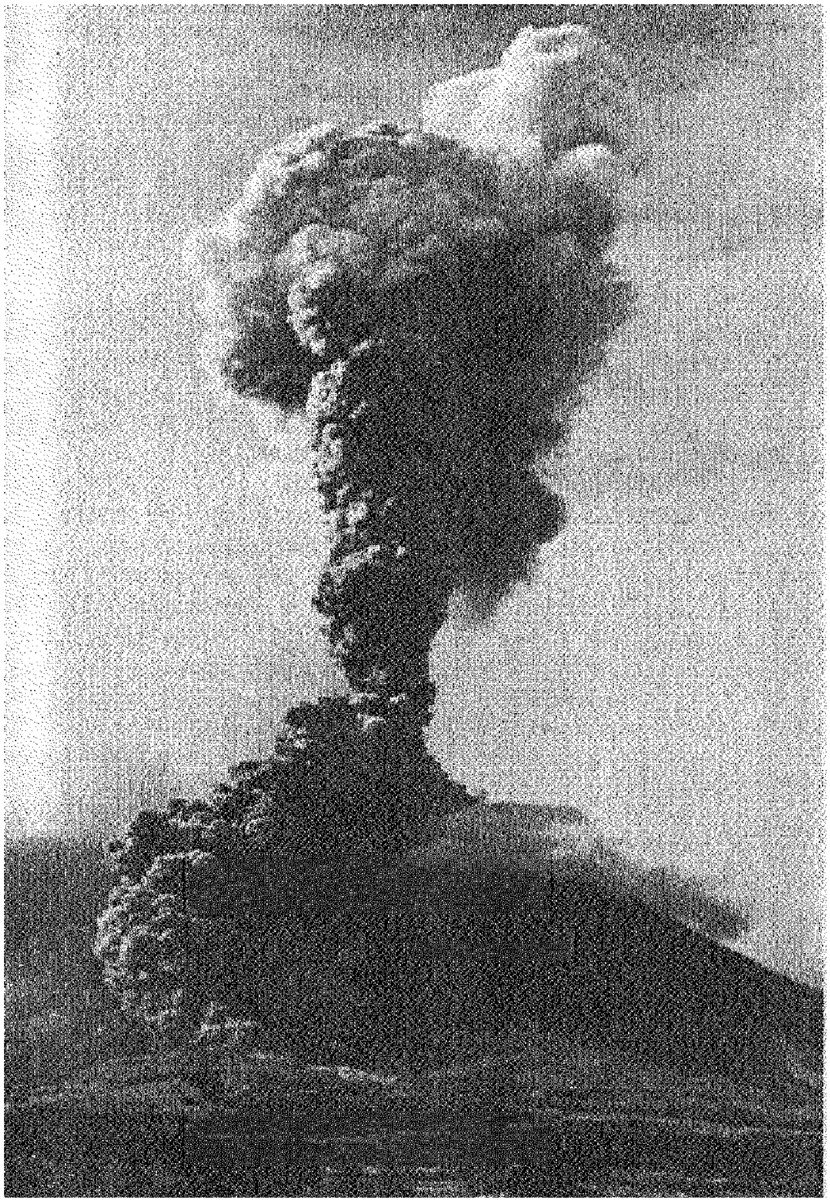

Plate 8. A glowing avalanche rushing down the flank of Mayon Volcano, Philippines, while a column of gas and ash rises from the summit during the eruption of 1968. The broad fans at the base of the mountain consist largely of older lahar deposits.

(Source: Dainty Studio, Daraga, Philippines).

Warning of the actual start of a lahar can at present only be given by direct visual observation, though perhaps instrumental methods can be developed in the future. At Merapi, thermal sensors were installed at the heads of the valleys to detect the passage of hot lahars or glowing avalanches, and to sound an alarm. They appear not to have been very successful, however, and they gave no warning whatever of cold lahars. Even if a warning can be given, the time available for people to flee to safety will, in most instances, be only a few minutes. It appears better to try to foresee the probable occurrence of lahars and evacuate the endangered areas in advance.

Some degree of protection from, and control of, lahars can be achieved by artificial structures. At one time, artificial hills were constructed near some Indonesian villages, on to which the villagers could climb to get above the reach of lahars. In general, however, the interval between any warning and the arrival of the lahar is so short that a person would have to be very close to the hill and react to the warning very quickly, in order to reach safety in time.

Where topographic conditions are favourable, barriers may be useful to divert lahars from certain localities, as has been suggested for lava flows. Many of the same technical and legal problems would be encountered, but the relatively smaller volume and lower viscosity of most lahars should make them more tractable. In 1969, a barrier was built near the foot of Merapi to divert lahars from the area of Blitar City. Dams were placed across streams at the foot of Kelud to impound lahars, but the volume of the flows was too great to be contained in the reservoirs, which quickly overflowed, and the advance of the lahars down the valley was only temporarily delayed. Crandell and Waldron (1969) have pointed out both the potential usefulness and the danger of larger reservoirs along streams likely to be affected by lahars. If a large reservoir is nearly empty, it can contain most lahars; but if it is full, the lahar will displace an equal volume of water over the dam, causing a flood lower down the valley and other consequences already mentioned in the case of glowing avalanches entering reservoirs. Where such large reservoirs exist, it appears desirable to estimate the volume of lahars that are likely to occur and, when conditions likely to lead to the generation of lahars are recognized, drain the reservoirs to a level such that they can contain the lahars.

Volcanic gases

Gases are given off by volcanoes not only during eruptions, but commonly for long periods following eruptions. Some fumarole fields have been active for hundreds of years without any superficial magmatic activity. Most collections of eruption gases contain water vapour, CO_2, CO, SO_2, SO_3, H_2S, HCl and HF, in addition to minor amounts of N, A, and other inert gases, but the proportions in different collections vary widely. In most collections water is reported to be the most abundant constituent, but in a series of 26 determinations made over a period of two hours at the same vent on Stromboli in 1963, its abundance ranged from 51 per cent to 0. In 21 determinations made on Etna in 1966 and 1969, water ranged from more than 50 per cent to 0, and in all of them CO_2 was at least as abundant as water (Tazieff, 1969). Likewise at the vent of the 1959 eruption of Kialauea, out of 8 samples, 6 contained less than 50 per cent water, and one contained only 6.6 per cent (Naughton, et al., 1963). Tazieff (1971) considers that when the effects of groundwater and air contamination are removed, the predominant gas becomes CO_2. HCl is present in very small quantity in the gas of Hawaiian eruptions, and HF has not been found. On the other hand, both are often moderately abundant in gases of continental volcanoes.

Water generally constitutes more than 95 per cent of fumarole gases. Of the other gases, some fumaroles (solfataras) give off predominantly sulphur gases, among which H_2S is often conspicuous by its odour. Others (mofettes) give off predominantly carbon gases, and still other halogen gases. In general, the gases of high-temperature fumaroles (above 650°C) contain a greater proportion of HCl, HF, CO, COS, and H. Mofettes generally have temperatures less than 100° C.

Volcanic gases cause trouble in various ways. Acid gases, and aerosols formed by their combination with water, may drift for long distances down wind from erupting vents or fumaroles, and may cause burning and withering of leaves of plants and dropping of fruit at distances as great as 50 km. Prolonged exposure to the gases may completely defoliate the plants and eventually kill them. Metal objects suffer corrosion, and sometimes destruction. Acid rains burned people's skin and damaged plants and metal objects as much as 575 km away from the volcano during the great Katmai eruption of 1912; clothes hung out to dry were damaged at distances greater than 2,000 km. Acid adhering to ash particles burned the leaves of plants and corroded metal during the 1963-65 eruption of Irazú, Costa Rica. During the 1947 and 1970 eruptions of Hekla, Iceland, thousands of grazing animals were killed by fluorine poisoning. The fluorine, probably in the form of a solution of HF in water, was carried down with falling ash, which adhered to grass and other vegetation eaten by the animals. Experiments showed that grass with a fluorine content of as little as 250 p.p.m. can kill sheep grazing on it within a few days (Thorarinsson and Sigvaldason, 1973). Rain gradually washes the fluorine away, and in 1970 the range became safe for grazing again in about 6 weeks.

Both CO_2 and SO_2 are poisonous, though SO_2 probably causes asphyxiation by contraction of the throat before enough of the gas can be inhaled to cause poisoning. Because of its heaviness, CO_2 sinks to the ground and may accumulate in undrained hollows or, under some wind conditions, in valleys. It is odourless and invisible. Many birds and animals wandering into these pools of CO_2 have been asphyxiated. During the 1947 eruption of Hekla, sheep congregating in hollows near the foot of the volcano were killed in this way, but the pools of gas were shallow enough so that men could walk through them unharmed. During the 1973 eruption of Eldafell, on Heimaey Island, the only human death was that of a man who went for shelter into a cellar filled with CO_2 and lesser amounts of CO and sulphur gases in the town of Westmannaeyjar.

Most of the rather rare deaths of men or animals by asphyxiation in pools of CO_2 probably can be avoided simply by awareness of the dangers. The absence of sufficient oxygen to support life is easily detected with a simple candle flame. Mild burning of skin by acid gases is easily counteracted with a wash of baking soda. Where it is unavoidable that persons be exposed to volcanic gases, ordinary general-purpose gas masks usually give sufficient protection, since there is usually enough air in the cloud to support life and it is only necessary to remove the noxious constituents. For prolonged use, it may be desirable to add a dust filter and clean it occasionally. If a gas mask is not available, a cloth dampened with water, or better, with a weak acid solution (e.g. vinegar or urine), and held over the face, is often adequate. Since the noxious materials are dissolved in the water, the cloth should be rinsed out frequently in fresh water. To enter deep hollows where heavy gases have accumulated, excluding air, a mask with an air tank may be necessary.

Fluorine poisoning of any large number of grazing animals probably cannot be prevented by moving the animals out of the affected area, simply because of insufficient time available. But it may be prevented by feeding with stored or imported feeds for a long enough period to allow the fluorine to be flushed from the vegetation by rainfall.

Metal objects exposed to acid gases or acid rain can be protected with acid-resistant paints or with grease.

Prevention or reduction of damage to plants by acid gases needs much more study. It may in some cases be accomplished by eliminating the source of gas. This was attempted at Masaya-Nindiri Volcano, Nicaragua. From 1924 onwards, gas liberated from a vent in the Santiago Crater of the volcano drifted westward (fig. 17), doing great damage to the coffee plantations on the Nicaraguan highland and to farms and a cement plant on the Pacific coast. German engineers undertook to cap the vent and pipe the gas to the crater rim, where it would be used to make sulphuric acid. About one kilometre of pipe, one metre in diameter, was installed. However, the vent was an elongate fissure, and in order to cap it more easily it was proposed to reduce its length by blocking part of it with rubble blasted down from the crater wall. In 1927 the blast was fired, but instead of blocking part of the fissure it caused the entire crater floor to collapse some 120 m. The pipeline was destroyed, but the vent was largely blocked by the rubble and the amount of gas being given off was reduced to about one-fourth. With this encouragement, additional blasts were set off to throw down additional rubble, with the result that the vent was completely blocked and the emission of gas ceased.

This suggested that other gas-emitting vents might be blocked in the same way, and indeed it was tried again at Masaya-Nindiri. The gas-free period after 1927 lasted for 19 years, but in 1946 gas emission and damage to the plantations resumed. A proposal to build a chimney 300m high, to lead the gases to a level high enough that they would (or might) drift over the highlands without doing serious damage, was rejected because of insecurity of the foundation on which it would have to be built and lack of guarantee that the vent would not shift its position (Wilcox, 1952). A suggestion that an atomic bomb be dropped into the crater to blast down the walls was rejected because of dangers from radioactive fallout. It was, however, felt that temporary blockage might again be achieved with conventional explosives. In 1953 two medium-sized bombs were dropped into the crater, but the reduction of gas emission was negligible (McBirney, 1956).

Local chemical treatment of plants to reduce the effects of acid gases is a possibility. One method, which has been tried to a limited extent, consists of spraying with a slurry of powdered lime to form a protective coating on the leaves. Unfortunately, in rainy regions the coating is soon washed off the plants, and frequent sprayings are necessary. The treatment is quite costly and is therefore limited by the economics of the situation. Other chemical methods will no doubt encounter the same economic limitations.

Methane is reported in some collections of volcanic gas, and its presence is usually due to contamination from sedimentary wall rocks at depth. It has been suggested that explosions during the 1933 eruption of Slamet were caused by ignition of appropriate mixtures of methane and oxygen. Destructive distillation of vegetation buried by lava flows may form methane and other hydrocarbon gases, which can be a

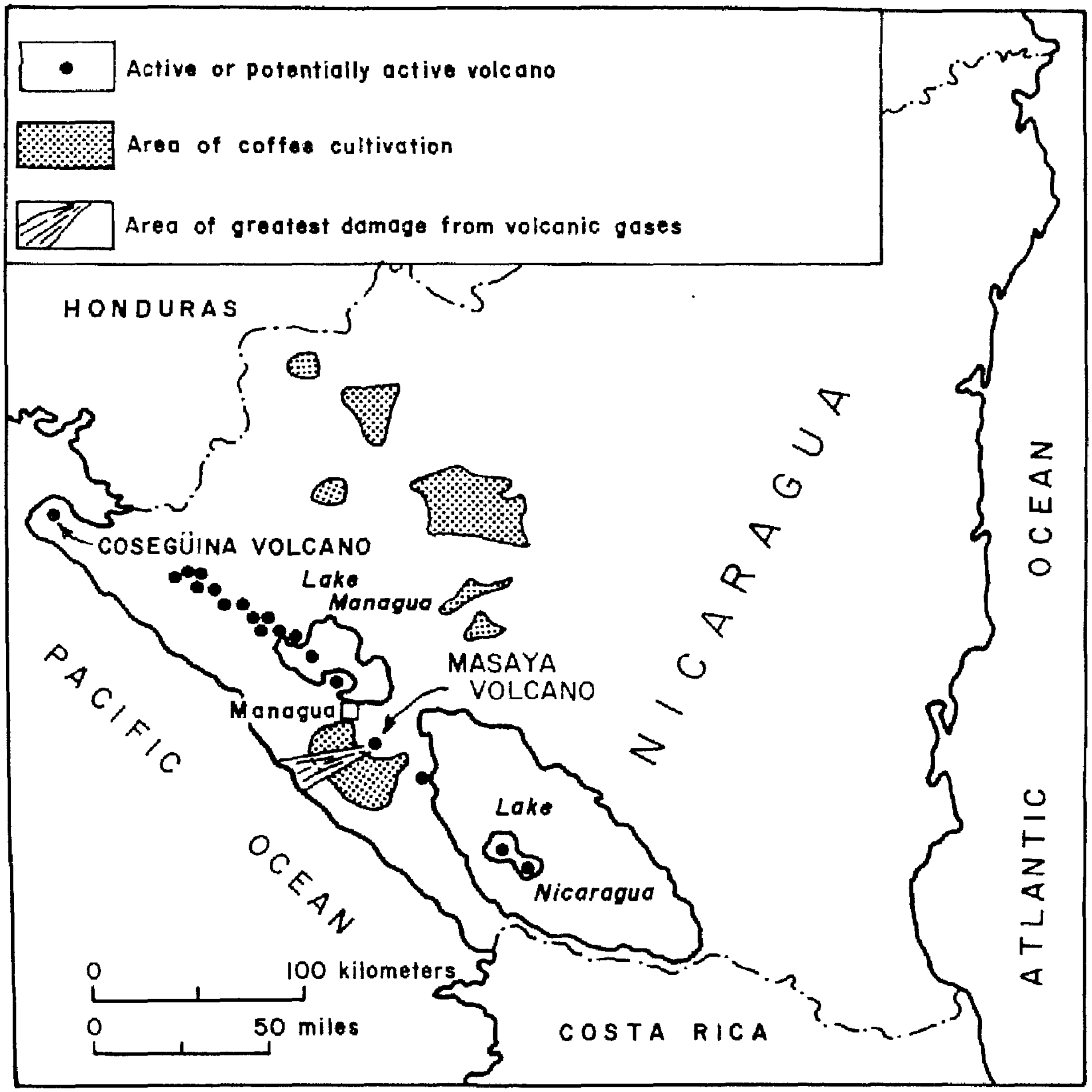

Figure 17. Map of Nicaragua, showing the location of Masaya Volcano and the area in the Nicaraguan highlands damaged by volcanic gases.

(After Wilcox, 1952).

menace to observers along the margins of active flows. Moving outward through lava tubes or other openings in underlying older flows, they mix with air and may become ignited, burning with pale blue flames or causing explosions which may throw fine debris as much as 150 m and fragments of rock up to 10 cm in diameter as far as 30 m.

Volcano-induced tsunamis

During the eruption of Krakatau Volcano, in 1883, tsunamis were generated that destroyed coastal villages on nearby Java and Sumatra and killed more than 36,000 people. The tsunamis were related in time to recorded explosions, but their actual generation may have been caused more by collapse of the sea floor during formation of a submarine caldera than to the explosions. Considerable evidence indicates that similar tsunamis were formed during the eruption and caldera collapse of Santorini (Thera) Volcano, about 1500 B.C., and that, sweeping southward, they may have seriously damaged Minoan cities on the shores of Crete. Tsunamis are to be expected during cataclysmic eruptions of other island volcanoes.