Chapter 3

HAZARD ASSESSMENT AND PREDICTION

3.1 General principles

For long-term planning of human settlements and investment in volcanic areas, it is useful, and indeed essential, to have some knowledge of the volcanic hazard, that is to say the chances of any particular area being affected by one or more of the destructive phenomena described in chapter 1.

Such knowledge can be obtained through geological studies of the past history of each volcano. Each past eruption has left traces in the form of lava beds, layered deposits of ash and scoria, etc., which can be mapped. Each deposit can be identified with a particular type of eruption, and in some cases dated with considerable precision. The frequency of past eruptions and the extent of the areas devastated by them can thus be reconstructed. Hazard maps can be prepared, showing the zones around each volcano where there is a risk to life and property, and estimates can be made of the probability of any particular area being affected by an eruption in a given period of time.

Such long-term hazard assessment is the subject of another handbook (Crandell *et al.,* 1984). The present book deals with the problems which arise when an eruption seems imminent or has already started. In such emergencies it is important to be able to foresee what is likely to happen in the immediate future. In other words, we are concerned here with the prediction of a single eruptive episode, in which the time-element is of vital importance. The term "prediction" in this context means a statement defining the type, magnitude, time of onset and duration of future phenomena, and the area likely to be affected by them.

As we have seen in chapter 1, the products of volcanic eruptions are various: pyroclastic flows and surges, mudflows, ash falls, lava flows, etc. Not all these phenomena are observed in each eruption. Individual volcanoes may behave in different ways at different times, but in general their eruptions fall into one or other of a few distinct types, identifiable by reference to the nature of their previous eruptions. In the absence of more specific guidance, it is reasonable to assume that future eruptions at any volcano will be of the same type as in the past, as revealed by geological studies of the deposits left by them.

There remains the problem of prediction in the sense defined above, so that appropriate action may be taken in time to safeguard the lives of the people in the areas likely to be affected. If it were possible to "see into" a volcano, to watch the ascent of the magma towards the surface, to monitor its physical and chemical state, to measure the pressures developing within it, while at the same time having access to data on the strength of the overlying rocks and of the volcanic edifice, one might be able to calculate at what moment the magma will reach the surface and what will be the magnitude, intensity and duration of the eruption. But one cannot see into volcanoes, nor can one hope to obtain, even with present-day technology, the data on the physical and chemical conditions inside a volcano which would make it possible to calculate its future behaviour. What, then, can be done?

As one might expect, a phenomenon of such violence and magnitude as a volcanic eruption does not occur spontaneously but is the final manifestation of a process that has been going on for a long time within the earth's crust: the rise of magma towards the surface. This process has certain physical and chemical effects within the crust which can be detected by suitable techniques and which, though not themselves the direct or immediate causes of an eruption, can nevertheless serve as indicators that the process leading to an eruption is under way. By detecting and measuring these precursory effects, and by discovering the relationships between their occurrence and the subsequent occurrence of eruptions at each individual volcano, it is possible to establish empirical methods of predicting eruptions. But it must be borne in mind that there is no direct causal relationship between the observed precursors and the eruption itself. Predictions based on them are therefore essentially probabilistic and should normally be framed in terms such as:

> Given a set of observational data on the recent occurrence of possible precursory effects, a comparison of these data with data on similar effects observed in the past and on the subsequent occurrence of eruptions at the same volcano, or at similar volcanoes, suggests that the probability of an eruption occurring at this volcano during the next *N* days (weeks, months), is *P* per cent.

3.2 Precursory phenomena

Various abnormal physical and chemical phenomena have been observed in the vicinity of volcanoes before eruptions, such as:

(a) *Seismic activity*

Increase in local earthquake activity;
Audible rumblings.

(b) *Ground deformation*

Swelling or uplifting of the volcanic edifice;
Changes in ground slope near the volcano.

(c) *Hydrothermal phenomena*

Increased discharge from hot springs;
Increased discharge of steam from fumaroles;
Rise in temperature of water in hot springs or of steam in fumaroles;
Rise in temperature of crater lakes;
Melting of snow or ice on the volcano;
Withering of vegetation on the slopes of the volcano.

(d) *Chemical changes*

Changes in the chemical composition of gas discharges from surface vents (e.g. increase of SO_2 or H_2S content).

All the phenomena listed above have been observed at one time or another before individual eruptions. Unfortunately for efforts at prediction, they do not *always* occur before eruptions, nor have eruptions always ensued when such effects have been observed. In fact, no perfectly reliable indicator of an impending eruption has yet been discovered. Nevertheless, the detection of such possible precursors is valuable, because it does make it possible to estimate the probability of an eruption occurring, by comparison with past experience, and to formulate predictions of the kind described in the preceding section.

3.3 Seismic activity

The occurrence of frequent shallow earthquakes beneath a volcano is one of the earliest, most common and easily detectable precursors to eruption. The most elementary form of continuous monitoring is therefore to maintain a single seismograph, as near as possible to, and preferably on the volcano. The signal from this instrument must be relayed continuously (generally by radio link) to a recorder which can be inspected as often as possible each day by a trained observer. It is desirable also to add a night-time alarm system, triggered by the occurrence of abnormally large or frequent local earthquakes. The presence of one seismograph is sufficient to detect the onset of abnormal local activity. As soon as this develops, it will be necessary to install a network of at least four seismographs around the volcano in order to determine the point of origin and the magnitude of each local earthquake. The number of earthquakes per day of various magnitudes, and hence the rate of seismic energy release, provides an indication of the amount of magma pushing through fractures towards the surface. A change in the pattern of seismic waves or a progressive decrease in focal depths will indicate that the magma is approaching the surface. There are several different types of ground tremor which can be distinguished on seismograms and which correspond to rock fracture, subsurface movement or effervescing of magma, explosions within a crater lake, etc. In some cases there is a change in the type of local earthquakes during the days or hours immediately preceding a new eruptive episode. The most common sequence is that fracture earthquakes are progressively replaced by explosion earthquakes, and finally by long periods of harmonic tremor, prior to the onset of eruption.

The level of local earthquake activity during periods of dormancy varies greatly from one volcano to another. It is therefore essential to maintain at least one seismograph in continuous operation at each potentially dangerous volcano in order to establish the level of normal background activity. It is primarily the *amount* and *rate of increase* of local earthquake activity, over the normal background level, which provide a measure of the increase of volcanic hazard.

Most eruptions, and especially the larger ones, are preceded by a distinctly abnormal level of local earthquake activity. In many cases, this has been detected many months before the onset of an eruption (e.g. Guadeloupe 1976, St. Vincent 1979). In other cases (e.g. Mt. St. Helens, 1980; Kliuchevskoi, 1960), local seismic activity has been detected instrumentally only a few days before small-scale explosions began. During the pre-eruption period, local earthquake activity often fluctuates considerably and there may be "swarms" of events, lasting for a few hours to a few days, which give rise to false alarms. Furthermore, to add to the difficulties of prediction on many volcanoes, for every local earthquake crisis (lasting from days to months) that has been followed by an eruption, there have been several that have ended *without* eruption.

By way of conclusion, it can be said that in most cases, large eruptions are preceded by abnormal local earthquakes that continue for days or months before the eruption begins, and often show a dramatic build-up in the hours preceding important explosive activity or lava emission. The longer and more detailed the record of local earthquakes at any volcano, the more likely it will be that reliable forecasts can be made.

3.4 Ground deformation

When magma forces its way upwards within a volcano one may expect it to cause some uplift or swelling of the volcanic edifice and its immediate surrounding, and this has indeed been observed on many occasions.

A spectacular uplift occurred at Usu volcano in Japan in 1944-45. An area about 1 km in diameter rose by 200 metres in 11 months and was finally pierced by an extrusion of viscous lava which formed a dome 300 metres in diameter and 150 metres high. Local inflation occurred during a period of at least four weeks prior to the devastating climax at Mt. St. Helens, USA, in 1980: an area on the upper flank of the volcano more than a kilometre in diameter bulged outward at an average rate exceeding one metre per day.

In general, however, the vertical movements associated with eruptions are much smaller and can be detected only by precise measurement. Various techniques have been developed for measuring slight ground deformations, either vertical or horizontal. Vertical movements can be measured either by optical levelling using standard survey instruments, or by means of tiltmeters which record small changes in slope. Water-tube or mercury pool tiltmeters are extremely sensitive but, since they only record changes in slope over relatively short distances, one cannot always be sure that they are not reacting to purely local influences. Repeated optical levelling by normal surveying techniques can cover larger areas and these techniques are more flexible in operation, though less precise. Both methods have been used on Kilauea and Mauna Loa volcanoes in Hawaii, with some notable successes in predicting eruptions of these volcanoes.

Relative horizontal displacement between fixed points can be readily detected by the techniques of electronic distance measurement. Optical triangulation can also be used but is somewhat less precise. By establishing a two-dimensional network for systematically measuring distances between selected points across and around a volcano, ground deformation can be identified and relative rates of strain can be determined. These techniques have been important for volcanic monitoring in Hawaii, on Mt. St. Helens, and elsewhere.

3.5 Hydrothermal phenomena

Although the temperature and rate of emission of water and steam from hot springs and fumaroles are the most obvious and easily measured indices in the thermal state of a volcano, they are very difficult to interpret.

This is because they depend not only on the state of the volcano itself but on the way in which water circulates within the volcanic edifice. This is strongly influenced by other factors, especially rainfall. Visual observations of steam emissions can be misleading, because the size and apparent density of a vapour plume depend also on the wind speed, the relative humidity of the air, the lighting, etc.

In general, changes in the hydrothermal régime are the result of complex changes taking place in the upper layers of a volcano and give only indirect evidence of what may be happening in the interior. They may nevertheless provide some indication of the likelihood of a phreatic eruption, that is to say an eruption caused by the contact of ground water with magma or hot rock in the volcanic edifice.

Of greater significance are changes in the temperature of crater lakes, where these exist. For instance, the mean annual temperature of the crater lake on Taal volcano in the Philippines remained steady from 1961 to mid-1965, varying only between 32.5 and 33.0 °C. In late June 1965 it began to rise, reaching 45 °C by the end of July, after which it decreased very slowly to 43 °C on 28 September, when a violent eruption occurred. During the period preceding the eruption, the water level in the lake had also behaved abnormally, rising in May and June contrary to the usual seasonal trend.

Notable increases in hot spring temperature were recorded at Usu volcano, Japan, over a period of 18 months prior to the 1977 eruption, showing close correlation with increases in the occurrence rate of local earthquakes. Both of these phenomena showed rapid increases immediately before the eruption.

3.6 Chemical changes

Very few volcanoes remain absolutely inactive during the intervals between eruptions. Gases from magma underlying the volcano continue to reach the surface through vents in the crater or on the slopes, and these gases carry with them valuable information on what is happening below, which can be revealed by chemical analysis.

The principal constituents of volcanic gas emissions other than steam (H_2O) are sulphur dioxide (SO_2), hydrogen sulphide (H_2S), hydrogen chloride (HCl) and carbon dioxide (CO_2). As these gases move up towards the surface, they are gradually cooled and some differentiation takes place, so that the temperature and chemical composition of the gas mixture arriving at the surface gives some indication of the depth of the magma below the surface. Changes in the relative concentrations, and particularly an increase in sulphur content relative to chlorine, may be taken as indications that the magma is approaching the surface. For instance, the S:Cl ratio in gas emissions form fumaroles increased by a factor of 3 during the months preceding explosive eruptions of Asama (Japan) in 1958 and of Kliuchevskoi (Kamchatka) in 1951. However, no such effect has been observed before eruptions of Kilauea (Hawaii).

The interpretation of changes in the chemical composition of gases from fumaroles is rendered difficult, firstly by the variety of factors which may affect the composition of these gases during their movement from the magma to the surface, and secondly because one cannot always be sure that any gas sample is representative of conditions in the volcano as a whole. Significant differences in composition are often observed between samples taken only short times or distances apart. Continuous monitoring techniques, such as those developed for hydrogen and sulphur dioxide, permit the study of short-term fluctuations in these gases.

The chemical analysis of volcanic gases and waters cannot yet provide a basis for identifying immediate precursors to volcanic activity. It may nevertheless give valuable indications of the general state of a volcano and of any trend in activity.

3.7 Summary

Although the science of predicting volcanic eruptions is still in its infancy, one may nevertheless expect that, if the history of a volcano has been thoroughly studied and if scientific measurements are made systematically and regularly during periods of dormancy as well as during eruptions, it will usually be possible to predict its behaviour well enough to be useful in making decisions about protective measures.

In order to serve a useful purpose, a prediction must satisfy the following criteria:

(*a*) The *lead time* of the prediction (that is to say, the time expected to elapse between the issue of the prediction and the onset of the predicted phenomenon) must be *longer* than the time needed to put into effect the appropriate protective measures;

(*b*) The *time-window* of the prediction (that is to say, the length of the time period during which the predicted phenomenon may be expected to occur) must be as *short* as possible;

(*c*) The prediction must be *reliable*, in the sense that the probability of its turning out to be a false alarm must be within limits acceptable to the community concerned; on the other hand, the chance of failure to predict a destructive eruption must be the minimum possible.

It is important that scientists bear these criteria in mind when deciding when and in what form to communicate their findings to the civil authorities or to the public.

Bibliography
(*Chapter 3*)

Booth, B., 1979. "Assessing volcanic risk", *Jour. Geol. Soc. Lond.*, vol. 136, pp. 331-340.

Crandell, D. R., *et al.*, 1984. *Source book for volcanic hazards zonation*, UNESCO, Paris, 97 pp.

Fournier d'Albe, E. M., 1979. "Objectives of volcanic monitoring and prediction", *Jour. Geol. Soc. Lond.*, vol. 136, part 3, pp. 321-326.

Lowestein, P. L., 1982. "Problems of volcanic hazards in Papua New Guinea", *Geological Survey of Papua New Guinea*, Report 82/7.

McKee, C. O., *et al.*, 1983. "Rabaul Caldera, Papua New Guinea: Volcanic hazards and eruption contingency planning", *Report 83/17 of the Department of Minerals and Energy*, Papua New Guinea, 38 pp.

UNESCO, 1972. *The surveillance and prediction of volcanic activity: a review of methods and techniques*, 166 pp.