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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).

$$(d^2\ )/dt^2) = A(d\ )/dt)a, \qquad (1)$$

where A and a are constants, and) is the strain, or

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 $N = N_0 e^{j(t-t_0)}$, where j is a rate constant (Main and Meredith 1991). Substituting for N in Eq. (2) then gives

$$d\,)/dt = (dc/dt)_0 m N_0 e^{j(t-t_0)}$$

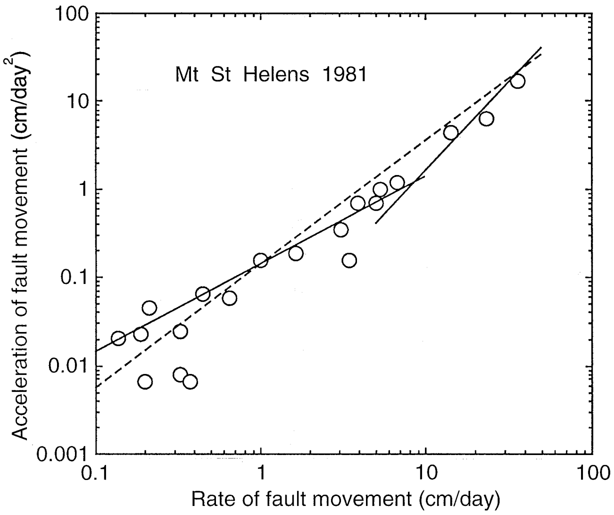

Fig. 1 Pre-eruptive deformation for mean values of a less than 2. Example shows d^2x/dt^2 vs dx/dt (fault acceleration vs fault velocity), where *x* is fault displacement (in cm) before the September 1981 lava dome eruption at Mount St. Helens (Voight 1988); it is assumed that $dx/dt = L d\Omega/dt$.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

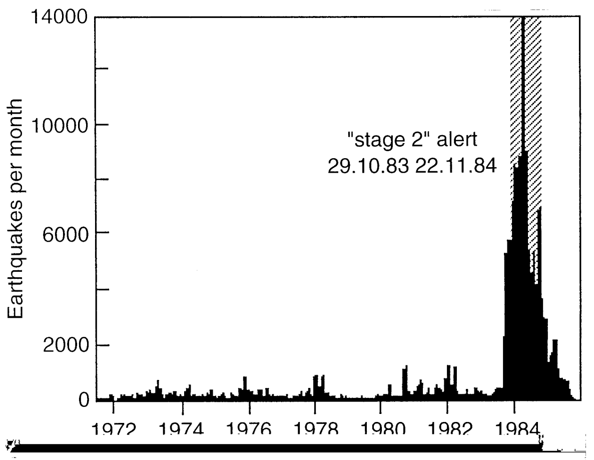

Fig. 2 The seismic and ground deformation crisis at Rabaul Volcano (Papua New Guinea) between 1983 and 1985, led to the declaration of a “stage 2 alert” (eruption expected within a few months). No eruption was forthcoming, however, and both seismicity levels and surface deformation events gradually fell 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

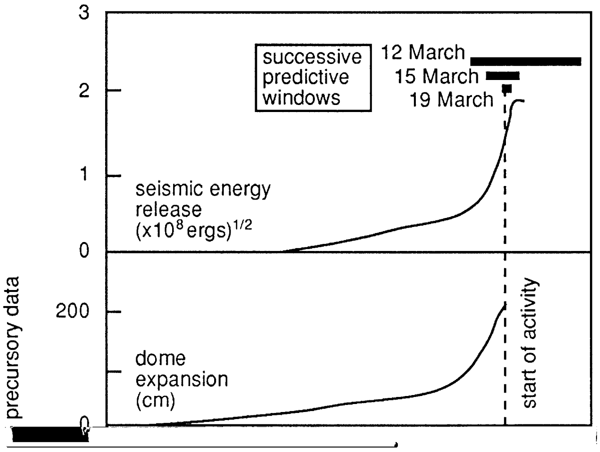

Fig. 3 Successive predictive windows at Mount St. Helens based upon acceleration of precursive activity. (From Swanson et al. 1985)

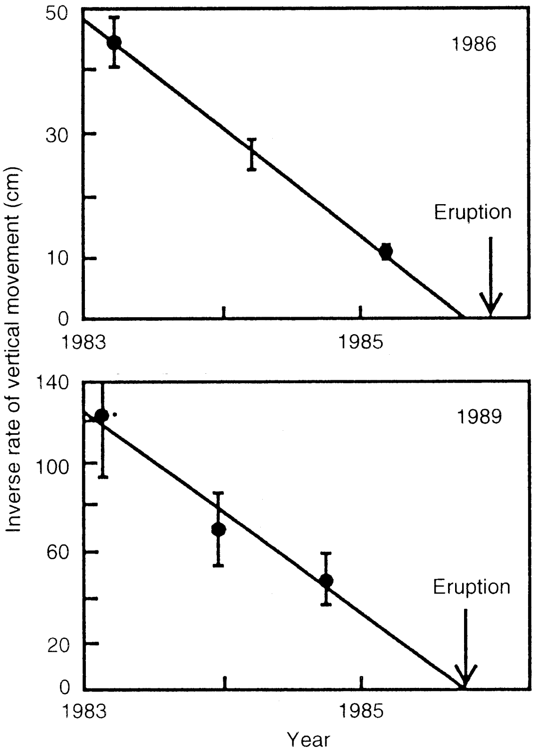

Fig. 4 Prediction of eruptions at Mount Etna based on inverse rate analysis of vertical ground deformation. (After Murray and Voight 1996)

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 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

Fig. 5 Pyroclastic ßows 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

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