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Forecasting volcanic eruptions

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Abstract

Forecasting is a central goal of volcanology. Intensive monitoring of recent eruptions has generated integrated time-series of data, which have resulted in several successful examples of warnings being issued on impending eruptions. Ability to forecast is being advanced by new technology, such as broad-band seismology, satellite observations of ground deformation and improved field spectrometers for volcanic gas studies, and spectacular advances in computer power and speed, leading to improvements in data transmission, data analysis and modelling techniques. Analytical studies of volcanic samples, experimental investigations and theoretical modelling are providing insights into the dynamics of magmatic systems, giving a physical framework with which to interpret volcanic phenomena. Magmas undergo profound changes in physical properties as pressure and temperature vary during magma chamber evolution, magma ascent and eruption. Degassing and cooling during magma ascent induce crystallisation and increases of viscosity, strength and compressibility, commonly by several orders of magnitude. Active magmatic systems also interact strongly with their surroundings, causing ground deformation, material failure and other effects such as disturbed groundwater systems and degassing. These processes and interactions lead to geophysical and phenomenological effects, which precede and accompany eruptions. Forecasting of hazardous volcanic phenomena is becoming more quantitative and based on understanding of the physics of the causative processes. Forecasting is evolving from empirical pattern recognition to forecasting based on models of the underlying dynamics. The coupling of highly non-linear and complex kinetic and dynamic processes leads to a rich range of behaviours. Due to intrinsic uncertainties and the complexity of non-linear systems, precise prediction is usually not achievable. Forecasts of eruptions and hazards need to be expressed in probabilistic terms that take account of uncertainties.

Keywords: volcanism; volcanic eruptions; forecasting; volcanic hazards

1. Introduction

Forecasting is a fundamental objective of volcanology. Civil authorities and the public need to know when and where eruptions will occur, the kinds of volcanic phenomena that might occur, how long eruptions will last, and whether populations near the volcano will be affected by hazards. These questions are much easier to ask than to answer. Recent advances are beginning to provide answers and to establish the scientific agenda. Volcanoes are complex dynamical systems controlled by interactions of many processes, which

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are commonly non-linear and stochastic. There are many uncertainties in the controlling parameters [1]. Further, volcanic systems have the potential for behaviours that are inherently unpredictable [2]. However, complex, sometimes chaotic, systems are not unconstrained and eruptions can show systematic evolutionary trends and quite regular periodic behaviours. Volcanic eruptions also are constrained by physical laws that can be elucidated both empirically and by modelling. Forecasting can be achieved and, under specific circumstances, with some confidence. Like the weather, volcano forecasting needs to be developed in terms of probabilities.

Several factors have advanced understanding of volcanic processes and bring the goal of robust forecasting closer. Several volcanic eruptions have been studied intensively by large multidisciplinary teams of scientists. Eruptions of Kilauea (Hawaii), Krafla (Iceland), and Mount Etna (Italy) have provided important datasets for understanding basaltic volcanism. Mount St Helens (1980–86), Mount Unzen (1991–1995), Mount Pinatubo (1991) and the Soufrière Hills Volcano, Montserrat (1995–present) are examples of well-documented andesite and dacite eruptions. Contemporaneously there have been major advances in monitoring techniques, data acquisition and data analysis, complemented by sophisticated analytical, experimental and theoretical studies and by orders of magnitude improvements in computer power and speed.

This review gives a flavour of the main developments and a sense of where volcanic forecasting is going. The article first considers monitoring techniques. A second section considers volcanoes as dynamical systems in which several non-linear processes are coupled and lead to complex behaviours. This leads into a third section where a probabilistic approach to forecasting is discussed. Newhall [3] provides a complementary article on Volcano Warnings.

2. Volcano monitoring

Volcanic activity is caused by the ascent of magma to the Earth's surface and its eruption. During ascent magma interacts with surrounding rocks and fluids. Monitoring involves geophysical or geochemical techniques that detect magma movements and associated sub-surface interactions, and can record eruptive activity.

2.1. Seismicity

Seismic monitoring can give real-time data and correlations have been established between magma movements, eruptive phenomena and seismicity. Before eruption, ascending magma has to push rocks apart and this perturbs stress distributions and pore fluid pressures, commonly resulting in fracturing and numerous small-magnitude earthquakes. Earthquakes above background levels are commonly the first warning signs of impending eruption, although an eruption may not happen. Indeed the majority of volcano-tectonic crises do not lead to eruption [3,4]. Once an eruption starts seismicity provides information on the

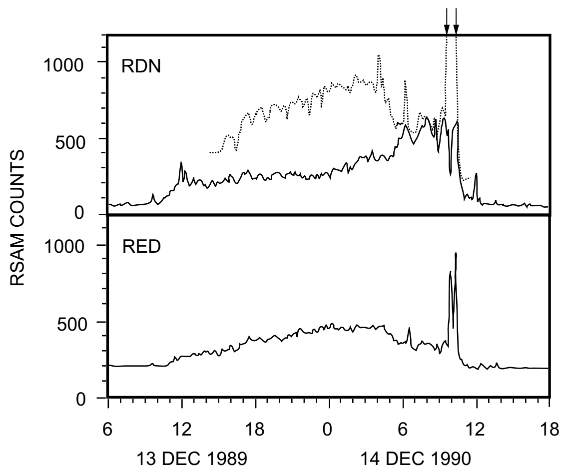

Fig. 1. Real-time seismic amplitude measurements (RSAM) for two stations (RDN and RED) before the explosive eruption of 14 December 1989 at Redoubt Volcano, Alaska (after [7]). The data show the changes in the intensity of shallow long-period earthquakes over a 24 h period prior to the onset of the explosive eruption shown by arrows marking the beginning and end of the eruption. The continuous and dotted lines show the raw and corrected data respectively (see [7] for details). Note that the RSAM data at RED reach a maximum about 6 h before the eruption. Such a response can be interpreted as weakening of the system approaching failure. RSAM is a measure of seismic energy.

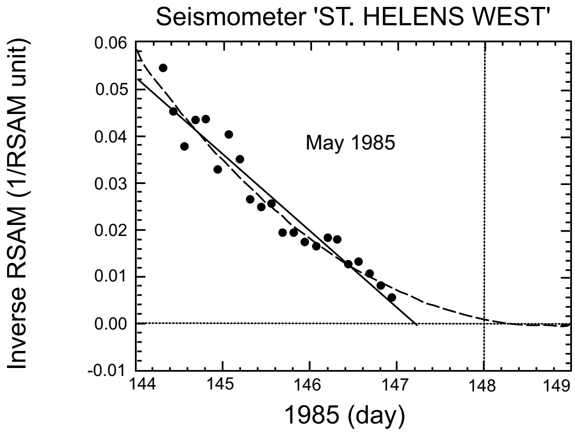

Fig. 2. Inverse (RSAM) from a seismic station during the Mount St Helens activity in May 1985 versus time. The data have been averaged over 3 h. The straight line is a best-fit linear inverse law and the dashed line is a fit to an inverse power law after Voight and Cornelius [8]. The vertical dashed line is the approximate time of eruption onset. The station is 4 km from the crater. Time is in GMT starting 24 May 1985.

style of activity and detects changes in the physical system.

Key developments in volcano seismology have been the recognition of different types of earthquake that can be linked to particular volcanic phenomena, and the recognition of long-period signals related to flow of volcanic gases and geothermal fluids [5–7]. These developments have been augmented by the installation of networks of three-component and broad-band seismometers. The eruption of Mount Redoubt, Alaska (1989–1990) illustrates a success story in seismic forecasting [7]. Here 11 swarms of long-period earthquakes were precursory to explosive eruptions. Warnings were issued for the explosive eruptions of 14 December 1989 and 2 January 1990 based on the characteristics of the swarms (Fig. 1). The forecast was based on two concepts. First the long-period events were interpreted as movement of pressurised fluids along fractures. Second the waxing and waning of the swarm intensity (Fig. 1) was attributed to mechanical weakening of the system before a catastrophic failure and explosive eruption.

Seismic data have been used to evaluate the materials failure forecast method (FFM) [8,9]. The FFM is based on laws of material failure in which failure time is forecast from the inverse relationship between time and a proxy for strain rate, such as ground deformation or seismic energy release. Retrospective analyses of seismic energy release patterns at Mount St Helens, Mount Redoubt and Mount Pinatubo indicate that the eruptions could have been predicted within a few hours or days using this approach (Fig. 2).

Seismologists can distinguish and interpret different types of earthquake signal. Several types of earthquake have been recognised at the Soufrière Hills Volcano, Montserrat [6,10]. Volcano-tectonic earthquakes are distinguished from shallow earthquakes that contain long-period components (Fig. 3). The former was prominent in the precursory as magma forcibly created a pathway to the surface. The latter were associated with growth of the lava dome; the occurrence of such earthquakes in November 1999 was used to recognise that dome growth had resumed after 20 months of inactivity [11]. Seismicity in dome-forming eruptions is also associated with rock-falls and pyroclastic flows generated by dome instability. Seismic signals have been used to locate flow pathways and to estimate their speed [12,13]. The seismic signal of a pyroclastic flow slowly emerges and then decays as the flow moves towards and then past the seismic station. This Doppler effect can be exploited because different stations record peak amplitude and signal duration that are controlled by flow position relative to the station. The signals can be calibrated to flow size and then related to models of flow run-out.

Fig. 4 shows the spectra over a 20 min interval of long-period seismicity leading up to a Vulcanian explosion on Montserrat [6]. The seismicity has several dominant spectral modes and there are systematic shifts of these peaks with an approximately exponential change of each peak frequency with time. The data provide an empirical basis for forecasting. Neuberg [6] interpreted these relationships as a consequence of the great sensitivity of seismic wave velocity to bubble content of the magma. He proposed that the spectral gliding is due to magma vesiculation and associated

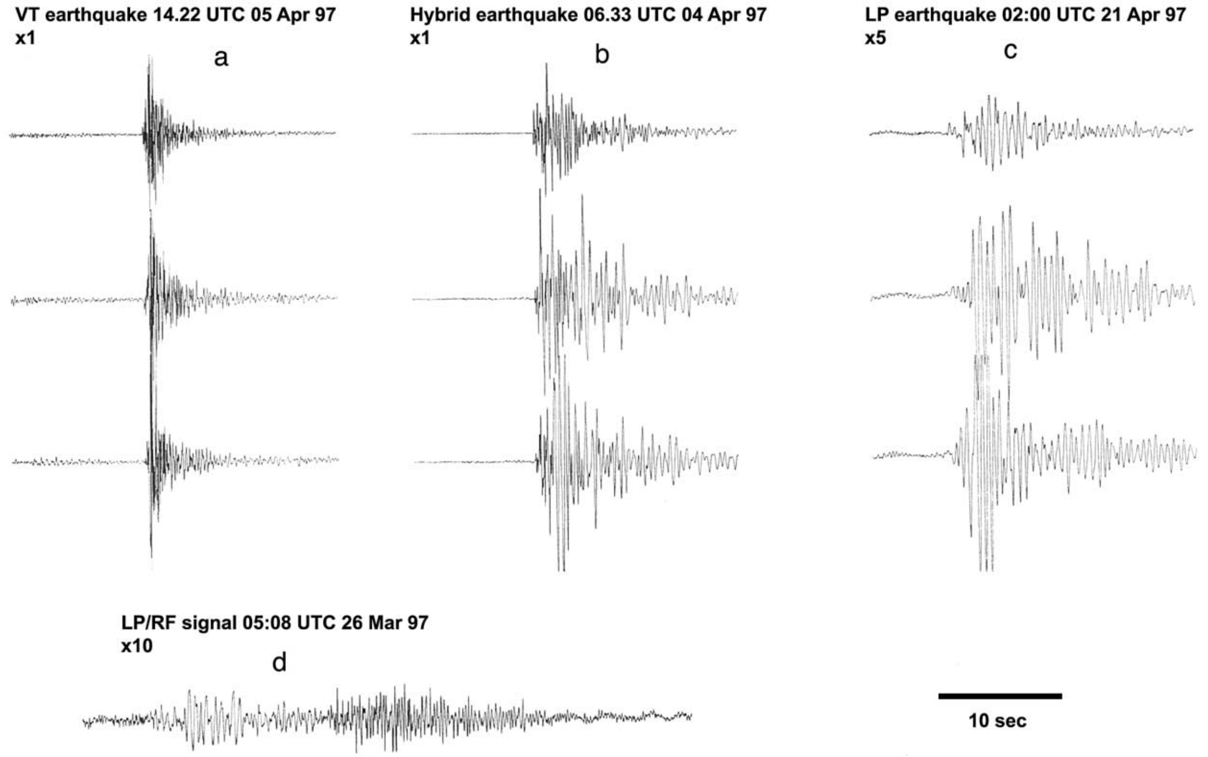

Fig. 3. Four major kinds of seismic signal recorded at the Soufrière Hills Volcano, Montserrat [10]. (a) Volcano-tectonic earthquake. (b) Hybrid earthquake. (c) Monochromatic long-period earthquake. (d) Typical pyroclastic flow or rock-fall signal preceded by a triggering long-period signal.

pressurisation in the upper conduit, developing conditions for an explosion.

2.2. Ground deformation

Magma stored in chambers and flowing along conduits varies in pressure leading to deformation of the surrounding crustal rocks. Most ground deformation techniques measure the resulting changes on or near the Earth's surface. Standard techniques include electronic distance measurements (EDM) using reflected laser or infrared light, measurement of ground tilt, use of the global positioning system (GPS), precise levelling and borehole sensors including strainmeters and tiltmeters. EDM, GPS, and precise levelling require networks of stations and are labour-intensive. The developments of continuous GPS and synthetic aperture radar (SAR) have provided a revolution in the quality and quantity of data [14,15]. Data are acquired rapidly and for SAR a continuous deformation field is documented (Fig. 5).

Ground inflation is commonly observed before the onset of eruption [16,17]. However, substantial ground deformation can occur due to magma intrusion without eruption [18,19] and can also be related to tectonics, isostatic adjustment and changes in geothermal systems. Some volcanoes erupt without any deformation being detected. Interpretations of deformation have generally been based on the Mogi model of a pressure source in an elastic half-space [20]. More elaborate models consider topography and variations in source geometry [15,21]. However, the models do not yet capture the full complexity of crustal responses to magma pressurisation. Since the crust becomes ductile at shallow depths ($\sim$5–10 km) below volcanoes it is unlikely that purely elastic models are adequate. Deformation can be measured earlier than other types of eruption pre-

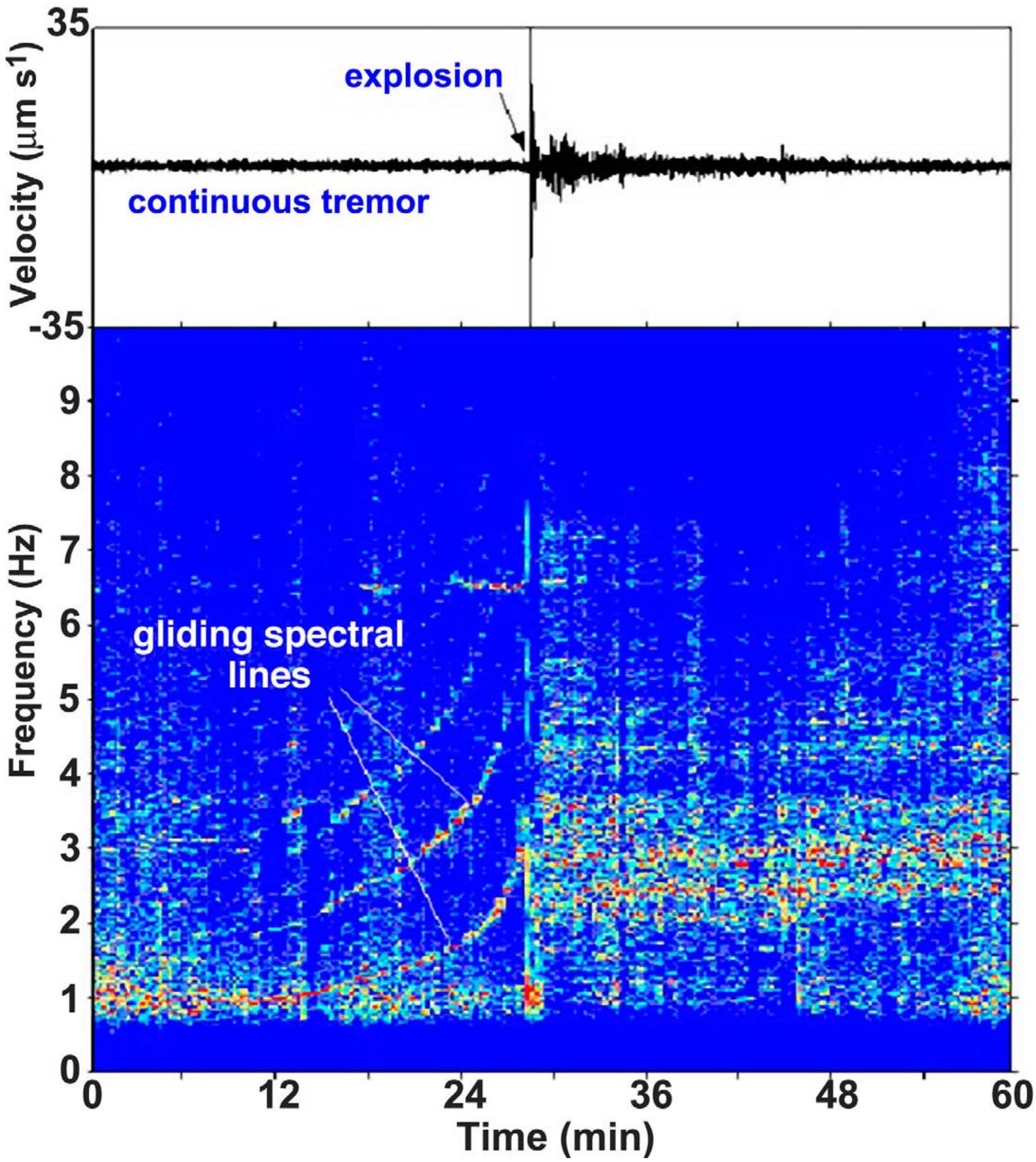

Fig. 4. Gliding spectral lines prior to a Vulcanian explosion on Montserrat at station MBRY on 7 January 1999 (details in [6]). The upper diagram shows the seismic signal of the explosion.

cursors; for example seismicity does not start until a strain threshold (typically about 10^{-4}) is exceeded.

Some hazardous volcanic eruptions involve flank instability. For Mount St Helens in 1980 magma intruded into the volcanic edifice and outward movement of the north flank of the volcano was recorded at 1–2 m/day [22]. The size of the eventual collapse was anticipated [23], but its timing was not predicted. The volcanic blast at Soufrière Hills Volcano, Montserrat was anticipated based on observations of ground deformation, which started in October 1996 [24] and led to a precautionary evacuation. The collapse did not take place until 26 December 1997. These examples highlight the difficulties in predicting the

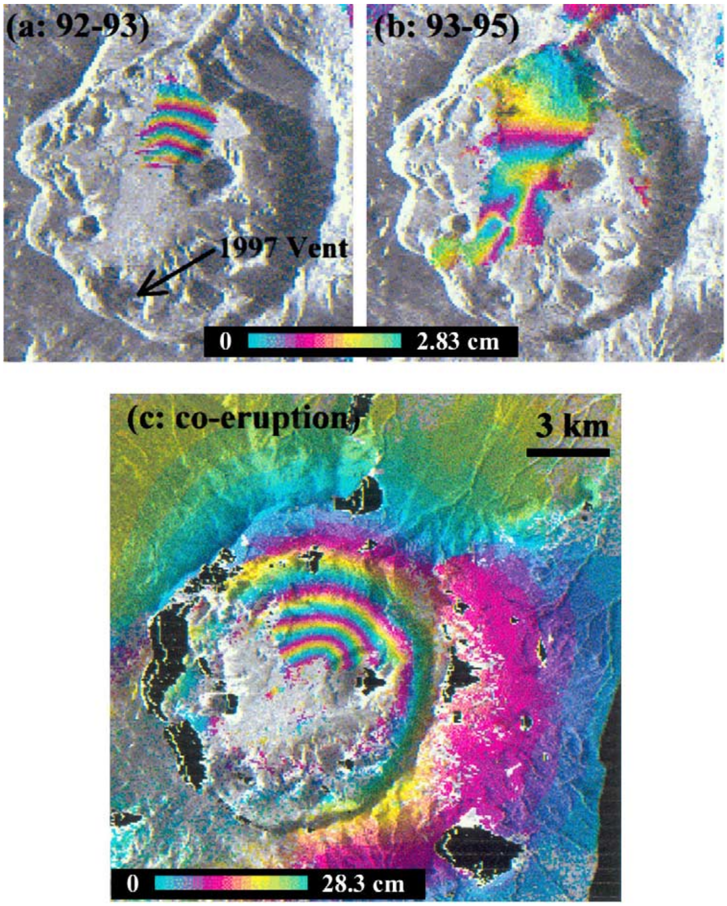

Fig. 5. Ground surface deformation before and during the 1997 eruption of Okmok Volcano, Alaska, detected by satellite radar interferometry (after [17]). Interferograms constructed from ERS-1/ERS-2 InSAR images indicated surface inflation of more than 18 cm between 1992 and 1995 (a,b) prior to an eruption in February–April 1997, and surface subsidence of more than 140 cm during the eruption (c).

structural stability of volcanoes and timing of failure [24].

Observations are becoming important using instruments in boreholes because this environment greatly reduces noise and instrument sensitivity. Borehole strainmeters can detect changes of 10^{-12} [25], and can be deployed at greater distances than other instruments. Their utility was demonstrated in the 1991 eruption of Hekla, Iceland [25]. Five borehole strainmeters located 15–45 km from the volcano recorded marked dilatational strain over a 30 min period during the propagation of a dyke to the surface (Fig. 6). The strain pattern, together with increased seismicity, enabled the 2000 Hekla eruption to be forecast [26]; based on warnings issued by the Icelandic scientists the national radio announced that an eruption would start in 15 min; it started after 17 min.

Tiltmeters have been used to forecast explosions at Sakurajima volcano, Japan [27]. Here inflationary radial tilt is observed for periods of 10 min to 7 h prior to explosions at the summit crater, allowing automated warnings to be issued.

2.3. Volcanic gases

Gas monitoring has been difficult because reliable data had to be obtained from high-temperature fumaroles often in hazardous circumstances.

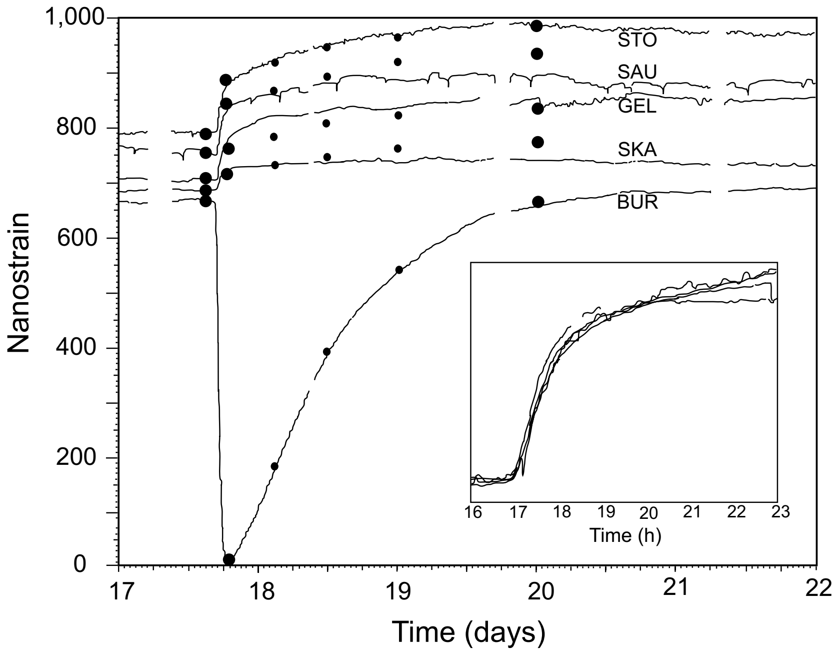

Fig. 6. Five days of strain data from borehole instruments located in Iceland, recording the January 1991 eruption of Mount Hekla, Iceland, after Linde et al. [25]. The curves are the continuous data with four of the stations showing expansion and the closest station to the volcano (BUR) showing contraction. The solid circles show a model in which magma ascends in a dyke from a magma chamber at 6.5 km depth and the chamber deflates over 2 days. The minimum in strain at BUR coincides with the approximate time of surface break-out.

However, remote spectroscopic methods from satellites and from ground-based instruments are greatly improving the quantity of data [28,29]. Significant correlations have emerged between gas fluxes and other geophysical signals [30,31]. Time-series of gas flux can now be produced comparable in detail and quality to seismic and geodetic studies [28].

Understanding of gas compositions is now good enough that the presence of magma at shallow depth can be distinguished from tectonic or hydrothermal degassing when volcanic unrest starts. At Pinatubo high SO_2 fluxes indicated that unrest was magmatic rather than hydrothermal in origin, and a decrease of SO_2 flux (in early June 1991) suggested that the system was sealing, pressurising and approaching conditions for explosive activity [32]. SO_2 measurements, combined with seismic and deformation data, helped the scientists to evaluate correctly the nature of the unrest, the state of the volcano, and to anticipate the eruption. At Montserrat dome growth ceased in March 1998. However, high SO_2 fluxes (1000–3000 tonnes/day) continued throughout the next 20 months before dome growth resumed in November 1999 [11]. This observation was critical in the assessment that the eruption had not ceased. Increases of CO_2 have also been used to indicate replenishment of magmatic systems [33,34].

2.4. Other methods

There are many other methods: gravity, remote sensing of temperature, electric fields, and acoustic emissions. As yet little studied phenomena concern unusual water emissions and changes in water tables prior to eruptions. Water poured out of fissures at Mont Pelée in 1902 [35] to form mud flows in the days before eruption. Water levels in boreholes around Mayon volcano, Philippines increased by several metres before eruption [36]. Several months before the Mount Usu (Japan) eruption in 2000 water levels in two boreholes dropped and then increased [37]. Water spouted out of the wells and out of eruptive vents at the beginning of the eruption [37,38]. These effects are likely caused by rising magma opening up fracture systems and disturbing groundwater systems.

2.5. Integrated datasets

Integration of datasets using several co-ordinated monitoring techniques is the key to successful forecasting. For Mount Pinatubo (1991) integration of data on precursory seismicity, ground deformation, and SO_2 emissions, together with geological studies [39] led to a successful forecast and timely evacuation of tens of thousands of people.

The Soufrière Hills eruption, Montserrat demonstrates the advantages of integrated data. In 1997 the MVO installed two tiltmeters on the rim of English's crater adjacent to the growing lava dome. The tilt data revealed correlations between ground deformation, swarms of hybrid (long-period) earthquakes and volcanic activity [40]. Periodic cycles of tilt were observed (Fig. 7) with periods lasting a few hours to a few days. In each cycle there was a seismic swarm associated with ground inflation. During the deflation there was low or no conduit seismicity, but rock-falls from the dome increased substantially. The cycle peaks were commonly characterised by vigorous ash venting and in early August 1997 by

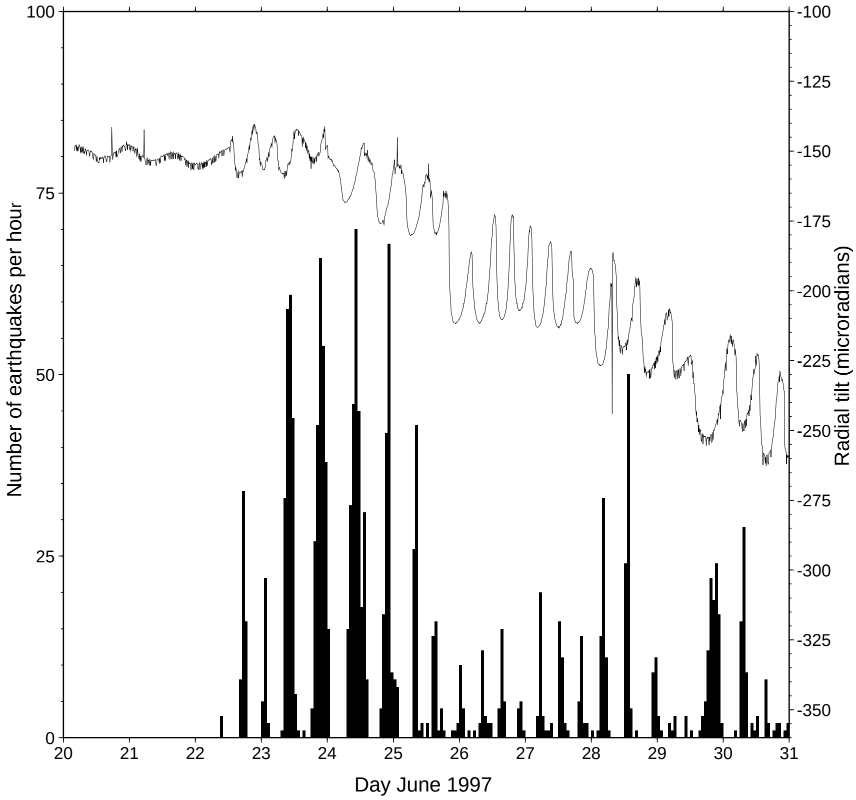

Fig. 7. The tilt pattern at Chances Peak and seismicity at the Soufrière Hills Volcano, Montserrat in June 1997 (after [40]). The tiltmeter was approximately 400 m from the centre of the dome with the tilt axis for data shown being approximately radial to the dome centre. The earthquake event frequency in events per hour (left hand vertical axis) at the Gage's seismometer is shown as histograms. The tilt variation in μradians (right hand vertical axis) is shown as the continuous curves. All the instrument output displays the cyclic pattern of deformation and seismicity, with hybrid earthquakes occurring in the inflation periods and rock-fall signals occurring during the deflation periods. Marked episodes of degassing were observed at the peaks in the tilt cycle and during deflation (see [40]).

Vulcanian explosions. These observations led to an interpretation of cyclic pressurisation of magma in the upper conduit, with a surge of dome growth and release of pressurised gas at the peak of a cycle and during deflation. The cycles were commonly highly regular in period for several days to a couple of weeks and the MVO used these patterns for forecasting [40].

3. Volcanoes as dynamical systems

Improvements in forecasting are closely linked to advances in understanding of the underlying dynamical processes. Volcanic flows are complex and applied mathematicians, engineers and physicists are becoming involved in modelling studies in collaboration with earth scientists. The strongly non-linear and time-dependent character of volcanic systems introduces fundamental issues for forecasting of uncertainty and complexity.

3.1. Physical properties of magmas and their surroundings

Magmas are complex materials with strong dependence of rheology on temperature, melt composition and water content [41]. Viscosity can vary between 10^0 and 10^{14} Pa s. Although pure melts are normally Newtonian, they can become non-Newtonian at high strain rates [41]. Magma rheology is greatly complicated by the presence of suspended crystals and gas bubbles [42,43], particularly at high concentrations where rheology becomes strongly non-Newtonian. Many other important properties that can influence flow dynamics, including magma density, thermal conductivity, compressibility, acoustic speed and diffusivity of dissolved gases, also vary widely. The Earth's crust with which magma interacts is made of complex and variable materials. Mechanical properties and responses to magma ascent and eruptions can be expected to vary as a consequence of geological and structural heterogeneities, stress variations, temperature, and disturbance of hydrothermal or groundwater systems. In some places the crust might deform as an elastic material and in others in ductile style, depending on factors such as strain rate, lithology, temperature and pore pressure. Magma flow can alter the surroundings by the action of magma pressure, heat transfer and chemical reactions. Flank instability highlights the need for geotechnical data as input to dynamical models [23].

3.2. Volcanoes as non-linear dynamical systems

Variations of physical properties of magmas and their surroundings are governed by non-linear, time-dependent processes, such as crystallisation and degassing in magma and fracture network evolution, pore pressure variations and strain weakening in a volcanic edifice. These processes are typically coupled, so that, for example, gas exsolution and heat loss in ascending magma can induce crystallisation and vesiculation [2,44,45]. Flowing magma is driven away from thermodynamic equilibrium by the changing pressure and temperature and towards equilibrium by processes such as crystallisation and gas exsolution. These changes are time-dependent, because crystallisation and vesiculation are controlled by complex kinetics and cause very large changes in rheology and flow behaviour. Similarly there are complex interactions between gas bubble nucleation, growth, coalescence, and segregation in ascending magmas which are themselves coupled to flow dynamics through the effects of bubbles on magma density, rheology and compressibility [43,46–48].

The rocks around a conduit, the edifice and the groundwater are expected to respond in non-linear ways to magma ascent and eruption [23,37]. Examples of external effects are stress corrosion, in which hydrothermal fluids attack and weaken country rock [49], mineral precipitation from hydrothermal fluids that reduce wall-rock permeability and inhibit degassing of ascending magma [50] and stress changes related to edifice growth or destruction [51].

Models are emerging to explain pulsatory and periodic behaviours in lava dome eruptions. In such eruptions fluctuations in magma discharge rate can vary on time scales from hours to decades [40,52]. Sometimes the pulsations are quite regular, as exemplified by the tilt cycles on Montserrat [40] and the 1980–1986 activity of Mount St Helens [53]. Dome growth can also be steady for many months or years [53]. Whitehead and Hellfrich [54] showed that a fluid with strongly temperature-dependent viscosity flowing through a conduit with lateral cooling displays periodic fluctuations in flow rate. For the short-time-scale (hours to days) cycles observed at Soufrière Hills and Pinatubo, models have linked the behaviour to the coupled processes of degassing, crystallisation and rheological stiffening of ascending magma together with stick-slip behaviour of non-Newtonian magma [40,55,56]. Melnik and Sparks [2] considered coupled conduit flow and lava dome extrusion, taking into account the coupling between gas exsolution, gas escape by permeable flow, and crystallisation kinetics with magma rheology and density. Barmin et al. [52] extended this model by considering unsteady flow evolution and simulating eruptive behaviours that resemble those observed at lava dome eruptions.

Fig. 8 illustrates a mechanism to cause periodic and complex behaviours in lava dome eruptions [52]. A chamber with elastic walls is supplied with magma at a constant rate. The ratio of output (eruption rate) to input is plotted against magma chamber pressure. The steady solutions to the mathematical description of this system yield a sigmoidal curve with an upper linear branch and a lower parabolic branch. The upper linear branch represents flows that are too fast for degassing-induced crystallisation to occur, whereas the lower limb of the parabolic branch represents the case of very slow flows where crystallisation occurs and the viscosity is higher. Multiple steady states exist such that at a fixed magma chamber pressure three possible eruption states exist. Such systems can be extremely sensitive to slight changes in conditions especially near cusp points. Periodic behaviour can be understood by starting at an arbitrary point on the lower branch (A). Since input to the chamber is greater than output the chamber pressure builds up and the output increases. Beyond cusp point B there is no steady solution so the eruption enters an unsteady regime and flow rate increases until the upper linear branch is reached at C where output is greater than input. At this stage chamber pressure reduces and the system evolves to cusp point D and then unsteadily back to A. Thus a cyclic pattern is established.

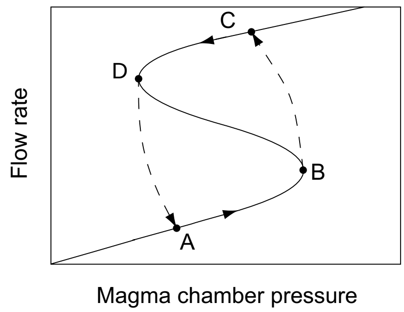

Fig. 8. A general schematic diagram of steady-state flow rate up a conduit against magma chamber pressure to illustrate the abrupt changes in flow regime that can occur. The two stable branches (A–B and C–D) relate, in the models of Melnik and Sparks [2] and Barmin et al. [52], to the kinetics of crystallisation (see text). The arrows indicate the variations of flow rate with chamber pressure. The dashed lines represent the unsteady transitions in the system.

Eruptive patterns similar to Mount St Helens and Santiaguito can be reproduced by such a dynamical model (Fig. 9), including both periodic behaviour and steady outputs. These models, however, are not yet fully realistic. For example, the models are one-dimensional and make simplifications such as constant input to the chamber and constant lava dome height. Massol and Jaupart [48] have shown that large lateral pressure gradients can develop across volcanic conduits and that there will be lateral coupling between degassing rates, crystallisation and rheology. Realistic models will need to take such two-dimensional effects into account. Additionally the models make simple assumptions about the response of the surroundings. Flow models will need to be coupled into models of edifice deformation and groundwater responses. This is a field in its infancy, but future studies promise to reveal rich behaviours. A system only requires three non-linearly coupled time-dependent variables to have the potential for chaotic behaviours.

Such models link flow dynamics with geophysical and eruptive phenomena. Melnik and Sparks [2] found that large magmatic overpressures develop in the uppermost parts of volcanic conduits due to rheological stiffening. This concept pro-

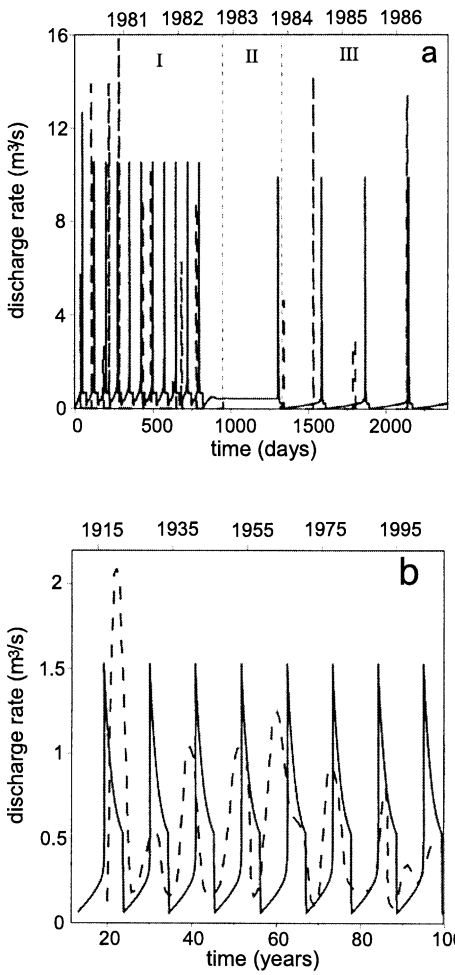

Fig. 9. Discharge rate versus time for (a) growth of Mount St Helens, USA (1980–1986) and (b) Santiaguito Volcano, Guatemala (1922–2000). Dashed curves are the observed fluctuations in discharge rate and solid lines are the best-fit model simulations (details in [52]).

vides an explanation for shallow pressure sources inferred from ground deformation, shallow seismicity and occurrences of sudden Vulcanian explosions in dome eruptions.

3.3. Eruption transitions

Forecasting explosive eruptions is a critical issue. At Mount St Helens in 1980 the major explosive eruption occurred near the beginning of the eruption and was followed by episodic lava extrusions and more moderate explosive activity in the 1980–86 period. At Mount Pinatubo in 1991 the catastrophic eruption of 15 June was preluded by a magnitude 7.8 earthquake on the Philippine fault in August 1990 [57]. Felt earthquakes occurred in March 1991 and the first phreatic eruptions began on 2 April. A brief 4 day period of escalating dome growth and explosive activity preceded the paroxysmal eruption on 15 June. Lascar volcano, Chile started a slow effusion of an andesite lava dome in 1984, but unexpectedly had a very high-intensity explosive eruption in April 1993 [58]. The Lascar case highlights the problem that relatively benign lava effusions can suddenly change to very hazardous explosive activity after many years of eruption.

The dynamics of gas escape during magma ascent controls the transitions between explosive and effusive activity. Taylor et al. [59] introduced the idea of a permeable magma foam. As pressure decreases gas bubble concentration increases and bubbles interact and coalesce. Once gas bubbles become interconnected the exsolving gas can escape through permeable magma and the conduit walls. Models of the coupling between gas exsolution, gas loss and eruptive styles [60,61] show multiple steady solutions to the mathematical descriptions so that sudden transitions between eruptive flow regimes (e.g. explosive versus effusive) can occur. These transitions may happen with little warning and forecasting may be problematic when a volcanic system is in an unstable or sensitive state.

4. Predictability, unpredictability and probabilities

Precise prediction is not achievable in many situations. Erupting volcanoes can become critical systems so that they can move from one state to another with only a very minor external or internal trigger. An example of an external trigger is the sector collapse of Mount St Helens in 1980. Here magma had been intruding into the edifice for several weeks, causing bulging of the northern flanks. The collapse and paroxysmal eruption on 18 May was triggered by a magnitude 5 earthquake [22]. Although the eruption was moving towards catastrophic eruption anyway [23], the eruption timing could have been significantly different without this trigger. Material failure is typically highly non-linear [8]. Thus the build-up to possible eruption might take years or months without ever being certain that the eruption will take place. Close to the threshold conditions for failure the system can accelerate and observations confirming that an eruption is inevitable may only be manifest a matter of days or hours before.

Multiple steady-state solutions are a significant feature of conduit flow models [2,60,61]. Thus, even if every controlling parameter were known exactly, behaviour would not be predictable without a very complete knowledge of the system's history. There are large uncertainties in the values of controlling parameters, and likewise the precise history will not be known. Thus in certain respects volcanoes are inherently unpredictable. As in other dynamical systems, very slight changes in initial conditions or slight changes in controlling parameters might have completely different long-term outcomes.

In forecasting volcanic hazards and assessing risks one needs to estimate the probability that a hazardous event will happen, the probability that the event will affect a particular place and the probability that the effects will include fatalities and property damage. Forecasting of volcanic hazards requires knowledge both of the dynamical phenomena and of uncertainties. For example, the assessment of tephra fall hazards is now quite advanced. Models have been developed to estimate the dispersal of tephra and to evaluate critical hazard parameters, such as threshold values of mass loading to cause roof collapse [62,63]. Results are expressed in probabilistic terms. Quantitative approaches are being developed for lava [64], lahars [65] and pyroclastic flows [66,67].

5. Discussion

This review of eruption forecasting indicates reasons for optimism. Magma ascent causes crustal deformations and disturbances that can be detected easily. The build-up to eruptions typically occurs over periods of days to years so that scientists can usually issue long-term warnings. However, there are still major problems in assessing whether detected subterranean magma movements will actually lead to eruption. The final system failure that just precedes the onset of an eruption typically can only be recognised over rather short time scales of days to only minutes. Theories, such as those based on materials failure or the changing seismic properties of pressurising bubbly magma, are promising from retrospective analysis, and have the potential to interpret geophysical data in real-time leading to quite accurate forecasts. However, confident forecasts may only be possible shortly before an event, giving little time for civil responses and evacuation. The value of forecasts will be negated if there are not very effective communication systems for rapid response by the authorities and if the community is not well-prepared [3]. Erroneous forecasts can also lose scientists credibility.

Once an eruption starts, then the principles behind the causative magmatic flows and their relationship to geophysical phenomena are beginning to be discerned. The new generation of models, together with investigations of the physical properties of magmas, indicate that volcanic systems are highly non-linear and in certain respects may be inherently unpredictable. Such models can simulate complex patterns of eruptive fluctuations and transitions and thus provide a conceptual framework for forecasting.

What is likely to happen over the next decade or so is development of ensemble models, which make volcanic forecasts that take account of both uncertainties and non-linear dynamics [1]. Considerable effort will be placed on reducing uncertainties, such as in material properties of magmas, and improving monitoring techniques, but overall uncertainties will remain. Integrated models of volcanic processes will be aimed at simulating the geophysical signals, eruptive behaviours and hazardous phenomena. These models can be evaluated with comprehensive integrated datasets. Data assimilation methods and Bayesian updates will be used to improve forecasting models. As in weather forecasting, ever increasing computer power will allow ensemble runs to build up probabilistic forecasts as well as testing model sensitivities. Inevitably there will be more eruptions to document and learn from. Such studies are likely to become inputs to inform systematic procedures for evaluating possible outcomes for volcanic activity, such as expert elicitation, construction of event trees and running risk assessment models for the ultimate purpose of issuing warnings and giving clear scientific advice [1,68,69].

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