smaller than HVO or CVO, was formed in March 1988.

El Chichón, Mexico, 1982 El Chichón Volcano (Chiapas, southeastern Mexico), erupted violently three times between March 28 and April 4, 1982. The eruptions destroyed a dome at the summit of El Chichón, leaving a 1-km-wide and nearly 300-m-deep crater in its place. Pyroclastic flows and surges wiped out all villages within a 7-km radius of the volcano (Figure 7), killing more than 2000 people [*Duffield et al.*, 1984; *Luhr and Varekamp*, 1984]. In addition to wreaking local havoc the eruptions attracted worldwide attention from atmospheric scientists because of their possible impact on global climate [e.g., *Rampino and Self*, 1984; *Galindo et al.*, 1984]. Although the El Chichón and Mount St. Helens eruptions produced about the same amount of silicate ejecta (0.3–0.5 km^3

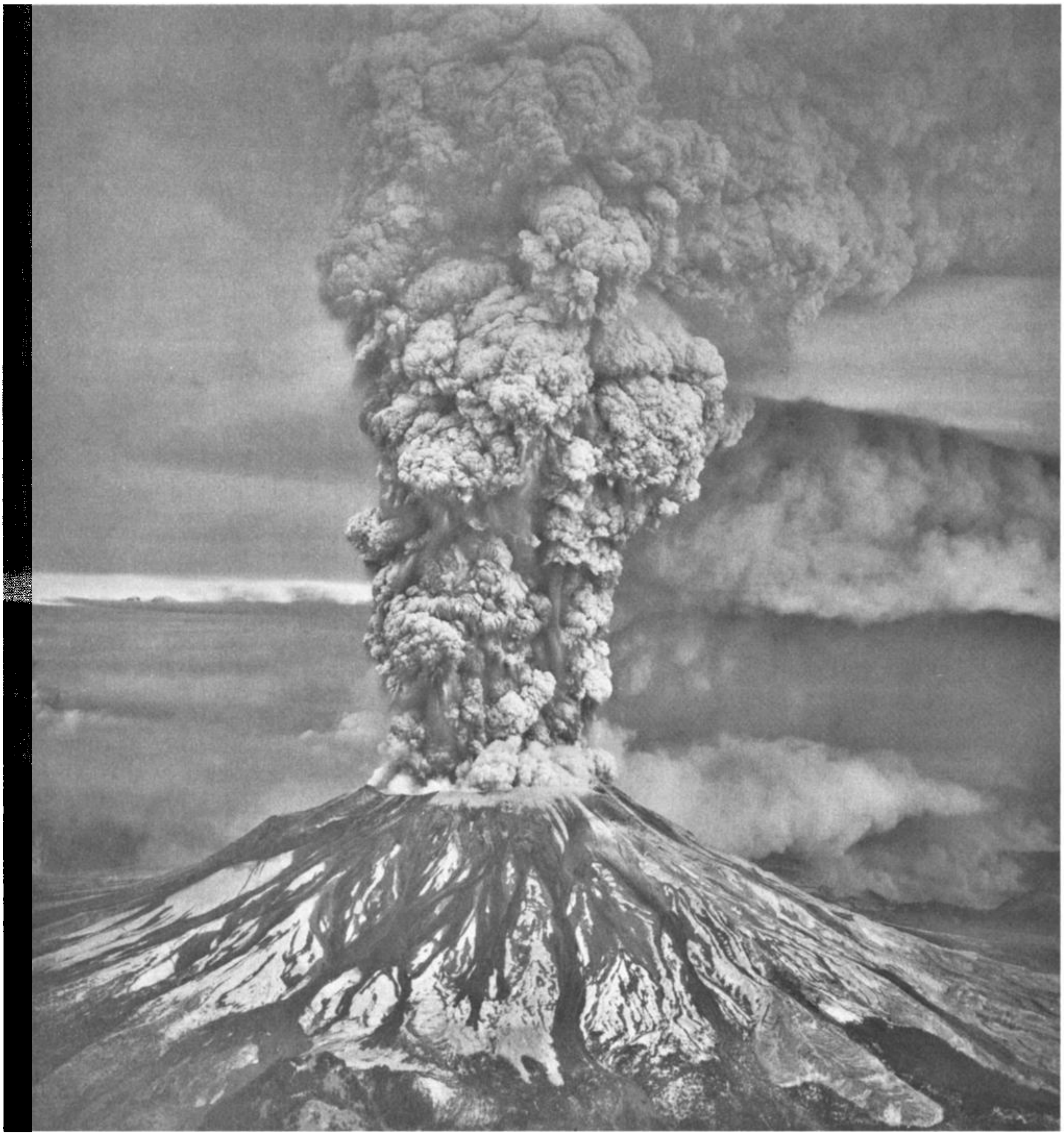

Figure 5. The tephra and gas plume attained a maximum altitude of about 24 km during the plinian phase of the climactic eruption of Mount St. Helens on May 18, 1980. The photograph was taken by R. M. Krimmel (U.S. Geological Survey) about 5 hours after the onset of activity.

dense rock equivalent), El Chichón injected much more aerosols, highly enriched in SO_2, into the lower stratosphere. Its stratospheric volcanic cloud, considered to be among the largest ones in the twentieth century [e.g., *Mitchell*, 1982; *Hofmann*, 1987], remained detectable until late 1985.

The 1982 outburst of El Chichón caused the worst volcanic disaster in Mexico's recorded history. Before 1982, El Chichón was an obscure, little studied volcano since its "discovery" in 1928 by *Müllerried* [1932], who believed that its last activity was during the early Pleistocene. It was not considered to be a high-risk volcano by scientists, officials, or the local populace. The 1982 resumption of activity came almost as a total surprise. There were no recognized immediate precursors to the 1982 eruption, although (in hindsight) earthquake activity, some felt by local inhabitants, increased for some months before the first explosion [*Havskov et al.*, 1983]. Moreover, during the period November 1980 to April 1981, two geologists, while doing fieldwork in connection with assessing the geothermal potential of the area, frequently heard loud noises and felt earthquakes. In their report [*Canul and Rocha*, 1981] they suggested the possibility of "subsurface magmatic activity and/or tectonic movements." They specifically concluded that "in this area there is a high volcanic risk that must be considered if one wishes to develop a geothermal field" (translation quoted by *Duffield et al.* [1984, p. 119]).

Reconnaissance studies after the 1982 disaster indicated that El Chichón was frequently and violently active during the past few thousand years, including major eruptive episodes occurring on average about every 600 (±200) years [*Tilling et al.*, 1984]. Might such information before 1982 have elicited a different response from scientists and officials to El Chichón's early signs of unrest in 1981? Unfortunately, we will never know the answer to this question.

Galunggung, West Java, Indonesia, 1982–1983 Several million people live in the shadow of Galunggung Volcano, which before 1982 had erupted in 1822, 1894, and 1918. Lahars of the 1822 eruption killed more than 4000 people, but the next two eruptions did little or no harm. In early April of 1982, Galunggung came back to life with virtually no precursory activity, and the eruption continued intermittently until early 1983 [*Katilit et al.*, 1986]. During the eruption's most energetic phase (mid-May through August), eruption columns rose 20 km into the atmosphere and ash fell on the capital city of Jakarta, 350 km to the west. Several pyroclastic flows swept down the principal valleys, draining the volcano, and many rainfall-triggered lahars occurred.

Fortunately, the initial activity of the eruption was relatively mild, and people living on or near the volcano were able to evacuate safely. While there were no reported human fatalities directly attributable to the eruption, the 9-month-long eruption of Galunggung, unusually prolonged by Indonesian standards, was a major volcanic disaster because it caused massive socioeconomic impact and adversely affected the daily lives of more than 600,000 people in West Java. More than 80,000 people were forced to evacuate; most were able to return home, but about 35,000 were left permanently homeless. Many hundreds of homes, schools, and other structures were destroyed; transportation and communications systems were disrupted; and some of the most productive agricultural lands and fishponds (growing fish for food) were ruined and/or threatened by lahars. In all, the total economic loss exceeded 100 million dollars (U.S. currency). While the long duration of the eruption strained the limited scientific resources of the Volcanological

Figure 6. Small eruption plume rises from the lava dome growing inside the large, amphitheaterlike crater formed by the May 18 climactic eruption of Mount St. Helens. The photograph was taken by L. Topinka (U.S. Geological Survey) in May 1982, when the dome measured about 850 m long, 800 m wide, and 230 m high.

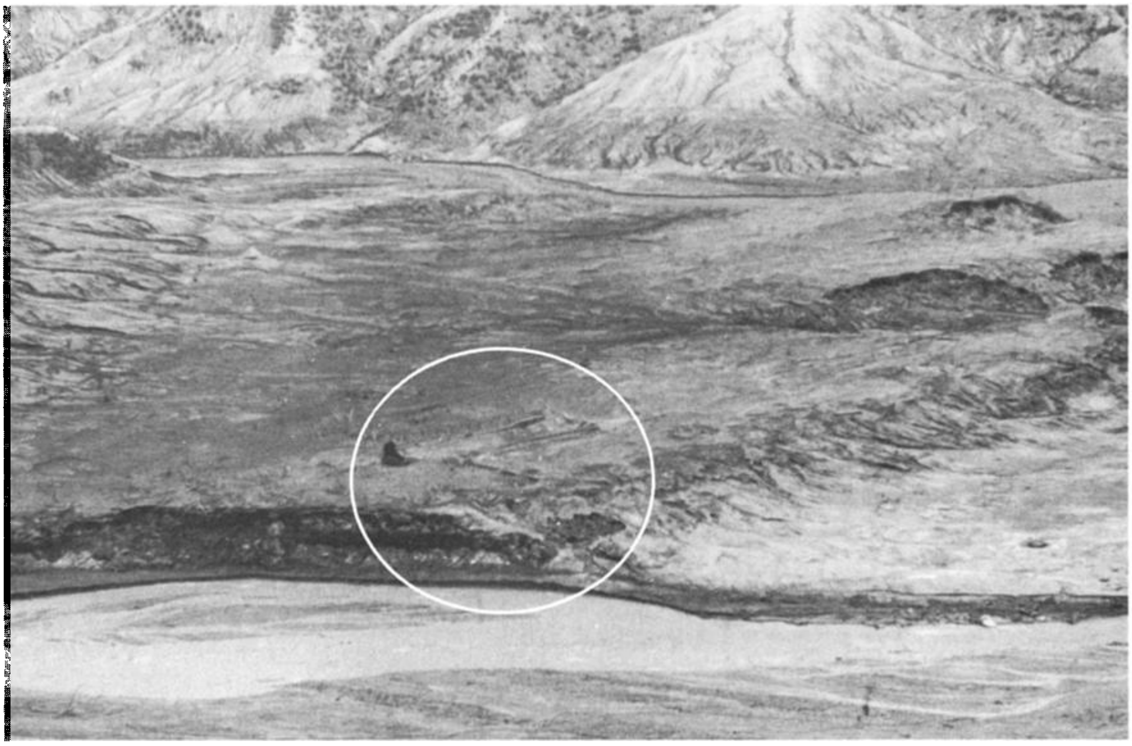

Figure 7. Oblique aerial view showing the site of Francisco León, one of several villages that was obliterated by pyroclastic flows and surges during the 1982 eruption of El Chichón Volcano, southeastern Mexico. Only the ruins of the church (circled) remain of the village, located about 7 km south of the volcano's summit. (The photograph was taken on June 2, 1982, by R. I. Tilling (U.S. Geological Survey)).

Survey of Indonesia, it also afforded an unprecedented opportunity to apply a combination of modern volcano-monitoring techniques not attempted previously on Indonesian volcanoes [*Katili et al.*, 1986].

The Galunggung activity also dramatically emphasized the threat of volcanic ash clouds to international aviation. On three occasions in the period May–July 1982, commercial jetliners encountered ash plumes from Galunggung, resulting in ash abrasion of cockpit windshields and/or engine failures. During two of these encounters the ingestion of ash caused the flameout of two or more engines of Boeing 747s and emergency landings at the Jakarta airport [*de Neve*, 1986]. Fortunately, because of rapid and skillful pilot responses to these air emergencies, disasters were averted. However, these incidents prompted the International Civil Aviation Organization (ICAO) to create, in September, a Study Group on Volcanic Ash Warnings (VAW), composed of volcanologists, pilots, and civil aviation specialists [*Scarone*, 1985]. In 1987, acting on recommendations of this study group, the International Air Transport Association (IATA) instituted the use of "experimental" forms (Special Air Reports) to be carried on all international flights for reporting of volcanic activity, as well as other measures to facilitate rapid communications between volcanologists, air traffic controllers, and pilots.

Nevado del Ruíz, Colombia, 1985 On the afternoon of November 13, 1985, a relatively small volume (0.029 km^3) explosive eruption began at Arenas Crater at the summit of Nevado del Ruíz, a 5389-m-high, glacier-capped mountain that is the northernmost active volcano in the Andes. The hot ejecta melted and mixed with snow and ice to form several highly destructive mudflows that raced down the narrow, steep valleys, draining the volcano and killing more than 22,000 people, the vast majority in the town of Armero in the valley of Río Lagunillas (Figure 8). In addition, the mudflows caused serious injury to another 5000 people, left about 10,000 homeless, and resulted in an economic loss totalling 212 million dollars (U.S. currency). The Ruíz catastrophe was the worst volcanic disaster in the recorded history of Colombia and the worst in the world since the 1902 eruption of Mont Pelée [*Herd and the Comité de Estudios Vulcanológicos*, 1986; *Naranjo et al.*, 1986; *Lowe et al.*, 1986; *Voight*, 1988*b*].

In contrast to El Chichón in 1982 the 1985 eruption and associated mudflows at Ruíz should not have come as a surprise. According to *Herd and the Comité de Estudios Vulcanológicos* [1986, Figure 2], at least 10 major eruptions and several smaller events have occurred at Ruíz Volcano during the past 4000 years. Its last major eruption was in A.D. 1595, which apparently produced huge

Figure 8. Remains of the village of Armero, devastated by lahars triggered by the relatively small magmatic eruption of November 13, 1985, at Nevado del Ruíz Volcano, Colombia. The deadly lahars surged from the canyon mouth of Río Lagunillas (upper right corner), killing more than 22,000 people. The photograph was taken by D. G. Herd (U.S. Geological Survey).

mudflows in the Río Lagunillas valley, upon which the town of Armero later developed [*Voight,* 1988*b*]. In February 1845 a lahar, generated by a large earthquake or a phreatic eruption, again swept down the Río Lagunillas and killed more than 1000 people; this mudflow also reached the modern site of Armero [*Herd and the Comité de Estudios Vulcanológicos,* 1986].

The story of the 1985 Ruíz tragedy began in late November 1984,when precursory signals (felt earthquakes, increased fumarolic activity, phreatic explosions, and even bursts of harmonic tremor) were first noticed [*Tomblin,* 1985; *Herd and the Comité de Estudios Vulcanológicos,* 1986]. Anomalous behavior continued into 1985, and, largely through the efforts of J. Tomblin, Office of the United Nations Disaster Relief Co-Ordinator (UNDRO, Geneva), efforts were made throughout the year to increase volcano surveillance (see *Herd and the Comité de Estudios Vulcanológicos* [1986] for detailed account).

By summer, rudimentary seismic monitoring had begun, and the Comité de Vigilancia del Riesgo Volcánico del Ruíz (Ruíz Volcanic Risk Committee) was formed. However, it was not until September 11 (when a strong phreatic eruption produced measurable ash fall at Manizales, the capital of Caldas Province (population 230,000), and some sizeable debris flows in valleys of Río Azufrado and Río Gualí) that the level of concern was heightened and additional international scientific assistance was requested. By October 7 a preliminary draft of the Ruíz volcanic hazard zonation map (Figure 2) was completed and released. By mid-October a monitoring network of five smoke drum seismometers and four "dry tilt" arrays was established. Meanwhile, intermittent phreatic activity continued even as seismicity waned, and Colombian scientists discussed the hazards map with local officials and briefed them on potential hazards.

The November 13 eruption began at 1505 (local time); explosions occurred intermittently, but the strongest ones happened shortly after 2100 LT (*Herd and the Comité de Estudios Vulcanológicos,* 1986; *Tomblin,* 1988]. The destructive mudflows did not begin striking populated areas in the affected river valleys until about 2230 LT. Despite various warnings and alerts given beginning around 1600 LT, "there apparently was little or no response to calls to evacuate. It is unclear if the general populace of Armero received an order to evacuate" (*Herd and the Comité de Estudios Vulcanológicos*, 1986, p. 459]. However, *Tomblin* [1988, p. 10] remarks that a partial evacuation, prompted by the first eruptions in the afternoon, "two hours later appeared to be unnecessary and then became unpleasant because of heavy rain and nightfall. Consequently, the report of new explosions at 9.00 [sic] that evening, which were not adequately described as significantly larger, met with scepticism from local authorities and populations over the need to evacuate."

Another contributory factor was that throughout the year-long volcanic crisis, the local populace received contradictory messages from government officials and other influential people. For example, on September 28 the Archbishop of Armero and a local medical doctor, who was a prominent civic leader, pronounced that "the alarm over the potential hazards from Ruíz was anti-social and irresponsible" (as quoted by *Williams and Meyer* [1988, p. 1554]). On November 13 the citizens of Armero were advised "eruption detected, but 'stay calm'" a few hours before the destructive mudflows struck. In the most detailed account to date, *Voight* [1986*b*, p. 30] concludes that the Ruíz tragedy "was not produced by technological ineffectiveness or defectiveness, nor by an overwhelming eruption of unprecedented character," but was caused "purely and simply, by cumulative human error—by misjudgment, indecision, and bureaucratic shortsightedness."

It remains unclear to this day what actually transpired during the critical hours between eruption onset and the arrival of the first mudflows in populated areas. In a systematic attempt to reconstruct what went wrong at Ruíz a group of Latin American geoscientists and social scientists is currently studying the scientific and public response aspects of the Ruíz catastrophe. In retrospect it is sobering to remember that the Ruíz eruption ejected only about 3% of the volume of ash produced during the May 18, 1980, eruption of Mount St. Helens. The Ruíz disaster emphatically demonstrates that in densely populated areas, even very small eruptions can cause widespread devastation and kill many people.

Volcanic Crises at Calderas

The most powerful but least frequent volcanic events are caldera-forming eruptions of ignimbrite (ash flow tuffs) from large-volume magmatic systems, such as the Mount Mazama eruption 6850 years ago that formed Crater Lake, Oregon [*Bacon*, 1983]. The Mount Mazama eruption vented about 50 km^3 of magma, about the same volume (dense rock equivalent) erupted during the largest known historical volcanic event (Tambora, 1815). Both the Mount Mazama and Tambora events are orders of magnitude smaller than the three enormous caldera-forming eruptions that took place at Yellowstone within the past 2 million years [*Christiansen*, 1984]. Fortunately, within recorded history, mankind has not experienced caldera-forming eruptions on the scale of Yellowstone, but there are geologic reasons to suppose that such eruptions surely will happen again.

From seismic and other geophysical evidence we know that a magma reservoir still exists beneath Yellowstone [e.g., *Eaton et al.*, 1975; *Iyer*, 1978; *Smith and Braile*, 1984]. Also recent geodetic studies indicate that the floor of the present Yellowstone caldera has undergone significant vertical displacements (tens of centimeters) during the past 60 years [e.g., *Pelton and Smith*, 1982; *Dzurisin and Yamashita*, 1987]. Yellowstone caldera does not pose an immediate volcanic threat. However, unrest at three other calderas during the 1980s has caused volcanic crises of serious concern to scientists, officials, and the populace affected.

Campi Flegrei, Italy, 1982–1984 Campi Flegrei (Phlegraean Fields) is a 12-km-diameter caldera centered about 15 km west of Naples, Italy. Caldera formation occurred during a major eruption about 34,000 years ago and was followed by several other successively smaller eruptions, the most recent being that of Monte Nuovo in A.D. 1538 [*Lirer et al.*, 1987]. Campi Flegrei has undergone large vertical movements since at least Roman times. Subsidence that prevailed since the 1538 eruption was reversed in the period 1969–1972, during which about 1.7 m of uplift occurred, accompanied by a modest increase in seismicity [*Corrado et al.*, 1976/1977]. For the next 10 years, ground displacements showed minor annual fluctuations of the order of 10–15 cm, and seismicity oscillated at low levels.

In the summer of 1982, rapid uplift began and continued for two years, accompanied by intense earthquake activity, resulting in another 1.8 m of uplift centered within the coastal city of Pozzuoli inside the caldera (Figure 9). Geophysical and geodetic measurements (gravity, leveling, EDM) as well as tide gauge data all indicated maximum uplift centered at Pozzuoli [*Berrino et al.*, 1984]. Several particularly energetic earthquake swarms, including magnitude 4 events, in October 1983 caused some of the older brick buildings in Pozzuoli to collapse and led officials to evacuate and resettle nearly 40,000 people. In response to the growing crisis the seismic and geodetic monitoring was augmented by geochemical monitoring of thermal springs and fumarolic gases [*Barberi et al.*, 1984*b*].

The uplift and seismicity peaked in early 1984 and then began to decline. By January 1985, there was little or no detectable seismicity, and a weak subsidence trend had

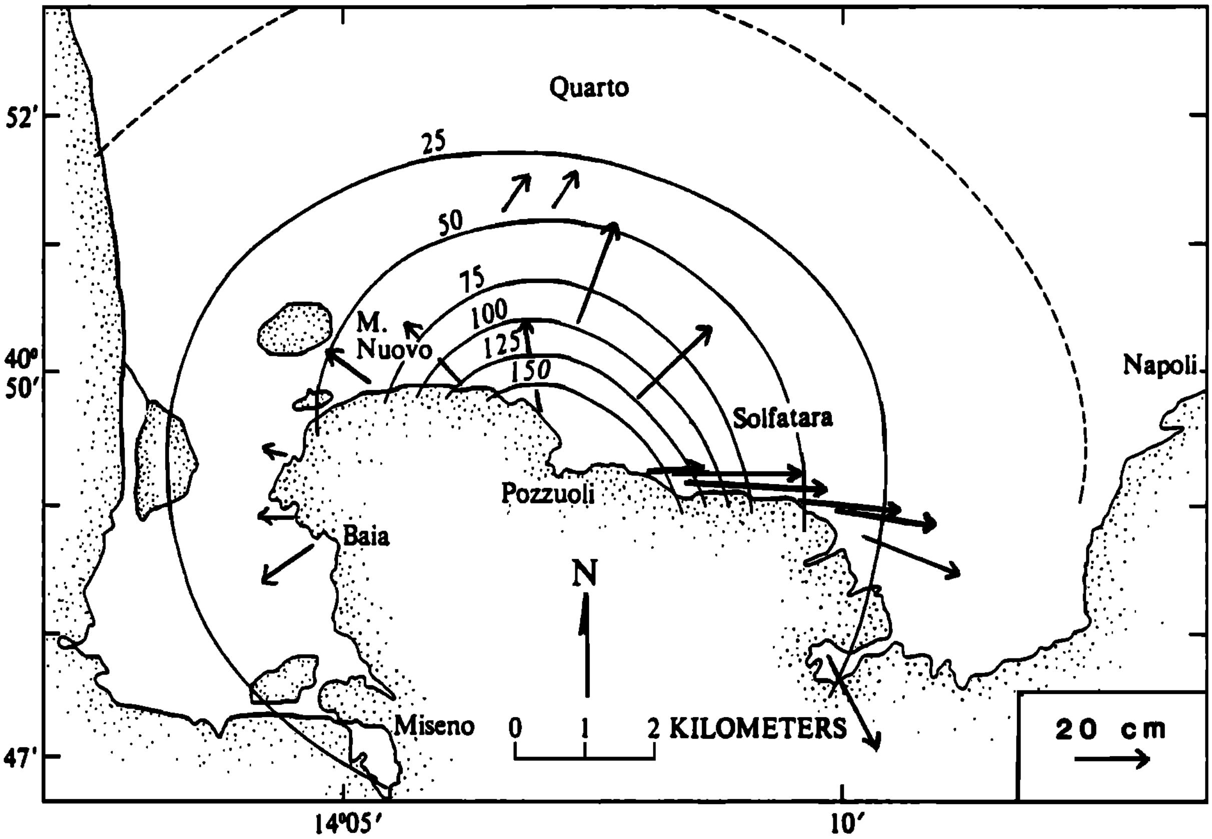

Figure 9. Ground deformation associated with the caldera unrest at Campi Flegrei, Italy. Contour lines show the vertical displacements of benchmarks (in centimeters) during the period January 1982 to January 1985; the vectors indicate horizontal displacements (in centimeters) for the period 1980–1983. The city of Pozzuoli lies within the center of maximum uplift [from *Berrino et al.*, 1984, Figure 12; *Decker*, 1986, Figure 10].

begun. Italian scientists (G. Luongo et al., in the work of *Scientific Event Alert Network* (*SEAN*) [1985, p. 5]) consider the net cumulative uplift (350 cm) since 1969 "the major geological event at Campi Flegrei in the last 180 years" and "comparable with that which occurred before the eruption of Monte Nuovo in 1538, and . . . consider this phase as a possible precursor (on a time scale of years) to new volcanic activity." Because of the population density of the Campi Flegrei region, about 200,000 people could be affected by even a minor eruption, say comparable to Monte Nuovo in 1538. With the 1982–1984 crisis abated, the people who were evacuated "have slowly been moving back into the town. The new settlement on the NW side of the caldera has almost been completed, but it is not certain that all of the people evacuated . . . will move in. The fears of an impending eruption are already gone, and the interest of the media has vanished" (G. Luongo and R. Scandone, in the work of *SEAN* [1986, p. 8]). In fact, many people returned to their original homes rather than moving into the new settlement.

Rabaul, Papua New Guinea, 1983–1985 The caldera at Rabaul (New Britain Island) is about the same size (14 km by 9 km) as Campi Flegrei. The volcano has produced three caldera-forming eruptions between 3500 and 1400 years ago as well as several small- to moderate-sized explosive eruptions in historical time. Its most recent eruptions were in 1937–1943, during which about 500 people were killed [*Johnson and Threlfall*, 1985]. Today, nearly 105,000 people could be affected by a catastrophic eruption, and about 70,000 by a moderate-sized explosive eruption.

Following two magnitude 8.0 regional earthquakes in 1971 in the nearby New Britain Trench, Rabaul began to exhibit signs of seismicity and ground deformation similar to those preceding previous eruptions [*McKee et al.*, 1985]. In August 1971 the monthly count of shallow earthquakes doubled to about 100. During the next 10 years, several seismic swarms occurred, each successively more intense (Figure 10). Leveling data and measurable uplift of beaches during this same period indicated that the central part of the caldera was elevated 1 m. In August 1983 the seismicity and rate of ground deformation increased abruptly. The monthly count of shallow (<4 km) earthquakes in August was about 330, in September was 2135, and by early 1984 exceeded 10,000 (Figure 10). The deformation rate accelerated correspondingly. Maximum tilt rates increased to between 50 and 100 μrad/month, and

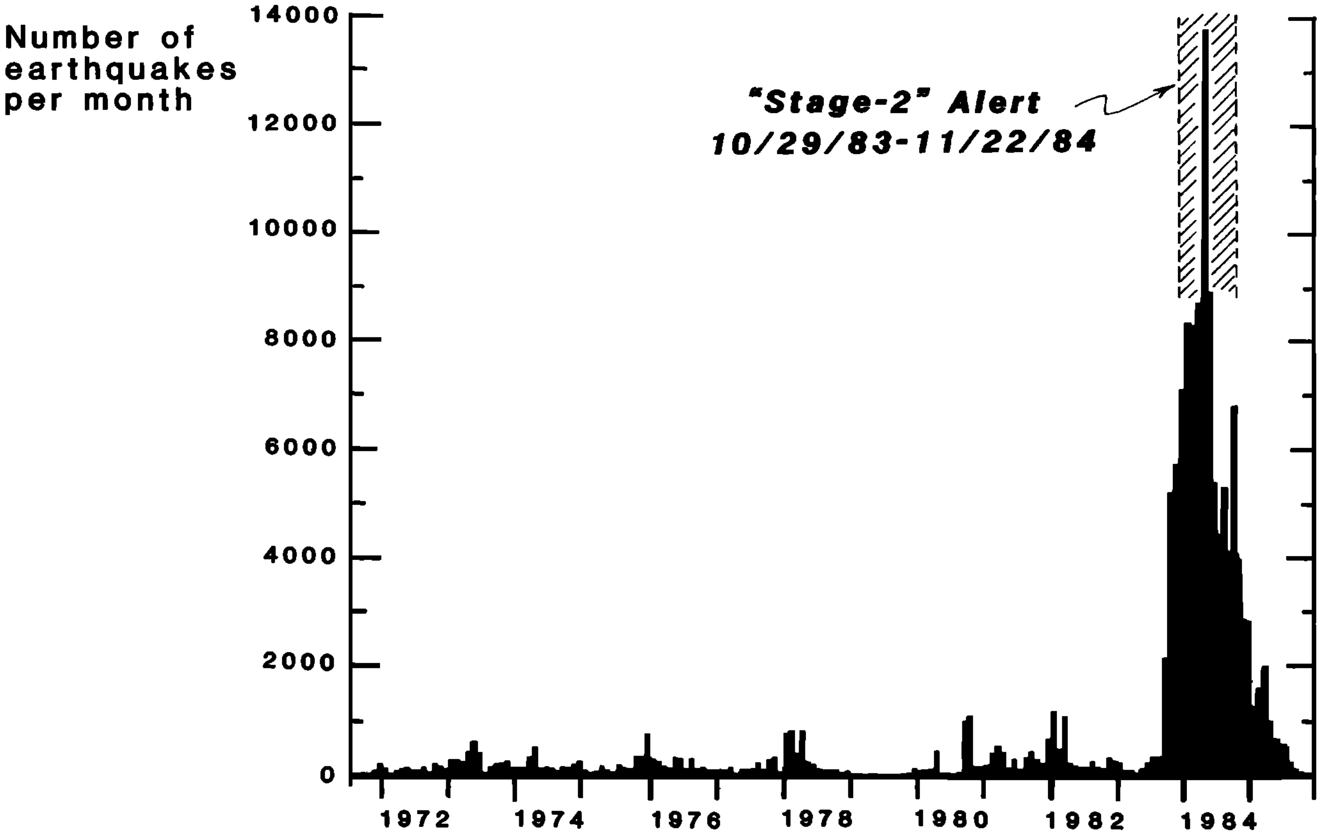

Figure 10. Seismicity beneath Rabaul caldera, Papua New Guinea, from July 1971 through late 1985 (modified from *Mori and McKee* [1987, Figure 1]). The seismicity and ground deformation peaked in April 1984 and then began to decline irregularly but sharply, returning to 1982 levels by May 1985. The hatched area indicates the period during which a government-imposed "stage 2" alert was in effect (see text).

the uplift rate in the area of maximum deformation increased to 5–10 cm/month. The Rabaul Volcanological Observatory (RVO) expanded its volcano monitoring by initiating tilt and horizontal deformation measurements.

On October 29, 1983, after considering the technical information from RVO and socioeconomic factors, government officials declared a "stage 2" volcanic alert, which implied that an eruption would occur within a few months. The seismicity and rate of deformation continued to increase through May 1984 and then declined irregularly for the remainder of the year. On November 22, 1984, officials downgraded the volcanic alert to "stage 1," which implied that the "anticipated eruption is not now expected to occur before several months to a few years" (P. L. Lowenstein, in the work of *SEAN* [1984]). However, at the end of 1984 the seismicity and ground deformation rate were still 1–2 times pre-1983 rates [*McKee et al.*, 1984].

In the period from 1985 to the present, activity at Rabaul has remained at a low level, with periods of standstill and localized deflation followed by a gradual resumption of inflation since March 1988. With the lifting of the stage 2 alert in November 1984 and the continuing relative calm at Rabaul, emergency preparedness measures begun when public concern was high remain unfinished, and progress also has stalled on initiatives to establish alternative monitoring capability should RVO be incapacitated or destroyed during an eruption [*Lowenstein and Mori*, 1987].

Long Valley, California, 1980–1984 Long Valley caldera, 17 × 30 km in size, is located on the eastern front of the Sierra Nevada. It was formed during the cataclysmic eruption of the Bishop Tuff about 0.7 million years ago; ash of the Bishop Tuff has been identified throughout much of the western United States, as far east as Nebraska and Texas [*Bailey et al.*, 1976; *Izett*, 1981]. The youngest of the postcaldera eruptions from the Long Valley magmatic system occurred 100,000 years ago, and other nearby magmatic sources (e.g., Inyo-Mono craters) fed smaller eruptions as recently as 550 years ago [*Miller*, 1985; *Achauer et al.*, 1986]. The resort town of Mammoth Lakes (population 4000) lies within the southwestern part of the caldera, and during the height of the winter ski season its population snowballs to 25,000.

Beginning on May 25, 1980, as Mount St. Helens produced an explosive eruption much smaller than the catastrophic eruption of a week before, the Long Valley area was rocked by four magnitude 6 earthquakes within

48 hours, accompanied and followed by myriad smaller-magnitude aftershocks [*Bailey,* 1982]. Not surprisingly, officials and people in the Long Valley area were anxious and concerned. On May 27 the USGS issued an earthquake "hazard watch," the second level in the three-tiered notification system then in use, because the unusual seismicity was thought at the time to be of tectonic origin. The hazard watch designation was used when information indicated "a potentially catastrophic event of generally predictable magnitude may be imminent in a general area or region and within an indefinite time period (possibly months or years)" [*Federal Register,* 1977, p. 19,292].

After May 1980 and continuing into 1983, several seismic swarms of varying duration and magnitude occurred sporadically within the southern part of the caldera. In late 1980, *Savage and Clark* [1982] found that the earthquakes were accompanied by uplift of the caldera's resurgent dome. This finding, coupled with the possibility that magma may exist at shallow depth (7–8 km) beneath the dome [*Hill,* 1976; *Ryall and Ryall,* 1981], suggested that renewed inflation of the magma reservoir might account, at least in part, for the increased seismicity and measured uplift. If so, then the potential for reactivation of the volcanic system would be increased. Of special concern was the possibility that a major tectonic earthquake in the region [*Hill et al.,* 1985] might trigger an eruption from the Long Valley's restless magma reservoir.

On the basis of continuing caldera unrest and a preliminary volcanic hazards assessment [*Miller et al.,* 1982] the USGS issued, on May 25, 1982, a "Notice of Potential Volcanic Hazard" in addition to the existing earthquake hazards watch, and systematic geophysical and geochemical monitoring studies were begun by the USGS and other organizations. The types of studies used to monitor Long Valley are described in detail by *Hill* [1984]. The issuance of the volcanic hazards notice created considerable consternation among the local officials and residents in the Mammoth Lakes area. In a comprehensive study of the public response during the crisis, *Mader et al.* [1987, p. 38] concluded, "Initially people . . . reacted to the notice with feelings of fear, confusion and denial. Local officials and businesses did not welcome the USGS notice. Community concern focused on the adverse economic impacts of the notice rather than on public safety." Eventually, however, "people seemed to believe they would be warned before an eruption and have time to escape the area. They relied on the USGS, the agency responsible for the objectionable notice, to provide that warning" [*Mader et al.,* 1987, p. 39].

Following a brief earthquake swarm in January 1983 the seismic activity at Long Valley largely returned to pre-1980 levels. In January 1984 the USGS, perhaps in part responding to the "public outcry" over the volcanic hazard notice at Long Valley, simplified the three-tiered hazards notification system into a single "hazard warning" procedure. The criteria for a "geologic hazard warning" in the new system are [*Federal Register,* 1984, p. 3938]

> a) a degree of risk greater than normal for the area; or a hazardous condition that has recently developed or has only been recently recognized; and b) a threat that warrants consideration of a near-term public response.

The Long Valley situation in early 1984 failed to meet the new criteria. Accordingly, both the notice of potential earthquake hazard and the notice of potential volcanic hazard were de facto discontinued; the volcanic hazard notice was formally terminated on July 11, 1984 [*Gori and Shearer,* 1987].

As of mid-1988, continued slow inflation of the caldera, at a rate much less than that during the 1980–1982 period, is still indicated by ground deformation monitoring (USGS, unpublished data, 1988). With the current reduced level of activity the crisis at Long Valley is rapidly fading from public memory. However, the intensive monitoring continues because the USGS still considers the Long Valley area to have potential for volcanic activity. A response plan for volcanic hazards, prepared in early 1984 [*USGS,* 1984], remains in effect.

Comparison of the Disasters

The four major volcanic disasters that have already occurred in the 1980s afford illustrative examples of the current state of the art in volcanic hazards mitigation in a global context. In Table 4 I have attempted to summarize my knowledge and perceptions of the circumstances surrounding the recent volcanic disasters; others may not fully share my views.

The response to, and handling of, the Mount St. Helens disaster appear to be adequate by the criteria listed in Table 4, in large measure because of the substantial body of knowledge about the volcano that was available to scientists and officials before the eruption. A long-term forecast that Mount St. Helens would be the most likely volcano in the conterminous United States to reawaken and erupt, "possibly before the end of this century," [*Crandell et al.,* 1975, p. 441] was made in 1975. A detailed volcanic hazards assessment followed in 3 years [*Crandell and Mullineaux,* 1978], delineating the most hazardous and vulnerable areas in the event of renewed eruptive activity. Little read at the time of its publication, this study later became the report most widely read by local officials and scientists between the onset of activity (March 27) and the climactic eruption on May 18, 1980.

The Crandell-Mullineaux report was duly submitted to the Department of Emergency Services of Washington State and other involved agencies. *Saarinen and Sell* [1985, p. 4] succinctly summarize the pre-1980 response:

> Mount St. Helens was the eighth notice of the new USGS hazard warning system. On December 20, 1978, a letter was sent to the Washington State governor's representative from the USGS notifying federal, state, and local officials of the potential hazard. The governor's representative misinterpreted the notification, thinking an eruption was imminent, and a special meeting involving representatives of many state of Washington government departments and the USGS officials was called in January, 1979, to clarify the situation. Although at the time this action was regarded an overreaction, the meeting might, in retrospect, have been useful in alerting state officials to the potential problem.

Despite the initial flurry of interest and concern, public officials were not convinced of the need to prepare long-range contingency or land use plans.

Ironically, the USGS itself failed to respond institutionally to a long-term forecast made by its own scientists. Because of budgetary constraints and other (at the time) higher-priority programmatic commitments, USGS officials (myself included) made no decision to begin baseline monitoring studies at Mount St. Helens. Earlier however, on his own initiative a USGS scientist (D. A. Swanson) had proposed in the winter of 1971–1972 a project titled "Geodimeter Studies of Cascade Volcanoes." In the summer of 1972, after consultation with D. R. Crandell and C. Hopson (University of California, Santa Barbara) regarding which volcanoes should have first priority, Swanson established five electronic distance measurement (EDM) lines at Mount St. Helens and one at Mount Hood (Oregon). According to Swanson (written communication, 1989), "clearly expediency played some role in deciding to do St. Helens first, but the overriding reason was the perceived high hazard and particularly the perceived likelihood that St. Helens would be the first Cascade volcano to erupt." The measurements were made using borrowed equipment and a loaned field assistant, and they constituted the only pre-1980 volcano monitoring conducted at Mount St. Helens. Because of the lack of funding and the subsequent unavailability of loaned equipment the project terminated by 1973.

The intensive predisaster volcano monitoring during the phreatic eruptive phase (March 20 to May 17) failed to provide diagnostic information for a precise short-term forecast of the May 18 magmatic eruption, even though the data clearly indicated that the north flank of the volcano was becoming dangerously unstable. In hindsight, some scientists speculate that the rate of growth of the "bulge" [e.g., *Lipman et al.*, 1981, Figure 97] might have increased prior to failure, if the deformation process had not been "short-circuited" by the magnitude 5.1 earthquake that triggered eruption. In any case, the possibility of a major avalanche, and a large magmatic eruption triggered by it, was recognized by the scientific team at Mount St. Helens and explained to officials before May 1 [*Miller et al.*, 1981; *Decker*, 1986].

A detailed account of hazards assessments at Mount St. Helens is given by *Miller et al.* [1981], who show the importance of updates of potential hazards as conditions change and of daily meetings with land use managers, in this case the U.S. Forest Service (USFS), to brief them on the hazards. The scientists provided the geotechnical and hazards information used in the preparation of the "Mount St. Helens Contingency Plan," issued by USFS on April 9, as well as in the establishment of restricted zones by Washington State and USFS officials. Had these zones of restricted access not been in effect on May 18, greater human loss and injury surely would have resulted.

In contrast to Mount St. Helens the El Chichón experience represents the worst possible case because of the total lack of predisaster volcanic hazards studies and emergency preparedness. Before 1982, virtually nothing was known about its past history of frequent and violent eruptions [*Tilling et al.*, 1984], and no volcano monitoring was conducted before or during the brief eruption. The

TABLE 4. Comparison of Four Volcanic Disasters Since 1980 in Terms of Volcanic Hazards Mitigation

	Scientific Community's Responsibility							*"Decision Making" Government Bodies' Responsibility*	
Volcanic Disaster	*Knowledge of Past Behavior*	*Predisaster Hazards Assessment*	*Long-Term Forecast*	*Short-Term Forecast*	*Long-Term Precursors (Weeks to Months)*	*Short-Term Precursors (Hours to Days*	*Predisaster Monitoring*	*Predisaster Contingency Planning*	*Emergency Management*
Mount St. Helens, U.S.A. (1980)	good	detailed	yes	no	yes	none	much	good	good
El Chichón, Mexico (1982)	virtually none	none	no	no	probably (but unrecognized)	?	none	none	none
Galunggung, Indonesia (1982)	fair*	rudimentary	no	no	none reported	little or	none	none	fair
Nevado del Ruíz, Colombia (1985)	fair†	preliminary	no	no	yes	?	limited	poor	poor

The rating scale is qualitative, from none to excellent. Figure 1 illustrates the division of primary responsibility between the scientific community and "decision-making" bodies shown in this table.

*Historical eruptive record known only.

†Both historical and prehistoric eruptive record known.

prophetic observations of *Canul and Rocha* [1981] about the possible reawakening of the volcano were contained in an internal report submitted in September 1981 to the Geothermal Department of the Comisión Federal de Electricidad (CFE), whose mission is to develop and manage the energy resources of Mexico, not to worry about potential volcanic hazards.

Fortunately, El Chichón is located in a relatively sparsely populated rural area; otherwise, its 1982 eruption would have caused considerably more deaths and destruction. Unfortunately, the present state of knowledge about many volcanoes in far more densely populated regions is not much better than that available for El Chichón before its deadly surprise. Immediately following the El Chichón disaster, there were some efforts made in Mexico to develop a national volcanic hazards program. To date, however, the Mexican government has neither developed such a program nor designated a principal institution to be responsible for volcano monitoring and hazards assessments. In the United States the USGS is the congressionally mandated organization (by the Disaster Relief Act of 1974) responsible for providing timely warnings of volcanic and related hazards.

The Galunggung and Nevado del Ruíz cases in some respects are intermediate between those for Mount St. Helens and El Chichón (Table 4). Prior to the disasters, some knowledge existed about their respective histories of past eruptions and associated hazards. In addition, volcanic hazards zonation maps were available for both volcanoes prior to the disasters (Figure 2) [*Sudradjat and Tilling*, 1984] to guide authorities in the preparation of contingency or evacuation plans and in taking emergency measures. And because of the abundance of active volcanoes in Indonesia the people and the officials are very accustomed to eruptive activity. Thus people needed little prompting from officials to evacuate when Galunggung began to erupt in April 1982 with virtually no warning. Luckily, the initial eruptions were sufficiently weak to permit safe evacuation. As mentioned earlier, the reasons why evacuation measures failed at Nevado del Ruíz are unclear and still under study. However, from what information is available it seems reasonable to conclude that "the scientific team performed remarkably well and provided timely warnings. . . . But despite their efforts, time ran out before effective plans could be implemented by the emergency-response authorities" [*Tilling*, 1985, p. 230].

Despite its limited scientific and economic resources, Indonesia, which contains more active volcanoes than any other country, has an effective natural hazards program that deserves greater recognition. During the past decade, Indonesia has successfully evacuated more than 140,000 persons threatened by volcanic activity in the successful mitigation of volcanic hazards. In comparison, civil authorities in the United States only have had to cope with, at most, a few hundred evacuees in response to volcanic crises in the past century. A National Coordination Body of Natural Disasters (BAKORNAS in Indonesian) is responsible for the coordination of government and private efforts in hazards mitigation in Indonesia. The Volcanological Survey of Indonesia is the government-designated organization responsible for volcanic hazards studies and directly interacts with BAKORNAS in the event of a volcanic disaster or crisis.

In contrast to Indonesia the country of Colombia, before 1985, had no national program for volcanic hazards studies nor a single institution designated to be responsible for such studies. In response to the Ruíz disaster the Colombian government, with substantial support of the Office of Foreign Disaster Assistance (OFDA) of the U.S. Agency for International Development (USAID), established the Observatorio Volcanológico Nacional at Manizales, under the management of the Instituto Nacional de Investigaciones Geológico-Mineras (INGEOMINAS). This new observatory, one of the best equipped and staffed volcano observatories in Latin America, is monitoring the continuing intermittent but weak eruptive activity at Nevado del Ruíz and initiating preliminary studies of nearby potentially dangerous volcanoes as well.

PROBLEMS AND CHALLENGES

In recent decades, significant advances have been made in understanding volcanic phenomena; these advances reflect progress in geophysical instrumentation, measurement techniques, observational capabilities, data collection and analysis (computerization), modeling studies, and theoretical formulations. Certainly, our basic knowledge of eruptive processes and products is increasing rapidly compared with a century ago. Few would dispute that volcanology has arrived as a modern science; yet for me, nagging questions persist about successful application of the science to societal problems. Have the advances in volcanology been fully translated into advances in hazards mitigation? Are we winning a few battles but losing the war? What more can or should geoscientists do to reduce volcanic risk?

The Most Pressing Problem

The incidence of human fatalities from volcanic hazards (Table 5) provides one, and perhaps the only, reasonably well documented measure in trying to address the above questions. Still, it must be remembered that the figures given in Table 5 represent an incomplete sampling, largely reflecting a few infrequent but highly destructive events in only a few countries (see Table 1). For example, the three

TABLE 5. Human Fatalities From Volcanic Activity, 1600–1986

Primary Cause of Fatalities	*1600–1899*		*1900–1986*	
Pyroclastic flows and debris avalanches	18,200	(9.8%)	36,800	(48.4%)
Mudflows (lahars) and floods	8,300	(4.5%)	28,400	(37.4%)
Tephra falls and ballistic projectiles	8,000	(4.3%)	3,000	(4.0%)
Tsunami	43,600	(23.4%)	400	(0.5%)
Disease, starvation, etc.	92,100	(49.4%)	3,200	(4.2%)
Lava flows	900	(0.5%)	100	(0.1%)
Gases and acid rains	...	...	1,900*	(2.5%)
Other or unknown	15,100	(8.1%)	2,200	(2.5%)
Total	186,200	(100%)	76,000	(100%)
Fatalities per year (average)	620		880	

Modified from *Blong* [1984, Table 3.2]. Values in parentheses refer to percentages relative to total fatalities for each time period.

*Includes the deaths caused by lethal gas bursts at two volcanic crater lakes in Cameroon, Africa: 37, Lake Monoun, August 1984 [*Sigurdsson et al.*, 1987]; and >1700, Lake Nyos, August 1986 [*Kling et al.*, 1987]. While investigators agree that the lethal gas (carbon dioxide) in both these cases is of magmatic origin, they disagree on the causative mechanism of gas release.

destructive eruptions in 1902 (Mont Pelée, Soufrière (St. Vincent), and Santa María) and the 1985 eruption of Ruíz alone would account for about 75% of the total deaths from volcanic activity in the twentieth century.

At face value the tabulation shows that the average number of fatalities per year for the 1900–1986 period (880) is higher than that for the 1600–1899 period (620). Table 5, however, does suggest significant improvement in the twentieth century in reducing the incidence of deaths caused by eruption-induced starvation and tsunami. The reduction in fatalities caused by posteruption starvation is real and reflects the existence of modern, rapid communications and disaster relief delivery systems. The apparent reduction in volcano-related tsunami casualties, however, stems from the fortunate fact that no large eruption-triggered tsunami has occurred in this century, even though a highly effective international warning system now exists for tsunami generated by distant events. No improvement is observed in the twentieth century for the number of fatalities associated with pyroclastic flows and mudflows.

Given the advances in volcanology in the twentieth century, the above noted observations are somewhat unexpected. Whether or not the differences in fatality data (Table 5) are statistically significant, they still reflect some or all of the following factors:

1. Virtually all the fatalities are caused by volcanic and related hazards associated with infrequent major explosive eruptions, for which reliable short-term forecasts are still not possible for most volcanoes. This situation mainly stems from insufficient funds and trained personnel to conduct the needed volcano monitoring and hazards assessment studies. Some volcanologists are confident that given adequate monitoring networks and prompt interpretation of the acquired data, it should be possible to "predict virtually any explosive eruption" (D. A. Swanson, written communication, 1988). However, as discussed later, volcanologists first must develop refined techniques and criteria to distinguish unambiguously, if possible, the diagnostic precursory patterns for explosive and nonexplosive eruptions.

2. Gains in hazards mitigation from scientific and technological advances (almost exclusively confined to the developed nations) are offset by the world population explosion in the twentieth century (largely in the developing nations). In any given area an eruption now, with no or ineffective hazards mitigation measures, would kill many more people than the same eruption in 1600 because of the increased population density with time. The world's human population was about 0.5 billion in 1600, became 5 billion in 1987, and is expected to grow to about 6 billion people by the year 2000; greatest growth is projected to take place in the developing countries [*Gwatkin and Brandel*, 1982; *Haub*, 1988].

3. Volcanic hazards mitigation is inadequate in the densely populated developing regions. While the developing countries suffer the most loss of life, the developed countries incur the greatest economic loss from damage to property [*Wijkman and Timberlake*, 1984]. For example, more than 99% of the eruption-caused deaths since 1900 occurred in the developing countries or regions (Table 1).

4. Advances in volcano monitoring, eruption forecasting, and hazards assessment have not been fully factored into effective volcanic emergency planning and management. This failure in part derives from the fact the scientific information generally is still not specific enough about the time, place, and magnitude of an anticipated hazardous event eruption to compel officials to take action.

Even from the limited information available it is abundantly clear that on a global basis, future advances in volcanic hazards mitigation should be in the developing countries, especially those in the circum-Pacific "Ring of Fire" [*Latter*, 1987]. While these countries contain most of the world's high-risk volcanoes, they lack the scientific and monetary resources to undertake the needed fundamental geoscience and volcanic hazards studies.

Simply stated, the most pressing problem in reducing volcanic risk in a global context is that the world's most dangerous volcanoes are the least understood and studied. This problem confronts both developed and developing countries, but it is especially acute for the latter. For the developed countries, tackling the problem would involve shifts in national priorities and the greater allocation of resources to volcanic risk mitigation programs. For the affected developing countries the ideal solution to this problem is to achieve self-sufficiency in volcanology and related socioeconomic capability in hazards mitigation. Such a solution involves a long-term process requiring decades in any realistic scenario. In the interim, geoscientists must work closely with international organizations to create workable, stable international programs of mutual assistance and rapid response during volcanic crises. These programs must also include preparation and/or upgrading of hazards assessments, acquisition of baseline monitoring data, and training/education for scientists, emergency management officials, and the public. Such programs cost relatively little but must be stably funded for long-term continuity to be effective. For example, the annual budget of a program proposed following a series of UNESCO-sponsored workshops in 1983 [*Yokoyama et al.*, 1984] would be a small fraction of the daily helicopter expenses incurred during the disaster relief efforts at Ruíz in 1985, or (I. G. Gass, written communication, 1986) "about a third of what is paid for a good soccer player!" *Tilling and Newhall* [1987, p. 61] conclude that effective volcanic hazards mitigation "will not be achieved by technology alone, but also requires overcoming national and international bureaucratic inertia to create needed long-term programs."

To date, international or bilateral programs have been ad hoc, ephemeral, and utterly inadequate, consisting mainly of "too little too late" responses to volcanic disasters. However, since 1984, a few small steps have been taken to initiate predisaster studies at a few high-risk volcanoes, mostly in Latin America. With the support of the OFDA/USAID the USGS has provided technical assistance and consultation to the Volcanological Survey of Indonesia in the period 1979–1988. In addition, the USGS, again in cooperation with OFDA/USAID, has begun a modest program of rapid response to volcanic crises (or of baseline acquisition and training exercises if no crises occur) called the Interagency Volcano Early Warning Disaster Assistance Program (VDAP) [*Banks*, 1986]. A special feature of this program, which is focused on Latin America, is the capability to dispatch on short notice a Volcanic Crisis Assistance Team (VCAT) to a volcanic trouble spot, in response to a request from the host country government through diplomatic channels. The World Organization of Volcano Observatories (WOVO), with funding from UNESCO, has coordinated volcano-monitoring assistance at Apoyo Volcano (Nicaragua) and Tacaná (Mexico-Guatemala). Also, a program jointly funded by OFDA/USAID and UNDRO is now in progress to increase studies of high-risk volcanoes in Ecuador. While these isolated small projects are helpful and illustrate some aspects of the work needed, they do not begin to address the problem on the global scale.

An International Decade of Natural Hazard Reduction (IDNHR) has been proposed as a global program for the 1990s [*Housner*, 1987; *DPB*, 1988*b*]. The IDNHR is a component of the proposed international Decade for Natural Disaster Reduction, endorsed by a resolution of the United Nations passed in December 1987 and by a resolution of the U.S. House of Representatives (H. Con. Res. 290) introduced in May 1988 [*Oaks*, 1988; *Sigurdsson*, 1988]. In May 1988 the U.S. Subcommittee of the International Association of Volcanology and the Chemistry of the Earth's Interior (IAVCEI) for the IDNHR presented in its report [*Heiken et al.*, 1988] to the U.S. Geodynamics Committee the following recommendations, in addition to continued fundamental research on volcanic phenomena, pertinent to global volcanic hazards mitigation:

1. Monitoring networks should be established on volcanoes deemed to be of "highest-risk" on the basis of preliminary geoscience, demographic, and socioeconomic studies.

2. After the Global Positioning System (GPS) is fully tested and shown to be routinely precise and accurate, it can be used in place of conventional, more labor-intensive, geodetic monitoring. To assure wide application of GPS data for eruption prediction, its costs, including maintenance expenses, must be reduced to be affordable for use in developing nations.

3. Presently, experimental geophysical methods of eruption prediction, including gravity, geomagnetic, and geoelectrical techniques, must be improved and continue to be tested on volcanoes well monitored by other techniques.

4. The equipment presently used for volcano monitoring must be simplified, miniaturized, and made more rugged. Lightweight, sturdy, and easy to use geophysical instruments will simplify volcano monitoring in developing countries, in field situations remote from the luxury of experienced electronic technicians and spare parts.

5. "High-tech" volcano-monitoring methods can be too expensive for developing countries. An emphasis should be made on research leading to "low-tech" monitoring techniques, which, though possibly less precise

and sensitive, can be applied locally, easily, and inexpensively.

6. Data from monitoring equipment have limited use and may even give false impressions unless adequate means are available to interpret them on a scientific and timely basis. Properly interpreted volcano-monitoring data must be presented immediately to the local civil defense authorities in a way readily understood.

Challenges to the Geoscience Community

Much remains to be learned in understanding how volcanoes work, especially those that characteristically produce explosive eruptions and the most destructive volcanic hazards. Even for the well-studied volcanoes in the developed nations, reliable short-term predictions of explosive eruptions are still not routinely possible. A major scientific challenge confronting volcanologists is the need to develop a reliable method, using pattern recognition in conjunction with newer approaches, to identify the diagnostic precursors of explosive eruptions.

Another serious problem is the lack of reliable criteria for distinguishing between the precursory pattern of an eruption and that of an intrusion. Magma intrusions are often, but incorrectly, considered "false alarms," but they are better termed "aborted eruptions" [*Walker*, 1982]. *Decker* [1988] suggests that intrusions may "outnumber eruptions by at least 2 to 1." Currently, the best hope for recognizing the differences, if any, between the precursory indicators of an eruption versus those of an intrusion lies in the careful, continuous monitoring of a volcano through many eruptive, intrusive, and dormant cycles to learn its full range of characteristic patterns. However, this is a process of trial and error, in which the errors can be minimized but probably never eliminated.

The technology to develop a more reliable predictive capability already exists, but the societal resolve and commitment to achieve the objective are lacking. Nonetheless, we must continue to refine existing monitoring techniques, to devise new ones, and to better recognize the onset and the nature of the premonitory signals of renewed eruption at explosive volcanoes. In particular, we must improve the instrumentation and systems to recognize, and to transmit real-time warnings of, dangerous events and products (e.g., lahars) as they occur. An important adjunct to hazards mitigation research is the better characterization of unrest at dormant calderas and its bearing on the probability of renewed caldera-forming eruptions. More than half of the 200 Quaternary calderas considered by *Newhall and Dzurisin* [1988] in a literature survey apparently exhibited some form of unrest within the past 100 years; such unrest does not necessarily culminate in an eruption, nor does it provide much information about the type and size of the eruption that might occur.

If, as I contend, the most pressing problem in international volcanic hazards mitigation cannot be solved by technological advances alone, but rather by wider application of existing technology to poorly studied volcanoes in densely populated regions, then the major challenges to the geoscience community are as follows:

1. Apart from their "regular" research on volcanic phenomena and/or volcanic hazards studies, scientists in both developed and developing countries must play a much more active and visible part in increasing public awareness of volcanoes and their potential hazards. *Peterson* [1986, 1988] discusses the role and responsibilities of volcanologists in society and believes [*Peterson*, 1988, p. 4161] volcanologists have "an ethical obligation to convey effectively their knowledge to benefit all of society."

2. For potentially dangerous volcanoes in regions still not heavily populated or developed, geoscientists must redouble efforts to prepare the most detailed hazards assessments as available data permit. Then they must be willing to work closely with decision makers, to encourage and persuade them to consider the volcanic hazard zonation maps in the development of local or regional land use plans.

3. For volcanically active areas that already are densely populated and have land use patterns fixed by demand, culture, or tradition, the only available options in hazards mitigation are to develop improved monitoring and predictive capabilities to enable scientists to give timely warnings to officials. In addition, the scientists must interact closely with civil authorities to devise and test contingency plans before any volcanic crisis strikes.

4. Geoscientists must try harder to convince decision makers that the convening of more international workshops and symposia to further study the topic of volcanic hazards mitigation would yield diminishing returns. I submit that the scope of the problem is sufficiently well defined to take decisive action to immediately implement programs repeatedly proposed. Monies earmarked for more "talking about" the problem would be better spent to make a hazards zonation map or baseline measurements at a high-risk volcano in a developing country.

5. Higher priority must be placed on the preparation of general interest publications, movie films, videotapes, training manuals, and other audiovisual aids in a concerted program to educate the emergency response officials and the general public about the types and nature of volcanic and associated hazards and their destructive potential. As a small step in this direction, under the auspices of IAVCEI, efforts are currently under way to raise funds to produce two 25-min video source tapes illustrating dramatic examples of volcanic hazards and their adverse impact. These videotapes will be used by volcanologists to assist in educating the decision makers and the affected public about the nature of the hazards and what can be done about them.

6. Scientists in the developed countries must overcome their reluctance to become involved in efforts to promote

and develop the needed international programs, to help train scientists from developing countries, and to try to educate officials and the public. This reluctance in part stems from the perception that these efforts, which generally do not lead to publications in refereed journals, are little appreciated and rarely rewarded within the scientific community. Another large obstacle is that too many scientists believe that their own work is too important to be interrupted for such nonresearch activities, even though for some, their research is funded by hazards reduction programs. Worse still, some scientists are the volcanological equivalents of "ambulance chasers." They are eager to experience the scientific excitement in observing an eruption or studying its impact and fresh eruptive products but unwilling to assume any responsibility in assisting the officials and public affected or to share their information with other scientists who are doing the real work in hazards mitigation.

7. Last but not least, to gain full cooperation from decision makers and the populace, and to maintain credibility in the eyes of the public, geoscientists must better handle the problem of "false alarms" or "crying wolf." As already noted, the occurrence of precursory activity often does not culminate in eruptions, thus compounding this vexing problem, which is not likely to be solved within the foreseeable future. Until distinction between precursory eruptive and intrusive behavior can be made routinely and unambiguously, *Banks et al.* [1989] make the following recommendation:

> It seems prudent to treat every occurrence of unmistakable precursory activity as having the potential for eruption and to advise emergency-response officials accordingly. With this prudent approach, "false alarms" (actually aborted eruptions) will be unavoidable. A current, and much needed, partial solution to the false-alarm problem is to educate the government officials and general public about the probabilistic nature of forecasts and predictions and of the limitations inherent in the scientific information upon which they are based. However, an equally serious challenge . . . is to minimize false alarms through more reliable pattern recognition. . . . If society wishes to maximize effective response to warnings of volcanic hazards, it must be prepared to accept the unavoidable false alarms. False alarms themselves can provide, through objective assessment of the scientific and public response to a volcanic crisis that ended without eruption, valuable lessons useful in making or improving contingency plans for the next crisis, which could culminate in an eruption.

In summary, the geoscience community itself must become more aware of the urgent need to develop stable long-term international programs needed to address the global problem of volcanic hazards mitigation on a systematic rather than an ad hoc basis. While refinements in methodology and new technologies will be needed to improve hazards assessments and eruption forecasts, significant gains are more likely to be obtained in the near term by wider application of existing technology to high-risk but poorly understood volcanoes in densely populated regions. The effective mitigation of volcanic and associated hazards on a global scale really boils down to a simple "have–have not" issue. The developing countries have most of the world's high-risk volcanoes but do not have the economic and scientific means to adquately study and monitor them. Clearly, in the short term the developed countries need to boost their technical assistance through bilateral or international programs until the developing countries attain self-sufficiency in volcanology. The primary challenge to both the scientific community and the "decision-making" bodies is to prevent volcanic crises from turning into volcanic disasters.

ACKNOWLEDGMENTS. My views on volcanic hazards mitigation on a global basis have been shaped by my experience in directly studying, or in helping to coordinate international scientific responses to, eruptions in Hawaii, at Mount St. Helens, El Chichón, Galunggung, Nevado del Ruíz, and elsewhere. Over the years I have learned much from colleagues within and outside the U.S. Geological Survey who have been at the forefront of volcanic hazards mitigation. I have been influenced by stimulating interactions and discussions with them during emergency as well as calm circumstances, and not all of them, I am certain, would fully share the opinions expressed in this paper. My deep thanks go to Wendell A. Duffield and William E. Scott, who thoroughly reviewed earlier drafts of the paper and offered detailed constructive criticisms and suggestions that materially improved it. I also appreciate receiving helpful general comments and reactions to earlier versions of this manuscript from the following colleagues: Roy A. Bailey, Thomas J. Casadevall, Dwight R. Crandell, Robert W. Decker, Richard S. Fiske, L. J. Patrick Muffler, Donal R. Mullineaux, Christopher G. Newhall, Donald W. Peterson, and Donald A. Swanson. In addition, I thank journal editor David W. Scholl for his helpful editorial suggestions and efficient handling of the manuscript. However, any errors of commission or omission, or of misplaced emphasis, rest solely with me.

Finally, I wish to dedicate this paper to Donald B. McIntyre, an inspiring teacher who introduced me to the wonders of geology when I was a student at Pomona College, California, many, many years ago.

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