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Forecasting volcanic events: some contemporary issues

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Abstract As the regions around active volcanoes succumb to large increases in population, particularly in the developing world where most of the high-risk volcanoes are located, the threat posed by eruptions becomes increasingly serious. Improvements in eruption forecasting are critical to combat this situation, for reducing injury and loss of life, and for minimizing the detrimental effects to local economies and to the fabric of society. Better-constrained forecasts are strongly dependent on geophysical and other data gathered during a program of volcano surveillance, and we reveal how, if interpreted in terms of static rock fracturing, analysis of changes in volcanic seismicity and ground deformation may be used to forecast more accurately the onset of eruptive activity. As illustrated by recent events at several volcanoes, studies of previous activity, increased levels of monitoring, and improved training of scientists are also all crucial to improving forecasts of impending eruptions.

Key words Volcanic hazards · Eruption forecasts · Subcritical rock failure

Introduction

Hazardous phenomena generated during volcanic eruptions have claimed over a quarter of a million lives since the beginning of the eighteenth century (IAVCEI IDNDR Task Group 1990), 78 000 since 1990, and approximately 30 000 over the past 15 years alone. Many tens of millions of lives have also been disrupted as a result of volcanic activity, through enforced evacuation, starvation, and disease, damage to the local environment, and disruption of the social and economic fabric. Notwithstanding improvements in monitoring technologies (McGuire et al. 1995; Scarpa and Tilling 1996), rapid population growth, particularly in developing countries where most active volcanoes are located, will ensure that the threat to life and property from volcanic eruptions increases as we enter the new millennium. Currently, approximately 10% of the world's population live on or near one of the planet's estimated 550 active volcanoes (Peterson 1986), approximately 50 of which exhibit some form of eruptive behavior in any single year (Simkin and Siebert 1994). Less than a quarter of all active volcanoes are monitored at all, and at many of these the monitoring is cursory at best, consisting often of a single seismometer or relying purely on visual observations by inexperienced personnel or local inhabitants.

Such a scenario highlights the increasing requirement for successful forecasting of volcanic phenomena, but also reveals the need for a contemporaneous increase in the general level of surveillance. Useful forecasts about the timing and nature of eruptions are invariably based on data from a range of monitoring methods (McGuire et al. 1995; Scarpa and Tilling 1996). Ideally, a comprehensive network consisting of seismic and ground deformation arrays, supported by other geophysical (e.g., microgravity, magnetic, and electrical) and geochemical (e.g., gas and water analysis) surveillance tools, should have been operational for several years prior to the reactivation of a volcano, in order to provide a record of its normal or baseline behavior. This will permit the recognition of any anomalous activity which presages the onset of an eruption.

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In the context of providing advance warning of impending volcanic activity, confusion often arises between use of the terms forecast and prediction. Swanson et al. (1985, p. 397) recommends adoption of the following definitions: A forecast is a relatively imprecise statement of the time, place, and nature of expected activity, whereas a prediction is a comparatively precise statement of the time, place, and ideally, the nature and size of impending activity. A prediction usually covers a shorter time period than a forecast and is generally based dominantly on interpretations and measurements of ongoing processes and secondarily on a projection of past history. Determination of the timing, nature, and scale of impending volcanic events remains an inexact science, and the term forecasting is typically more appropriate than prediction with respect to constraining future activity.

Forecasting the timing of volcanic eruptions

Provided sufficient monitoring data (most usefully relating to seismicity or ground deformation) are available, it may be possible to make a more specific prediction about the timing of an eruption. Constraining when an eruption will occur often reduces to an exercise in determining the timing of rock failure. Volcanoes and the upper crust on which they rest are fractured, brittle structures. Fractures occur at all scales, from intragranular cracks to major faults (Scholz 1990; Main and Meredith 1991). These fractures are preferred sites for deformation when rocks are strained by new magma arriving close to the surface. The strain increase is normally detected by changes in volcanic seismicity or in surface deformation and, before an eruption, both these changes accelerate at increasing rates in a manner consistent with tertiary creep.

Increasing acceleration may be driven by a progressive increase in applied stress, or by a progressive weakening of the rock being deformed. It is common for the first interpretation to be implicitly assumed when investigating pre-eruptive phenomena, i.e., that accelerated deformation reflects an accelerated accumulation of magma. It is equally feasible, however, to consider an injection of magma as a rapid event to which the volcanic edifice responds in two stages: an initial deformation which partially relieves the new magmatic stresses, followed by deformation under remaining stresses which stay almost constant until eruption begins. In this case measured accelerations in pre-eruptive processes may result from progressive rock weakening during the second stage of deformation.

Subcritical cracking is a ready mechanism for weakening rock under near-constant stress. Small cracks nucleate and grow for an extended period of time, until they coalesce to open a major pathway for feeding an eruption (Lockner et al. 1991; Main and Meredith 1991; Main et al. 1993). Such failure by static fatigue is an integral feature of crystal seismicity (Scholz 1990) and, applied to volcanoes, could explain why eruptions commonly start only weeks or months after new magma first arrives close to the surface (e.g., Chester et al. 1985; Giberti et al. 1992).

Static fatigue is also implied by the empirical Voight–Fukuzono (VF) relation, proposed for modelling pre-eruptive rates of volcanic deformation (Voight 1988, 1989).

$$(\mathrm{d}^2\Omega/\mathrm{d}t^2) = A(\mathrm{d}\Omega/\mathrm{d}t)^{\alpha}, \qquad (1)$$

where A and α are constants, and Ω is the strain, or a surrogate quantity, whose rate of change measures the rate at which catastrophic failure is being approached. Common surrogates for Ω are ground deformation and seismic energy release, both of which can be linked directly to strain release. The constants A and α are determined empirically from available deformation data and, when they are known, Eq. (1) can be integrated to yield an estimate of the time to major failure.

Equation (1) has been found to describe measured changes in Ω days or more before some eruptions (Voight 1988; Cornelius and Voight 1995; Murray and Voight 1996). Remarkably, α in each case is close to 2 (typically $1.4 < \alpha \leqslant 2$), independent of whether it is Ω or a surrogate quantity that is being measured. As shown below, $\alpha \approx 2$ is expected if the VF relation is interpreted in terms of subcritical rock fracture.

Although several processes may contribute to subcritical crack growth (Kranz 1980; Lankford 1981; Costin 1983; Atkinson 1984; Swanson 1984), stress corrosion is especially important in crustal rocks, where migrating fluids, notably water, chemically weaken the tips of existing cracks (Main and Meredith 1991). As with other driving mechanisms, stress corrosion is a thermally activated rate process and, for N cracks in the volume under constant normal stress, S (tensile or compressive), the bulk strain rate $\mathrm{d}\Omega/\mathrm{d}t$ can be expressed in terms of the strain rate from each crack ($\mathrm{d}\gamma/\mathrm{d}t$) as (Lockner 1993)

$$\mathrm{d}\Omega/\mathrm{d}t = N\,\mathrm{d}\gamma/\mathrm{d}t = N(\mathrm{d}\gamma/\mathrm{d}t)_0 m e^{a\Omega}, \qquad (2)$$

where $m = e^{-a\Omega_0}$, $a = BS^2/YkT$, Y is Young's modulus, k is Boltzmann's constant, T is temperature (assumed constant), B is a geometric factor, and the subscript 0 denotes values at a reference condition.

Equation (2) shows a self-feeding dependence of strain rate on strain. As cracks lengthen and open, bulk-rock deformation increases and, hence, also the measured strain. At the same time, crack formation releases strain energy stored in the surrounding rock (Lawn and Wilshaw 1975) and this can be used to accelerate the rate of cracking and thereby increase the observed strain rate.

Laboratory studies (Lockner et al. 1991; Main and Meredith 1991) indicate that, before coalescence, new cracks form at a rate proportional to the existing number of active cracks, so that $N = N_0 e^{\lambda(t-t_0)}$, where λ is a rate constant (Main and Meredith 1991). Substituting for N in Eq. (2) then gives

$$d\Omega/dt = (d\gamma/dt)_0 m N_0 e^{\lambda(t-t_0)} e^{a\Omega} \qquad (3)$$

which yields, after differentiation with respect to time,

$$d^2\Omega/dt^2 = \lambda d\Omega/dt + a(d\Omega/dt)^2 \qquad (4)$$

(using, for convenience, initial values to define the reference parameters).

Equation (4) is a composite VF relation. At low strain rates, bulk deformation is driven by the appearance of new cracks and Eq. (4) approximates $d^2\Omega/dt^2 \approx \lambda d\Omega/dt\,(\alpha = 1, A = \lambda)$. As the strain rate increases, bulk deformation becomes increasingly limited by the rate of crack extension, for which Eq. (4) tends to $d^2\Omega/dt^2 \approx a(d\Omega/dt)^2\,(\alpha = 2, A = a)$.

When a surrogate quantity is used instead of strain, Eq. (4) maintains the same structure, but with modified forms of the non-differential terms on its right-hand side. For example, suppose x is a fault displacement proportional to strain, such that $\Omega = x/L$, where L measures the initial length over which strain is accumulating. Equation (4) then becomes

$$d^2x/dt^2 = \lambda\, dx/dt + (a/L)\,(dx/dt)^2 \qquad (5)$$

yielding, for slow and fast fault movement, the limits $d^2x/dt^2 = \lambda\, dx/dt$ and $d^2x/dt^2 = (a/L)\,(dx/dt)^2$.

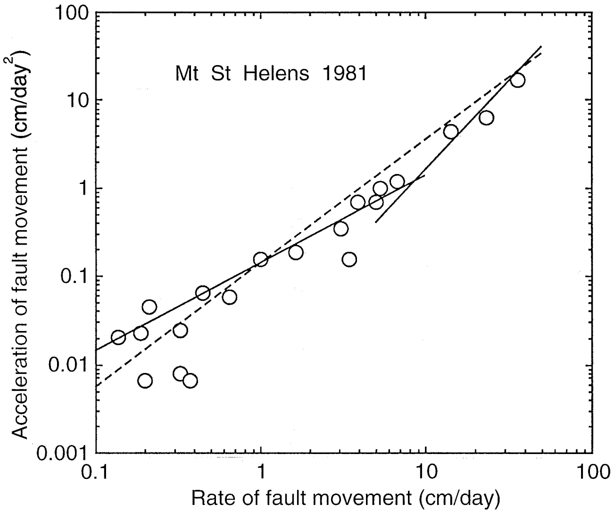

Fig. 1 Pre-eruptive deformation for mean values of α less than 2. Example shows d^2x/dt^2 vs dx/dt (fault acceleration vs fault velocity), where x is fault displacement (in cm) before the September 1981 lava dome eruption at Mount St. Helens (Voight 1988); it is assumed that $dx/dt = L d\Omega/dt$. With logarithmic scales, gradients of lines through the data yield values for α (Eq. (1)). The *solid lines* follow trends for $\alpha = 1$ (small displacement rates) and $\alpha = 2$ (high displacement rates). The data suggest that α increases as deformation accelerates, in a manner consistent with Eq. (5). From the intercept with $dx/dt = 1$ [$\mathrm{Log}(dx/dt) = 0$], the solid line for $\alpha = 1$ yields $A = \lambda \approx 0.13\ \mathrm{cm\,day}^{-2}$, whereas that for $\alpha = 2$ implies $A = a/L \approx 0.015\ \mathrm{cm\,day}^{-2}$. The dashed line shows the trend previously inferred assuming that α is constant and determined in this case to be 1.4 (Voight 1988)

Equations (4) and (5) show that, in agreement with field data (Fig. 1), α is expected to increase from 1 to 2 as deformation proceeds, resulting in a mean value between these limits. Pre-eruptive values of mean α close to 2 thus imply that rates of crack growth normally dominate the final acceleration to major failure.

Subcritical rock failure provides a plausible physical basis for using the VF relation to supply well-constrained forecasts, and even predictions, for the onset of volcanic events. It accounts for observed limits on α, relates A to material properties in a manner open to testing by future studies (Fig. 1, caption), and explains why diverse observational parameters can be substituted for strain e.g., surface movement will follow both bulk-rock dilation as more cracks open and bulk displacement along extending zones of weakness, whereas rates of crack advance directly control rates of seismic energy release (Scholz 1990).

Over longer time periods, repeated edifice fatigue may also determine eruption frequencies at volcanoes persistently charged with high-level magma (e.g., Stromboli and Etna). Especially important is the role of pore fluids in driving stress corrosion. Through a number of feedback mechanisms, pore fluids in fractured rock can establish critical equilibria for crack and stress distributions (Main et al. 1994). Critical equilibria favor a chaotic time series for episodes of major failure (Bak et al. 1988; Main et al. 1994) and such patterns are becoming proposed more frequently for eruption sequences at single volcanoes (Shaw 1987; Sornette et al. 1991; Grasso and Bachèlery 1995; Luongo et al. 1996). Further investigations of static fatigue at active volcanoes have thus considerable potential both for improving eruption forecasts, and for better understanding earth's long-term rates of volcanic activity.

Forecasting the initial stages of eruptive activity

The static-failure mechanism has yet to be tested in the field and, even when verified, is unlikely to emerge as the only process controlling how quickly a volcano approaches eruption. Forecasting how, when, and if a reactivated volcano will erupt remains a formidable problem, even where there is a lengthy record of baseline behavior (Tilling 1995).

The first dilemma faced by the monitoring scientists lies in determining whether or not a change in baseline behavior is precursory to an eruption (Fig. 2). Such a decision has major implications for the response of the civil authorities and local population in terms of

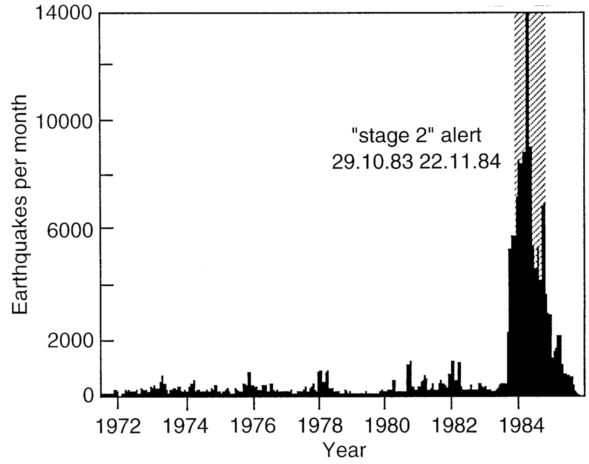

Fig. 2 The seismic and ground deformation crisis at Rabaul Volcano (Papua New Guinea) between 1983 and 1985, led to the declaration of a "stage 2 alert" (eruption expected within a few months). No eruption was forthcoming, however, and both seismicity levels and surface deformation events gradually fell to low levels during 1985. Such periodic increases in activity without eruption are common at "restless' caldera volcanoes, such as Rabaul, and cause considerable problems for both observing scientists and the civil authorities. To highlight further difficulties with eruption forecasting at such volcanoes, a major eruption of Rabaul did occur in September 1994, following only 27 hours of premonitory seismicity. Modified from Tilling, 1995

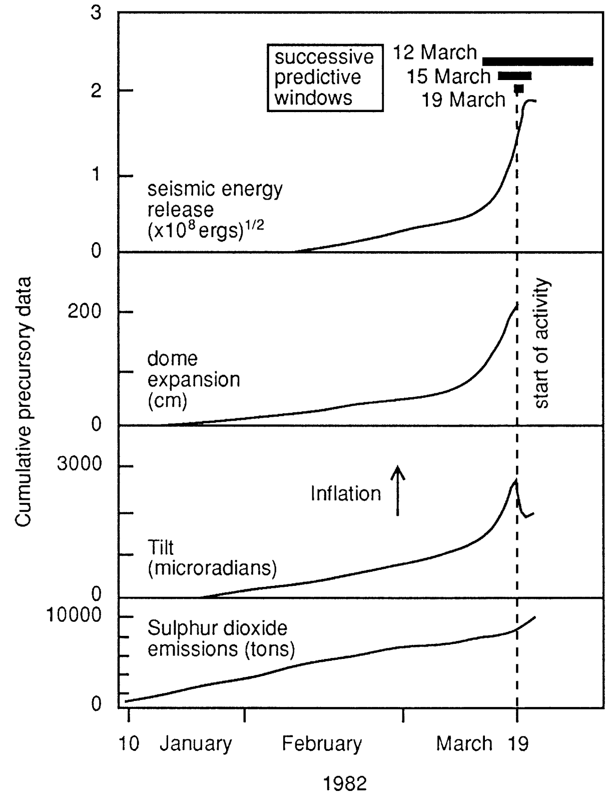

Fig. 3 Successive predictive windows at Mount St. Helens based upon acceleration of precursive activity. (From Swanson et al. 1985)

activating contingency plans, evacuation programs, and the establishment of temporary shelters, emergency medical facilities, and feeding stations. Bursts of anomalous seismicity at the Soufriere Hills Volcano on Montserrat (Caribbean) over the past century provide an excellent example of the problem. Before the turn of the century, in the 1930s and again during the 1960s, seismic swarms under the volcano suggested that an eruption might be imminent (Wadge and Isaacs 1988). In all cases, however, the seismicity tailed off without any eruptive activity. In contrast, a similar pattern of seismic events during July 1995 heralded the first eruptive activity for over 300 years, and a cycle of lava-dome growth and collapse which continues at the time of writing.

Once monitoring data indicate that magma has been emplaced at shallow depths, within or below the volcano, the question arises of when the eruption will start and what form it will take. As discussed previously, the static-fatigue model may permit the timing of the onset of activity to be constrained, provided appropriate seismic and ground deformation data are available (Figs. 3 and 4). The precise nature of the initial stages of an eruption depends, however, on numerous factors including magma chemistry and water content, the duration of the repose period, the geometry and mechanics of the plumbing system, and local factors which, taken together, make each volcano unique. The best guide to how an eruption will start is likely to come from

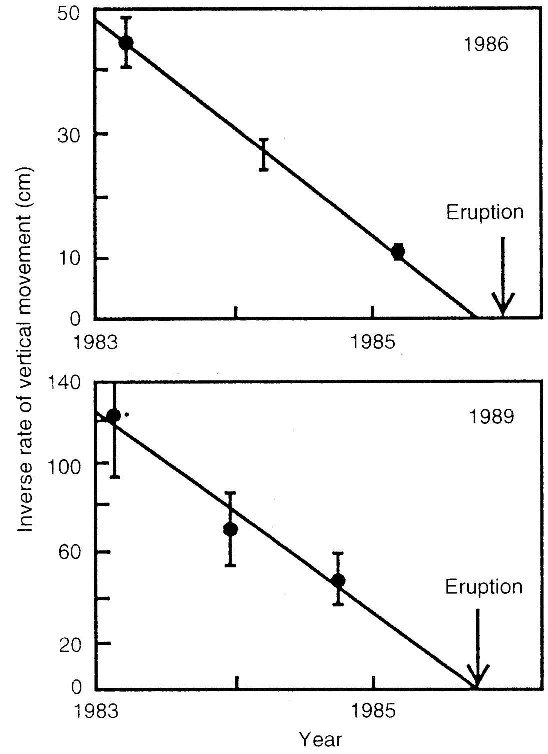

Fig. 4 Prediction of eruptions at Mount Etna based on inverse rate analysis of vertical ground deformation. (After Murray and Voight 1996)

observations of previous eruptions or, where the length of the repose period prevents this, from studies of older deposits.

At basaltic volcanoes such as Etna (e.g., Murray and Pullen 1984; McGuire and Pullen 1989; Rymer et al. 1993), Kilauea (Hawaii; Dvorak and Okamura 1985; Okamura et al. 1988) and Piton de la Fournaise (Réunion Island, Indian Ocean; e.g., Lenat and Bachèlery 1988; Toutain et al. 1995), a distinctive pattern of shallow seismicity typically marks the opening of a magma-filled fracture (dyke) which normally intersects the flanks within hours to form an eruptive fissure. In contrast, at volcanoes characterized by more siliceous compositions, the initial emplacement of a fresh mass of high-viscosity magma at shallow depths is typically marked by hydrovolcanic explosions caused by the interaction of hot magma and the local aquifer. Such behavior presaged magmatic eruptive activity at Mount St. Helens (USA) in 1980, Pinatubo (Philippines) in 1991, and at Soufriere Hills in 1995.

Forecasting the development of an eruptive cycle

At effusive volcanoes, such as Kilauea and Etna, eruptive fissures normally feed the growth of one or more lava flow fields, whose volume can sometimes be estimated from the degree of pre-eruptive ground deformation. Forecasting the nature and scale of succeeding events at explosive volcanoes, however, is considerably more difficult and relies on the correct interpretation of monitoring data and visual observation, augmented by evidence for the evolution of eruptive activity from studies of previous eruptions and their deposits. The range of potential scenarios of very different characteristics and scales must be determined if a successful forecast is to be made.

At Mount St. Helens, for example (Lipman and Mullineaux 1981), the initial hydrovolcanic blasts were succeeded by the preferential intrusion of viscous magma into the northern flank of the volcano. Observations of the resulting bulge at the surface led scientists at the Cascades Volcano Observatory to successfully forecast flank collapse and a lateral blast to the north. Although the scale of the blast was underestimated and the expected time poorly constrained, the forecast ensured that the threatened area had been largely evacuated and that casualties were minimal.

Post-hydrovolcanic activity at Pinatubo followed a different pattern (Tilling 1995), with the growth of a dacitic lava dome followed by the generation of successive, large Plinian eruption columns. The explosive phase culminated in a climatic event which ejected 5–7 km^3 (dense rock equivalent) of magma and sent pyroclastic flows to over 19 km from the summit. Because Pinatubo had not erupted during historic times, forecasting both the nature and scale of the climatic eruption relied heavily on rapidly undertaken mapping of older deposits. In this respect, the hazard zonation maps constructed during the course of the eruption and the extent of the evacuated zone were based entirely on how the volcano had behaved in the past. Fortunately, the forecasts proved remarkably accurate, and thousands of lives were saved as a result.

At Soufriere Hills on Montserrat, the emplacement of magma at shallow depths during July 1995 was again accompanied by hydrovolcanic explosions and cold surges. In contrast to both Mount St. Helens and Pinatubo, this was followed by the relatively quiet appearance of viscous magma at the surface which, during the following several months, formed an endogenous lava dome within the existing summit crater. Progressive dome destabilization led to a number of collapse events between May and September 1996 that generated block-and-ash flows. On 17 September major dome collapse (Figs. 5 and 6) triggered an explosive eruption consisting of a directed explosion and the formation of an eruption column, 14 km high, that was sustained for approximately 45 min (McGuire 1996). This event constitutes the climax of the eruption to date, although growth and collapse of a new dome continues at the time of writing (January 1997). As at Mount St. Helens and Pinatubo, the broad nature of eruptive activity at Soufriere Hills was forecast prior to the start of the latest eruption, on the basis of the type and distribution of the products of previous eruptions.

Fig. 5 Pyroclastic flows triggered by collapse of the lava dome at Soufriere Hills, Montserrat, on 17 September 1996

Fig. 6 Aftermath of the dome explosion around midnight on 17–18 September 1996 at Soufriere Hills, Montserrat

This information permitted the construction of hazard-zonation maps (Wadge and Isaacs 1988) which formed the basis of an evacuation program as current activity escalated.

A pattern of dome collapse with a periodicity of 10–14 days had already been recognized from events during July and August, and observers had anticipated another collapse on or about 17 September. Although the potential for explosive eruptions had been considered, there were no compelling reasons to expect such a phenomenon at that time in particular. The failure to allow for an explosive event demonstrates how observers had come to expect a certain pattern of behavior, reflecting the general problem of forecasting sudden and unexpected changes in eruptive style during long-lived periods of activity.

The future

Scientists monitoring active volcanoes pursue two principal goals: firstly, to increase the number of successful forecasts of impending activity, and secondly, to replace forecasts with specific predictions. The successful achievement of both goals relies on the acquisition of more high-quality data about the normal behavior of a volcano, especially during the critical period of reactivation and, for long-duration eruptions, throughout the whole period of activity. Increasing the level of data acquisition is essential, both at individual volcanoes and in terms of increasing the total numbers of active volcanoes being monitored. Particularly in the developing world, both objectives may be accomplished by the availability of cheaper, modular instruments, such as seismometers and tiltmeters, which require less-advanced technical expertise to keep them operational. In terms of monitoring a larger number of volcanoes, observations from satellite platforms are expected to play an increasingly important role (Francis and Rothery 1987). Unhindered by problems of accessibility and politics, satellite-based instruments are already theoretically capable of monitoring both thermal and ground deformation changes at active volcanoes anywhere on the planet.

The quality of monitoring data is also expected to improve with the increased use of instruments better able to constrain the location and movement of subsurface magma. Worthy of mention in this respect are the applications of broad-band seismology to tracing the passage of magma from depth, and of the Global Positioning System (GPS) to detecting the new magma within a reactivated volcano (Nunnari and Puglisi 1995).

While critical to improving our ability to forecast volcanic phenomena successfully, improved monitoring is not the sole necessity. At least as important for constraining the nature and scale of impending activity is a more detailed and extensive mapping of the products of older eruptions. For most of the planet's active volcanoes this information is simply not available, making forecasts about future activity of very limited use.

Finally, the experience and levels of expertise of observing scientists are critical to making accurate forecasts about impending activity. In this respect, increasing effort must be focused on training greater numbers of scientists, particularly those in developing countries where active and potentially active volcanoes are concentrated. One way to accomplish this is to view each new erupting volcano as a training opportunity for scientists from around the world. As at Soufriere Hills, such a situation can be used to expose the scientists of the country responsible (in this case the United Kingdom) to the problems of trying to forecast eruptive behavior, as well as providing experience for external researchers through a program for visiting scientists.

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