Volcanic Hazards, Volcanic Catastrophes, and Disaster Mitigation

Volcanic eruptions have occurred since the Earth formed about 4.6 billion years ago. Each year, about 60 of the roughly 550 active volcanoes on Earth erupt. The frequency, magnitude, and type of eruptions of volcanoes are unlikely to change in the foreseeable future. One in every six of the active volcanoes on Earth (5% of all eruptions) has led to a loss of lives through its activity. About 260 000 people have died as a result of volcanic eruptions since A. D. 1600 (383) (Fig. 13.1). Cities and entire regions have been devastated. Disastrous volcanic eruptions are characterized by a rapid onset of their climactic phase and by a wide variety of eruptive behavior and effects: high and low temperatures, especially mass flows of different types (such as debris avalanches, pyroclastic flows and debris flows), but also including atmospheric transport of ash for hundreds of kilometers. During very powerful eruptions, huge masses of gases are injected into the stratosphere, forming aerosol veils that globally affect the climate and the ozone layer for years (such as following the Pinatubo eruption in 1991; Chap. 14).

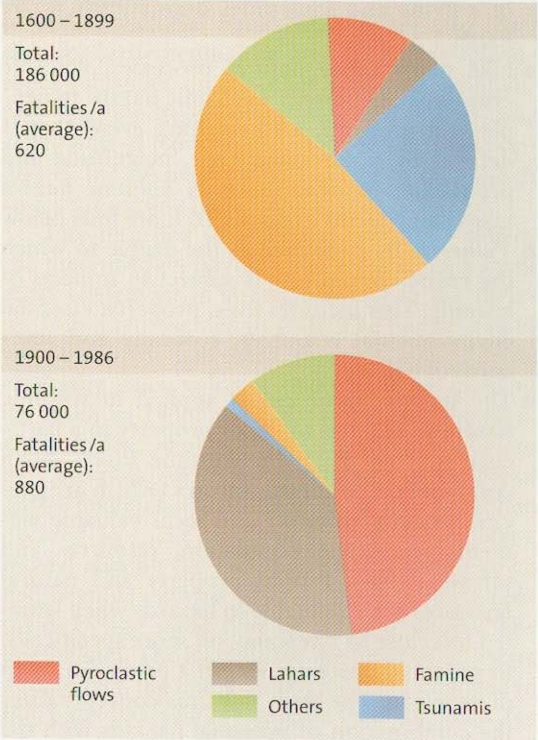
Volcanic and other types of natural disasters are certain to increase in the future because the degree of vulnerability of societies is rapidly rising. The reasons are manifold. Volcanic soils are very fertile and therefore eminently suitable for land use. Population density in agriculturally cultivated areas around many volcanoes is high and constantly increasing. People settle higher and higher on some active volcanoes. Hence, the number of victims in such areas is likely to rise significantly in the future.

Major disruption is preprogrammed in areas where active volcanoes are in close proximity, especially where mass flows of various types are a major type of eruptive activity. Similarly, in developing countries, increasing investment in communication, power lines, pipelines, transportation lines, etc. have greatly increased vulnerability. The rising population density in sprawling urban areas and giant megacities close to active volcanoes are particularly acute cases of rising vulnerability. Other cases include local and regional air traffic across chains of active volcanoes. In addition, the complexities of energy, communication and supply networks are ever increasing.

Storms and subsequent flooding of large areas, caused by the altered radiation balance of the atmosphere, are increasing worldwide. Greenhouse gases have led to global warming and the warm air can absorb more water that is released in large storms. Increased precipitation combined with the massive ash supply following major volcanic eruptions will drastically increase the generation of lahars, one of the major long-term volcanic hazards.

While there were no volcanic eruptions with more than 1 000 fatalities during the 1970s, more than 25 000 people lost their lives during several devastating volcanic eruptions in the 1980s. If there had not been major scientific effort and well-organized disaster mitigation measures prior

> **Volcanoes are in fact indexes of danger, and the absence of them is the best security**
>
> *James D Dana, US Exploring Expedition, Philadelphia, 1849*



◄ Fig. 13.1. Main causes of deaths following volcanic eruptions in the time windows 1600 – 1899 and 1900 – 1986 (381) to the 1991 eruption of Pinatubo (see below), perhaps as many as 10 000 people might have lost their lives. As a result of our increasing knowledge of the precursors to volcanic eruptions, each year thousands of people have to leave their homes for weeks or months, and some forever.

Terminology

The dictum in the Old Testament "Conquer the Earth" has dominated the attitude of western societies toward nature for centuries. Such may have been the background to the title of a book "Volcanoes declare war" by the famous volcanologist Jaggar in 1946. Our tendency to subdue nature has led to a *cul de sac*, as shown by the last quarter of the last century that saw increasing use of terms such as *natural catastrophes* or *natural disasters.*

Nowadays, an attitude is developing of how to *live with volcanoes.* In other words, society increasingly comes to accept often unpredictable and sometimes monstrous eruptions, to recognize the hazards when living close to potentially active volcanoes and to protect itself prudently to avoid a catastrophe.

In order to more fully appreciate the different aspects of the term *volcanic disaster* some terms need to be clarified to better understand the relationship between hazards, material effects, risks, coping and disaster.

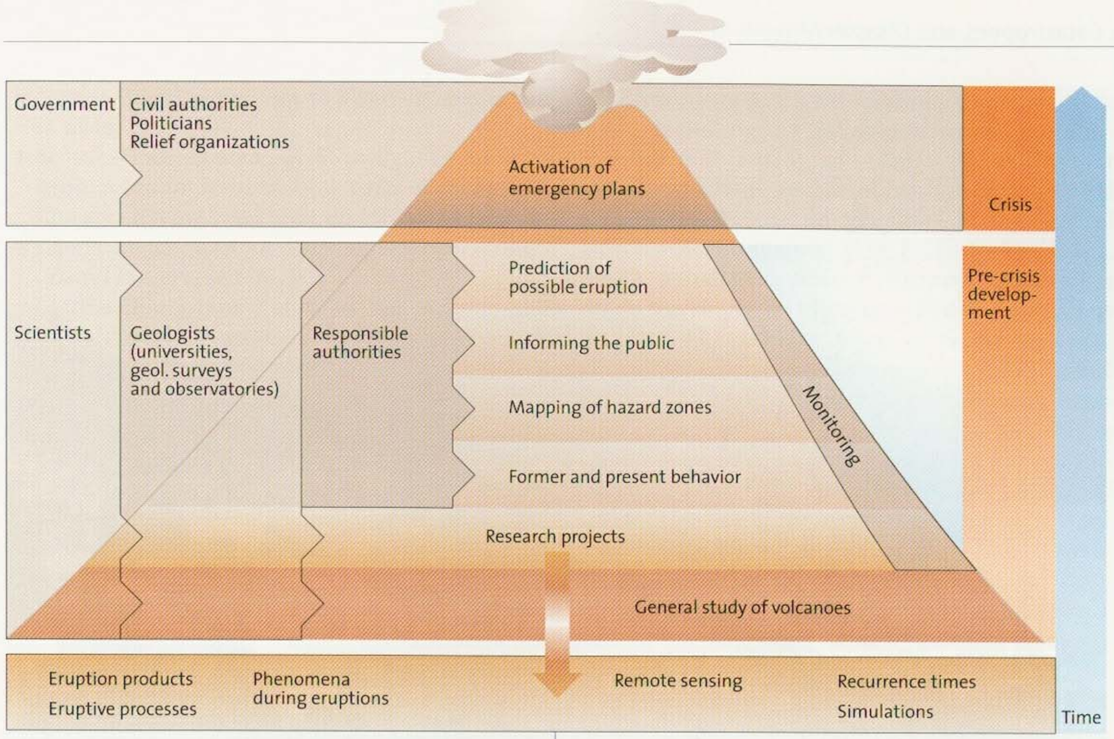
- A *volcanic eruption* is a natural event that is the dynamic expression of processes in the interior of a living and sometimes dramatically active Earth
- Like many other natural processes, volcanic eruptions can present a volcanic hazard to people and property, a threatening event that is defined by a particular type, magnitude and probability of occurrence. A *volcanic hazard* takes many forms as discussed more fully below
- *Vulnerability* is defined as the degree to which the entire community is subject to impacts of hazards. This includes lives, property, essential environmental resources, economy and standards of living
- The term *volcanic risk* is applied to volcanic hazard in relation to life or property in a particular spot and at a particular time. *Risk* is then a combination of hazard features (which are specific to each volcano) and local valuable elements (including population, resources and infrastructure). People, property and natural resources are vulnerable to hazards when situated too close to a volcano, or, more specifically, to potential processes within a particular form of eruption. The term *risk* thus conceptualizes the combination of potential hazards with the value (in a broad sense) of elements potentially subject to the hazards
- *Disasters* result from the interaction of natural events with political, economic, social and technological processes. Disasters occur when people do not recognize the potential hazards of a volcano or particular types of volcanic eruptions, warnings by the volcano itself or by scientists, and hence do not protect themselves through mitigation and emergency response plans. In addition, political issues and insufficient communication between scientists, community leaders and emergency managers often lead to the worst types of volcanic disaster
- A volcanic disaster or catastrophe strikes when the scale or particular nature of a volcanic event exceeds the *capacity of a community to cope. The ability to cope* depends on the economic potential of a community or country and strength of private or public institutions capable to quickly and effectively respond to a hazardous natural event
- *Disaster mitigation* includes all activities toward reducing risk, either the hazards (via physical interventions, e.g. *sabo dams*) or vulnerability (via *hazard mapping, land use planning*). It also includes preparation of responsible administrative bodies and civil protection authorities as well as full information of the public and eventually of evacuation measures (Fig. 13.2). This is a formidable task since the spectrum of volcanic eruptions and therefore hazard types is large. When volcanoes have not erupted for hundreds or thousands of years, societies usually lose their sensitivity vis-a-vis hazards and do not develop appropriate disaster mitigation measures. The old adage often applies, the next disaster strikes when the memory of the last is lost. In many areas, people continue to live close to volcanoes that had a long history of disastrous eruptions. Some communities even expand increasingly closer to the main hazardous areas. Some volcanoes characterized by frequent explosive eruptions as well as high population density are listed below.

Volcanic Hazards

Sometimes the eruption magnitude (e.g. the volume of material erupted) is equated with the degree of hazard or risk, in other words, the larger the eruption, the greater the hazard or risk. This correlation commonly does not hold, however, other factors generally being more important.

Population Density

Whether a volcanic eruption leads to major loss in human lives or not depends on the population density in the proximity of a volcano and its state



◄ Fig. 13.2. Research steps and disaster prevention measures required in the face of an active potentially erupting volcano (382)

of preparedness and organization. It does not generally depend on the volume of magma erupted or the type of eruptive processes.

For example, the eruption with the largest volume of magma erupted in the past century (Katmai, 13 km^3, 1912) did not result in human victims because it occurred in an extremely remote area of Alaska (Fig. 11.5). It did, however, lead to large environmental impacts, both locally and globally with respect to climate. On the other hand, the magma volumes of some well-known and deadly volcanic eruptions in the last century were tiny. Eruptions resulting in more than 20 000 fatalities such as Mt Pelée (Martinique, 1902) (Fig. 13.3) and Nevado del Ruiz (Colombia, 1985) had eruptive magma volumes of much less than 1 km^3.

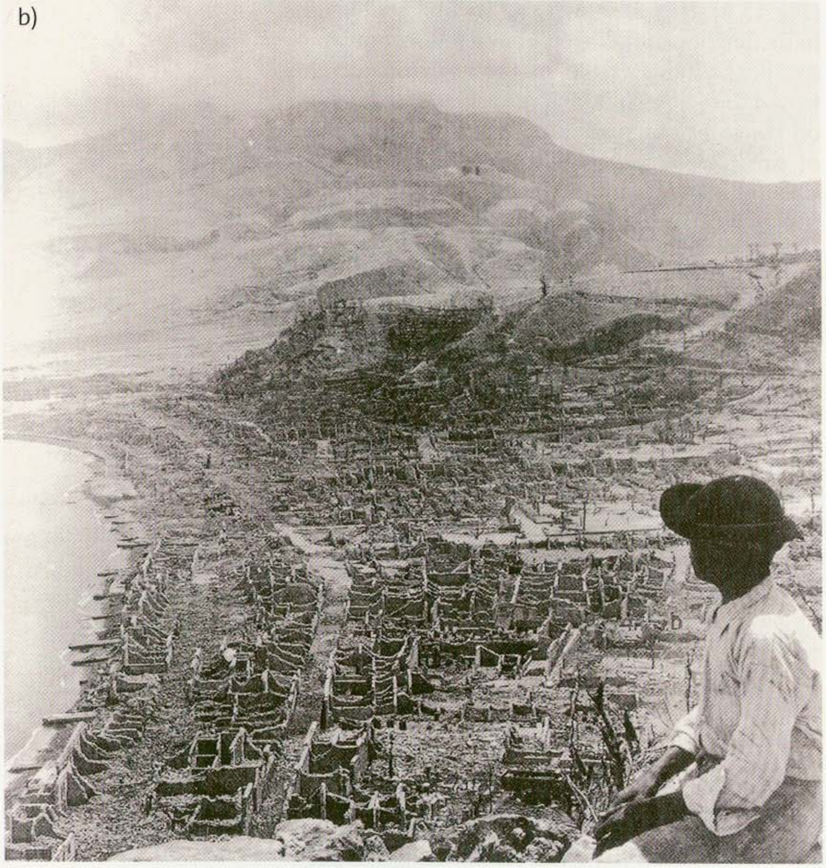
The 8 May 1902 catastrophic eruption of Montagne Pelée was characterized by high velocity pyroclastic density currents, which destroyed the town of St. Pierre, with block-and-ash flows being channeled in the north. Similar eruptions took place during 20 and 26 May, 6 June and 30 August 1902. In contrast, only block-and-ash flows spawned by a growing and episodically collapsing lava dome were generated during the next major eruptive stages (1929–1932). Most were deposited in Rivière Blanche at the foot of a major collapse scarp.

During the famous eruption of Mount St. Helens in 1980 with less than 1 km^3 magma, very few people perished, not only because of the timely and effective disaster prevention measures, but also because the area within about 50 km of Mount St. Helens was sparsely inhabited.

There are two main reasons for the fundamental contrast in the impact on society between these two eruptions. In the case of Montagne Pelée, the town of some 29 000 inhabitants was right in line of high-speed pyroclastic currents (Fig. 13.3). Had the town and smaller settlements in its neighborhood been built a few km north or south, the lethal effects of the volcanic currents would have been minimal. But then, major valleys on the slopes of volcanoes, commonly the zones of earlier sectorial flank collapse, are also ideal sites for settlements. The area of Katmai/Novarupta volcanoes, on the other hand, was uninhabited. Had the huge 10-km-wide and 20-km-long valley west of Novarupta crater been densely populated, the disaster would have been of a much larger magnitude than in the case of St. Pierre.

Life returned to St. Pierre after 1902 slowly, the present town having been reduced to a small quiet settlement in strong contrast to the thriving hub it represented in 1902. The question as to why the town had been resettled is legitimate especially since volcanic deposits came close to the town in 1930. Some 83 years after the catastrophic demise of St. Pierre, the town of Armero in Colombia was also annihilated with about 23 000 fatalities. The Colombian government then decided to make the area a national cemetery, moved also by the fact that the site of the town had been devastated twice in the preceding centuries by the same type of volcanic debris flow (see below). The hazards for the town of St. Pierre and, in fact, the entire valley, have not changed in the past 100 years. However, the methods for

▶ Fig. 13.3. St. Pierre (Martinique) prior to (a) and after (b) the disastrous eruption of May 8 1902. Commercial postcards



monitoring volcanic activity and recognizing important precursors early enough to enact timely evacuation have vastly improved during the past three decades. On the other hand, time spans between highly destructive volcanic events are generally significantly larger than a generation's lifetime. Thus, the fundamental benefits from maintaining at least part of the pre-disaster social structure and other benefits such as agriculture or favorable transport location override the fear of distant disasters.

Cities and megacities with high population densities and major growth rates within the reach of active volcanoes and thus places of major potential volcanic risk include:

- Tokyo, 100 km east-northeast of Mt. Fuji in Japan, a volcano that shows recent signs of awaking from its slumber since 1707
- Quito (Ecuador) some subburbs having been built on prehistoric and historic lahars from Cotopaxi volcano, 60 km to the southsoutheast, and close to the very active Guagua Pichincha volcano, last active in 2000 and Reventador last active in November 2002
- Mexico City (Mexico) in sight of the huge Popocatépetl volcano, which entered a new eruptive phase, starting about 1995
- Yogyakarta (Indonesia), at the foot of almost permanently active Merapi

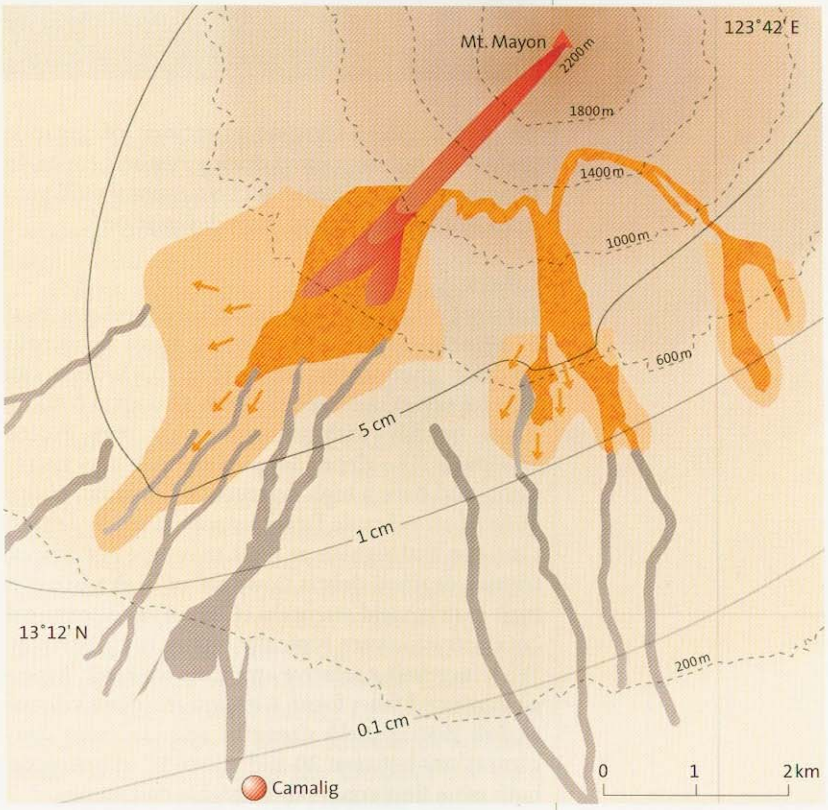
- Naples (Italy) at the foot of Vesuvius, last active in 1944
- Seattle–Tacoma area (USA) in sight of presently quiet Mount Rainier some parts of the sprawling area having been built on Holocene lahars;
- Goma at the foot of very active Nyiragongo (Zaire) last erupted in 2001
- Manila (Philippines) close to Taal volcano, the last disastrous eruption having occurred in 1965
- Auckland (New Zealand) spreading across a Holocene volcanic field and
- Managua (Nicaragua) built on many young volcanoes, nearby active Masaya volcano having erupted violently by magma-water interaction in the late Holocene.

Pyroclastic Density Currents

All types of mass flows pose the greatest hazard to communities, because people tend to live in valleys that are the most convenient areas to settle since soil and water resources are nearby. Volcanic mass flows include pumice-rich pyroclastic flows, dense block-and-ash flows and lahars. While the first two are gas-inflated, lahars are debris-water mixtures. High velocity, hot, particle-poor blasts are especially dangerous because their pathways are not confined to valleys. The main loss of lives and the largest economic losses in the past century from volcanism resulted from pyroclastic flows, hot blasts and lahars. Examples include Mount Pelée (Martinique, 1902), Nevado del Ruiz (Colombia, 1985) and Pinatubo (Philippines, 1991).

Hot pyroclastic flows, which consist of gas and particles, at temperatures sometimes exceeding 800 °C, speed down the flanks of a volcano and may cover thousands of square kilometers (Chap. 11). They are characteristic for explosive eruptions of volcanoes above subduction zones (Figs. 13.3–13.5; Chaps. 8, 9). Pyroclastic pumice flows or block-and-ash flows are generated each year during many volcanic eruptions. People caught within their flow paths have little chance of surviving. Buildings, crops and forests are destroyed and warning periods are extremely short. On the other hand, the most likely pathways, i.e. the valleys, can be clearly delineated in hazard maps. Administrators responsible for land planning can effectively reduce the hazards when restricting settlements in valleys that are likely pathways for volcanic mass flows.

Pyroclastic flows and block-and-ash flows are commonly associated with surges, hot highly diluted turbulent currents that race ahead of, or spread laterally from, the denser valley-confined gravity flows. The destructive power of these currents unfolds when they expand above slopes and hills. On 3 June 1991, for example, 43 people were killed, including the world-famous volcano photographers Maurice and Katia Krafft, by hot surges, which expanded above the depositional area of hot block-and-ash flows at the foot of Unzen volcano (Japan) (Fig. 11.4). In May 1902, dilute pyroclastic density currents raced 8 km down the slopes of Montagne Pelée within a few minutes to reach the town of St. Pierre. Here, almost the entire population was killed (29 000 people). The actual pyroclastic block flows, however, were restricted to the valley of Rivière Blanche. Surges led to the death of about 2 000 people during the eruption of the remote El Chichón volcano in southern Mexico in April 1982. About 70 people died in 1994, when a pyroclastic block flow descended a valley on the slope of Merapi, the most active volcano of Indonesia, generating a lethal surge (Fig. 11.30). The top of volcanoes can collapse during or after large pyroclastic flow eruptions into the partially emptied magma chamber, to form calderas (Chap. 9). For-



▲ Fig. 13.4. Typical areal distribution of four different types of products of a major explosive volcanic eruption: (a) Lava flows restricted to the upper part of a volcanic cone; (b) pyroclastic flows extending to the foot of a volcano; (c) lahars continuing into the foreland (d) more widely distributed fallout tephra. Eruption of Mount Mayon (Philippines) in 1968 (232)

▶ Fig. 13.5. Surface of a pyroclastic block flow generated during a dome explosion of Augustine volcano (Alaska) in 1976

tunately, caldera-forming eruptions of gigantic scale have not happened during historic times. In densely populated areas, such an event would generate unimaginable and utter devastation.

Lahars

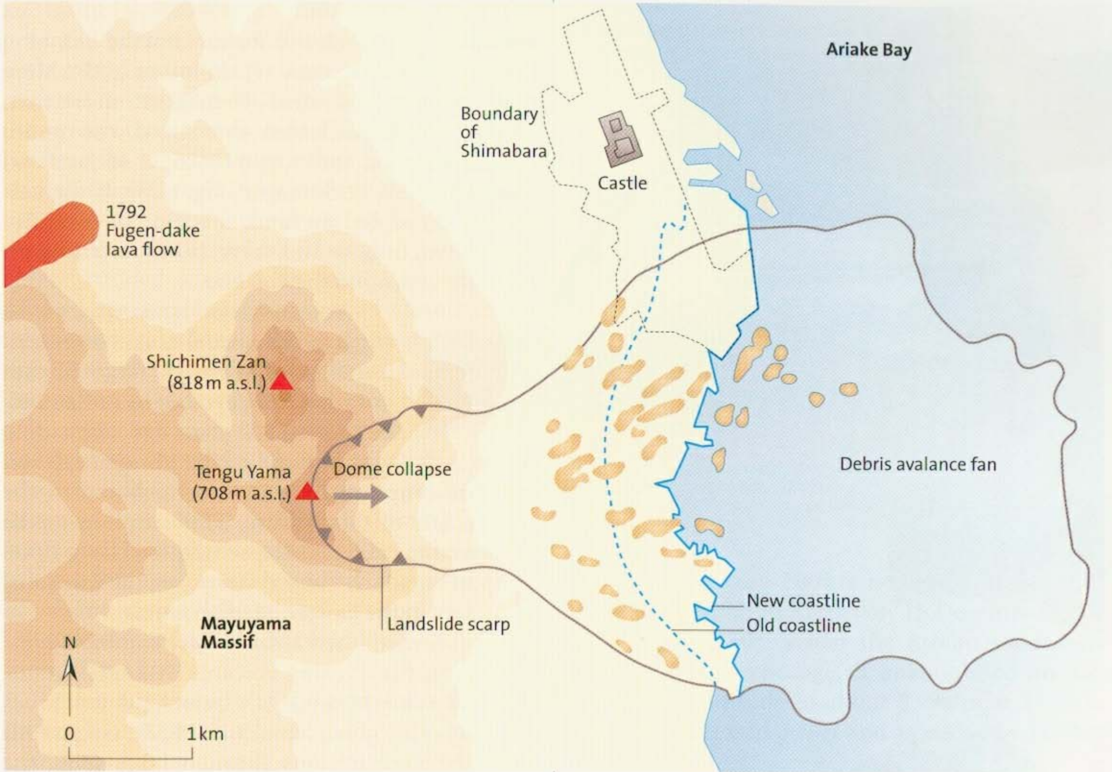
Lahars (volcanic debris and mud flows) are, next to pyroclastic flows, some of the most dangerous volcanic phenomena (207) (Fig. 13.4). They can flow for several kilometers, rarely also up to 300 km, move quickly with velocities that may exceed 100 km/h (!) – depending on particle concentration - and have a high destructive potential. About 10 % of all volcanic fatalities are caused by lahars. One can distinguish at least two types of lahars. Coarse-grained debris flows are of high viscosity, high matrix yield strengths (Chap. 4) and sediment concentrations are typically higher than 60 vol %. With increasing relative amounts of water, *hyperconcentrated flows* form, with intermediate viscosity, low matrix yield strengths and sediment concentrations between 20 and 60 vol %. In principle, both mass flow types can be highly destructive.

Many lahars form when pyroclastic flows s.l. enter riverbeds. The hazard potential is especially high when pyroclastic flows erupt on snow or glacier-clad volcanoes. A lahar formed in this manner during the relatively small eruption of the glaciated Nevado del Ruiz (Colombia) in November 1985. Hot surges and small pyroclastic flows and hot bombs melted the surface of the glacier. The debris-laden floods so generated mixed with the water of the river Lagunillas and incorporated large volumes of sediment before flowing to the town of Armero, more than 60 km away, killing about 23 000 people (147, 401, 402). Lahars are commonly associated with phreatic and phreatomagmatic eruptions because such wet deposits become easily mobilized on steep slopes.

In tropical areas, cloudbursts and cyclones (hurricanes) are common. These can wash freshly deposited ash and rocks from volcano slopes, to produce lahars, as during the eruption of Irazú volcano in Costa Rica over several years (8). In this way, lahars are commonly triggered for many years following a volcanic eruption. Lahars from the slopes of Pinatubo, which erupted on 15 June 1991, are expected to continue until at least the year 2005 (264). Lahars can also form directly during volcanic eruptions, for example in eruptions through crater lakes such as Ruapehu (New Zealand) and Kelut on Java (Indonesia) (see below).

Magma Composition and Tectonic Environment

The explosivity of an eruption is not only governed by the chemical composition of a magma and therefore its gas content, but also by the viscosity of a melt. Mixing of magma with ground- or seawater may also play a major role (see below). The higher the concentration of SiO_2 in a



◄ Fig. 13.6. Source area (scar) of major debris avalanche and distribution of depositional fan generated in 1792 by collapse of a dome in Mayuyama Massif, south of the town of Shimabara (*dotted line*) (Unzen volcano, Kyushu, Japan). Most of the debris avalanche was deposited in the sea. The deposits pushed the old coastline (*dashed line*) into the sea and formed small hills and islands. The debris avalanche generated tsunamis when entering the sea. About 15 000 people died along the 120-km-long coastal strip around Ariake Bay, and 6 000 houses and 1 600 fishing boats were destroyed (329). See also Fig. 9.17

magma, the more viscous the magma and lower the gas diffusivity rates, the more explosive the eruption. Most active explosive volcanoes characterized by SiO_2-rich andesitic, dacitic and rhyolitic magma composition have grown above subduction zones, such as around the Pacific (Ring of Fire), in the Caribbean (Lesser Antilles) or in the Central (Aeolian Islands) and Eastern (Cyclades) Mediterranean. Many developing countries are thus strongly affected by volcanic eruptions, such as Latin America, the Caribbean, and the Southwestern Pacific, especially Indonesia and the Philippines.

The most active volcano on Earth, Kilauea on Hawaii is a major attraction to tourists and an ideal volcano for detailed scientific study, but the erupted lavas are neither explosive nor very dangerous (apart from the very rare phreatic and phreatomagmatic eruptions).

Sector Collapse, Debris Avalanches, Tsunamis and Environmental Factors

Dormant volcanoes can be deceptive, even for specialists. Under certain conditions, a volcanic edifice can suddenly collapse and produce extremely mobile gravity-controlled debris avalanches (Chap. 9). These accelerate downhill and can flow at more than 100 km/h over several tens of kilometers. Such collapses of entire volcano flanks, be it in connection with eruptions or after extreme rainfalls, can be highly destructive. About 2 000 people died when the upper flank of Casitas volcano (Nicaragua) collapsed in 1998, following sustained cloud bursts generating rapid debris-laden floods.

Debris avalanches and debris flows when entering the sea, may generate *tsunamis* (e.g. during flank collapses on Hawaii or the Canary Islands). These can be highly destructive and represent a major hazard for the commonly densely populated coastal areas (Figs. 13.6, 13.7). Limestones found at 325 m a.s.l. on the Island of Lanai in the Hawaiian archipelago were interpreted (226) as the result of giant flood waves, generated during flank collapse of the southern flanks of the Island of Hawaii. This interpretation has recently been questioned, but the fact remains that volcano flanks collapse around the Hawaiian Islands with a periodicity of less than 100 000 years. These seem to occur mainly during the late stages of shield volcano growth (239). Submarine and subaerial flank collapses in the Canaries are even more frequent than in the Hawaiian Islands and also occur during very late stages of volcanic evolution (182, 308, 412) (Fig. 9.39). In 1792, the collapse of a parasitic lava dome of Unzen volcano (Japan) caused a tsunami resulting in about 15 000 fatalities (Fig. 13.6). The disastrous tsunamis when Krakatau volcano erupted in August 1883 (Fig. 13.8) may have been due to the entry of voluminous pyroclastic flows into the sea or a major phreatomagmatic (?) explosion (337). More than 36 000 people died when giant, more than 15-m-high flood waves devastated the entire coastal strip on the northern coast of Java and southern coast of Sumatra (Fig. 13.8). If the volcano had erupted on land, the zone of complete destruction would have been restricted to valleys around the volcano.

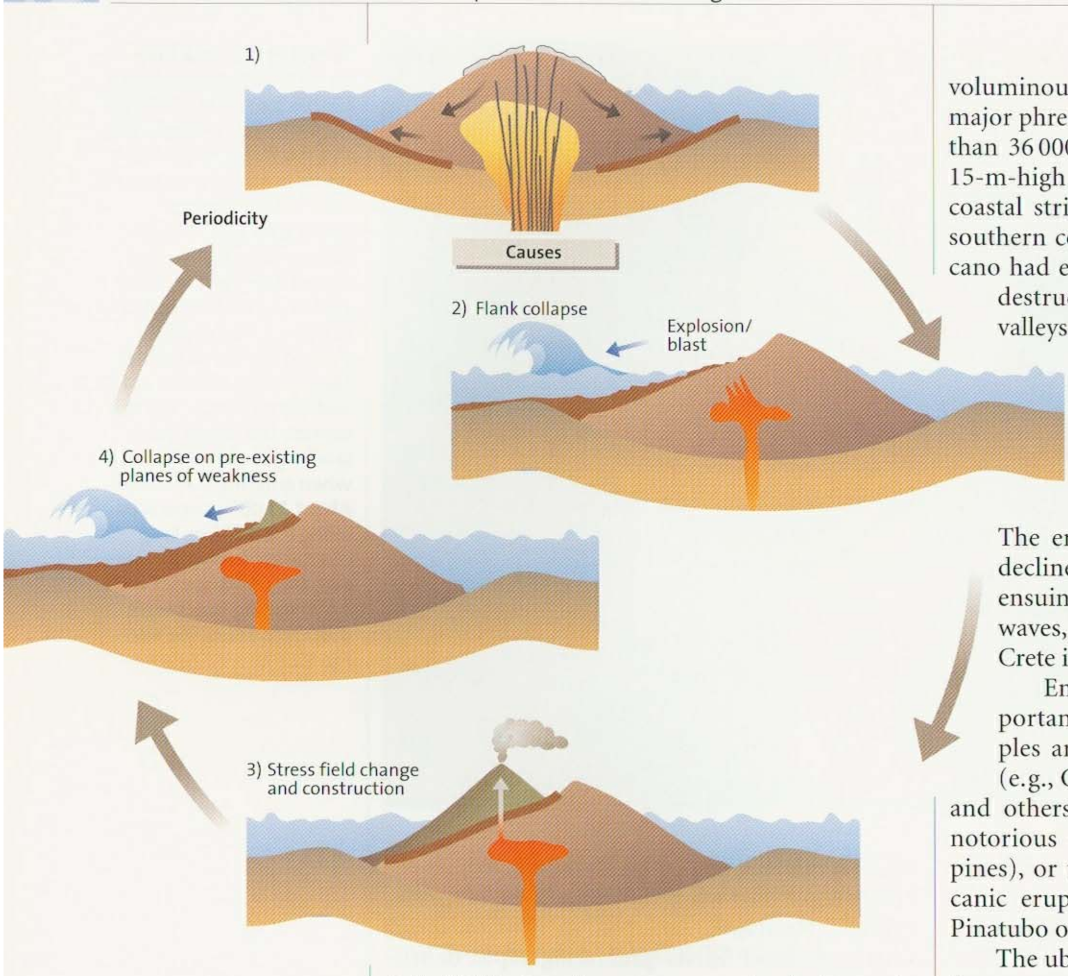
Volcanogenic tsunamis can be triggered by several causes or a combination of them. A large Plinian eruption destroyed parts of Santorini about 3 500 years ago, coinciding with the end of the Minoan culture. The eruption may have contributed to the decline of this culture. This eruption or the ensuing caldera collapse triggered large flood waves, which caused havoc on the Island of Crete in the eastern Mediterranean.

Environmental factors are commonly important in causing volcanic disasters. Examples are eruptions of glacier-clad volcanoes (e.g., Cotopaxi, Nevado del Ruiz, Grimsvötn and others), eruptions through lakes (e.g., the notorious and dangerous Taal volcano, Philippines), or the synchronous occurrence of a volcanic eruption and a taifun (hurricane) (e.g., Pinatubo on 15 June 1991).

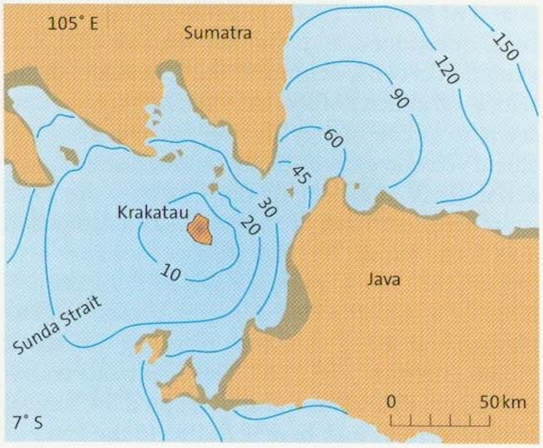
The ubiquitous rivers that drain volcanic edifices pose a major hazard when blocked by volcanic landslide or massive tephra sedimentation. Uncontrolled collapse of such dams can devastate downstream areas for long distances. An example is a large lake accumulated behind a temporary tephra dam at a constriction in the Rhine river canyon during the late stages of the eruption of Laacher See volcano, about 12 900 years ago in the Eifel (Germany) (Fig. 11.33). This lake was up to at least 18 m deep but drained catastrophically when the unstable dam collapsed a few weeks or months after it had formed. This generated flood waves, whose deposits can be found as far north as Bonn, 50 km to the north and possibly even in the Netherlands (Chap. 11) (255). Pyroclastic flows blocked the Agatsuma River about 10 km downstream from Asama volcano in Japan during the famous 1783 eruption. More than 1 000 people were reported to have been killed by a lahar or flood waves when the dam collapsed 5 days after the beginning of the eruption.

Eruption Columns

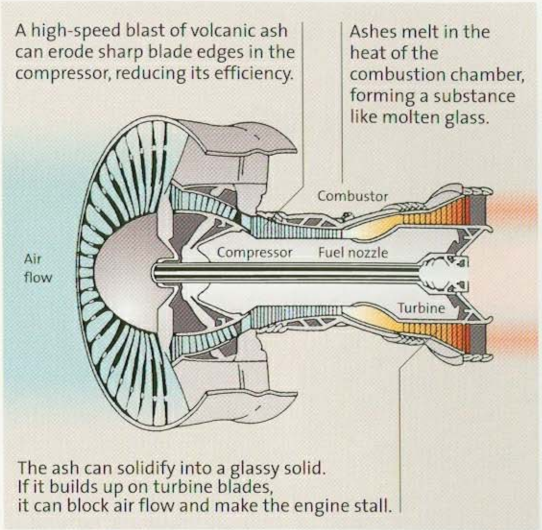
Of the roughly 60 volcanoes erupting each year, about 10 % are characterized by eruption columns that rise into the stratosphere (i.e., 8 – 16 km). As



▲ Fig. 13.7. Sector collapse processes and cycles in oceanic islands
1) Sector collapse causes include: swelling due to intrusion of a new magma batch with or without eruption; hydrothermal alteration of interior of volcano; repeated dike injection along rift zones; oversteepening of one flank of a volcano due to long-term sustained erosional attack, etc.
2) Flank collapse generating steam blast and tsunami and asymmetric unloading of magma reservoir
3) New volcano growing in the scar left by the collapse
4) Renewed collapse on pre-existing plane of weakness (412)



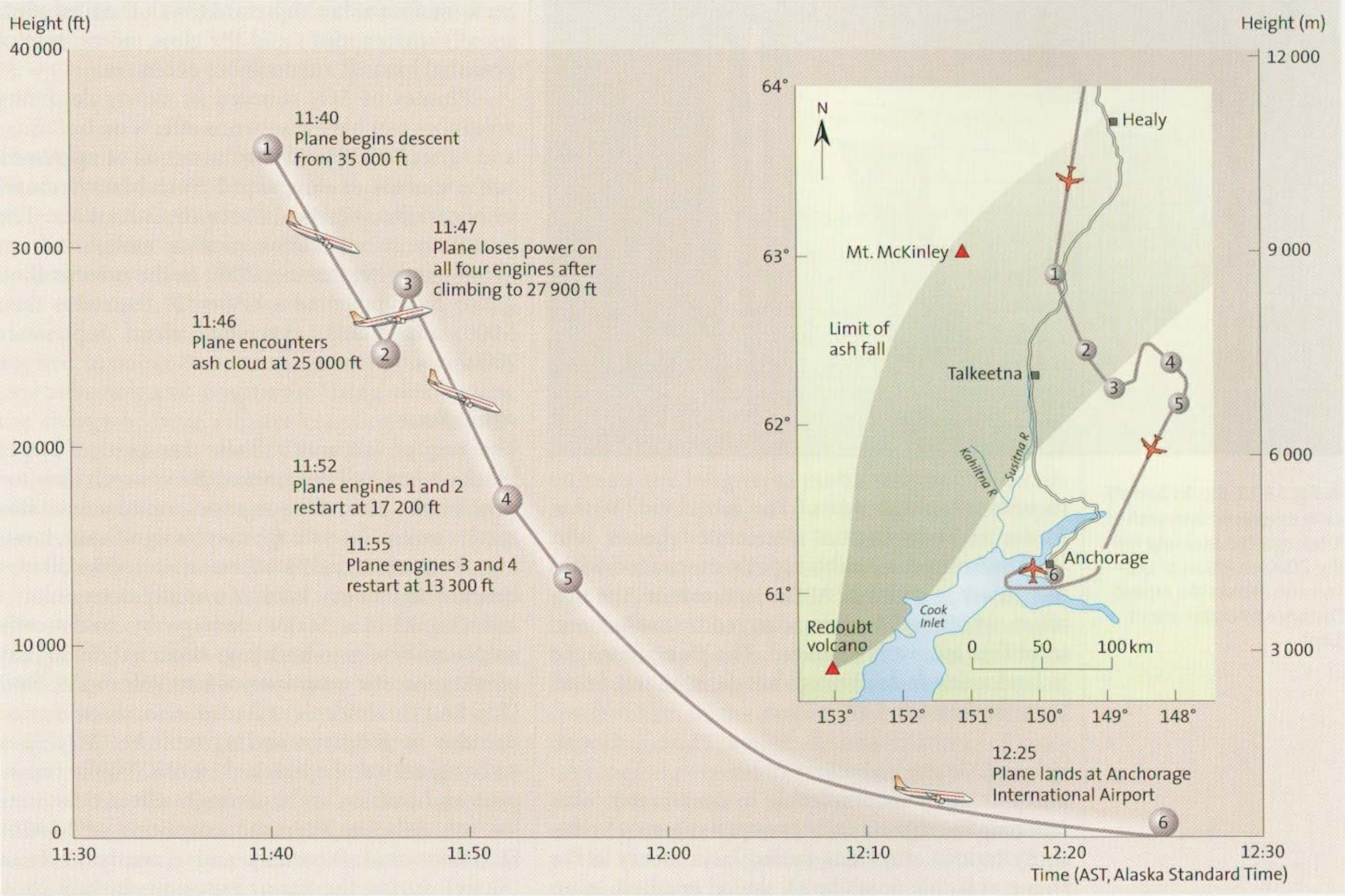
► Fig. 13.8. Time zones (minutes) of propagating tsunamis, generated when pyroclastic flows sourced in a collapsing eruption column impacted the sea during the eruption of Krakatau volcano in August 1883. The dark-colored coastal zones of Java and Sumatra became flooded by the tsunamis. About 36,000 people perished (337) air traffic is increasing dramatically, so is the potential hazard from the interaction of aircraft with eruption columns and more distant ash clouds. During the past 2 decades, beginning with the unexpected eruption of Galungung volcano (Indonesia) in 1982, more than 80 modern jets were damaged when inadvertently flying through volcanic ash (49) and almost 10 large aircraft experienced in-flight loss of engine power and barely avoided a crash. In June 1991, about a dozen large airplanes experienced almost-catastrophes when suddenly flying through the eruption column rising above Pinatubo volcano. Thereafter, Manila airport was closed for several days, a precautionary manner, which is now routine in many airports, such as Quito during explosive eruptions of Guagua Pichincha in 2000 and Reventador in 2002, or Catania (Sicily) in July 2001 and October-November 2002 when Etna volcano was spectacularly on fire. The main cause of engine thrust loss is the accumulation and solidification of ash on the turbine nozzle guide vanes (Fig. 13.9).



◀ Fig. 13.9. Jet engine cutaway showing areas of damage by volcanic ash (272)

A famous example is the near-crash of a new Boeing 747–400 with more than 300 passengers aboard, more than 200 km northeast of erupting Redoubt volcano in Alaska on 15 December 1989 (272) (Fig. 13.10). When the jumbo started its descent into Anchorage, it encountered an ash cloud at an altitude of about 8,000 m at 11:46 h. The crew increased power and ascended by 1 000 m

▼ Fig. 13.10. Map showing flight path of KLM 867 and limits of detectable ash fall lobe from 15 December 1989 eruption of Redoubt volcano (Alaska). *Numbers* show main events:
1) plane starts to descend from 35 000 ft at 11:40;
2) plane encounters ash cloud at 25 000 ft;
3) power loss on all four engines after climbing to 27 900 ft;
4) engines 1 and 2 restarted at 17 200 ft;
5) engines 3 and 4 restarted at 13 300 ft;
6) plane lands at Anchorage at 12:25 (49)



◄ Fig. 13.11. House buried by ashes generated during a phreatomagmatic eruption of Capelinhos volcano off the coast of Fayal (Azores). See also Fig. 12.2

▲ Fig. 13.12. Blocks ballistically emplaced into wall of Kindergarten building during 2000 eruption of Usu volcano (Hokkaido, Japan). Distance to crater about 1 km

in order to climb out of the ash cloud. Within 1 min, all four engines decelerated below idle. Within 5 min the jumbo rapidly descended without power to 4 000 m. At the last minute, the turbines, which had become clogged by molten and solidified ash, were restarted. The plane managed to land safely in Anchorage but damage amounted to more than US-$ 80 million.

Volcanic Gases

Volcanic gases accumulating in deep crater lakes and erupting episodically can spell disaster. Several mysterious eruptions during last century in the Dieng volcanic area (Java), which resulted in up to 150 fatalities, remained unexplained until recently, and are now interpreted to be due entirely to suffocation by quietly liberated gases (191). The catastrophes of the Monoun and Nyos crater lakes (Cameroon) in 1984 and 1986, during which more than 1 700 people died by a descending CO_2 cloud, were apparently not related to a volcanic eruption. Most likely, CO_2, dissolved at high pressure at depth to near-saturation level in the crater lake, was suddenly released. The causes for this sudden release are not entirely clear (177). CO_2-saturated deep waters were probably forced upward by an abrupt subaquatic landslide, became oversaturated at the lower pressure and discharged the liberated CO_2 in a dense cloud that flowed downhill and inundated the village.

The hazard of gas release for buildings is small, but economic losses such as the death of cattle can be significant. The early warning of an impending gas eruption is extremely short. Even the emission of gases (CO_2, SO_2, etc.) from fumaroles in active volcanoes can cause major damage to crops and are a significant health hazard (362). Detailed studies of such eruptions and the close monitoring of potential hazards are therefore necessary.

Plumes of SO_2 sourced in slowly degassing volcanoes can have disastrous effects on buildings and agriculture due to the formation of aggressive sulfuric acids as downwind from Masaya crater in Nicaragua, or Poas crater in Costa Rica. The unusually strong sulfur dioxide emission from Miyakejima (September 2000 to the present (Fig. 4.25)) has prevented a return of the more than 5 000 inhabitants, evacuated since September 2000.

Ash Fallout

The rain of ash and ballistic transport of larger blocks is generally of immediate concern only for people who live near volcanoes, up to a few kilometers away. The damage may be significant, however, even at larger distances, when roofs collapse beneath the heavy load of rapidly accumulated ash (Fig. 13.11). Major damage by ballistically emplaced blocks to buildings occurred during explosive phreatic eruptions of Usu Volcano in 2000 (Fig. 13.12). Volcanic ash can also cause major damage in industry and agriculture. Machines and engines can be blocked by ash. Public transport and traffic can be strongly affected by major ash falls, as after the eruptions of Mount St. Helens and Pinatubo and recently at Etna (Sicily) during the major eruptions in July 2001 and the fall of 2002. At great distances, the ash can also be a health hazard, particularly if free silica is present. Silicosis, asthma and other respiratory problems may occur when particles are fine enough to be inhaled. In addition, acidic compounds, often associated with ash, can be a major environmental health hazard.

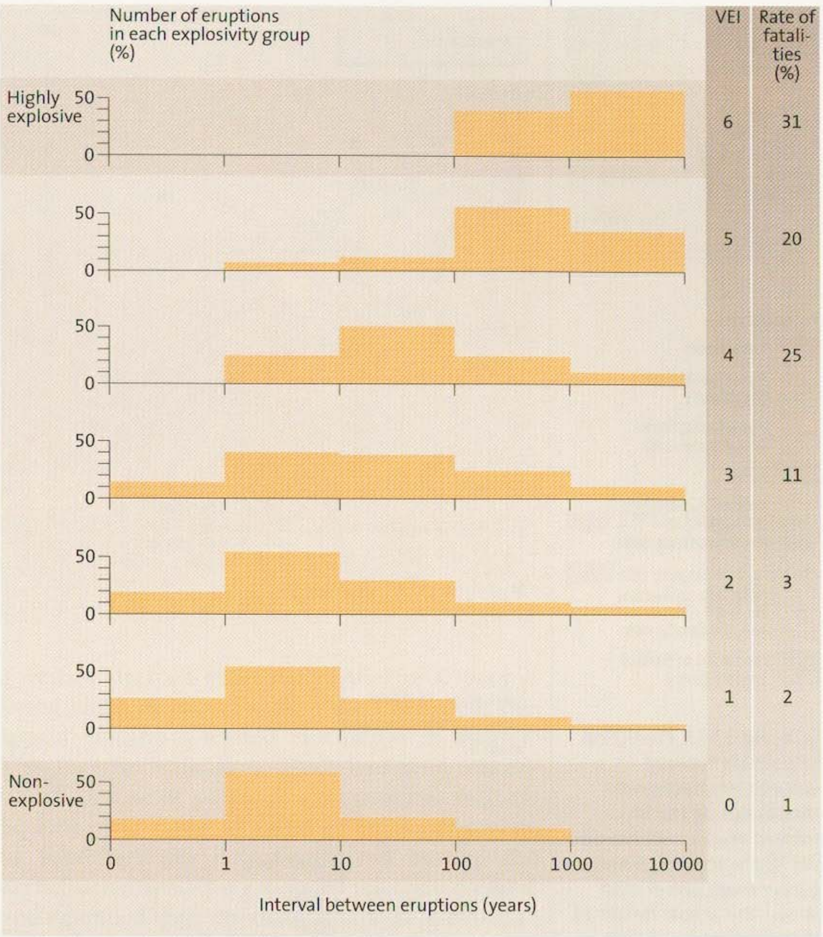
Dormant Volcanoes

Generally, the longer a volcano has been dormant, the larger and more explosive a new eruption is. Hence, the most hazardous volcanoes are commonly those in which eruptive phases are separated by hundreds or thousands of years of quiescence, as shown by the example of Pinatubo (1991; see below). A major cause of vulnerability is also the attitude of people who live in proximity to a long-term dormant volcano. It is thus commonly difficult to evacuate people from potentially affected areas. A recent example is the Soufrière Hills volcano on the island of Montserrat in the Caribbean. This volcano was not active since the island became colonized early in the seventeenth century. It started to erupt after a two-year-long phase of seismic unrest on 18 July 1995 and is still going strong in 2003 (357, 440). When volcanoes believed to be extinct erupt, catastrophes often follow, such as at Mount Lamington (Papua New Guinea, 1951) (374) or El Chichón (Mexico, 1982).

The Volcano Explosivity Index (VEI)

Newhall and Self (250) proposed a *volcano explosivity index*, based on subjective, qualitative descriptions plus some quantitative criteria (total volume of erupted products and height of eruption columns). The VEI has eight overlapping classes of increasing explosivity and can be applied to about 80 % of the known, dominantly explosive volcanic eruptions. Using this system, the energy of large effusive eruptions with only minor tephra production (VEI = 0) is not properly assessed, however. On the other hand, these large effusive eruptions are generally not particularly hazardous to humans with the exception of the great Laki eruption in 1783 (Chap. 14).

In general, one can assume that highly explosive volcanic eruptions (VEI 3 to 6) have lethal effects. The periods of quiescence between these especially dangerous eruptions are very long, sometimes hundreds to tens of thousands of years (Fig. 13.13). Of the 21 most explosive volcanic eruptions (VEI 2 to 5) of the past 10 000 years, 17 erupted for the first time in recorded history (338). The hundreds of years of quiescence of so-called dormant, large, explosive volcanoes are thus quite deceptive.

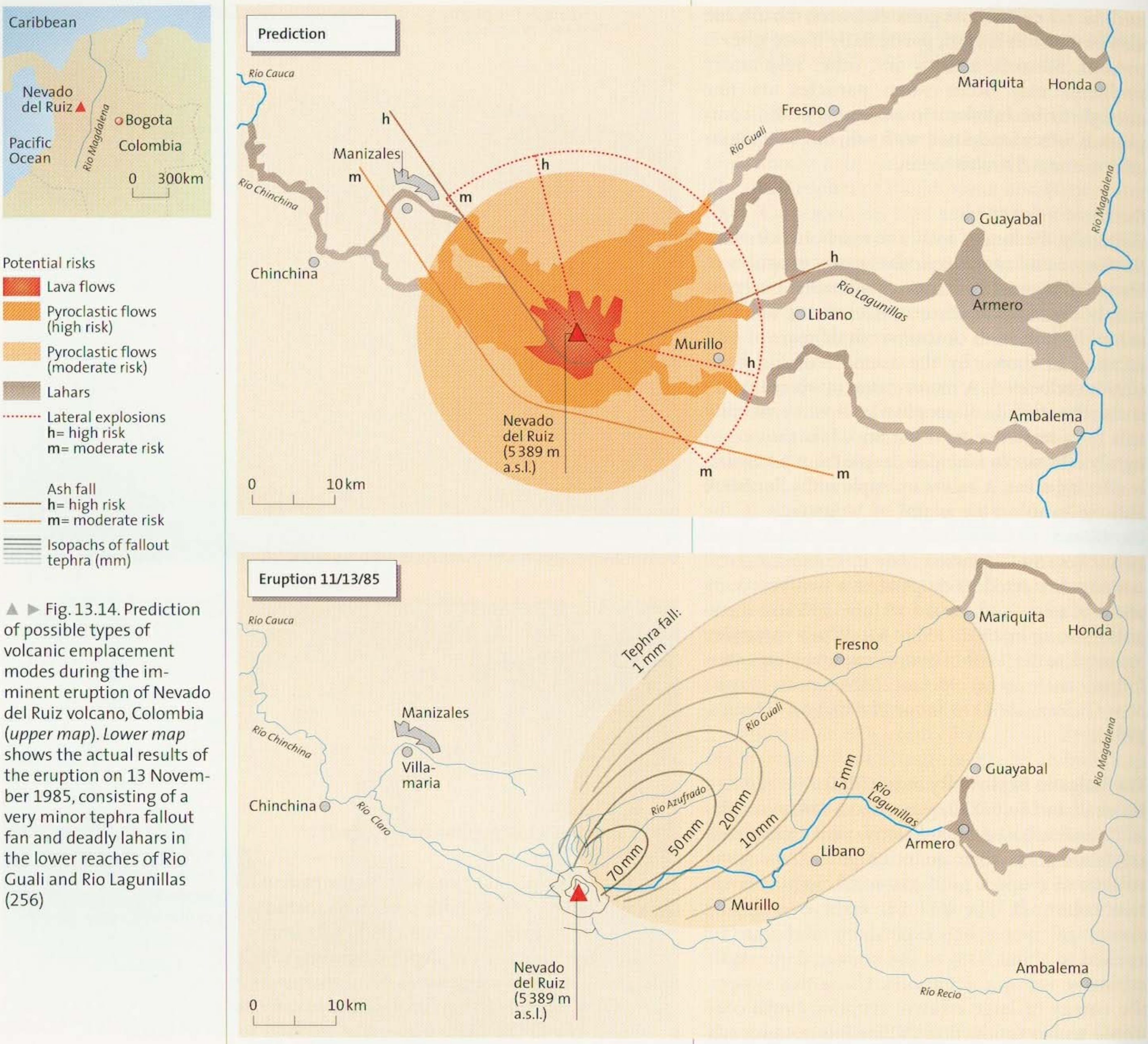


▲ Fig. 13.13. Frequency distribution of historic volcanic eruptions differing in explosivity. VEI = volcano explosivity index (250, 338)

Can Volcanic Catastrophes be Avoided?

Diagnosis

A good doctor will take time with a new patient to find out about earlier health problems, including those of their family. This information is important for the subsequent in-depth diagnosis, which is later followed by suggestions for a therapy. By analogy, the careful analysis of the early history of a volcano is still the most important method to estimate the long-term probability of the occurrence of certain types of eruptions and their specific energy. Volcanoes commonly harbor an excellent historic and prehistoric event stratigraphy and chronology. This history can be reconstructed when the deposits are mapped, subdivided stratigraphically, structurally analyzed and dated. In addition, the chemical and mineralogical composition of the erupted lavas and pyroclastic deposits, and careful documentation of volcanological parameters (volumes, grain sizes, particle characteristics, eruptive and fragmentation mechanisms, etc.) provide important information of the earlier eruptive behavior of a volcano. This relies on the principle of uniformity, that is, a vol-



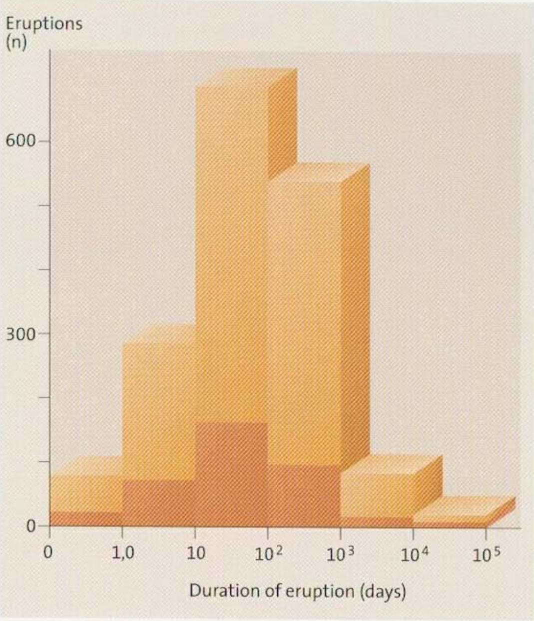
▲ ► Fig. 13.14. Prediction of possible types of volcanic emplacement modes during the imminent eruption of Nevado del Ruiz volcano, Colombia (*upper map*). *Lower map* shows the actual results of the eruption on 13 November 1985, consisting of a very minor tephra fallout fan and deadly lahars in the lower reaches of Rio Guali and Rio Lagunillas (256)

cano is likely to behave in the future as it has done in the past. From this data, hazard maps can be constructed, in which the distribution of the several types of eruptive products are shown (including lava flows, pyroclastic flows, tephra falls, lahars, volcanic debris avalanches and possibly tsunamis) (Fig. 13.14). The apparent probability that a volcano that erupted once historically, will erupt again is larger than in a volcano that appears to be dormant or extinct. Nevertheless, the periods of quiescence between eruptions in many volcanoes last much longer than the few hundreds or thousands of years of recorded human history. Large volcanoes that have erupted very frequently in the past include Kilauea volcano, Vesuvius (although the next event after the large eruption of 1944 is overdue), Hekla (Iceland), Etna (Sicily), Mayon (Philippines), Merapi (Java), Sakurajima (Japan), Komagatake (Japan), Arenal (Costa Rica) and Augustine volcano (Alaska). The best-known continuously active – but presently unstable – volcano is Stromboli in the Tyrrhenian Sea, with eruptive phases that last a few minutes to hours. What causes irregular intereruptive periods between different volcanoes is unknown and complex. The episodicity probably depends on factors such as the rate of magma generation in the source areas, the rates of ascent, the complex processes in magma chambers and the interaction with ground or surface water.

A volcanic eruption can last a few minutes, or hundreds of years, depending on how one defines it. The mean duration of volcanic eruptions on converging plate margins is about 65 days, in others (mainly intraplate volcanoes) 31 days (Fig. 13.15) (338). These are minimum values, however, because most of the energy is spent in the beginning of an eruption, while the slowly declining late phase is commonly not accounted for in the incomplete descriptions of older historic eruptions.

The prediction of volcanic eruptions, based on the statistical analysis of past events, is not exact enough to forecast eruptions precisely (e.g., to a particular date). Experience shows that people settle in volcanic areas in which eruptions can only be predicted with a probability of decades.

In addition to geological studies, the monitoring of volcanoes is a very important method to predict future eruptions, not only in time, but also the type of eruption and its vent location.



◄ Fig. 13.15. Duration of volcanic eruptions with volcano explosivity index VEI > 3 (338)

🟧 1779 volcanic eruptions above subduction zones

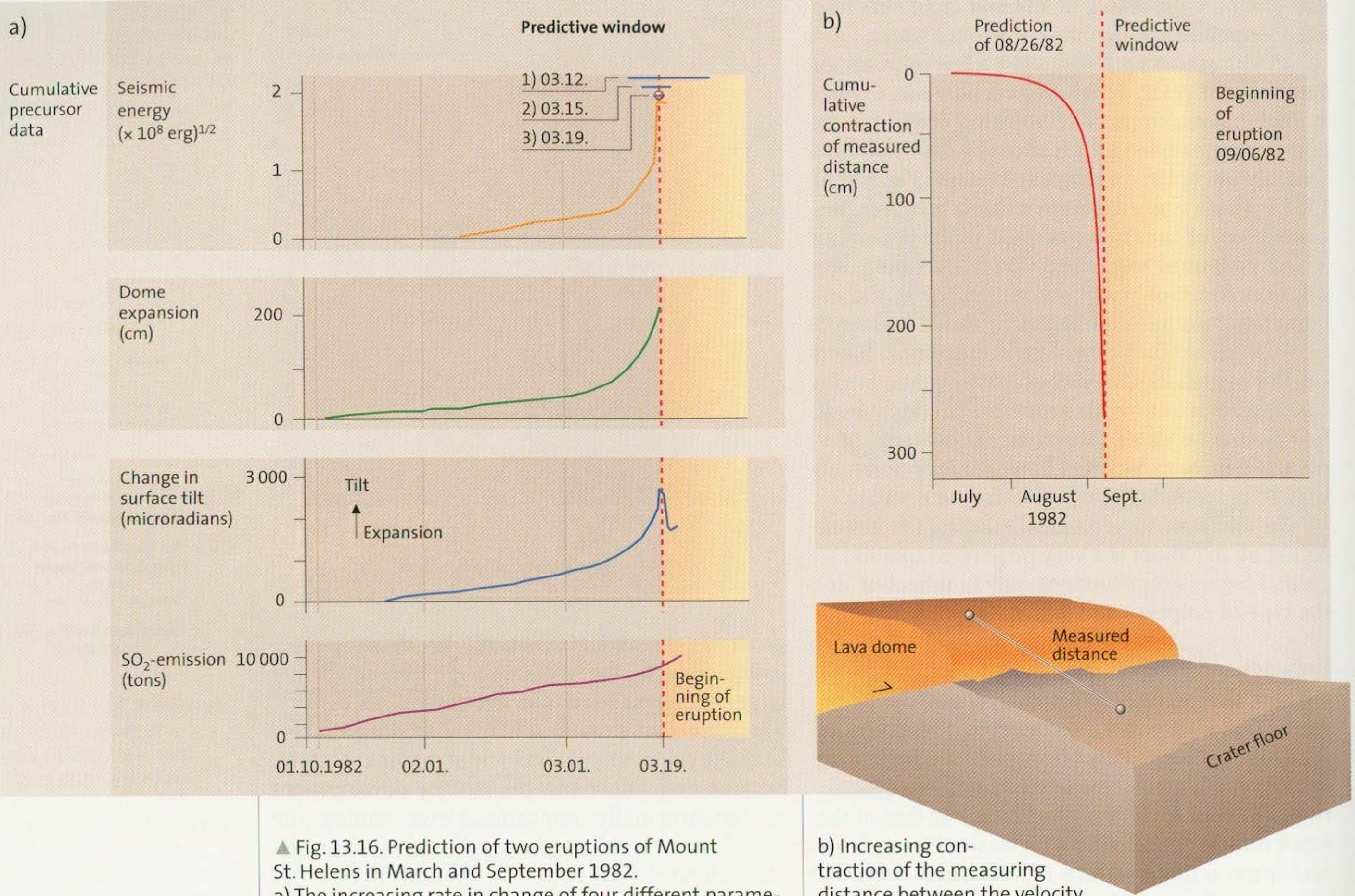
▨ 360 eruptions mainly of intraplate volcanoes

Forecast and Prediction

One of the premier goals of volcanological research has always been to improve the ability to predict eruptions. This is especially important in densely populated areas to enable timely evacuation. But even for volcanologists, in the face of the small number of scientists, expensive instruments and often remote setting of volcanoes, accurate timely predictions are essential to plan strategic measuring campaigns, prior to, during and after an eruption. If an eruption can only be predicted with a moderate probability, catastrophes cannot be avoided. Because periods of quiescence between eruptions in many volcanoes last much longer than a generation, people are more willing to accept risks rather than an evacuation. On the other hand, premature warnings and evacuations prior to events, which do not eventuate, have the paralyzing effect that nobody listens to the next warning, the cry-wolf syndrome.

Two classical examples, Guadeloupe and Hawaii, illustrate this dilemma. The Soufrière volcano on the island of Guadeloupe in the Caribbean started to show unrest in July 1975. The frequency of earthquakes increased so much that, when the volcano started to spew ash on 8 July 1976, catastrophic pyroclastic flow eruptions were anticipated. One expected events similar to those in 1902 on the neighboring islands of St. Vincent and Martinique (97). The daily number of earthquakes rose to 6000 in August, and scientists thought that the erupted ash not only contained pulverized older rocks but also particles of fresh lava. At the suggestion of scientists on hand the governor decreed evacuation. All 75000 people living close to the volcano were evacuated, the largest volcanism-related evacuation in history. The uncertain situation, which had been exacerbated because of political and economic factors, became even more complicated by development of fundamentally opposing views among the French scientists. Two groups of scientists formed and defended their opposing opinions in newspaper and television interviews. One group expected an explosive catastrophe, for which the other group saw no sign. In view of this rift, the French government asked a commission of international experts to convene in Paris. The panel agreed with the second group and saw no reason for concern. The volcano followed this suggestion, quieted down and has not erupted to this day. Should the signs for a larger eruption of Soufrière volcano be repeated in the near future, it would probably be difficult to convince the people evacuated in 1976 to leave their homes again.

A similar series of events began when a scientist of the Hawaiian Volcano Observatory dared to predict an imminent flank eruption to take place in 1976 on Mauna Loa, the largest volcano on Earth. He predicted it would occur at an altitude of 2800–3000 m asl. People prepared for the eruption (198), which occurred, as predicted in all detail – but only eight years later, in 1984 (199). The premature prediction of the flank eruption of Mauna Loa was based mainly on statistical or probabilistic analysis. For decades, summit eruptions of Mauna Loa had been followed by flank eruptions within a few years. Only after the summit eruption of 1975 was the volcano ill behaved;



▲ Fig. 13.16. Prediction of two eruptions of Mount St. Helens in March and September 1982.
a) The increasing rate in change of four different parameters since early 1992 allowed to progressively decrease the predictive windows between 12 and 19 March and to predict the eruption precisely within hours

b) Increasing contraction of the measuring distance between the velocity of the lava dome slowly creeping out of the crater allowed the publishing of a predictive window prior to the eruption on 6 September 1982 (370)

the expected flank eruption was significantly delayed.

Against the background of such experiences, with eruptions that did not occur or were not as soon as predicted, and the resulting political and social consequences, some scientists distinguish two types of prediction (370). A *forecast* is the general announcement that a volcano will probably erupt some time in the near future (months, years, decades), based either on an analysis of its former activity (like the forecast of the Mount St. Helens eruption in this century; Chap. 10) or on qualitative signs of unrest (drastically increasing number of seismic events, increased degassing, heating up, increased fumarole activity, changes in gas composition and rates in emission, etc.).

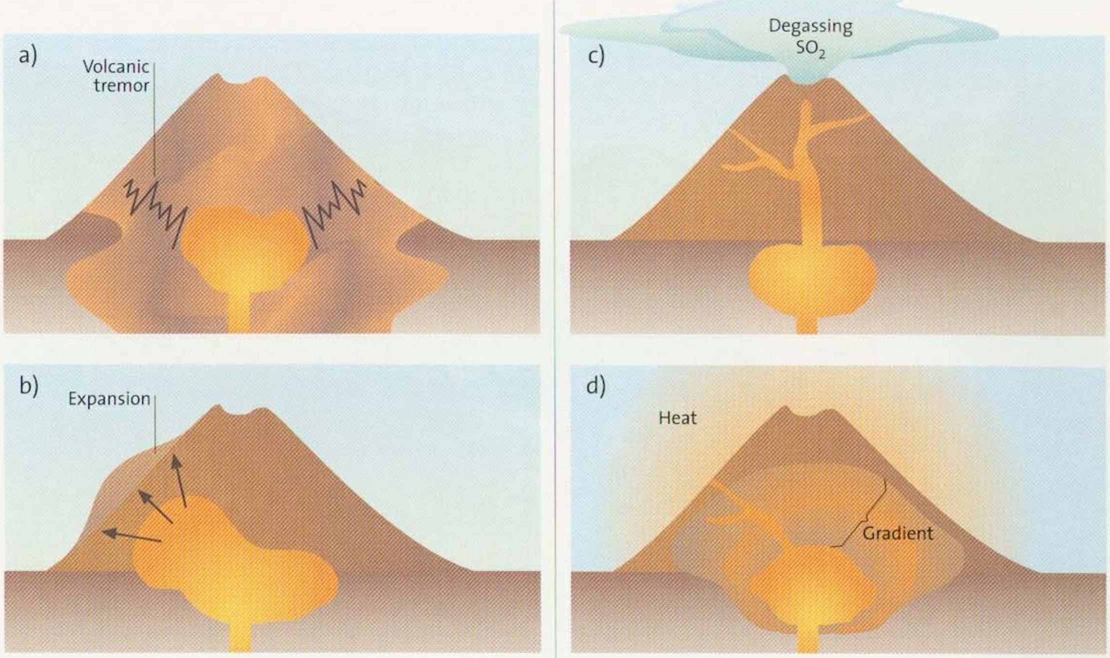
The term *prediction* is used for the relatively precise statement, concerning the probable vent location, the time of the eruption (at Mount St. Helens two to three weeks to a few hours prior to an eruption; Fig. 13.16) and the probable type of an eruption. Only if these predictions are made with utmost care and are validated by the volcanic events themselves, credibility can be achieved and successful mitigation measures realized. As our knowledge of the types of precursors inside a volcano improves, predictions will increasingly be based on deterministic and less on probabilistic models.

Monitoring

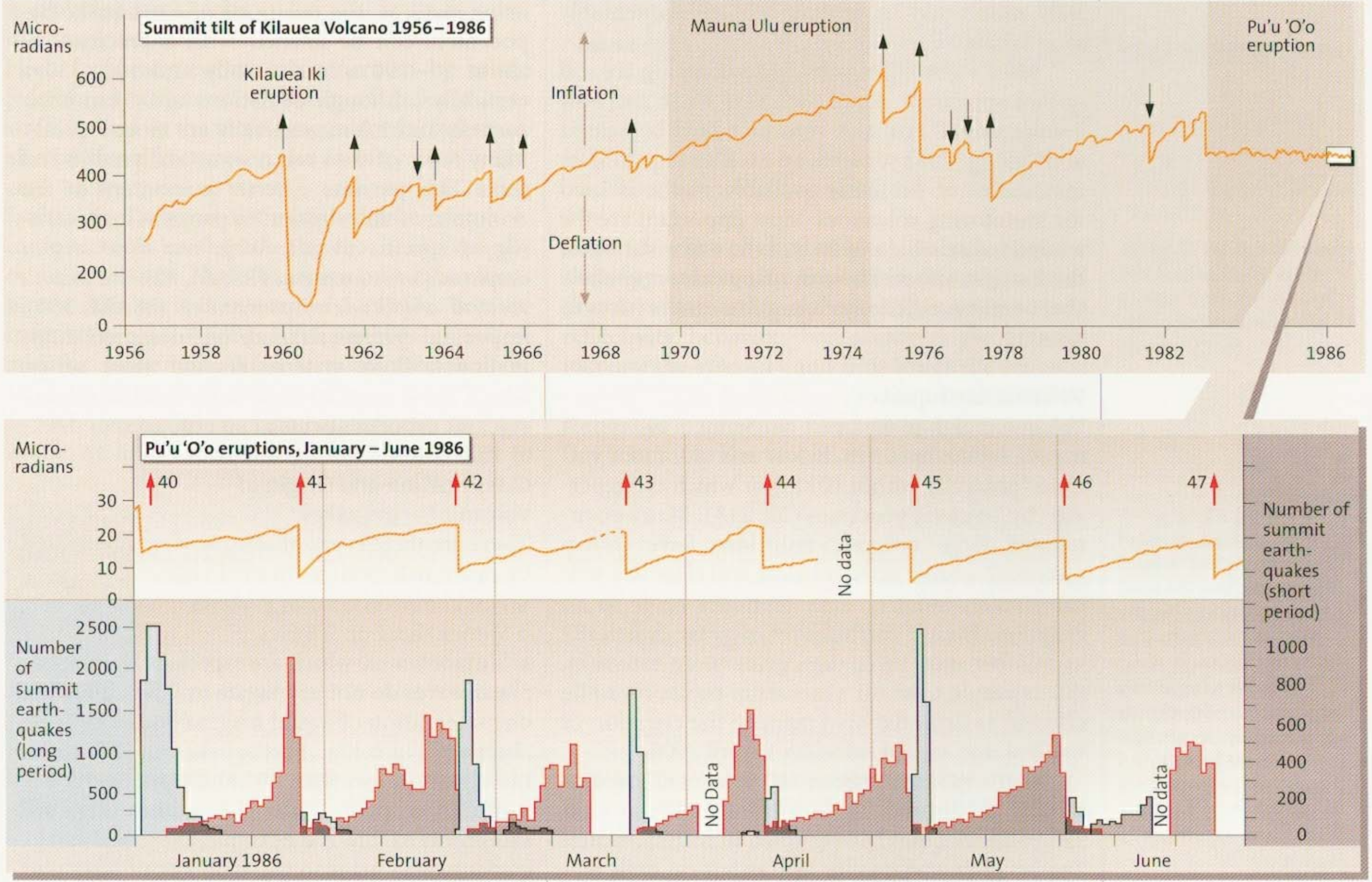
The four most important changes in a volcano, caused by the rise of a magma prior to an eruption, are (Fig. 13.17)

1. Volcanic earthquakes
2. Expansion of magma chambers (leading to surface deformation) (Figs. 1.10, 13.18, 13.19)
3. Increased gas flux
4. Heating

These physical and chemical processes and other less clear signs, such as changes in the electric, magnetic and gravity field of the Earth, are regu-



◄ Fig. 13.17. Cartoon of four different types of precursors of volcanic eruptions:
a) Volcanic earthquake
b) Swelling of volcano flanks due to high-level emplacement of magma
c) Increased gas release
d) Heating



▲ Fig. 13.18. Swelling and subsidence of the summit of Kilauea volcano between 1956 and 1986 with major eruptive periods (Kilauea Iki, Mauna Ulu and Pu'u 'O'o). For the Pu'u 'O'o eruption (January-June 1986) the frequency of short- and long-period earthquakes are also shown (386)

▶ Fig. 13.19. Collapsed house next to fault scarp with 10 m displacement, the result of domal uplift during the 2000 eruption of Usu volcano (Hokkaido, Japan)

larly monitored in several, but still lamentably few, volcanoes.

Most methods of volcano monitoring are still quite imprecise in detail such as if, when and how a volcano will erupt. A volume edited by Scarpa and Tilling (298) presents an excellent up-to-date assessment of presently available methods used for monitoring volcanoes. Most important are the analysis of seismic events and the deformation of the Earth's surface. These in many cases may allow short-term prediction of eruption onsets (days to hours).

Volcanic Earthquakes

Volcanic earthquakes can be defined as seismic events, which occur in, below and close to a volcano (generally within 10 km) or which are generated by volcanic processes (52, 218). Many documented large volcanic eruptions have shown increased seismic activity below and close to a volcano years, months, days or hours prior to an eruption. Even if earthquakes increase drastically in number only three days prior to an eruption, this is ample time for evacuation measures to be effected as demonstrated prior to the eruption of Usu Volcano in Hokkaido on 1 April 2000.

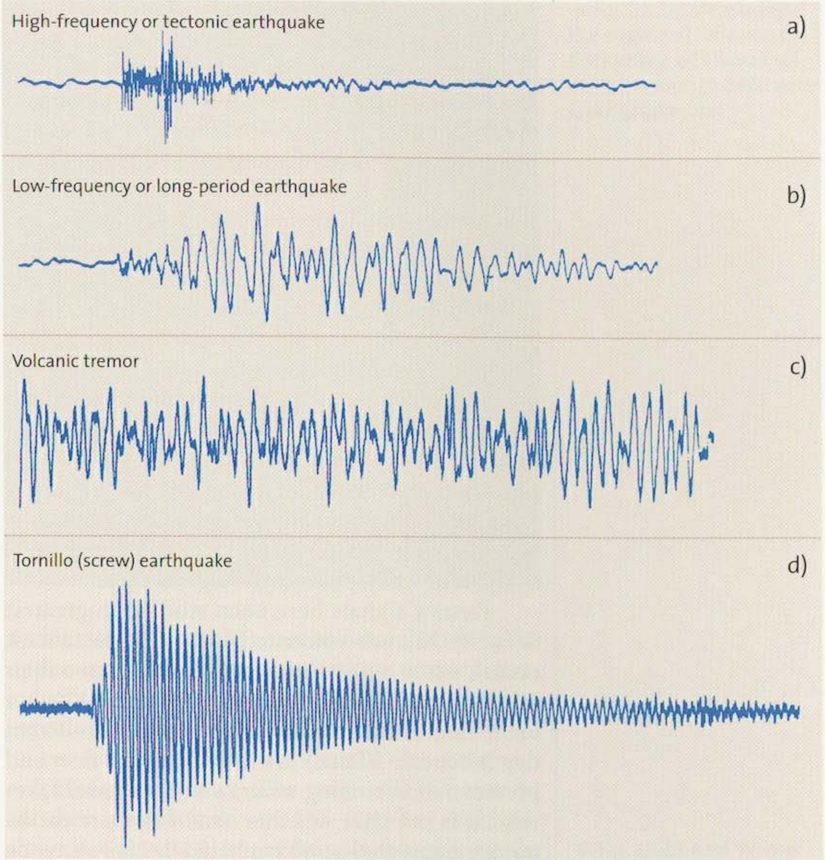
At the moment, about 200 volcanoes are seismically monitored, about a third of the around 550 volcanoes that have erupted in historic times. The number and quality of stations on each volcano are quite variable, however. The development of modern computers has allowed dramatic improvements in the speed and precision of locating earthquakes and determining the properties of seismic waves. With relatively close-spaced measuring stations, the positions of earthquake hypocenters can be located with a precision of about 50–100 m horizontally and 100–130 m vertically (although deviations of 0.5 km horizontally and 1.0 km vertically are more typical). Many types of data can now be analyzed in real time. This permits a better assessment of the evolution of an eruption in progress and warning of specific events. With *real-time seismic amplitude measurements* (RSAM, 92) and *seismic spectral amplitude measurements* (SSAM, 360), important parameters can be measured automatically. Both systems register time series, which allow scientists to follow the evolution of volcanic processes prior to an eruption.

Classification and Origin of Volcanic Earthquakes

There are three types of seismic waves generated by earthquake sources in the Earth:

- Fast compressional or P-waves
- Slower shear or S-waves
- Surface waves, which are especially destructive

Shear waves do not propagate in fluids, allowing documentation of liquid magma bodies by their absence (Fig. 6.17). Earthquakes in volcanoes mostly occur less than 10 km deep, directly beneath an eruptive center. Sometimes there are exceptions to this. For example, the initial earthquake swarm prior to the eruption of Pinatubo occurred 5 km northwest of the volcano. Twelve days prior to the climactic eruption, the frequency of earthquakes decreased and strong earthquake activity started beneath where the caldera would form. During the large eruption of



▲ Fig. 13.20. Typical waveforms of volcanic earthquakes from the area of active Redoubt volcano (Alaska) (218)

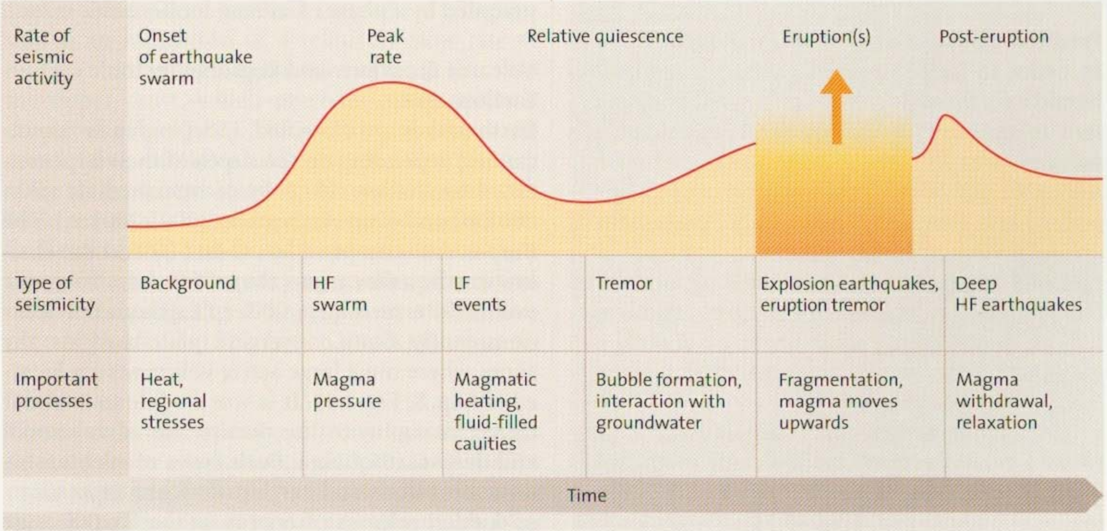
Katmai volcano (1912), the distance between the collapse structure (Mount Katmai) and the actual Novarupta crater eruptive center amounted to 10 km. Earthquakes can thus occur all around an active volcano where stresses have built-up. These locations must not necessarily be exactly the spot where the magma rises and eventually erupts.

Many different types of seismic signals are generated beneath and within active volcanoes. Seismic waves can be generated by movements along fractures, opening of cracks or pathways, during fluid transport, by interaction of magma with the walls or fractures or vents and other fluid dynamic processes, as well as by explosive eruptions, pyroclastic flows, rock falls and collapse of entire segments of volcanoes. Today, four main types of seismic events are distinguished from each other (218; 224) (Figs. 13.20, 13.21):

- *high frequency earthquakes*, also called A-type earthquakes
- *low frequency earthquakes*, also called B-type earthquakes
- *explosion earthquakes*
- *volcanic tremor*

High frequency events are generated by brittle fracture in magma chamber roof rocks, due to stress caused by the increasing magmatic pressure, also by shear fractures in the country rock (adjacent to fractures or vents), and motions along faults, etc. They are distinguished from non-volcanic tectonic earthquakes in that they typically occur in swarms. High frequency or A-type events have a dominant frequency of 5–15 Hz. Because magmas can rise from great depth over large areas and for some time, high frequency earthquake swarms can last very long.

At depths of 1–3 km, significant changes occur. At first, the volatiles in a magma start to form a free gas phase (bubbles). This changes the rheology and acoustic impedance of a magma and therefore its earthquake wave transmission and reflectivity behavior. For example, gas bubbles increase the viscosity and thus lower the acoustic velocity (218). A seismic event that is generated by resonance in a magma-filled space, is hence of low frequency. On the whole, the origin of most low



Type of seismicity	Background	HF swarm	LF events	Tremor	Explosion earthquakes, eruption tremor	Deep HF earthquakes
Important processes	Heat, regional stresses	Magma pressure	Magmatic heating, fluid-filled cauities	Bubble formation, interaction with groundwater	Fragmentation, magma moves upwards	Magma withdrawal, relaxation

◄ Fig. 13.21. Different types of volcanic earthquakes and processes beneath and around a volcanic edifice prior to and after volcanic eruptions. A similar evolution of earthquake types and distribution was observed and measured during the eruption of Mount Pinatubo (Philippines) (218). *HF* High frequency; *LF* low frequency

frequency earthquakes is related to fluids, not only the formation of bubbles and their collapse in magmas, but also the flow processes of rising magma and heated groundwater. Low frequency events commonly show P- but rarely S-waves and their frequency is in the range of 1–5 Hz.

The most typical volcanic earthquakes are characterized by relative constant amplitudes and frequencies, and are probably caused by turbulent motions in a rising magma column. They are called *volcanic tremor* or *harmonic tremor* (Fig. 13.20). Volcanic tremor is a continuous signal, which can last for minutes or days. The main frequency of tremor, 1–5 Hz, resembles those of the low frequency events. Harmonic tremor or spasmodic tremor are special cases of the general volcanic tremor. Harmonic tremor is of low frequency with a monotonous sinusoidal tremor with slowly changing amplitude, whereas spasmodic tremor is a high frequency, pulsating, irregular signal.

Tremor signals have been studied in greatest detail at Kilauea volcano. Most of these seismic events, up to several hundred per day, have their origin (hypocenter) at a depth of 2–4 km. Whether or not other earthquake sources at ca. 20–30 km depth beneath Kilauea are also caused by flow and pressure of the rising magma is uncertain. Likewise, it is not clear whether or not the rare earthquakes generated at 60 km beneath Hawaii really signal the beginning of magma ascent (Fig. 13.18).

Earthquakes, generated during explosive eruptions, are characterized by atmospheric shock waves, which can be registered on seismograms. Additional less common deep earthquakes, generated at 10–40 km depth, are commonly observed following large eruptive phases. These earthquake swarms probably reflect changes in the local stress field after partial emptying of a deep magma reservoir.

Prediction Based on Volcanic Earthquakes

In order to judge whether volcanic earthquakes herald a forthcoming eruption or not, it is important to monitor the background seismicity in a volcanic area for several years. Increased seismic unrest in active volcanoes can be caused by increased heat flow beneath a volcano; movement of groundwater, volcanic gases or magma; and motions of glaciers and rock falls or landslides. Only if one has learned to interpret seismic signals of these events with some assurance, can earthquakes that herald an eruption be interpreted in a plausible manner.

Well-documented case histories allow to postulate a general sequence of volcanic earthquakes swarms, which comprise some or all of the following components (218) (Fig. 13.21):

- background seismicity
- swarms of high frequency events
- relative quiescence after the peak of seismic activity (but before an eruption)
- low frequency events
- volcanic tremor
- eruption
- deep earthquakes following an eruption

Earthquakes of small and intermediate magnitudes ($M < 5$) occur in calderas or during sector collapse events. Volcanic earthquake swarms are distributed log-normally and generally last about 5 days. High frequency earthquake swarms last longest and do not always terminate in eruptions. On the other hand, low frequency swarms and volcanic tremor are shorter in duration and commonly occur directly prior to an eruption. Because intrusion and extrusion cause similar types of seismic signals, false alarms probably cannot be avoided, given the present state of knowledge.

Perhaps, an eruption could be described based on an empirical law, which describes fatigue of the material (FFM = failure forecast method) (401). Failure can mean a brittle fracture of rocks or fluid-saturated porous rocks, critical point of fluid pore pressure or the opening of fractures. This analysis is aided by using RSAM- and SSAM-systems (see above), which use the average absolute amplitudes of seismic signals from several seismometers.

Earthquakes in larger volcano structures, such as calderas, may not herald an impending eruption, or commonly begin long before an eventual eruption. For example, at Rabaul caldera in Papua New Guinea, strongly increased seismicity was recorded in the general caldera area from 1981 onward. A large eruption only occurred 13 years later, on 19 September 1994, being immediately preceded by a phase of intense local seismic unrest.

Volcanic Eruptions and Regional Tectonic Earthquakes

Earthquakes are classified, independently of volcanoes, depending on the depth of their hypocenter, into shallow (0–70 km), intermediate (70–300 km) and deep earthquakes (300–700 km). The deep events comprise less than 5 % and the shallow earthquakes more than 75 % of all seismic events. Intermediate and deep earthquakes occur dominantly along convergent plate margins, the zones where most large active volcanoes are located (Chap. 8, Fig. 8.1). It is worthwhile to look for causes common to the occurrence of volcanoes and deep earthquakes. Both types of events, volcanic eruptions and earthquakes, are expressions of sudden releases of energy in the Earth's crust and mantle. Large earthquakes may trigger or accompany volcanic eruptions or at least disturb the volcano-magma system including the hydrothermal system. Nevertheless, the precise temporal, areal or genetic connection between tectonic earthquakes and volcanic eruptions is poorly understood. Examples where earthquakes apparently triggered eruptions, are the eruption of Cordón Caulle, 48 h after the huge (M = 9.5) earthquake in Chile in 1960, small summit eruptions of Kilauea volcano shortly after the magnitude 7.1 Kalapana earthquake of 1975, and the 1707 Mt. Fuji eruption. A large M 7.3 earthquake in Landers (California) in June 1992 generated earthquake swarms in 17 volcanic areas in the western USA, at distances of up to 1 250 km. Perhaps the seismic waves significantly influenced the volatile pressure in a magma in some as yet poorly understood manner (36, 157) (Chap. 4).

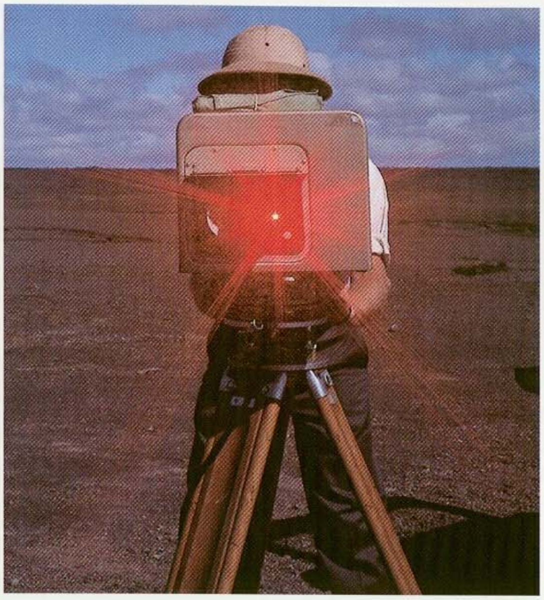
An areal and temporal relationship may exist between large fracture zones and volcanoes in Central and South America, an area characterized by shallow overthrusts (45). The volcanoes in these areas are generally inactive for a few years to decades prior to large earthquakes but begin to erupt a few months or years after such large earthquakes. Examples include Coseguina (1835) in Nicaragua and Santa Maria (1902) in Guatemala, the two largest volcanic eruptions in Central America in historic time.

Expansion of Magma Chambers

Beginning with the pioneering work of Eaton and Murata (90), measuring tilt on the roof of volcanoes is the premier method to detect an accumulation of magma in the interior of Kilauea volcano. Monitoring using tilt meters indicates whether a volcano swells or not. The expansion of the surface of a volcano can be measured very precisely with modern geodetic instruments. Expansion is an indication of a relatively slow rise of magma into a magma chamber or from this into the upper crust, which precedes many volcanic eruptions (Fig. 13.22). Tilt and distance measurements have also been used successfully in much more difficult terrain (steep slopes, covered with loose material or glaciers etc.), such as on Mount St. Helens (370) and Etna. A spectacular example of uplift and accompanying graben formation occurred during the 2000 eruptions of Usu Volcano in Hokkaido (225, Figs. 1.10, 13.19).

Degassing

The amount and/or composition of gases that are released from a volcano (Fig. 13.23), can change prior to an eruption. SO_2-emissions may increase months or years prior to volcanic eruptions. New undegassed magma appears to have risen into the upper crust releasing gases without immediately erupting lava or tephra. On the other hand, CO_2-emission can drastically decrease a few days prior to an eruption, such as prior to the Pinatubo eruption (see below). The ratio of F/Cl may be another useful indicator to monitor volcanic activity. The acid HF may impact strongly on the environment due to its excellent solubility in water and its rapid adsorption on ash particles or vegetation. Adsorption on vegetation is a serious problem to agriculture in areas that are subject to volcanic gases for long periods.



◄ Fig. 13.22. Measuring the degree of inflation of the surface of Kilauea volcano (Hawaii) in 1970 with laser geodimeter

▼ Fig. 13.23. Late Werner Giggenbach, famous gas-geochemist, using the Giggenbach bottle to sample gases rising from a mineral spring in the Eifel (Germany)

▶ Fig. 13.24. Measuring temperature in a hot block that traveled with a pyroclastic block flow on the slopes of Augustine volcano in 1976 (Alaska)

Heating

Measuring temperature is a standard monitoring technique in active volcanoes (Fig. 13.24). A volcano is heated up only slowly, however, when new magma is emplaced into its interior. A rise in temperature can be measured directly in the surface soils or via infrared monitoring by aircraft or satellite. There are commonly indirect effects of ground heating, such as the increasing temperature in springs near a volcano, sudden melting of snow or change in the magnetic field.

Remote Sensing

The rapid development in remote sensing by satellites during the past two decades has greatly increased the potential to monitor volcanoes in the entire electromagnetic spectrum. Remote sensing is simply detection and measurement of electromagnetic radiation emitted from the surface of a volcano, by lava flows or by ash clouds rising above it (100, 296). The sensor can be fixed to the ground or be installed in a plane or satellite. The radiation can be reflected sunlight, as in a photographic image, heat as in the case of a thermal infrared receiver, or the reflected pulse from a radar system that bombards a volcano with microwave energy.

Remote sensing not only compliments ground observations and monitoring using conventional methods, but also offers entirely new methods such as detection of crustal deformation via synthetic aperture-radar. For most volcanoes not monitored on the ground, satellite-based remote sensing is the only possibility to rapidly acquire data on the precursors of eruptions and also the subsequent eruptions themselves.

Satellite-based volcano monitoring presently focuses mostly on eruptions in progress, including monitoring of ground deformation, thermal changes, and various parameters of eruptive columns. Since about 1980, measurement of SO_2 emissions of volcanoes has been carried out using the TOMS (total ozone mapping spectrometer) instrument on the Nimbus-7 and Meteor-3 satellites. This method is ideal to estimate SO_2 fluxes during an eruption, as well as estimating global mass fluxes of volcanic SO_2. The importance of sensors in the visible part of the electromagnetic spectrum is limited because of the common cloud cover of volcanoes. Radar satellites, by contrast, allow signal reception during any type of weather, but they cannot register thermal radiation. Multispectral sensors with high areal resolution are less suitable for repeated monitoring of volcanoes than sensors with a lower resolution.

Many new developments are currently under way, however, be it new satellites or, more importantly, the development of computer-based methods that are able to digest and interpret the huge amount of data. There is always some delay in monitoring actual eruptions. The other problem is the enormous cost. Like all monitoring techniques, possible precursors for an imminent volcanic eruption can only be estimated realistically when background behavior is known. In other words: a volcano must be observed over some time to recognize significant deviations from its "normal state".

Extinct Volcanoes?

One of the most common questions asked by laypeople and journalists centers around the problem whether or not a certain volcano can be regarded as extinct. Such questions are very difficult to answer. As discussed above, several apparently extinct volcanoes have caused catastrophes by their unexpected re-awakening. Volcanoes and volcano fields can be active for millions of years with relatively short periods of volcanic activity alternating with long periods of quiescence (hundreds, thousands or millions of years).

There are no precise or generally accepted definitions for the terms *active volcano*, *sleeping* or *dormant volcano* and *extinct volcano*. All volcanoes that have erupted within the past 10 000 years are commonly regarded as active (338). The recent (2002) adoption of this age limit by the Japan Meteorological Agency has resulted in the "increase" in number of active volcanoes in Japan from 86 to 109, previous definitions being based on an upper age limit of 2 000 years B.P.. Sometimes, all volcanoes that erupted since the boundary between the late Pleistocene and Holocene (in Central Europe the Holocene started about 11 000 years ago) are defined as active. The geological boundary between the last ice age and the Holocene was chosen as it is often easy to define. To use such definitions, however, one has to distinguish between different types of volcanoes; for some either definition would be misleading.

The most important criteria for regarding volcanoes as extinct or dormant, are the total lifetime of a volcanic complex or volcanic field and the overall frequency of individual eruptions. This requires very precise analysis to arrive at reasonable estimations of the probability of future eruptions. We can visualize periods of years, decades and possibly hundreds of years. But even geologists, who are familiar with geological dimensions (i. e., with the past 4.6 billion years) often resort to the perception of non-specialists and regard volcanoes that have not erupted for several generations as extinct.

The significance of this problem becomes very obvious with respect to long-term storage of nuclear waste. Billions of dollars have already been spent to prepare the storage area for all nuclear waste generated in the US at Yucca Mountain (a huge cave system dug into Tertiary ignimbrites in Nevada). The age of the youngest scoria cone, Lathrop Wells, 15 km south of the storage area, is about 0.07 – 0.1 million years. This has to be compared to a period of 10^4 to 10^5 years until the radioactivity of high-level waste has decayed. The question of whether or not volcanic eruptions may occur in the area of the deposit is therefore crucial to the final decision to house waste at Yucca Mountain (65).

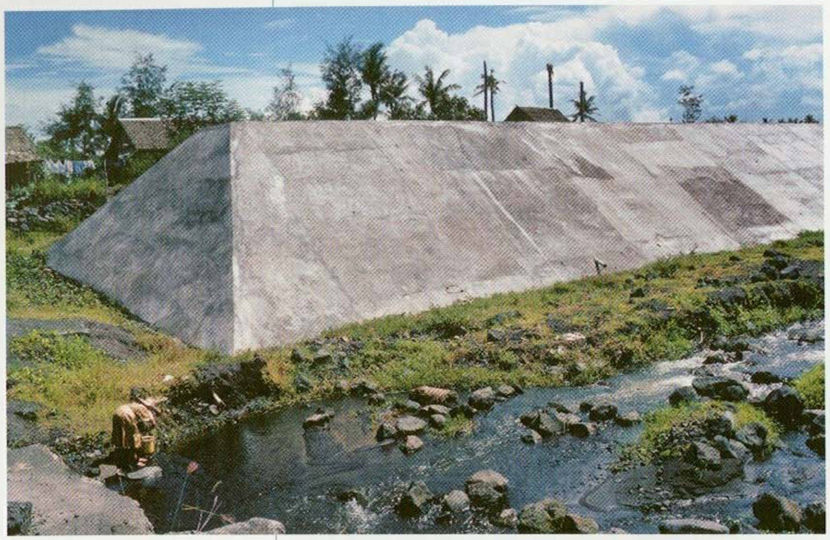
Volcanic Hazard Mitigation

Volcanic eruptions cannot be influenced by man now or in the foreseeable future. They are governed by processes that start deep in the Earth and that may reach into the stratosphere. When a volcanic catastrophe occurs, the reasons are often rooted in society itself. There are, however, limited possibilities to reduce some of the effects of volcanic eruptions.

Most important is to define hazard zones, which are based on a very detailed analysis of the early history of a volcano, as well as an estimate of the possible scale and nature of eruptive processes at a particular volcano. Each volcano behaves differently, requiring careful analysis of the local factors.

The path of some lava flows can be influenced slightly by building barriers, unless they flow with high velocity and/or high effusion rates. This has been done on Etna volcano in Sicily several times, but the success has been limited (51). An ingenious method was attempted to slow a lava flow on the Icelandic island of Heimaey. The flow was about to close the entrance of this important fishing port. The Icelanders sprayed the advancing lava flow front with copious amounts of seawater so that it would cool and build itself a barrier, which it could not overcome (419). After months of water spraying, the flow stopped. It was not clear, however, whether the water stopped the flow progress or whether it was a drop in effusion rates as the eruption finished. In any event, the cost of rebuilding the town itself would have been several times the cost of spraying, including the large pumps ships brought in to assist.

Two principal types of *sabo dams*– a Japanese term literally translated meaning *sand protection*– are installed on the slopes of many volcanoes in Japan, a country characterized by steep mountains, high precipitation and many young and active volcanoes. Sabo dams are generally built at right angles to the drainage. Many thousands of such dams have been built on Japanese mountains, including practically all major volcanoes. They break the velocity and, therefore, the erosional energy of mass transport down steep drainage paths, and act as temporary sediment traps. They include massive concrete structures or more modern rock dams (Figs. 13.25 – 13.27), and some are augmented by video cameras or wires to monitor advancing lahars or pyroclastic flows. During the 2000 eruption of Usu volcano (Hokkaido, Japan), sabo dams were effective sediment traps for lahars (Fig. 13.27), preventing more extensive damage to buildings. Sabo dams at



▲ Fig. 13.25. Lateral dike protecting a village at the foot of Mt. Mayon (Philippines). Lahars commonly rush through this valley (see also Fig. 13.4)

Sakurajima volcano in Japan are also monitored by video cameras, or other optical devices and wire sensors devices. *Dikes* parallel to valleys have been constructed on several volcanoes in Japan, Indonesia and the Philippines to direct the course of block-and-ash flows and lahars. This can be effective at least for small-volume lahars. Dikes and sabo dams are most effective on volcanoes that erupt frequently, such as Mount Mayon (Philippines), and Merapi (Java), Tokachi (Japan), or Sakurajima (Japan), where the channels used by volcanic mass flows are well-known and the individual eruption volumes relatively small. Sabo dams are not effective when the flow volumes are very large, e.g., when glaciers or snow melt. Moreover, sabo dams and dikes are very expensive to build.

Temporary lakes commonly form during an eruption by very rapid accumulation of large masses of tephra within river channels. These tephra dams are naturally very unstable and can collapse easily as shown by the examples of Asama and Laacher See volcanoes discussed earlier in this chapter. Countries that can afford the expenditure thus spend much money to drill tunnels through such natural dams, as was the case following the eruption of Mount St. Helens in May 1980. A very instructive example of how to control the effects of volcanic eruptions is Kelut volcano in Indonesia. This volcano ejected its crater lake during each eruption, which led to the formation of catastrophic lahars on its densely populated flanks. An eruption in 1919 killed more than 5 000 people. To prevent a further catastrophe, tunnels were dug to significantly lower the lake level. There were only seven fatalities during the next eruption in 1951. In the 1960s, a large water volume re-

► Fig. 13.26. Aerial photograph of Lake Toya, town of Toya and two of the more than 60 craters formed during the almost entirely phreatic eruptions in 2000. Several sabo dams on the outskirts next to the town proved very useful to retard the advance of lahars which destroyed several houses on the outskirts of Toya. Recent Showa Shinzan dome in background, main crater of Usu dome complex at right and site of enlargement of sabo dam (arrow) shown in Fig. 13.27. Photo courtesy Hokkaido Regional Development Bureau mained in the crater. Zen and Hadikusumo (441) voiced concern of another catastrophe during the next eruption, which they thought would occur in the next five years. These fears were sadly verified. Kelut erupted in the spring of 1966 with lahars killing some 200 people. New tunnels were dug and when the volcano erupted in 1990, no people perished by lahars, although 32 lives were lost when buildings collapsed as they became overloaded with tephra (Smithsonian Institution 1990).

Near-vent areas most prone to volcanic impacts can be relatively easily delineated. These include notches in the upper part of a volcano and major valleys down its flanks. Thus *mitigative measures* (such as evacuation and land-use restrictions) can be carried out in time to minimize losses. At greater distances from volcanoes, it is possible to evacuate people early enough in well-monitored volcanoes. Warning periods of several hours, days or weeks in many cases can be achieved. A challenge with scientific monitoring is to provide important volcano status information and predictions in a form understandable to non-specialists. Other formidable tasks are to convince local authorities of the threat and to distribute timely and accurate information in leaflets, print and electronic media. Plans for evacuating people in case of imminent danger must be worked out in detail ahead of time. The communities must also be informed of fundamental aspects of evacuation scenarios and on the mitigative actions that they themselves can carry out. It is useful to carry out community disaster training as is done at regular intervals around the almost permanently active Sakurajima volcano in Japan.

The issues of disseminating scientific warning information effectively came to a head following the catastrophic results of the eruption of Nevado del Ruiz in Colombia on 13 November 1985. Among the several contributing factors to this disaster was a failure to effectively communicate warnings to administration and emergency management authorities. Following several discussions, IAVCEI along with UNESCO produced a video, in which volcanic hazards and their impacts are explained and portrayed very drastically. Maurice and Katia Krafft (both of whom perished in June 1991 at Unzen volcano) took a major role in preparing this video. It was ready in early 1991 when Pinatubo (Philippines) started to show signs of unrest in April 1991. This video was quickly distributed and shown with great success during education and warning programs in many villages surrounding Pinatubo. Newhall (pers. comm., 1991) estimates that up to 10 000 lives may have been saved because the willingness of people to become evacuated rose significantly after having seen the video.

▲ Fig. 13.27. Enlargement of sabo dam by rock fill on the flanks of Usu volcano near Toya following the eruption in 2000

The main risk management problems encountered during eruptions of Mount St. Helens (1980) and Pinatubo (1991) were (251):

- the time for monitoring, data analysis and dissemination of warnings was very short (in each case 2–3 months prior to the large eruptions)
- the skeptical attitude of the local administration and other local authorities and also the general public. Purely scientific arguments were not very effective
- the unrealistic public expectation of how accurately volcanologists were able to predict an eruption. The public expected simple answers, not the discussion of different possible scenarios
- the necessity to work on the main types of hazards close to a volcano meant that risks at larger distances were neglected
- extreme pressure was exerted on volcanologists to provide accurate and timely warnings as well as to make decisions on predictions and evacuations. Along with emergency management officials, volcanologists were extremely overworked during weeks prior to an imminent eruption. This had the potential to lead to mistakes or poor decisions in some cases
- the manpower, financial support, and monitoring systems or equipment were often insufficient or delayed until after the main phase of activity.

Lessons Learned From Two Large Volcanic Eruptions

Two recent major volcanic eruptions show dramatically how catastrophes either develop (Nevado del Ruiz), or can be avoided (Pinatubo).

Nevado del Ruiz

Precursors and Early Stages

Eruptions of Nevado del Ruiz had generated lahars with catastrophic results already in A.D. 1595 and 1845. The town of Armero was built 72 km east of the crater of Ruiz in the 1930s, on the deposits of the largest lahars of 1845. Steam eruptions of the volcano were noticed in late 1984. The activity increased slowly during the next few months. A stronger eruption on 11 September 1985 generated a lahar that flowed 27 km. Teams of volcanologists from several countries studied the volcano and reached the conclusion that a large eruption was very likely (147, 402). Lahars generated during such an eruption could flow as much as 100 km. The teams suggested:

- a hazard map for Ruiz (Fig. 13.14) to be published in the local press (done on 10 November 1985). The zones of maximum hazard on this map strongly resemble the actual distribution of lahars of 13 November 1985
- a delineation of safe areas, into which the population could be evacuated in case of a likely catastrophe
- permanent visual monitoring of the volcano
- constant communication with the areas in danger to relay warnings immediately after the onset of an eruption (20).

Course of the Eruption and Effects

Following weak explosions on the afternoon of 13 November 1985, a stronger eruption started in the evening. Hot surges started to melt the ice and snow caps on the summit of the volcano. Descending melt-waters eroded and incorporated loose debris along their path. Local radio stations asked the people to remain calm and stay indoors because of the possible ash fallout from the eruption. An order of evacuation made by the Red Cross never reached the town of Armero. The first lahars arrived in Armero one and a half hours after the strongest eruption. People in the town were fully unprepared and three quarters of the population of Armero did not survive the catastrophe (Fig. 13.28).

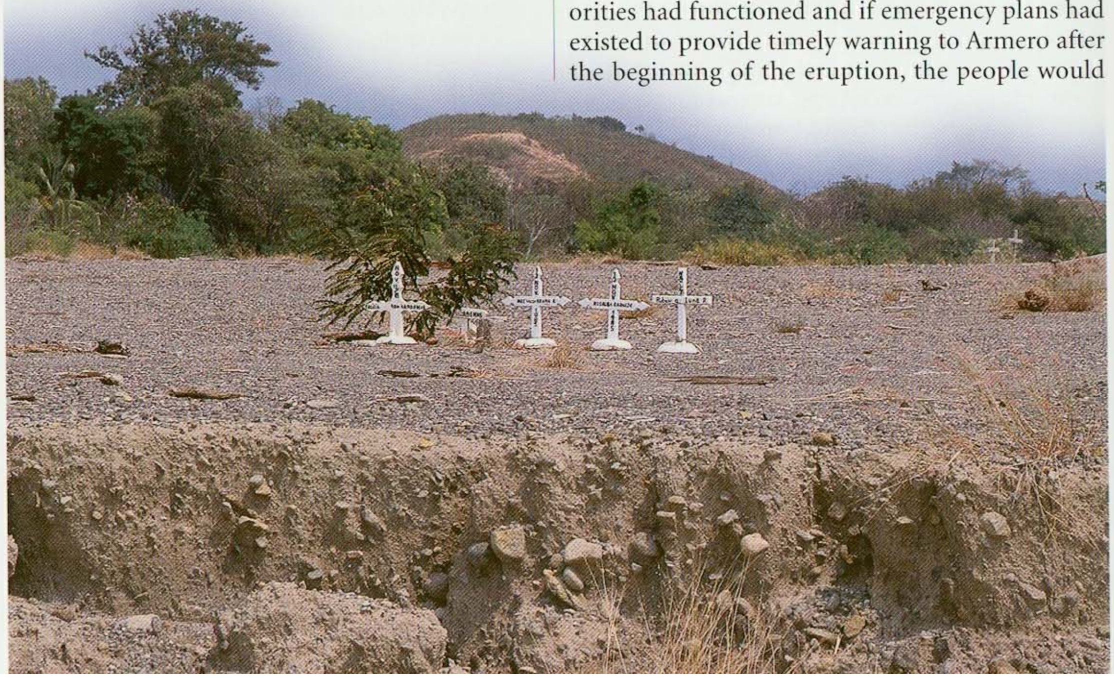
Nevado del Ruiz (Colombia) (Figs. 13.14, 13.28)

Location: Colombia
Elevation: 5 390 m a.s.l.
Glacial cover: glacier cap with an areal extent of $25\ \text{km}^2$ prior to November 1985
Characteristic activity: highly explosive pyroclastic flows, lahars, volcanic debris avalanches
Rock composition: andesitic-dacitic
Tectonic position: subduction zone
Date of eruption: 13 November 1985
Major historic eruptions: 1595, 1845
Recent eruptions: several smaller eruptions since 1985
Was the volcano known to be dangerous? Yes
Were warnings published? Yes
Were emergency plans ready? No
Were there indications of an imminent eruption? Yes
Was the catastrophe avoided?
No. Approx. 23 000 fatalities (1985)
Damage: 5 092 houses, 50 schools, 2 hospitals, 58 factories and ca. 3 400 ha agricultural land were destroyed by lahars (total value exceeding US$ 1 billion)
Is the volcano now monitored? Yes

Nevado del Ruiz has remained active following the eruption of 13 November 1985 and is now monitored more closely. On several occasions since 1985, thousands of people were ordered to evacuate from areas near the volcano. However, despite the tragic example of Armero, most people did not want to leave their homes.

Lessons to be Learned

If the communication between scientists and authorities had functioned and if emergency plans had existed to provide timely warning to Armero after the beginning of the eruption, the people would



▶ Fig. 13.28. Debris flow deposit, about 1 m thick, laid down by the lahar that devastated the town of Armero following the eruption of Nevado del Ruiz (Colombia) on 13 November 1985. About 23 000 people were killed by the lahar. The area has been declared a national cemetery by the Colombian government have had one hour to leave the dangerous zone. Although the town would have been destroyed, losses of live could have been minimized.

In areas at larger distance from well-monitored volcanoes, warnings can be issued up to several hours before impact, so that people can be brought into safety relatively easily. The lack of such monitoring at Nevado del Ruiz was the reason that a timely warning of the approaching lahars did not reach the town. It is also tragic that the administration of Armero did not take seriously the earlier general warning issued by geologists. On the other hand, the town should have never been built at this place, because of the previous inundation by even larger volcanic debris and mudflows in 1595 and 1845.

In hindsight, Voight (402) listed the main steps that would have helped to avoid the catastrophe of Nevado del Ruiz in November 1985:

- recognition and documentation of the hazard
- preparation of a priority list of the vulnerable elements, communities and areas
- open public discussions of the scientific risk assessments, despite social anxiety
- early planning of critical decisions, since time is the most important variable
- early testing of the warning system to check its reliability
- early assessment of possible technical problems of warning systems
- careful integration of different types of media for public announcements.

Pinatubo

Precursors and Early Stages

On 16 July 1990, an earthquake with a magnitude of 7.8 occurred about 100 km northeast of Pinatubo, along the large Philippine fault. This may have influenced the magma reservoir beneath Pinatubo at a depth of 9–11 km. In hindsight it became clear that there had been weak signs of reawakening of the volcano for many years, and thus an imminent eruption. The signs included changes in the composition and temperature of the hot springs, increasing fumarolic activity, chlorine-rich, strongly acid fluids in geothermal wells (1988–1990), which, because they were not productive, had been terminated.

Two and a half weeks following local earthquakes, steam explosions on 2 April 1991 showed that Pinatubo had re-awakened. From late April to early June, the oldest deposits of Pinatubo were studied by a crash team, mainly from the US Geological Survey, and quickly dated. It became clear that larger eruptions had also occurred in the recent past, in which voluminous pyroclastic flows dominated. Past events were separated from each other by hundreds to thousands of years. The amount of SO_2 emitted rose from 500 t/d on 13 May to more than 5 000 t/d on 28 May. Together with permanent seismic activity, these data suggested that magma had risen beneath Pinatubo to such a height that its volatiles could be released as a free gas phase. In the preceding weeks, the rising SO_2 was probably dissolved in groundwater, so that a strong SO_2 emission may have reflected a vaporization of the hydrothermal system in the interior of the volcano. On 1 June, earthquake hypocenters

Pinatubo (Philippines)

Pinatubo based largely on papers in the excellent volume by Newhall and Punongbayan (251) (Figs. 13.29, 13.30)

Location: Philippines, Luzon Peninsula, about 120 km northwest of Manila

Altitude: 1 745 m a.s.l. prior to, 1 485 m a.s.l. after the eruption

Volcanic history: active at least during the past 30,000 years. Non-eruptive intervals lasting from a few hundreds to several thousands of years

Characteristic activity: highly explosive, pyroclastic flows, lahars, debris avalanches

Rock composition: dacite, partly hybridized by mixing with basaltic magma

Tectonic position: part of a chain of compound volcanoes that form the Luzon volcanic arc, about 100 km east of the eastward dipping Manila subduction zone

Date of eruption: 15 June 1991

Earlier prehistoric eruptions: Unknown

Population on the volcano flanks: 30 000 people near the volcano and a further 500 000 in towns and villages on the ring plain that surrounds the volcano. The US Clark Air Base was 25 km east of the volcano and the US Subic Bay Navy Base about 40 km to the southwest

Post-1991 eruptions: minor intermittent eruptions

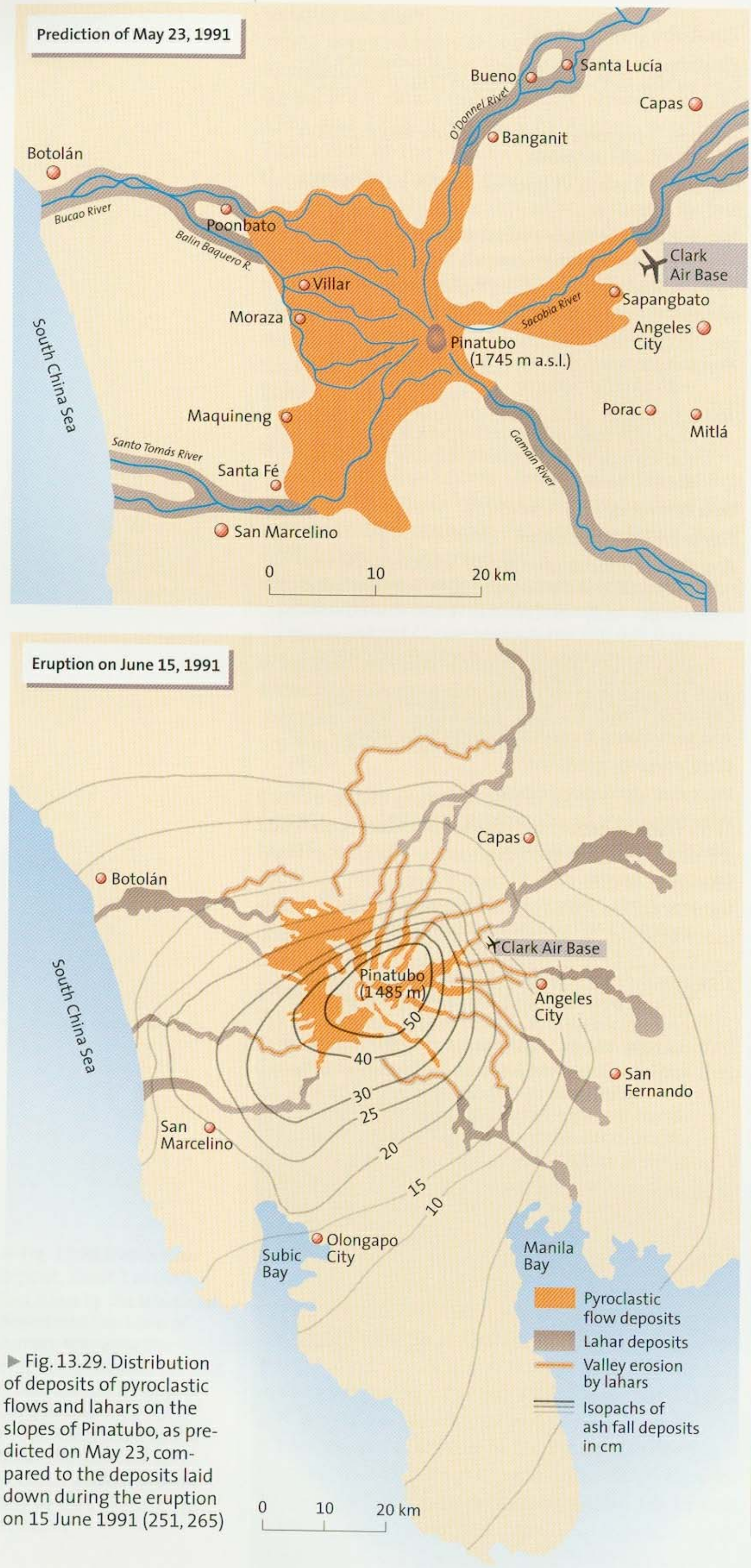
Was the volcano known as potentially dangerous?	No
Were warnings published?	Yes
Were emergency plans ready?	Yes
Were there signs for an imminent eruption?	Yes
Was the catastrophe avoided?	Yes

Fatalities: Approx. 350

Damage (1991–1992): 8 300 houses destroyed completely, 73 400 partially; economic loss totaling more than US $ 700 million

How was the catastrophe avoided? Good communication between scientists and administration, emergency plans were ready and timely warning was possible. Strong logistic support by the American and later Philippine Air Force. Difficulties in communication were mostly due to the isolated position of the large volcanic complex and different administrative districts with differing political agendas and allegiances

Is the volcano now monitored? Yes



▶ Fig. 13.29. Distribution of deposits of pyroclastic flows and lahars on the slopes of Pinatubo, as predicted on May 23, compared to the deposits laid down during the eruption on 15 June 1991 (251, 265)

were registered between the surface and a depth of about 5 km, about 1 km northwest of the summit. These earthquakes probably formed because the rising magma was opening a vent between the magma reservoir and the summit. At the same time, the SO_2 emission rate decreased from 1 800 t/d on 30 May to 1 300 t/d on 3 June and 600 t/d on June 5. On 3 June seismicity under the volcano increased, small ash eruptions occurred and a brief period of harmonic tremor was registered. In addition, the outer flanks of the volcano started to swell. On 5 June warning level 3 was announced with the possibility that a larger eruption with pyroclastic flows could occur within the next two weeks. On 6 and 7 June, the precursors intensified, steam clouds rose on June 7 to 8 km. Warning level 4 was announced with the possibility of a large eruption within the next 24 h; more people were evacuated. On 10 June, 14 500 people were evacuated from Clark Air Base. Following the first larger explosive eruption on 12 June the main radius for evacuation was extended to 30 km; the total number of evacuated people rose to about 60 000. Three days later, the largest volcanic eruption in the second half of the twentieth century occurred, topped only by the eruption of Novarupta volcano (Katmai) during which more magma (ca. 13 km^3) was expelled.

Cause and Effect of the Eruption

After the start of the eruption on 15 June, the instruments stopped working at 13:42 h, because they had become saturated. Ash and pumice fragments, up to 4 cm in diameter fell at 14:30 h on Clark Air Base. Satellite data showed that the eruption column had reached the stratosphere at 15:40 h with a diameter of 400 km and a height of 35 km in the center and 25 km on its eastern margin. The main phase of the eruption began to decrease slowly after 3 h. The climactic eruption had come to an end at 22:30 h. The collapse of a caldera probably began at 16:30 h and lasted until 20:30 h. Sporadic small ash eruptions occurred until early September. A lava dome grew inside the caldera from July to October 1992.

Unfortunately, the eruption occurred when taifun Yunya had just reached the Luzon Peninsula on 15 June. The load of water-saturated ash falls caused many roofs to collapse, including hangars on Clark Air Base. Fallout pumice and ash fell simultaneously with ash flows, which had proceeded through the valleys. The tephra fall volume was estimated as 3.4 – 4.4 km^3, that of the ignimbrites as 5 – 6 km^3.

The ethnic group of the Aeta that lived on the forested slopes of Pinatubo was completely uprooted. They lived from wild fruit and animals and had their own specific religion. The two