PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The causes and consequences of eruptions of andesite volcanoes: concluding remarks

R. S. J. Sparks

Phil. Trans. R. Soc. Lond. A 2000 **358**, 1725-1729
doi: 10.1098/rsta.2000.0611

THE ROYAL SOCIETY

The causes and consequences of eruptions of andesite volcanoes: concluding remarks

By R. S. J. Sparks

Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK

The Discussion Meeting has confirmed that volcanological research is at a particularly exciting stage. The advances made over the last decades of the 20th century have been profound, yet the science is still in many ways immature. To a large extent, volcanologists often cannot say when, where and how an eruption will take place, and few of the 50 or so eruptions on Earth per year are well documented from a scientific point of view. Basalt volcanoes erupt frequently and perhaps the advances in monitoring and forecasting have been most pronounced here. However, with andesite volcanoes there is a great deal to do and to understand. Despite this unsatisfactory state of affairs, there can be no doubt that the tools for understanding volcanoes are now available, and the results of this meeting demonstrate not only recent successes, but the great potential to make rapid progress. My opening remarks suggested that technological advances and detailed studies of particular eruptions by multidisciplinary teams were key factors in advancing the science. The 14 contributions to the meeting illustrate that this is indeed the case. Ideas are certainly in a state of flux, and long-cherished paradigms are being challenged. In these concluding remarks I distil my perceptions of some of the important issues and discoveries presented in the meeting by the speakers who represent well the broad cross-section of modern cutting-edge volcanological research.

There have been major advances in analytical methods applied to volcanic rocks, e.g. the development of microbeam techniques and advances in mass spectrometry, which have seen remarkable improvements in precision and in the ability to investigate microscale variations of mineral compositions. Simon Turner considered one aspect of this ongoing revolution, namely the study of short-lived decay products of the U-series. These studies are giving new data that constrain the time-scales of magma genesis in the range of hundreds of thousands of years to a few years. As in many burgeoning areas, the new data are both answering important questions, which could not be tackled before, and providing new enigmas. The isotopic data indicate that the addition of fluids from the slab to the mantle wedge involves time-scales of hundreds of thousands of years, yet Ra excesses imply that primitive magmas in arc settings rise from their deep mantle source in periods of a few thousand years at most. At the same time, crystals from magmas sometimes give ages that are much older than the eruptions' age, implying very substantial residence times of the magmas within the crust, or, alternatively, mixing of new magmas with crystals derived from older magmas. Ra excesses, implying very short transit times, are dominantly from basaltic–andesites and andesites, whereas the mineral isochrons implying (possible) residence times of a few kyr are generally from more silicic rock samples, which tend not to have Ra excesses. There appears to be some link between time and composition.

To some extent these different isotopic systems seem to be implying very different time-scales even in the same magmatic system. Although not covered in the meeting explicitly, there have also been significant advances in the dating of young volcanic rocks, using $^{39}Ar/^{40}Ar$ geochronology and dating using cosmogenic isotopes, which means that at last volcanology is in a position to establish detailed quantitative histories of volcanoes. Combining precise geochronological, isotopic studies of short-lived radionuclides and microbeam studies of individual crystals is going to provide the opportunity to develop new paradigms for the nature of magmatic systems.

A long-cherished concept of several decades is the long-lived magma chamber, which remains stable below a volcano throughout its life-span. In such chambers, magmas remain at approximately fixed pressure, with magma compositions slowly changing as cooling and crystallization take place. The concept is still central to much of the thinking about volcanic systems, but is being seriously challenged as a universal paradigm, not only by enigmatic isotopic data, but by field data and petrological investigations.

John Eichelberger reviewed some of the evidence that many andesite and dacite magmas in arc systems are derived from open systems in which stagnant and crystal-rich magmas residing at shallow depths are remobilized into eruption by basaltic magmas from greater depth. Magma mixing is often a major process in replenishment, with, in addition, transfer of heat and mass from the basalt to the resident andesite or dacite magma. In some cases it may even be that the resident end-member magma is so crystal rich that it might be better regarded as a region of partly melted intrusive rock rather than as a conventional magma. It is worth remarking that ideas on the importance of magma mixing, pioneered by Eichelberger, were regarded as preposterous only 25 years ago by many in the scientific establishment, who thought that andesites were formed directly by melting the subducted slab, an idea that is nowadays regarded as of little importance. Characteristically, Eichelberger now proposes a radical new idea that departs from conventional wisdom. Large-scale explosive eruptions of compositionally zoned magma bodies are usually interpreted as the emptying of a long-lived magma body that has acquired stable compositional stratification over substantial periods of time. Eichelberger reviewed observations of the eruption of Mount Katmai, Alaska, in 1912 and its eruption products to argue that this eruption involved the intersection of a rhyolitic magma from deep in the crust with a shallow-level andesite and dacite magma body beneath Mount Katmai. The case is quite compelling. He further speculates that many other zoned chambers are likewise due to rhyolitic replenishment. It is quite likely that this idea will be not be well received in many quarters, so it will be interesting to see if, again, today's apparently ridiculous idea turns out to be tomorrow's conventional wisdom!

Kathy Cashman and Jon Blundy provide another attack on conventional wisdom. They make the case, which I find rather convincing, that the dacite magma of Mt St Helens is governed by decompression during magma ascent from a deep source. They suggest that during ascent the dacite magma crystallizes extensively once water-saturated conditions are reached. The magma arrives at the surface as a typical crystal-rich dacite. They produce arguments and data to show that the residual rhyolitic glasses in glass inclusions and the matrix reflect a history of decompression rather than constant pressure crystallization in a magma chamber. They also show that the glass compositions are correlated with eruption rate, suggesting a kinetic quenching to preserve glass reflecting a range of pressures. Mt St Helens dacite is a fairly typical orogenic magma, and so an intriguing question is how such very different interpretations of crystal-rich orogenic intermediate magmas can come about.

The importance of fluid dynamical modelling in understanding volcanic processes was well illustrated in the contributions by Claude Jaupart, Juergen Neuberg and Andy Woods. Almost all volcanic processes and associated geophysical phenomena involve some kind of fluid flow. The advances in computer power allow investigations of complex multiphase flows and the coupling of flow with deformation of the volcanic edifice and conduit walls. Geophysical manifestations, notably earthquakes, are responses that can be monitored, so there is a strong incentive to understand how they relate to flow processes and to the physical properties of magmatic systems.

Claude Jaupart demonstrated that a volcanic edifice modifies the stress distribution in the crust so that conditions for magma to reach the surface and erupt change as the edifice grows. In particular, for a given pressure in the source region (presumed to be a magma chamber), there is a threshold density above which the magma is prevented from eruption. Jaupart's analysis of the elastic deformation of the conduit walls in a system loaded by a volcanic edifice suggests that magmatic intrusions will bulge near the surface, providing a mechanism for storage of magma at very shallow depths, perhaps accounting for formation of a magma chamber. As an edifice grows, magmas have to evolve to more silicic compositions to be able to erupt, suggesting to Jaupart that edifice growth feeds back into magma evolution. This is a concept that is different to those of other speakers, where the role of deep magma bodies and magma ascent from great depth is emphasized.

Jeurgen Neuberg concerned himself with what is perhaps the most important kind of geophysical manifestation: volcanic earthquakes. Here, fluid flow and fluid properties play a crucial role in the origin of shallow earthquakes. Characteristic features of many shallow volcanic earthquakes are their long-period components and repetitive nature, with almost identical clones repeating many times in an earthquake swarm. Neuberg also showed quite beautiful systematic spectral shifts with time in many earthquake episodes. In some examples of explosions from the Soufrière Hills, Montserrat, there are systematic spectral shifts during the several minutes before an explosion, indicating that there is a real prospect of prediction. On the basis of modelling, Neuberg interprets long-period signals as related to the movement of high-pressure gases and the impedance contrast between pressurized vesiculating magma in the conduit and denser wall rocks. The strong association of earthquake swarms to ground-deformation patterns and eruptive activity on volcanoes like the Soufrière Hills, Montserrat, also suggests that this fluid movement along fractures is related to the degassing mechanisms of the rising magma within the uppermost parts of the conduit. Neuberg presents some very instructive models that help explain what information is actually recorded. His models show that small amounts of vesiculation of the rising magma in the conduit dramatically reduce the seismic velocity, and this, together with the strong impedance contrast of the magma with the wall rock, can trap most of the seismic energy within the conduit, which acts as a waveguide.

His conduit model for shallow seismicity illustrates three important facets of current advances in volcanology. First, advanced instrumentation (in this case three-component broadband seismometers) combined with great computer power allows collection of remarkable high-quality data, as exemplified by the Soufrière Hills eruption on Montserrat. Second, modelling of coupled fluid flow, conduit conditions and seismic wave generation and propagation can provide new explanations for volcanic earthquakes, which will facilitate much improved interpretations. Third, shallow volcano seismicity is strongly related to degassing, pressurization and magma flow, so it is clear that advances will be made in this subject through cooperation between seismologists, petrologists and fluid dynamicists.

Andy Woods considered the behaviour of pressurized lava domes when they collapse and developed a model for the origin and dynamics of volcanic blasts. It is becoming clear that in eruptions of very viscous magma, like that of the Soufrière Hills volcano, large excess pressures can develop in the upper parts of the conduit and in the lava dome itself. When a pressurized dome collapses, as happened on Montserrat on 26 December 1997, the pressurized gases expand as the dome rock disintegrates. Woods first calculated the typical pressure distribution in the dome and then looked at the expansion of the gas as the rock mass disintegrates using a model adapted from the mathematical description of nuclear explosions. An important result of the modelling is that the explosive expansion results in a gas and particle cloud several hundred metres in diameter in just a few seconds. Strong gradients in particle concentration and grain size are predicted, so that the resulting density current or volcanic blast is strongly stratified. This work is another good example of the power of modern mathematical models in providing increasingly realistic descriptions of volcanic flows. Rick Hoblitt also considered volcanic blasts more from the observational standpoint. He presented a very detailed analysis of the photographic and satellite information on the volcanic blast associated with the eruption of 18 May 1980 on Mt St Helens. He made a compelling case that there were two pulses in this eruption, the second being more powerful than the first. His paper shows that even 20 years after the event there are still many things to learn about this eruption, and that well-documented eruptions are vital to the progress of the science.

Another problem relating to major volcanic hazards is the stability of volcanic edifices, including newly constructed and growing domes like that on the Soufrière Hills volcano, Montserrat. Barry Voight summarized the advances in the understanding of edifice and dome stability, much based on his own pioneering studies. He showed how the combination of advanced theoretical models of slope stability, empirical engineering approaches, measurements of geotechnical properties of volcanic rocks, and close monitoring provides a framework for understanding edifice and dome failures. A key point is that geological systems are complex, so all the parameters needed for prediction of failure will never be known precisely. There are more parameters than there are equations, and many have large degrees of uncertainty. This fundamental indeterminacy means that careful monitoring will always be critical to anticipating edifice failure.

There have been some dramatic advances in the monitoring techniques available to volcanologists. Remote sensing in particular is providing remarkable new data and approaches. Dan Dzurisin reviewed the progress in monitoring volcano deformation from space using synthetic aperture radar (SAR) interferometry, as well as ground-based techniques, such as the global positioning system. SAR can achieve instantaneous information of entire deformation fields on volcanoes if the conditions are favourable. In many ways, this technology transforms ground-deformation studies, because the results from a single interferometric map can give the deformation field over hundreds of square kilometres and provide data equivalent to many months of field surveying, as well as data in places that may be inaccessible. Of course, there

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

still has to be some ground truth to help interpret SAR images. Bill Rose illustrated the remarkable progress in imaging and interpreting remotely sensed data on volcanic plumes. Satellite data provide information on global volcanism, so that almost all eruptions across the Earth can now be documented. Satellite data are providing critical new information on gas and particle fluxes from volcanoes. Some of these data are proving surprises: for example, it is becoming clear that the amount of very fine volcanic ash and dust (less than 20 μm) is substantial and significantly larger than ground-based studies would suggest. Volcanic gas monitoring has also benefited from development of remote techniques, as reviewed by Peter Francis. Monitoring of SO_2 fluxes using the correlation spectrometer (COSPEC) is now routine on many volcanoes, and some outstanding datasets have emerged. It is clear from such data that patterns vary considerably and are complex. Similarly, the recent development of Fourier transform infrared spectroscopy (FTIRS) to monitor gas compositions remotely is allowing a much more detailed inventory of volcanic gases to be made. What is now needed, perhaps, is the development of degassing models that allow these data to be better interpreted.

The importance of understanding volcanic activity for the mitigation of hazardous processes was well illustrated at the meeting. Richie Robertson described the 1995–1998 eruption of the Soufrière Hills volcano on Montserrat, and Marta Calvache described the problems associated with the recent eruptions of Galeras and Nevado del Ruiz in Colombia. In both cases, the communication of scientific results and ideas was vital to the task of saving lives. There were remarkable parallels between the three cases, with the credibility of the scientists being a critical factor in the response of the public and the reaction of politicians to scientific advice. There are no easy answers. Unfortunately, in general we know too little about how volcanoes work to really give certain predictions, and potentially dangerous situations do not always evolve into a dangerous event. The best policy seems to be openness and honesty with the public about the limits of our knowledge and in our ability to forecast, but at the same time, work to educate the public and decision makers about the dangers that they might face and help them to understand the uncertainties in natural phenomena. Another modern issue for the volcanologist is the hazards posed to aviation by volcanic ash. There are many major airline routes close to active volcanoes, such as the northern Pacific and the Aleutian islands, where there are very busy airline routes. Tom Casadevall reviewed this problem, giving hair-raising examples of near catastrophes. Fortunately, this seems to be a problem in which scientists and observatories can play a role together with modellers of atmospheric circulation by providing warnings to traffic controllers about the occurrence of new ash injections. It is not clear, however, that all airlines take this problem as seriously as they might, and one hopes that a real catastrophe will not be the mechanism that makes the aviation community more aware.

Modern volcanology is advancing at a fast rate. I guess I would like to be around at the end of the new century when I suspect that advances will be even more profound and surprising than today's advances would be to Alfred Lacroix or Tempest Anderson. However, it will be the academic great grandchildren of some of the speakers at this meeting who will be discussing them!