FORECASTING VOLCANIC Eruptions

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In the fourth gulf of the eighth circle of hell are those who presumed to foretell the future, their heads fixed face-backward on their necks.

Dante, Divine Comedy (early 14th century)

INTRODUCTION

Forecasting natural events such as landslides, earthquakes, and volcanic eruptions is a difficult problem compounded by conflicting expectations. Society wants accurate warnings of these events, yet the scientific community is not able to provide forecasts as accurate as desired because these natural events are only partly understood. The present situation is an uneasy compromise, with Earth scientists recognizing that public support requires that major efforts be made to forecast potential natural disasters, and the public becoming increasingly aware that probabilistic forecasts—though fraught with uncertainty—are useful in decision making.

Effective forecasting of natural events that could have a major impact on society involves cooperation among three groups who are not always accustomed to working closely with one another: scientists, who are responsible for making the forecasts and for estimating their degree of uncertainty; public officials, who are responsible for the safety and welfare of their constituents; and the news media, who are responsible for accurate communication of information to the public. There is no way to win in a natural disaster; one can only hope to reduce the losses. Close cooperation among these three groups, with each understanding the different problems faced by the others, can lead to significant reductions in public risk. On the other hand, lack of trust, understanding, or cooperation can easily

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exacerbate a disaster or potential disaster, or even lead to a false alarm. Some false alarms are bound to occur; that is inherent in probabilistic forecasting. However, with better public understanding of the uncertainties involved, the reduction in losses resulting from correct forecasts can far outweigh the problems of false alarms. Present trends indicate that the accuracy of forecasting is improving, and there is reasonable hope that unless scientists promise—or the public expects—too much too soon, scientific forecasting of natural events such as volcanic eruptions will become a valuable and respected endeavor.

Volcanic eruptions worldwide have killed on average about 640 people per year in the twentieth century through 1982 (Blong 1984) and have caused an estimated total of about $10,000,000,000 (present value) in property damage. Catastrophic eruptions occur at widely scattered intervals. For example, the eruption of Mont Pelée in the West Indies annihilated the 29,000 inhabitants of the port of Saint Pierre in 1902, but other years have been devoid of destructive eruptions. Figure 1 shows the episodic nature of fatalities caused by volcanic eruptions.

![Figure 1](image_url)  
*Figure 1* Cumulative plot of deaths caused by volcanic eruptions. More than half the deaths occurred during a single eruption that destroyed the city of St. Pierre. [From Latter (1969), with permission.]
An ideal forecast of volcanic activity would include the location, timing, character, and magnitude of the potential eruption, and a quantitative estimate of the probability of each of these factors. We are far from this goal; nevertheless, the present state of the art is encouraging. As to location, it can be said in general that future eruptions will occur at or near the sites of known volcanoes. The birth of a new volcanic province is a rare event, even in geological time. More specifically, following the subsurface locations of a migrating earthquake swarm beneath a volcano provides a good estimate of where an eruption may occur. Seismologists at the Hawaiian Volcano Observatory have guided the field geologists by radio to within a few hundred meters of the outbreak locations of all the eruptions of Kilauea Volcano since 1979.

Forecasting the approximate timing of a volcanic outbreak has proved successful in several cases over the past decade. Some of these instances are discussed in later sections. Forecasting the timing of the climax and the duration of an eruption has proved more elusive, and from a hazards point of view this information may be much more important than the onset time.

Forecasts regarding the probable character and magnitude of an eruption can be made in a general way based on the tectonic setting of the volcano and on its previous recorded and recent geologic history. Statistically, small-magnitude eruptions occur far more frequently than large ones, but there is no monitoring technique presently available that can anticipate the specific character and magnitude of a forthcoming eruption.

At present most of the probability statements in forecasts are couched in only semiquantitative terms such as high, low, or significant. These words mean different things to different readers. The goal of numerically quantitative probability statements is still many years away.

The hazards from volcanoes are closely related to the character of their eruptions. Effusive eruptions of molten lava, as in most Hawaiian eruptions, pose little danger to people but can be very destructive to property. In this century, only one person has been killed by a volcanic eruption in Hawaii; however, during this same period, 5% of the island of Hawaii has been covered by new lava flows. During explosive eruptions, debris avalanches, lateral blasts, ash flows, and mudflows travel at speeds that cannot be outrun, and thus all of these pose major dangers to both life and property. In the Mont Pelee eruption, hot pyroclastic flows (nuées ardentes) traveling at high speeds killed nearly the entire population of Saint Pierre. (Out of a population of about 29,000 people, there were only two known survivors.)

Forecasting volcanic eruptions has a distinct advantage at this time over forecasting major earthquakes. Magma moves upward from depth to the surface before an eruption begins, and this movement (which may take
hours to years) can be detected by present techniques. However, rising magma may stop before reaching the surface, and may instead form a shallow intrusion rather than an eruption.

The use of the word forecasting in this review, rather than prediction, estimation, or anticipation, is deliberate. Weather forecasting is an established science based on probabilities; the forecasts are not certain, but the public understands that even with this limitation, they are much more useful than no forecasts at all. It is this connotation of utility but uncertainty that has become established for the word forecasting that makes it my choice.

Several comprehensive reviews of forecasting volcanic behavior have been published in English in the past 15 years (Gorshkov 1971, Minakami 1971, Civetta et al 1974, Walker 1974, Decker 1978, Fournier d'Albe et al 1979, Martin & Davis 1982, Tazieff & Sabroux 1983, Souther et al 1984). Some of these previous reviews are much more detailed than this one, and they should be consulted by any serious student of the subject.

An anecdote about forecasting volcanic activity says that every active or potentially active volcano should be studied by a geologist to find out what did happen, by a geophysicist to determine what is happening, and by a lobbyist to tell the government what might happen. This review is organized along those lines: an approach based on the historic and prehistoric eruptive record; a monitoring approach based on current geological, geophysical, and geochemical data; and the societal considerations of assessing volcanic hazards and reducing volcanic risk.

**APPROACH BASED ON ERUPTIVE RECORD**

Worldwide, more than 1300 volcanoes have erupted during the past 10,000 yr (Simkin et al 1981). However, the recent geologic histories of fewer than 10% of these potentially destructive volcanoes have been studied in detail. This is unfortunate, for the track record of a potentially active volcano provides the best method of assessing its future volcanic hazards on a long-term basis. These hazards assessments are made by studying the historic records and the geologically recent deposits on and around a volcano to establish the frequency and character of past eruptions. This record is then extrapolated to provide a general forecast of future activity.

A major problem in assessing the hazards from future eruptions is that many of the most destructive eruptions in the past occurred at volcanoes that had been dormant for hundreds to thousands of years (Figure 2). This creates the paradox that often the most potentially dangerous volcanoes have relatively poor records of past eruptive activity.

Another major problem is that even volcanoes with well-documented
records of many historical eruptions show both a wide variation in the repose times between eruptions and large variations in the character of these eruptions. For example, Asama Volcano in Japan has erupted thousands of times since its first recorded eruption in A.D. 685 (Kuno 1962). Since 1900, the shortest repose times were less than one day, and the maximum repose time was five years. Most eruptions were moderate explosions of ash, but the disastrous eruption of 1783 involved large ash explosions, pumice falls, pyroclastic flows, and mudflows.

Despite these shortcomings, some long-term hazards assessments based on historical records and geologic mapping have shown remarkable success. For example, Crandell & Mullineaux's (1978) hazards assessment for Mount St. Helens Volcano in the northwestern United States was prophetic. They concluded that Mount St. Helens had been more active and more explosive during the preceding 4500 yr than any other volcano in the contiguous 48 states. In that period the volcano produced viscous lava domes, pumice falls, pyroclastic flows of hot, fluidized rock fragments, lava flows, and mudflows. The average interval between eruptive periods was 225 yr. On the basis of their study of the past behavior of Mount St. Helens

Figure 2  Degree of explosiveness and time intervals between eruptions. For each volcanic explosivity index (VEI) number, eruptions are grouped by increasing time intervals between eruptions. The number of eruptions considered in groups 0 to 6 are, respectively, 354, 338, 2882, 617, 102, 19, and 8. Examples of VEI numbers are Krakatau, 1883 = 6; Mount St. Helens, 18 May 1980 = 5; typical Hawaiian eruption = 0 to 1. [From Simkin et al. (1981), with permission.]
In the future Mount St. Helens probably will erupt violently and intermittently just as it has in the recent geologic past, and these future eruptions will affect human life and health, property, agriculture and general economic welfare over a broad area. The volcano's behavior pattern suggests that the current quiet interval will not last as long as 1,000 years; instead an eruption is more likely to occur within the next 100 years, and perhaps even before the end of this century.

Rarely does a long-term forecast get so quickly evaluated. A swarm of earthquakes beneath Mount St. Helens began on 20 March 1980, followed by small ash eruptions beginning March 27. The climactic eruption occurred on 18 May 1980. It was apparently triggered by a magnitude 5 earthquake that caused the failure of the north slope of the mountain into a 2.7-km³ debris avalanche. The north flank of Mount St. Helens had become oversteepened by the intrusion of a large, shallow mass of magma during late March, April, and May that produced a 1.8-km-diameter bulge about 150 m high on the north face of the mountain. Failure of the oversteepened north slope released the pressure on the shallow intrusion and its surrounding hydrothermal system, causing northward-directed blasts of steam and rock fragments that devastated an area of 600 km² (Figure 3). This was followed by a 9-hr vertical ash cloud eruption that reached heights in excess of 20 km, causing ash fallout of a few centimeters over much of central and eastern Washington State. Destructive floods and mudflows descended the streams draining westward from Mount St. Helens. These entered the Columbia River and caused severe shoaling of the shipping channel. A few smaller explosive eruptions occurred in 1980, and a lava dome has been growing since late 1980 in the 2-km-wide horseshoe-shaped crater formed by the May 18 avalanche and eruption (Lipman & Mullineaux 1981, Decker & Decker 1981).

Almost every part of Crandell & Mullineaux's (1978) long-term forecast occurred. The eruption did occur in this century, 57 people were killed, and property damage amounted to about $1,000,000,000. However, the magnitude of the avalanche and the lateral blast greatly exceeded their expectations.

At volcanoes with many recorded eruptions, statistical analysis of the time series of eruptions may reveal characteristic patterns that could aid in forecasting the timing of, and in planning for, future eruptions. Wickman (1966) has used this approach to show that some volcanoes show a random pattern in the timing of their historical eruptions, whereas others show patterns of increasing or decreasing probability of eruption as the repose period between eruptions increases. Mauna Loa Volcano in Hawaii has a random pattern, with an average repose time of nearly 4 yr, whereas Hekla Volcano in Iceland has an average repose time of 58 yr and a pattern of
Table 1  Eruptions and dormant intervals at Mount St. Helens since 2500 B.C. (Crandell et al 1975)*

<table>
<thead>
<tr>
<th>A.D. 1900</th>
<th>Dormant interval of 120 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>Tephra eruption, mudflows</td>
</tr>
<tr>
<td>1700</td>
<td>Apparent dormant interval of ca. 150 years</td>
</tr>
<tr>
<td>1600</td>
<td>Pyroclastic flows</td>
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<td></td>
<td>Dome eruption, mudflows</td>
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<tr>
<td>1500</td>
<td>Tephra eruptions, pyroclastic flows</td>
</tr>
<tr>
<td>1400</td>
<td>Pyroclastic flows</td>
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</tbody>
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**SCALE CHANGE**

| 1300      | Apparent dormant interval of 400-500 years |
| 1200      | Tephra eruption                     |
| 1100      | Apparent dormant interval of 400-500 years |
| 1000      | Tephra eruption                     |
| 900       | Apparent dormant interval of 400-500 years |
| 800       | Tephra eruptions, mudflows          |
| 700       |                                      |
| 600       |                                      |
| 500       |                                      |
| 400       |                                      |
| 300       |                                      |
| 200       | Tephra eruptions                    |
| A.D. 100  | Lava flows                          |
| 0         |                                      |
| B.C. 100  | Pyroclastic flows, mudflows         |
| 200       | Pyroclastic flows                   |
| 300       | Pyroclastic flows, tephra eruptions, mudflows |
| 400       | Tephra eruptions, mudflows          |

**SCALE CHANGE**

| 500       | Apparent dormant interval of 400-500 years |
| 1000      | Repeated eruption of large pyroclastic flows, domes, and tephra; mudflows |
| 1500      | Apparent dormant interval of ca. 400 years |
| 2000      | Intermittent tephra eruptions of large volume, pyroclastic flows, eruptions of domes; mudflows |
| B.C. 2500  | Apparent dormant interval of 4000 years |

*The circles represent specific eruptions that were observed or that have been dated or closely bracketed by radiocarbon age determinations; the vertical boxes represent dormant intervals.
increasing probability of eruption as the repose time increases. Rose & Stoiber (1969), using Wickman's technique, show that the probability of an eruption of Izalco Volcano in El Salvador is 3% a month for several months following an eruption, but that after a repose period of 2 to 3 yr, the probability of an eruption decreases to 2% per month. This result indicates that eruptions of Izalco tend to cluster into groups, with longer periods of repose between the groups of eruptions.

Klein (1982) has recently analyzed the eruption patterns of Kilauea and Mauna Loa volcanoes in Hawaii. He finds that most Hawaiian eruptions are largely random in their timing, with an average repose time at Kilauea of 501 days compared with Mauna Loa's 1412 days. However, large-volume eruptions of both volcanoes tend to be followed by longer repose periods, summit (or flank) eruptions of Kilauea tend to cluster, and the

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Figure 3  Schematic diagram of the initial stages of the 18 May 1980 eruption of Mount St. Helens. (1) Earthquake triggers avalanche on bulging north face of volcano. (2) Start of debris avalanche. (3) Steam and gas explosions occur as shallow magma body and hydrothermal system are decompressed. (4) Magnitude of explosion increases as hot debris and blast enter Spirit Lake. (5) Blast spreads across topographic ridges; debris avalanche flows down river valley; Plinian explosion of magma begins from the central conduit. [From Ui & Aramaki (1983), with permission.]
longest periods of repose at each volcano appear to be associated with increased eruptive activity at the other volcano.

Although forecasting based on the historical and prehistoric activity of a volcano is effective and inexpensive, Scott (1984) points out several caveats to the method. He notes that the older record becomes more obliterated by subsequent events; this is particularly true in heavily glaciated areas prior to 10,000 yr ago. The wide range of repose intervals makes the average repose interval a very uncertain estimate of the timing of future eruptions. Eruption habits may change and past behavior may then be misleading. Events may occur that are unprecedented at a specific volcano, and changes in the size and shape of a volcano with time may change the locations of hazardous areas.

Before leaving this subject, several classic studies of the recent geologic history of specific volcanoes and volcanic areas should be mentioned: Asama Volcano, Japan (Aramaki 1957), São Miguel Island, Azores (Booth et al 1978), Cascade volcanoes, USA (Crandell & Mullineaux 1975), Oshima Volcano, Japan (Nakamura 1964), Mount Etna, Italy (Romano 1982), and Hekla Volcano, Iceland (Thorarinsson 1967). Different volcanoes and areas present different problems, and these papers show an interesting spectrum of approaches to solving some of these problems.

**MONITORING APPROACH**

Monitoring an active or potentially active volcano involves ongoing geological, geophysical, and geochemical observations, particularly of changes in data. Newhall (1984b) has recently summarized current volcano monitoring techniques. Important monitoring observations during periods of dormancy may include visual estimations of the quantity, color, height, and drift direction of volcanic fume; temperature of fumaroles; volume and chemistry of fumarolic gases; gases in soils, such as hydrogen, helium, mercury vapor, and radon; seismicity—both earthquake locations and volcanic tremor; geodesy—particularly the elevation and diameter of calderas, craters, and rift zones; electromagnetic data such as self-potential (ground voltages), magnetic and magnetotelluric fields, and conductivity to both direct and alternating currents; and thermal radiation. The rationale of these observations is to establish the “normal” levels of the volcano under study (so-called baseline data), to determine its subsurface structure, and to discover changes that may give some evidence of its dynamics. Any other changing phenomena on the volcano not included in the list above may also merit observation and recording. For example, an area of dying vegetation may be the first evidence of newly heated ground.

Observations during eruptions are even more important. The physical
and chemical character, volume, and volume rate of eruption products, as well as their distribution and effects, need to be carefully observed and recorded on a chronological basis. Geophysical and geochemical data may be changing rapidly during eruptions and should be measured continuously or at least at short intervals. The location of seismic swarms can often be a guide to deciding where to focus other observations.

Long-term monitoring of volcanoes has two primary objectives: (a) an understanding of how volcanoes work, and (b) the establishment of patterns, whether empirical or understood, that will aid in forecasting eruptions (Klein 1984). It takes time to establish the necessary observations—perhaps 30 yr on a volcano like Kilauea in Hawaii that erupts frequently; perhaps 300 yr on Mount St. Helens, which has a much longer repose time between periods of eruption.

This need to study many eruptions illustrates the paradox as to why more is known about “safe” volcanoes like Kilauea, which erupts frequently compared with more dangerous volcanoes like Mount Rainier or Mount Fuji. Nevertheless, the monitoring techniques developed in Italy, Japan, Hawaii, and the Soviet Union, and the experience gained by visits to eruptions in Indonesia, Central America, and the Philippines, were extremely valuable to the scientists studying and forecasting the course of the recent eruptions at Mount St. Helens.

How can long-dormant volcanoes be adequately monitored? One solution is to obtain baseline data on these volcanoes and repeat the observations a year or two later. If no changes have occurred, seismometers can be installed to keep tabs remotely on the potentially dangerous volcano. Any substantial change in seismicity, either in number or pattern, would then be a signal to redo other observations.

In this way a single volcano observatory can monitor 10 to 20 volcanoes in a region. Financial support for volcano observatories tends to go up sharply after a major eruption and then to diminish over the next several years as other societal problems appear more urgent. Any long-term volcano monitoring program must therefore be cost-effective.

Progress in volcano monitoring has been spurred in the past few years by the eruptions of Mauna Loa and Mount St. Helens volcanoes, and by the subsurface “unrest” at the calderas of Rabaul, Pozzuoli, and Long Valley. Even though the current rates of seismicity and surface deformation have diminished at these three calderas and there have been no eruptions to date (October 1985), the monitoring observations on these potentially dangerous volcanoes have greatly improved knowledge of their subsurface structure and dynamics. The following sections provide more specific information on each of these monitoring investigations.
Mauna Loa Volcano, Hawaii

Seismicity beneath the summit region of Mauna Loa increased in 1974 and remained at high levels for several months preceding a summit eruption in 1975 (Koyanagi et al. 1975). Following this brief eruption, Lockwood et al. (1976) forecast on the basis of previous eruption patterns that a northeast rift eruption would occur within a few years. Mauna Loa seismicity remained low, however, and did not increase again until 1980–1981.

During the period from 1976 to 1981, increases of 10–20 cm in the caldera diameter and uplift of 15 cm of the summit area indicated slow reinflation of a shallow magma reservoir at a depth of 3 to 4 km beneath the summit. The volume of inflation during this period was about $20 \times 10^6$ m$^3$. Seismicity increased rapidly in 1983 (Figure 4), and a forecast was published stating that “the probability significantly increases for an eruption of Mauna Loa during the next 2 years” (Decker et al. 1983). An eruption from the summit and northeast rift zone began 25 March 1984 and lasted for 3 weeks (Lockwood et al. 1985). During that period, basaltic lava flows with a total

![Figure 4 Earthquakes of magnitude greater than 1.5 beneath the summit area of Mauna Loa Volcano preceding the 1975 and 1984 eruptions. [From Lockwood et al (1985), with permission.]](image-url)
volume of $220 \times 10^6 \text{ m}^3$ covered an area of 48 km$^2$. Since the eruption volume greatly exceeded the new magma storage volume between 1975 and 1984, it is apparent that most of the erupted magma in 1984 had accumulated beneath Mauna Loa prior to 1975. Flows extended from their rift vent for 25 km toward the city of Hilo but stopped about 5 to 10 km away. Contingency plans were made to evacuate parts of the city, but they did not have to be put into operation.

During the eruption, the summit of Mauna Loa subsided 63 cm and the caldera decreased in diameter by about 30 cm. The pattern of deformation and the composition of the volcanic gases indicate that the magma supplying the eruption had been withdrawn from storage at a depth of 3 to 4 km, the same location where magma had been slowly injected prior to the eruption. The monitoring established that Mauna Loa has a shallow magma reservoir system, an important new concept about Hawaiian volcanoes. It is now evident that the interior magma storage system in Hawaiian volcanoes grows upward in pace with the external height of the lava pile. The caldera, rift zones, and shallow magma reservoirs begin early, on and beneath the seafloor, and all evolve upward with the growing volcano.

**Mount St. Helens Volcano, Washington**

The first small phreatic eruption at Mount St. Helens occurred on 27 March 1980 and was followed by hundreds of small steam and ash eruptions until the major eruption of 18 May 1980 (Lipman & Mullineaux 1981). The March 27 eruption was preceded by 7 days of intense local seismic activity that clearly signaled the high probability of the first eruption. Although the disastrous climatic eruption of 18 May 1980 occurred without any distinct short-term warnings, the longer-term precursory events were numerous and dramatic. The seismic swarm had continued with high and nearly constant energy release for 60 days. Bursts of volcanic tremor, generally interpreted as indicating magma movement at depth, began on March 31, continued intermittently through April 5, and recurred on April 12 and May 8. Major visible deformation of the north summit area was first seen on March 27 and was monitored with surveying instruments after April 23. The large rates of deformation—about $2 \text{ m day}^{-1}$ in an area with dimensions of $1.5 \text{ km} \times 2 \text{ km}$ on the high north flank of the mountain—were of major concern. The close connection in time and space between the earthquake foci and the bulging area led most of the scientists studying the eruption to conclude that a shallow intrusion of magma was taking place beneath an area just north of the summit. Barry Voight (of Pennsylvania State University) suggested in an
internal report on May 1 that both a major avalanche and an explosive eruption were possible.

Seven days of volcanic tremor preceded the moderate explosive eruption on May 25. Nine hours of tremor preceded a similar eruption on June 12, and by this time short-term forecasts of possible impending activity were being issued to people working near the volcano. By August 1980, public forecasts were being issued by the US Geological Survey and the University of Washington.

Swanson et al (1983) document that 13 eruptions (5 explosive, and all except 1 involving growth of the lava dome in the 18 May 1980 crater) from June 1980 through December 1982 were predicted tens of minutes to a few hours in advance. The last 7 of these eruptions were predicted between 3 days and 3 weeks in advance. This remarkable record was achieved by monitoring precursory seismicity, deformation of the crater floor and lava dome, and gas emissions.

Figure 5 shows an example of the deformation monitoring, which provided the earliest warning of many eruptions. An active thrust fault on the floor of the crater near the active lava dome was being driven by the growing dome. Daily measurements show the accelerating shortening across the thrust fault prior to the outbreak of new lava on the dome. Deformation of the crater floor by 26 August 1981 indicated that a new pulse of magma was beginning to inflate the dome. A prediction was issued that a dome-building eruption was likely during the two-week period 2–16 September 1981. Increasing seismicity supported the deformation data.

Figure 5  Shortening of the taped distance across an active thrust fault on the floor of the Mount St. Helens crater prior to the September 1981 dome-building eruption. The arrow indicates the date a prediction was issued, the black box is the time period in which the eruption was expected, and the dashed line is the date of the actual eruption. [From Swanson et al (1983), with permission.]
(Figure 6; Malone et al 1983), and on September 6 at 8 a.m. the prediction was updated to state that “a dome-building eruption accompanied by increased fume but little or no ash emission will probably begin within the next 12 to 48 hours.” Such an eruption began in midafternoon or early evening on that same day.


**Rabaul Caldera, Papua New Guinea**

Significant increases in seismicity and inflation began at Rabaul in September 1983 (McKee et al 1985a). This followed 12 yr of relatively slow inflation and gradually increasing seismicity. From September 1983 to October 1984, 92,000 shallow earthquakes were recorded beneath the caldera. Figure 7 shows well-located earthquakes representative of this swarm (McKee et al 1985b). The largest earthquake had a magnitude of 5.1, and many were felt by the 69,000 residents who live near the great harbor formed by the caldera.

Deformation measurements show that the caldera was widening and inflating, with two centers of uplift within the ellipse of earthquake epicenters (Figure 8). Maximum cumulative uplift from September 1983 to October 1984 was 63 cm, and the volume change was about $40 \times 10^6$ m$^3$. The pattern of deformation indicates that the northern center of inferred magma intrusion was 1–2 km deep, whereas the southern center was about 3 km deep.

During an eruption at Rabaul in 1937, 506 people were killed and 7500 were evacuated (Lowenstein 1982). The recent crisis represented a period of greatly increased probability of a new eruption at Rabaul, and detailed contingency plans were made to evacuate the area if necessary. By August 1985, however, the rates of seismicity and inflation had diminished. Unless these rates begin to increase rapidly again, the likelihood of an eruption has also diminished, but has not disappeared.

**Pozzuoli, Italy**

Pozzuoli is a city of 70,000 people located in the Campi Flegrei (fiery fields) west of Naples. The area lies within a complex 12-km-diameter caldera formed 35,000 yr ago by the eruption of about 80 km$^3$ of pumice and ash (Barberi et al 1984). The latest eruption in the Campi Flegrei occurred in 1538 and formed a large cinder cone called Monte Nuovo. Hot springs and
Figure 6  The square root of seismic energy release at Mount St. Helens per half day from November 1980 to November 1982. Surface events are plotted separately from earthquakes. The cumulative square root of seismic energy released during a 2-week period (a 4-week period in the March 1982 and August 1982 eruptions) around each of the eruptions is shown in boxes. Light lines indicate the energy of surface events, and heavy lines represent the energy of shallow earthquakes. Vertical dashed lines indicate the beginning of eruptions. [From Malone et al (1983), with permission.]
fumaroles occur throughout the area. The caldera has undergone some remarkable uplifts and subsidences through the centuries. Marble columns of a Roman market built at Pozzuoli in the second century B.C. are still standing, and mollusk borings into the columns record both submergences and reemergences since Roman times (Figure 9). Slow subsidence totaling 10 to 12 m predominated from the time the columns were built until the tenth to eleventh centuries A.D., a rate of about 1 cm yr \(^{-1}\) (Parascandola 1947, Yokoyama 1971, Caputo 1979, Bianchi et al 1985). This was followed by slow uplift until the sixteenth century. In 1538 rapid uplift of 6 to 10 m was followed by the eruption of Monte Nuovo. Following the eruption, the area sank again to about 2 m below sea level. Beginning in 1969, the area was rapidly uplifted until 1972, gaining about 150 cm in elevation. This inflation was accompanied by moderate microearthquake activity. From

Figure 7 Epicenters of well-located earthquakes beneath Rabaul Caldera from September 1983 to November 1984. About 95% of the hypocenters occurred at depths of 3 km or less. The horizontal and vertical grids are in kilometers. [From McKee et al (1985b), with permission.]
Figure 8  Inflation of Rabaul Caldera as shown by tilt vectors (in microradians) for the period September 1983 to November 1984. The black circles are the centers of inferred maximum uplift. Small, sun-shaped symbols show volcanic centers and peaks. [From McKee et al (1985b), with permission.]

1972 until 1982 the area remained relatively stable, but in 1982 to 1984 another pulse of rapid uplift raised the port of Pozzuoli an additional 160 cm, making most of the shipping docks unusable. The volume of the 1969 to 1985 uplift was about $150 \times 10^6$ m$^3$, with an inferred magma intrusion depth of about 3 to 5 km.

The 1982 to 1984 uplift was accompanied by more severe swarms of shallow earthquakes (up to magnitude 4+). These small-to-moderate (but nearly continuous) earthquakes slowly shook many of Pozzuoli's weaker buildings into ruins, and thousands of the inhabitants from the city center left the area.

The recent uplift (Figure 10) and earthquake swarm ceased during the fall of 1984. Whether this is the end of the crisis or just another pause in the subsurface activity similar to the quiet period between 1972 and 1982 is not known.
Long Valley, California

Long Valley is an elliptical caldera 17 by 32 km wide formed by an enormous eruption of 600 km³ of silicic magma about 700,000 yr ago (Bailey et al 1976). The area is located on the eastern fault scarp of the Sierra Nevada range, a region of ongoing tectonic activity. The most recent volcanic activity in the caldera is a line of rhyolite domes that erupted about 500 to 600 yr ago (Miller et al 1982).

Seismic activity beneath the caldera began to increase in 1979 but was not considered unusual until a swarm of four earthquakes of magnitude 6 to 6+ occurred during 25–27 May 1980 (Ryall & Ryall 1981, 1983). These were followed by intermittent swarms of thousands of smaller earthquakes (Figure 11), particularly during 1980, 1982, and early 1983. Increases in temperature and volume of hot springs in the area were also reported (Miller et al 1982).
Uplift of the interior of the caldera occurred over a 30-km-wide area, with a maximum measured increase in elevation of 40 cm. This inflation and changes in horizontal distance across the caldera have been modeled to estimate an intrusion of $100-200 \times 10^6$ m$^3$ of magma at a depth of 5 to 10 km beneath the surface (Savage & Clark 1982, Hill et al 1984, Rundle & Whitcomb 1984; Figure 12).

Since 1983, seismic activity in Long Valley has decreased. Nevertheless, the area has remained one of the most seismically active localities in California into 1985.

Although most geologists studying the unrest at Rabaul, Pozzuoli, and Long Valley conclude that magma has recently been intruded at shallow depths beneath these calderas and that the probability of surface eruptions was, and to a lesser extent still is, greater than during periods of quiet, they do not have any quantitative estimates of the probability of a new eruption occurring at these locations. Newhall et al (1984) conclude on the basis of a major search of the world literature that both eruptions and periods of unrest without eruptions at large silicic volcanic calderas during the past 100 yr are not uncommon. They found that during an average year, 3 to 4 silicic calderas worldwide exhibit some form of unrest (i.e. some noticeable
Figure 11  Epicenters (black dots) of 13,000 earthquakes located by the US Geological Survey beneath Long Valley Caldera (the large oval) and the Eastern Sierra Escarpment (south of Long Valley) during the period June 1982 through July 1984. Most of the hypocenters occur at depths of less than 10 km (Cockerham & Pitt 1984, Hill 1984).

change in seismicity, ground deformation, or fumarolic activity), and that 45% of these periods of unrest (70 cases out of 149) eventually led to eruptions. They caution, however, that precursory activity is better recorded for volcanoes that have erupted than for those that have not. The actual figure for unrest at silicic calderas that leads to eruptions is therefore probably much less than 45%.

BASIC RESEARCH

Forecasting based on empirical data may work on a limited basis, but in the long run it will not approach the potential accuracy that may be achieved by understanding how volcanoes work. Basic research into the origin,
evolution, structure, and dynamics of volcanic systems should provide this understanding.

Volcanoes provide a natural laboratory whose roots reach deep into the Earth's interior and whose ashes are often hurled into the stratosphere. Understanding volcanoes requires an eclectic approach by scientists from many disciplines: geologists mapping both active volcanoes and the insides of extinct volcanoes exposed by erosion, geophysicists monitoring active volcanoes and probing the structure and dynamics of the Earth's interior, geochemists analyzing volcanic gases and studying the composition and evolution of magmas and the mantle, and meteorologists studying the effects of volcanic gases and aerosols on the atmosphere. Some volcano observatories should have basic research as their primary function. Many
of the monitoring measurements made on active volcanoes can be used not only for pattern recognition but also for testing of theoretical models of subsurface structure and dynamics.

In my opinion, there are ultimate limits to the accuracy of forecasting volcanic eruptions. I think that forecasts will always be probabilistic rather than deterministic. For example, we may be able someday to accurately measure the state of stress within Kilauea Volcano. However, each time magma fractures the carapace of the volcano and forms a new shallow intrusion or eruption, it changes the strength of the volcano. These changes may be small and subtle, but they could affect the timing, location, and possibly the character of the next eruption. I cannot envision how these small changes in the volcano's overall strength can be determined, except in hindsight.

SOCIETAL CONSIDERATIONS

The hazards and the areas at risk from volcanic eruptions can be estimated by geologists (Blong 1984). However, the problems of reducing the risks to life and property from volcanic eruptions are much more complex and involve the interaction of geologists, sociologists, government officials, journalists, businessmen, and the public (United Nations 1976, Sheets & Grayson 1979, Shimozuru 1981, Fiske 1984). Approaches to these problems of reducing risk include informing the public of hazards without causing undue panic or complacency, land-use planning, hazards zoning (Crandell et al 1984), contingency planning, providing shelters and emergency supplies, and eruption insurance.

Special problems are raised by lava diversion plans (Lockwood & Torgerson 1980, Lockwood & Romano 1985) or other possible modifications of volcanic behavior. Natural disasters are considered "acts of God" by most legal systems, and God cannot be sued for damages. However, if humans divert a lava flow, or perhaps even attempt to divert a flow, they may be held responsible for any subsequent damage done by that flow. Although lava diversion in some cases appears to be technically feasible, I think that with our meager present knowledge, "acts of God" should be left to God. This does not imply that research on these problems should be abandoned. Only by increasing our knowledge may we someday be able to interfere with beneficial results.

Most well-known volcanic eruptions owe their notoriety to the deaths and destruction they have caused. Stories of successful forecasts that lead to saving thousands of lives are less well known. One such example occurred in 1983. Colo Volcano, on a small island in Indonesia, was shaken by an earthquake swarm that began on July 14, and small explosive eruptions
began on July 18 (Katili & Sudradjat 1984). On the basis of the past behavior of Colo and similar volcanoes in Indonesia, geologists from the Indonesian Volcanological Survey recommended to the local governmental officials that the island be evacuated. The officials concurred, and all 7000 inhabitants were evacuated by boat. The climax eruption occurred on July 23, sweeping the island with hot pyroclastic flows. All livestock, housing, and coconut plantations were destroyed. It will take years to rebuild the island’s economy, but the people survived.

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Literature Cited


EPILOGUE While this article was in press, the eruption of Nevado del Ruiz in Colombia on 13 November 1985 caused the worst volcanic disaster since the eruption of Mont Pelée in 1902.

A relatively small eruption of magma triggered the release of a large volume of melt water from the glacier-covered summit of the 5400-m-high volcano. The flood of water and debris swept down the steep canyons on the volcano’s flanks, particularly the Rio Lagunillas. The resulting mudflows killed about 25,000 people, mainly in the town of Armero, 50 km east of and nearly 5000 m below the summit of Nevado del Ruiz.

This disaster emphasizes the great need to put the words in this review article into action. Volcanic eruptions will continue to occur, but more of their dangers can be anticipated, and the risk can be reduced.