Chapter 1

THE NATURE OF VOLCANIC HAZARDS

Volcanic eruptions are among the most awesome and most feared of natural phenomena. Myths, legends and recorded history abound in testimonies to their destructive power, and the geological record shows that volcanic processes have been important throughout the earth's history. These processes continue at the present time, often with profound effects on human life and activity.

Figure 1 shows the world-wide distribution of volcanoes. More than 500 have been active in historical times. There are also many hundreds of others now dormant which show evidence of eruptive activity in the recent pre-historic past. Some of these will undoubtedly erupt again; eruptions have also occurred at volcanoes previously thought to be extinct. In addition, entirely new volcanoes are formed from time to time within volcanic zones.

Molten material within the earth's crust is called magma. It is a complex mixture of silicates, containing dissolved gases and sometimes crystallized minerals in suspension. When it works its way up towards the surface, the pressure decreases and this enables the dissolved gases to effervesce, driving the magma upward through the volcanic vent. The degree of violence of the eruption is determined mainly by the amount and rate of effervescence of the gases and by the viscosity of the magma itself.

Eruptions vary widely in magnitude and duration, not only from one volcano to another but even at the same volcano. The frequency of eruptions also varies, from volcanoes which are in almost continual eruption to those which erupt only at intervals of hundreds or even thousands of years.

In general, the volcanoes of the major rift systems (including the mid-Atlantic and East African rifts) or mid-oceanic upwellings (such as Hawaii) produce lava of a low viscosity which flows easily and may spread over large areas, either in broad sheets or in long narrow lobes. In contrast, the volcanoes of the great subduction zones around many ocean margins usually emit lava of high viscosity which tends to build up into domes or to form relatively short, thick flows. Furthermore, the high viscosity of the magma within these volcanoes allows high gas pressures to build up, so that when the gas is finally released its expansion is explosive, and it carries with it large amounts of solid or molten lava in suspension. All varieties of eruptive behaviour are observed, from the quietly effusive to the violently explosive, depending mainly on the composition and gas content of the magma.

Volcanoes affect the lives of people in both negative and positive ways. Any volcanic eruption, whatever its degree of violence, can be dangerous to people in its neighbourhood. Yet, during their periods of inactivity, volcanoes attract human settlement because of the fertility of volcanic soils and the often spectacular beauty of volcanic landscapes. Large numbers of lives and large economic investments may therefore be at risk when an eruption occurs.

Most eruptions are preceded by premonitory signs which, if recognized and heeded, can give timely warning of the impending events. However, these signs may be subtle or complex, and may demand careful and detailed study before they can be interpreted correctly. Some of history's greatest catastrophes have been caused by eruptions whose early signs were unrecognized, misunderstood or ignored.

One cannot abandon or prevent all settlement of the areas where volcanic hazards exist; what is important is to learn to live with them as safely as possible. For this, it is essential to know each volcano's history, the frequency and character of its eruptions, and to understand the process which leads up to them.

The principal products of volcanic eruptions may be grouped into several broad categories according to the type of material ejected and its mode of transport from the vent to its place of deposition. These are: ash falls, pyroclastic flows, lava flows, and gas emissions.

Several other hazardous phenomena are directly associated with eruptions : e.g. ground fracture, ground subsidence (sudden or gradual), debris avalanches, mudflows (lahars), glacier bursts, volcanic earthquakes and tsunamis. In this volume we shall focus attention only on those which pose sudden and urgent threats to life or property i.e. ash falls, pyroclastic flows, mudflows, lava flows and tsunamis. The loss of life resulting from these phenomena in the more disastrous historical occurrences is given in table 1. Volcanic earthquakes frequently precede or accompany eruptions but by themselves are rarely of sufficient magnitude or intensity to cause severe damage. Famine has sometimes resulted from the destruction of crops by ash falls or by loss of farm animals killed by toxic volcanic gases or deposits.

TABLE 1

Volcanic disasters since 1700 involving a thousand or more fatalities

Volcano	*Country*	*Year*	*Primary cause of fatalities* *Pyroclastic flow*	*Mudflow*	*Tsunami*	*Famine*
Awu	Indonesia	1701....		3 000		
Oshima-Oshima	Japan	1741....			1 475	
Cotopaxi	Ecuador	1741....		1 000		
Makian	Indonesia	1760....		2 000		
Papandajan	Indonesia	1772....	2 957			
Laki	Iceland	1783....				9 336
Asama	Japan	1783....	1 151			
Unzen	Japan	1792....			15 188	
Mayon	Philippines	1814....	1 200			
Tambora	Indonesia	1815....	12 000			80 000*
Galunggung	Indonesia	1822....		4 000		
Mayon	Philippines	1825....		1 500		
Awu	Indonesia	1856....		3 000		
Cotopaxi	Ecuador	1877....		1 000		
Krakatau	Indonesia	1883....			36 417	
Awu	Indonesia	1892....		1 532		
Soufrière	St. Vincent	1902....	1 565			
Mt. Pelée	Martinique	1902....	29 000			
Santa María	Guatemala	1902....	6 000			
Taal	Philippines	1911....	1 332			
Kelud	Indonesia	1919....		5 110		
Merapi	Indonesia	1951....	1 300			
Lamington	Papua New Guinea	1951....	2 942			
Hibok-Hibok	Philippines	1951....	500			
Agung	Indonesia	1963....	1 900			
			61 847	22 142	53 080	89 336
TOTAL FATALITIES..........................			226 405			
Percentage..............................			27	10	23	40
Percentage, excluding famine.............			45	16	39	

* This is the estimated life loss through famine as a direct result of the destruction of crops by volcanic ash fall over a wide area in Indonesia It does not include losses through famine in other parts of the world due to severe climatic abnormalities during the summer of 1816, which were attributed to the "dust veil" caused by volcanic ash in the stratosphere

1.1 Ash falls

CHARACTERISTICS

Explosive eruptions occur when gas expands suddenly as it escapes from magma, or when surface or ground water is abruptly vaporized by contact with hot magma. The magma is shattered into liquid and solid fragments, which are blasted upward from the vent to form a column or cloud of airborne material, of which the finer particles drift with the wind. The larger fragments fall out quickly on the area close to the volcano. Smaller fragments travel greater distances, and the fine dust may be carried many hundreds or even thousands of kilometres downwind.

Ash falls vary widely in volume and intensity. The volume of pyroclastic material ejected and deposited during some large eruptions in the past has reached tens and even hundreds of cubic kilometres, but events of this magnitude are rare and during historical times most ash falls have been of much smaller volume, generally less than one cubic kilometre.

Ash falls may occur simultaneously or alternately with other eruptive phenomena. In particular, they often accompany pyroclastic flows (see below) and ash fall material is often found in the upper layers of pyroclastic flow deposits.

Ash falls are perhaps the most common of all eruptive phenomena; almost every volcano emits some material of this kind. In circum-oceanic (subduction zone) volcanoes, they usually represent a high proportion of all material emitted; in contrast, they represent only a small proportion of the material emitted by mid-oceanic (rift zone) volcanoes.

EFFECTS ON LIFE AND PROPERTY

Ash falls vary widely in their effects, depending mainly on the volume of material erupted and the duration or intensity of the eruption. Clouds of air-borne dust and small particles may remain in the atmosphere for long periods (days or weeks) and may spread over great distances (hundreds or thousands of kilometres). Indeed, fine material from some great eruptions has been observed to travel round the world at high levels in the atmosphere and has had detectable effects on world climate.

In the neighbourhood of an erupting volcano, heavy ash falls may cover agricultural land, destroying crops or rendering the land temporarily unworkable (figure 2). Ash accumulating on the roofs of houses may cause them to collapse (figure 3). Even though most fragments have cooled enough to solidify before reaching the ground, some may still be hot enough to start fires. Dust in the air may make breathing difficult for both man and animals. It may also contain toxic chemicals, such as fluorine, which can contaminate water supplies or poison grazing land. However, although ash falls often cause widespread inconvenience, they have never been directly responsible for major loss of life in historical times, and represent a much less serious hazard than certain other eruptive phenomena.

EXAMPLES

In historical times, thick and widespread ash falls have been associated with many eruptions, including those of Vesuvius (Italy) in A.D. 79 and 1906, Tambora (Indonesia) in 1815, Krakatau (Indonesia) in 1883, Paricutín (Mexico) in 1943-52, Hekla (Iceland) in 1947-48 and 1970, Mt. St. Helens (USA) in 1980, El Chichón (Mexico) and Galunggung (Indonesia) in 1982.

During the major eruptive climax at Mt. St. Helens on 18 May 1980, the vertical eruption column rose rapidly in a series of pulses. It reached a height of over 18,000 metres within ten minutes, and of 27,000 m after 30 minutes. As more and more ash was pumped upwards in turbulent clouds, these began to drift downwind, gradually dropping their load of sand- and dust-sized particles. Within six hours of the eruption onset, the clouds had travelled 400 kilometres downwind, creating near-total darkness and causing breathing difficulties for people and animals unable to take cover indoors. Road traffic was brought to a standstill because drivers could not see where they were going and because engine air filters became choked with fine dust. Air traffic was similarly threatened: aircraft windshields were sandblasted and leading edges of wings stripped of paint. Radio communication was lost. In the downwind sector, which widened with increasing distance from the volcano, the whole countryside was blanketed with ash; at a distance of 40 km from the volcano, it was 7 cm thick.

The volume of ash erupted vertically from Mt. St. Helens during the climax of 18 May 1980 is estimated to have been equivalent to about one quarter of a cubic kilometre of magma. This eruption was small in comparison with the world's largest historical eruption, that of Tambora in Indonesia in 1815, which emitted several tens of cubic kilometres of ash and fragmented material, and which loaded the earth's stratosphere with so much fine dust that there were widespread effects on the climate in many parts of the world. According to reliable geological reconstructions, the largest prehistoric eruptions were as much as ten times greater than that of Tambora.

1.2 Pyroclastic flows

CHARACTERISTICS

Some explosive eruptions produce horizontally directed, rapidly moving blasts of gas containing ash and larger fragments in suspension, called pyroclastic flows. This term is used here to cover the various related phenomena described by different authors as glowing avalanches, glowing clouds, *nuées ardentes,* ash flows, pumice flows, etc. It also covers various kinds of pyroclastic surge, such as base surge and ground surge.

Because of the heavy load of dust and lava fragments which they contain, these flows are substantially denser than the surrounding air and therefore rush like snow or rock avalanches down the flanks of the mountain (cover photo). They travel at great speed: gas continues to be emitted by the larger lumps of red-hot pumice and ash, and this creates a continuously expanding cloud in which the solid or semi-solid fragments are carried.

Volcanologists have recognized and distinguished between several mechanisms of pyroclastic flow. Glowing avalanches (*nuées ardentes*) are relatively dense, stay close to the ground and are generally confined to valleys. Pyroclastic surges, being of relatively low density, are less confined to valleys and tend to cover broad areas. A third variant is the directed blast, which tears large volumes of material from the upper flanks of the volcano and has an initial explosive, directed, ballistic impetus, but subsequently behaves like the hot pyroclastic flow or surge. The features that characterize all pyroclastic flows are their high speed of movement (up to 540 km/h at Mt. St. Helens in 1980), their mainly horizontal direction and the high temperature (up to 1,000 °C) of the material in suspension. This high speed and coherent nature of the flow mean that some of the material reaches its site of deposition while still very hot, even incandescent or molten; in the latter case it forms a solid crust of welded tuff. Temperatures of more than 700 °C were recorded in pyroclastic flow deposits on the lower flanks of Mt. St. Helens two days after they were emplaced.

Pyroclastic flows vary widely in volume, duration and composition. The largest recent flow was that erupted by Katmai (Novarupta) volcano in Alaska in 1912, which deposited about 7 km^3 of material in what was later called the Valley of Ten Thousand Smokes. Some prehistoric pyroclastic deposits reach hundreds of cubic kilometres. Pyroclastic flows last from a few minutes to a few tens of minutes, but they may be repeated at irregular intervals during eruptions and in extreme cases may continue intermittently for several years.

At volcanoes with summit craters, pyroclastic flows emerge predominantly over the lowest parts of the crater rim and are channelled down the valleys descending from them. Hence the areas of highest hazard can be mapped as a function of the topography of the mountain and especially that of the crater rim. Pyroclastic flows may originate explosively from the volcanic vent or from the partial or complete disintegration of a lava dome, or alternatively may form by the collapse of the outer parts of a vertical eruption column. In all cases, they will follow the easiest routes downhill, and will be channelled mainly down the deeper valleys on the flanks of the volcano. The greatest distances travelled by such flows in historical eruptions have been about 35 km.

EFFECTS ON LIFE AND PROPERTY

Pyroclastic flows are the most lethal and destructive of all volcanic phenomena: they burn and destroy everything in their path (figures 4 and 5). The chance of any form of life surviving the direct impact of a pyroclastic flow is virtually nil; the effects of concussion, impact of suspended material, suffocation and intense heat, individually and in combination, are deadly. However, some people have survived exposure to the fringes of such flows.

The effects on buildings and structures are equally devastating. Those in the direct path of the flow are destroyed and buried; those to the side or just beyond the range of the flow are blasted, abraded and severely damaged.

Pyroclastic flows often remove completely the forest vegetation from the flanks of the volcano, uprooting and stripping the branches and bark from fully-grown trees, sweeping them downslope and snapping them like matchsticks.

Pyroclastic flows constitute a significant part of the activity of volcanoes of the circum-Pacific subduction zones and the West Indies. They are less common at volcanoes in the mid-oceanic and continental rift zones, although large prehistoric eruptions of this kind have been identified from deposits in the Canary Islands, Ethiopia, and one mid-continental area (Yellowstone) of the USA.

EXAMPLES

One of the most destructive examples of pyroclastic flow is that which wiped out the town of St. Pierre in Martinique (French West Indies) on 8

May 1902, killing 29,000 people. Large, hot pyroclastic flows of magmatic origin also occurred during the eruptions of Katmai (Alaska) in 1912, Hibok-Hibok (Philippines) in 1951 and Mt. Lamington (Papua) also in 1951. The large clastic flows at Bezymianny (Kamchatka, USSR) in 1956 and Mount St. Helens (USA) in 1980 were emitted as directed blasts which became surges and which were composed mainly of ancient, cold rocks and ash.

During the May 1980 climax at Mt. St. Helens, several pyroclastic flows of glowing avalanche type were also emitted during the eruption of 18 May. More hot pyroclastic flows occurred during the climaxes of 12 June, 22 July and 7 August 1980. The hot pyroclastic flows on 18 May devastated an area of 15.5 km^2, which was much less than the area devastated (about 500 km^2) by the directed blast which contained mostly rock and ice torn from the pre-existing volcanic cone. Among the 24 best-documented eruptions involving pyroclastic flows from other volcanoes, 18 devastated areas of more than 10 km^2, 12 destroyed more than 20 km^2, 4 exceeded 100 km^2 and the largest (Katmai, Alaska, 1912) covered an area of some 750 km^2. From geological reconstructions based on the distribution of pyroclastic deposits, it has been shown that eruptions of enormously larger scale have occurred in several parts of the world in prehistoric times, devastating areas of over 15,000 km^2 in single eruptive episodes, such as that around Lake Taupo in New Zealand which was covered by deposits of this kind about 1,800 years ago. A large area in Southern Kyushu, Japan, was similarly destroyed about 6,300 years ago.

1.3 Volcanic mudflows (*lahars*)

In any eruption producing large amounts of ash and coarse fragments (and that includes most large eruptions), loose material accumulates on the slopes of the volcano, sometimes to a depth of several metres close to the crater.

When heavy rain falls on these loose deposits, they are transformed into a dense but fluid mixture like wet concrete which flows easily downhill. Such mudflows from volcanoes include material, such as lava blocks, much larger in size than the particles found in ordinary mud. Mudflows are particularly common at volcanoes in the humid tropics, and in Indonesia the term "*lahar*" is used to describe them.

The rate of flow depends on the volume and viscosity of the mud, and the slope and roughness of the terrain; it may often reach 50 km/h and in exceptional cases 100 km/h or more. The distance they travel depends on their volume and on the nature of the terrain, but in extreme cases has exceeded 100 km.

Most mudflows are triggered by heavy rain after an eruption has been in progress for some time, but they can also be triggered by any condition that causes large amounts of water to mix with loose material on a volcano, such as the release of water from a crater lake, the rapid melting of snow or ice, or, when material on moderate or steep slopes is already near water-saturation and is vibrated and liquefied by earth tremors. Depending on how and at what stage of the eruption the flow originates, a mudflow may be hot or cold, but it is never hotter than the boiling point of water, although individual, newly erupted rock fragments within the mudflow may be considerably hotter than 100 °C.

Although they are not strictly mudflows in that they may be mainly water with only few solids in suspension, mention should be made of the glacier bursts ("jökulhlaups") that occur during eruptions of ice-capped volcanoes (e.g. Grimsvötn and Katla in Iceland). When eruptions occur beneath an ice cap, huge volumes of water are melted and emerge from under the ice, flooding the areas at the foot of the volcano.

EFFECTS ON LIFE AND PROPERTY

After pyroclastic flows, mudflows are among the most dangerous of volcanic phenomena. Their high density combined with their fluidity means that they are capable of uprooting and destroying virtually everything in their path. When they finally come to a halt they may deposit material tens of metres thick, and in certain cases they have buried entire towns, or changed the courses of large rivers.

Mudflows present a hazard to life not only because they may overwhelm people as they flow down river valleys at speeds of up to several tens of kilometres per hour, but also because, after coming to rest, their deposits are often too deep, too soft and too hot to cross. People may thus be trapped in areas vulnerable to subsequent pyroclastic flows. This was the cause of many of the 1,565 fatalities during the 1902 eruption in St. Vincent, West Indies.

Mudflows are commonest on volcanoes in regions of high rainfall. In the West Indies, three days before the catastrophic eruption of Mt. Pelée in 1902, a mudflow from the volcano overwhelmed a sugar mill near St. Pierre, killing nearly a hundred workers. Volcanoes in Java are particularly noted for the repeated mudflows (locally called *"lahars"*) that have occurred at Merapi, Kelud, Galunggung and elsewhere.

During the 1980 eruption of Mt. St. Helens, mudflows were produced soon after the first explosive climax, when the newly deposited pyroclastic material high on the flank of the volcano mixed with water from melted snow and ice as well as from rivers on the lower slopes. The result was a hot, viscous, muddy liquid which flowed for more than 20 km down the main river channels, sweeping away bridges and houses, and filling the lower parts of the river valleys in which it came to rest (figures 6 and 7).

During the 1877 eruption of Cotopaxi volcano in Ecuador, massive mudflows travelled over 300 km, as far as the Pacific coast, within 17 hours. On 24 December 1953, water which had been accumulating gradually in the crater of Ruapehu volcano (New Zealand) since the 1948 eruption and had formed a lake 600 metres across, breached the side of the crater and generated a mudflow which swept down a river valley and destroyed a railway bridge just two minutes before an express train was due. The train plunged into the mudflow and 151 people lost their lives.

1.4 Lava flows

Characteristics

Lava flows are formed by the molten rock which issues non-explosively from a volcano and spreads by flowing over the surrounding land. The rate of spreading depends on the rate of lava emission, its viscosity, its total volume and on the angle of slope. Highly viscous lava moves very slowly (from a few metres per day to a few metres per hour). It often piles up to form dome-like structures or short, thick flows. The outer surface of such a flow is often blocky in aspect; as the flow moves, blocks on the sloping front and sides split off and roll down, sometimes forming small hot avalanches. Highly viscous flows may range in length from a few tens of metres to several kilometres, in width from a few metres to several hundred metres and in thickness from a fifth to about half their width.

Basaltic lava of low viscosity is produced especially by volcanoes situated in the mid-oceanic rift zones where major slabs of the oceanic crust separate and molten rock emerges from greater depths. It spreads out rapidly either in tongue-like lobes or in broad sheets, depending on the topography of the surroundings (figure 8). Lobe-shaped flows may be several tens of kilometres long and more than a kilometre wide; their thickness may vary from less than a metre to several tens of metres. Sheet flows may cover areas of up to several hundred square kilometres. Advancing fronts of free-flowing lava travel at speeds ranging from tens of metres to tens of kilometres per hour; on steep slopes, low-viscosity lava streams have been observed moving at more than 60 km/hour.

EFFECTS ON LIFE AND PROPERTY

A lava flow, no matter whether of high or low viscosity, destroys virtually everything that cannot move, or be removed, from its path. Areas covered by lava cannot be used or cultivated for many years, but weathering gradually transforms the solidified lava into soil whose richness in minerals makes it extremely fertile.

The rate of movement of most lava flows is slow enough for people and animals to move to safety. On steep slopes fluid lava can move faster than most people can run, and adjacent flows may coalesce, trapping people between them. In general, however, lava flows do not present a great danger to human life.

EXAMPLES

Viscous lava flows from Etna and Vesuvius in Italy have on many occasions destroyed settlements on the flanks of these volcanoes (figure 9). The largest lava flows in recorded history were those from the fissure eruptions in Iceland; the Eldgja eruption of A.D. 950 and the Laki eruption of 1783. In the latter, about 12 km^3 of free-flowing lava spread over an area of several hundred square kilometres. Apart from the destruction caused by the lava itself, great loss of animal life (including livestock) was caused by the acid fumes emitted from the eruptive fissures and deposited on the surrounding vegetation.

One of the most destructive lava flows in recent years was that from Nyiragongo (Zaire) in 1977. Within less than an hour, over 20 million cubic metres of low viscosity lava drained from the lava lake in the summit crater through fractures on the flanks of the volcano and flooded the surrounding countryside, destroying some 400 houses and killing 72 people (figure 10).

1.5 Volcanic gases

CHARACTERISTICS

Volcanic gases are emitted in every eruption. Indeed, it is the release of gas from magma and the expansion of this gas as the magma moves upward towards the surface that triggers most eruptions. While gas is a product of every eruption, whether explosive or effusive, it may also be emitted by a volcano during periods of quiescence. Most eruptions are followed by copious gas emissions which may decline fairly rapidly but which sometimes continue for many years. Some volcanoes, especially those which are repeatedly active, have fumaroles that emit gases continuously.

The composition of the gases varies from one volcano to another and also varies from time to time at a single volcano. Common constituents include water vapour, carbon dioxide, carbon monoxide, sulphur dioxide and hydrogen; others are hydrogen sulphide and other sulphur compounds, hydrochloric acid, chlorine, fluorine and methane. Small amounts of metallic elements, such as mercury and iron, may sometimes be detected.

Effects on life and property

In spite of the essential role played by gases in volcanic activity, they are rarely the direct cause of injury or death. However, they do represent a danger to all living things and, because gas emissions may continue between eruptions, they constitute a permanent risk in the vicinity of active volcanoes. Several of the common volcanic gases (e.g. carbon monoxide) are lethal; even in very low concentrations they can cause distress or discomfort. The non-toxic gases of density greater than air, such as carbon dioxide, can also be dangerous when they collect in low-lying places or in the cellars of houses, and may cause death by suffocation. Prolonged exposure to volcanic gases such as sulphur dioxide, chlorine compounds or fluorine can stunt the growth of plants, and even intermittent exposure can damage crops or forests.

Little is known about the long-term effects on human health of frequent or continuous exposure to low concentrations of volcanic gases. Persons with heart or respiratory difficulties are likely to be more susceptible.

Most volcanic gases are acidic and are corrosive to metals. Hence, in the neighbourhood of active volcanoes, most structures, vehicles and machinery are subject to chronic corrosion unless specially protected.

Examples

On the morning of 20 February 1979, 142 inhabitants of the village of Kaputjukan on the Dieng plateau in Java (Indonesia), alarmed by seismic and volcanic activity of the nearby volcano Sinila, left the village and fled towards the neighbouring town of Batur. The following morning, they were all found dead at the roadside, having unwittingly walked into a pool of carbon dioxide emitted by the volcano and been asphyxiated by this colourless and odourless gas. In Iceland, sheep are sometimes killed in the same way when they wander into hollows in which carbon dioxide has accumulated during eruptions.

Sulphur dioxide is an irritant and hydrogen sulphide is highly toxic. In low concentrations, their strong smells give unmistakable warning of their presence and it is rare for people to be caught unawares by them. In higher concentrations, however, hydrogen sulphide numbs the olfactory nerves and gives the false impression that the gas is no longer present. There have been cases in Japan of mountain climbers and skiers being overcome by hydrogen sulphide fumes in a valley near the Kusatsushirane volcano, and an automatic detection and audible alarm system has been installed.

1.6 Tsunamis

CHARACTERISTICS

"Tsunami" is a Japanese word meaning a giant ocean wave or series of waves produced by a large-scale disturbance of the ocean floor.

Tsunamis are generated when an abrupt movement of the ocean floor or sea bed displaces a large mass of water, usually as the result of a submarine earthquake but occasionally as the result of crater floor collapse at a volcano close to or below sea level, or landslide off the flanks of a volcano. The movement of the water spreads outward in all directions in the form of a wave which travels at a speed proportional to the square root of the depth of water; in the deep ocean it reaches 1,000 km/h. In the open sea the movement is imperceptible, but when the wave reaches shallow water near a coast its speed decreases and it forms a steep front which may be as high as 30 metres. On low-lying coasts tsunamis sometimes consist of a single wave but more often of a train of waves (up to about 10) which arrive at intervals of 20-30 minutes.

EFFECTS ON LIFE AND PROPERTY

It can be easily imagined that a turbulent wall of water, up to 30 metres high, advancing inland at 100 km/h or more, has devastating effects, which are completed when the water drains back into the sea after the forward passage of the wave. Only the strongest buildings and structures remain intact and the chances of survival of any living creature caught outdoors by a large tsunami are very small indeed.

Volcanic tsunamis are fortunately rather rare phenomena but history nevertheless records some notable disasters (see table 1). The collapse of the greater part of Santorini volcano in about 1400 B.C. is believed to have generated a huge tsunami which devastated the coasts of Crete and the Aegean islands, destroying the maritime power of the Minoan empire and leading to the end of this first European civilization. Many centuries later, it gave rise to the legend of Atlantis.

At the Japanese volcano Unzen in 1792 a tsunami was generated by the entry of a debris avalanche into the bay, and killed some 15,000 people. The greatest disaster in recent times was caused by tsunamis resulting from the eruption of Krakatau in 1883, which killed 36,000 people on the nearby coasts of Java and Sumatra. The tsunamis at Krakatau have been attributed to the submarine collapse of the caldera floor, but may also have been caused by the entry of large pyroclastic flows into the sea. The 1982 eruption of Mt. Colo on Una-Una island in Indonesia produced a small tsunami which destroyed nearby coastal settlements (figure 11).

1.7 Cataclysmic eruptions

Very occasionally, explosive volcanic eruptions occur on a scale far beyond the experience of modern man. Within the past 50,000 years, cataclysmic eruptions of this kind have occurred, for example, once in the Naples area of Italy, three times in the North Island of New Zealand, three times in Kyushu, Japan, and once each in Guatemala, Sumatra, Greece and the western United States. The average frequency of cataclysmic eruptions somewhere in the world is about once in every thousand years or so. Known occurrences in the past 10,000 years are Crater Lake, Oregon (7,000 years ago), Kikai Caldera, Japan (6,300 years ago), Santorini, Greece (3,400 years ago), Taupo, New Zealand (1,800 years ago), and Tambora, Indonesia (170 years ago). There are probably several others of similar age which have not yet been identified and/or dated.

Volcanologists lack any experience of the precursory symptoms of cataclysmic eruptions beyond holding a general, though perhaps not well-founded, expectation that seismic activity and ground deformation would be on such an unprecedentedly large scale as to give unequivocal warning of an impending major disaster.

An eruption of such magnitude would create volcanic hazards on an unprecedented scale. If it were to occur in a populous area such as Indonesia, Japan or Italy, it would either entail evacuation on a scale larger than has ever before been attempted, or would cause loss of life on a scale never before experienced in a natural disaster. Several million people might be involved and tens of thousands of square kilometres devastated.

This handbook deals with volcanic eruptions of magnitude and violence such as have already been experienced within the present century. It cannot prescribe measures to deal with cataclysmic eruptions which are outside our practical experience. In the mean time, however, research by volcanologists in several countries is aimed at finding out more about such eruptions. The next "thousand year" volcanic event may well not strike for hundreds of years yet, but like nuclear war, it remains a vague threat which, if it materialized, would almost certainly exceed the capacity of existing disaster prevention, preparedness and relief services.

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