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

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

R. S. J. Sparks

Phil. Trans. R. Soc. Lond. A 2000 **358**, 1435-1440
doi: 10.1098/rsta.2000.0596

THE ROYAL SOCIETY

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

By R. S. J. Sparks

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

1. Introduction

Mythology provided the earliest explanations of volcanoes and their eruptions. The Greeks linked volcanoes with giants, several of whom were giving a lot of trouble. So Zeus grabbed some mountains from the Earth and flung them on top of the giants to keep them quiet. Thus, eruptions of Vesuvius and Mount Etna were clearly the expressions of annoyance from the giants buried beneath. Another giant called Talos had melting feet and flung rocks at Jason and the Argonauts as they passed the volcanic island of Santorini. Japanese legends considered explosive eruptions to be a fight between giant serpents. Madame Pelée, the goddess of Kilaeua, was thought to be beautiful, but very easily upset. At the end of the 20th century, volcanoes continue to inspire, fascinate and sometimes terrify. There is now of course some scientific understanding of how volcanoes work, but there are many volcanic processes that still surprise and remain poorly understood.

At the beginning of the 20th century the eruption of Mont Pelée, Martinique, in the Caribbean, caused one of the great volcanic disasters. Only one of the 29 000 inhabitants of the town of St Pierre survived the terrible volcanic blast of 8 May 1902; the others perished within a few minutes. This tragedy awakened the world to the terrible dangers when long-dormant volcanoes erupt, and was a landmark in the development of volcano science. Classic descriptions of the eruption by Lacroix (1904) and by Anderson & Flett (1903) in a report to The Royal Society were major advances in the understanding of volcanic processes. In particular, the phenomenon of nuées ardentes, or glowing clouds, was documented and correctly interpreted. Lacroix (1904) recognized three different mechanisms of nuées ardentes by gravitational collapse of a lava dome, by vertical explosion, and by laterally directed volcanic blast. At the close of the century, another andesitic volcano in the Caribbean, the Soufrière Hills volcano on Montserrat, has once more engaged public and scientific attention. Although there have been limited fatalities, this eruption has severely disrupted a small island nation, and has caused a major emergency involving the British government, since Montserrat is an overseas territory of the UK.

This Meeting came at an appropriate moment at the end of the 20th century, and as the activity at Soufrière Hills declined. The Meeting allowed the scientific community to review the advances of a century of scientific research on understanding andesite volcanoes. The threats posed by such volcanoes are becoming greater and more diverse. As the world's population increases, the flanks of many volcanoes are now crowded with people. Some of the world's megacities, such as Mexico City and Naples, are close to highly dangerous andesite volcanoes. New problems also arise in the modern world with major passenger airline routes passing over volcanically active regions like the Aleutians. Injection of ash into the stratosphere can occur unexpectedly and pose serious problems for aviation safety. Large injections of aerosols also exacerbate the effects of anthropogenic chemicals on the ozone layer. It seems that andesite volcanoes will pose significant problems in the next century and so the Meeting can perhaps contribute by looking forward to the advances that will help mitigate the effects of andesite volcanoes.

2. Why andesite volcanoes?

Andesite is defined in an entirely arbitrary way as a volcanic rock with certain chemical characteristics, in particular bulk silica content should be in the range 57–63 wt%. Alkali contents are also used to define andesite, and rocks that exceed certain alkali content limits are no longer defined as andesite. In reality, volcanic products have a continuous compositional range, and, therefore, choosing a particular range of compositions for the subject of a meeting does not seem very scientific. However, there is a rationale for focusing on volcanoes that produce dominantly magmas of intermediate composition, provided one is fairly relaxed about including volcanoes and eruptions that slightly depart from the strict chemical classification to include dacite eruptions like Mount Unzen and Mt St Helens, and more esoteric intermediate magmas like those of Vesuvius.

The empirical observation is that andesite volcanoes (defined *sensu lato*) have provided, and are likely to continue to provide, the greatest threat. Basaltic volcanoes are largely under the sea at ocean ridges. Basaltic volcanoes on land often erupt frequently, are usually weakly explosive, and largely produce lava. While considerable economic damage is possible, basaltic volcanoes rarely threaten life, and the areas that they can affect are reasonably predictable and they are usually not capable of generating large amounts of ash. There are exceptions, like the huge Laki fissure eruption in Iceland in 1783, but very large basaltic events are rare. At the other end of the spectrum are rhyolitic volcanoes, which are undoubtedly dangerous and usually highly explosive. Large rhyolitic volcanoes erupt infrequently, so infrequently in fact that there are very few eruptions that can be cited that have had major impact within the short time-span of recorded history. While major explosive eruptions of rhyolitic volcanoes like Long Valley (California), Taupo (New Zealand) and Yellowstone (Idaho, USA) would be truly terrible events on a global scale and must eventually happen, they fall into a category of extremely rare events. Rightly or wrongly, such rare events have not been a cause for concern outside the scientific community. Civilization has rarely been troubled by eruptions of such great magnitude, like the Monoan eruption of the late Bronze Age on Santorini in Greece. Volcanoes of intermediate composition, in contrast, erupt sufficiently frequently and can have such large impact that, in practical terms, they are the major preoccupation of volcanological work and the causes of most major historic crises.

Mont Pelée and the Soufrière Hills volcano illustrate why some andesite volcanoes can give such particular trouble. Both are relatively small andesite volcanoes and, in common with many other andesite volcanoes, are areas of considerable natural beauty and natural resources, which make them attractive places to live. Neither volcano erupts frequently compared with the human lifespan and so there is no apparent threat, even if there were terrible eruptions decades or centuries before. In the case of the Soufrière Hills volcano, the last eruption occurred about 400 years ago, before colonization in 1632. There was no collective memory or experience of eruptions, even though the Soufrière Hills volcano was recognized as a dormant volcano by the scientific community (Wadge & Isaacs 1988). Despite the terrible events of 1902, St Pierre quickly became repopulated with about 5000 people, illustrating that the attractions of the area outweighed the risks in the perceptions of many people only a few decades after the tragedy and a fairly substantial eruption in 1933–1934. Another problem with andesite volcanoes is their propensity for false alarms. There are many failed eruptions and small poorly understood minor phreatic eruptions at andesite volcanoes. Failed eruptions make it harder to anticipate when a really serious andesite eruption will occur and harder to persuade populations that there is a potential problem when they have become used to occasional earthquake swarms and minor phreatic explosions. The Soufrière Hills volcano in Montserrat had significant seismic swarms and enhanced fumarolic emissions in 1897–1898, 1933–1937 and 1966–1967 that did not result in eruption. Volcanology is still struggling with the problem of finding reliable ways of forecasting when such phenomena will inevitably lead to a major eruption.

Once started, andesite eruptions still pose considerable problems because of the wide range of time-scales of activity and the unpredictable nature of many dangerous phenomena. In some eruptions, like Mt St Helens, Mount Lamington (Papua New Guinea) and Mont Pelée, the most explosive and dangerous activity occurs early on. Populations can be persuaded to move away (as at Mount Pinatubo, Phillipines, in 1991) or terrible tragedies take place, as at Mont Pelée in 1902 and Mount Lamington in 1951 (Taylor 1958). However, there are increasing numbers of andesite eruptions that do not behave according to the paradigm, and the most dangerous activity can occur months or years after the start of the eruption. The Soufrière Hills volcano in Montserrat had its first major magmatic explosive eruption 15 months after the eruption started, and its most destructive event, a volcanic blast similar to that of 8 May 1902 on Mont Pelée, on 26 December 1997, 2.5 years after the start (Robertson *et al.*, this issue). Lascar volcano, Chile, started a cycle of dome growth and minor explosive activity in 1984 (Matthews *et al.* 1997), but a major Plinian explosive eruption with generation of pyroclastic flows occurred nine years later on 20/21 April 1993. Experience at Montserrat indicates that it is very hard to keep a population alert to the dangers over a protracted eruption lasting many months or years.

Unfortunately, the onset of dangerous activity, particularly explosions and slope failures of lava domes and flanks, still presents problems of forecasting. The deaths of scientists and journalists at Galeras volcano, Colombia, and Mount Unzen, Japan, illustrate that dangerous events can occur without warning after many weeks or months of apparently benign activity. The occurrence of sudden transitions to highly dangerous activity is a characteristic of andesite volcanoes and has meant that elaborate warning systems for aviation safety have had to be set up to warn of sudden ash injections into the stratosphere.

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

3. Technical advances

In the 1951–1956 eruption of Mount Lamington, Taylor (1958) was the only professionally trained geologist to document and study the eruption. Indeed, for the first several decades of the 20th century, such solo efforts were often characteristic of volcanology, with relatively little equipment except for seismometers. Such approaches contrast with the end of the century, where volcanoes are now documented by substantial teams of scientists with a wide variety of expertise and advanced instrumentation. Typically, tens of scientists may be involved using satellites, sophisticated broad-band and three-component seismometers, several ground-deformation methods (EDM, GPS networks, tiltmeters, bore-hole strainmeters, and synthetic aperture radar), instruments for remote sensing of volcanic gas, such as COSPEC and FTIRS, and many other geochemical and geophysical methods. Laboratory studies of samples include a great range of advanced analytical techniques (e.g. microbeam methods, electron microscopy and mass spectrometry) to characterize the products and constrain conditions within and below the volcano. There are also increasingly sophisticated experimental studies of the physical properties and dynamic behaviour of magma (see, for example, Dingwell 1998).

Perhaps the biggest impact of all comes from the advances in information technology and computer power of the last two decades. The dramatic increase in computer power allows signals of advanced instrumentation to be processed and analysed in real time so that new information and new forms of information are at the disposal of the volcanologist charged with making rapid judgements. The huge potential of the Internet is only just beginning to be explored. Information can be transferred to sophisticated resources for analysis, and, potentially, an observatory has access to all the best expertise in the world. One small example serves to illustrate the potential. During the Soufrière Hills crisis there was a concern about a major landslide occurring and causing a tsunami that might affect other Caribbean islands. The Montserrat Volcano Observatory was able, via the Internet, to consult one of the world's top tsunami-modelling groups in France. Within about two weeks numerical models had been run on the behaviour of tsunamis from Montserrat due to sector collapse. These calculations were reassuring, since it became clear that sector collapses of the sizes anticipated for Montserrat were not going to cause tsunamis sufficiently large to cause regional problems. Any observatory in any far flung corner of the world now potentially has the world's experts at their fingertips.

Multidisciplinary and large-team investigations of eruptions over the last two decades are transforming understanding of andesite volcanoes. Eruptions like those at Mt St Helens (1980–1986), Mount Unzen (1991–1995), Mount Redoubt (1991–1993) and Soufrière Hills (1995–1999) are providing rich datasets and systematic quantitative documentation that are forming the basis for developing and testing models of andesite volcanoes. Underlying these advances is the concept of integrated science. It is increasingly clear that understanding volcanic processes requires close collaborations of different fields and expertise. To some extent the barriers between traditional disciplines have inhibited progress. However, as becomes evident from this issue, understanding seismicity and ground-deformation patterns in erupting volcanoes will require close collaborations of seismologists, modellers and petrologists. The impetus for advance comes from the interdisciplinary science that major volcanic crises engender.

4. Magma dynamics

The fundamental cause of volcanism is the ascent of magma to the Earth's surface. the core of volcano science must, therefore, be understanding magma movements and interactions of magma with its rocky and sometimes fluid environments. To a considerable extent, the study of magmas (igneous petrology) over the last 100 years has been more concerned with understanding large-scale geodynamic questions—such as the chemical differentiation of the Earth and the formation of different parts of the Earth, such as the mantle and crust—through igneous processes. On the whole, rather less attention has been given to the dynamic aspects of magmatism and, in particular, magma properties in relation to volcanic processes. This is changing with the increasing involvement of colleagues with mathematical and physical science backgrounds in modelling magmatic and volcanic flows, efforts to measure and understand relevant physical properties such as viscosity, and the work of some petrologists to focus on understanding textural features of volcanic rocks and the processes that control them, such as vesiculation and groundmass crystallization. There are also geochemical tools becoming available that address questions of time-scales in volcanism. It is only recently that techniques, such as $^{39}Ar/^{40}Ar$, U series dating, and cosmogenic isotopes, have allowed the typical ages of most volcanoes (tens to hundreds of thousands of years) to be investigated in detail. Microbeam techniques and U series studies are also enabling reconstructions to be made on time-scales of magma generation and crystallization prior to eruption.

It is probably unwise to make statements about where the important developments will be, and even more unwise to forecast how the science will develop in the 21st century. However, I will do so and assert that linking magma dynamics to geophysical and other monitoring data is the approach that is currently most exciting and most likely to occupy the centre ground for volcanology for some time to come. This enterprise again requires close collaboration between disciplines with integration of theoretical models, experimental research and field observation.

For andesite eruptions, perhaps one of the most important issues is to understand degassing. Andesite volcanoes have two main styles of activity: explosive and effusive. The sudden transitions between effusive and explosive activity are the cause of the most dangerous phenomena, such as volcanic blasts and pyroclastic flows, and these transitions pose particular problems for forecasting. In many cases these transitions cannot be attributed to differences in magma composition and appear to relate to the extent to which gas is lost or retained during ascent (Jaupart & Allègre 1991; Woods & Koyaguchi 1994; Jaupart 1998; Cashman & Blundy, this issue). Recently, studies of volcanoes, such as Mount Unzen and the Soufrière Hills volcano, have demonstrated that ground deformation and much of the seismicity are controlled by shallow processes in the upper parts of conduits and that degassing is a critical phenomenon (Voight *et al*. 1999; Melnik & Sparks 1999). Perhaps most remarkable are the cyclic patterns of seismicity and deformation that can be correlated with eruptive activity. At Soufrière Hills and at Mount Pinatubo such patterns have led to a variety of new concepts in which the strongly nonlinear interactions between degassing, rheological stiffening of the rising magma and deformation of the conduit wall rocks can interact to generate cyclic patterns and pulsations in eruptive behaviour (Sparks 1997; Voight *et al*. 1999; Denlinger & Hoblitt 1999; Melnik & Sparks 1999). Certainly, there has been an increasing appreciation of the profound effects of gas exsolution on the properties of rising magma with orders of magnitude increases in viscosity and development of strength in the magma as crystallization is induced by gas exsolution (Cashman 1992; Sparks 1997).

5. Summary

Andesite volcanoes have been a major preoccupation of volcanologists and will continue to be in the 21st century. Increasing numbers of people are living next to andesite volcanoes and their violent and still unpredictable behaviour will pose problems. However, the science is making major advances as the century closes and the next few decades of research may well prove to be the most interesting stage in volcanology yet.

References

Anderson, T. & Flett, J. S. 1903 Report on the eruptions of the Soufrière St Vincent, and a visit to Montagne Pelée in Martinique. Part 1. *Phil. Trans. R. Soc. Lond.* A **200**, 353–553.

Cashman, K. V. 1992 Groundmass crystallization of Mt St Helens dacite, 1980–1986—a tool for interpreting shallow magmatic processes. *Contrib. Mineralogy Petrology* **109**, 431–449.

Denlinger, R. P. & Hoblitt, R. P. 1999 Cyclic behavior of silicic volcanoes. *Geology* **27**, 459–462.

Dingwell, D. B. 1998 Recent progress in the physical description of silicic magma relevant to explosive volcanism. In *The physics of explosive volcanic eruptions* (ed. J. S. Gilbert & R. S. J. Sparks), vol. 145, pp. 9–26. Geological Society Special Publication.

Jaupart, C. 1998 Gas loss from magmas through conduit walls during eruption. In *The physics of explosive volcanic eruptions* (ed. J. S. Gilbert & R. S. J. Sparks), vol. 145, pp. 73–90. Geological Society Special Publication.

Jaupart, C. & Allègre, C. 1991 Gas content, eruption rate and instabilities of eruption in silicic volcanoes. *Earth Planetary Sci. Lett.* **102**, 413–429.

Lacroix, A. 1904 *La Montagne Pelée and ses eruptions*. Paris: Masson.

Matthews, S. J., Gardeweg, M. C. & Sparks, R. S. J. 1997 The 1984 to 1996 cyclic activity of Lascar Volcano, Northern Chile; cycles of dome growth, dome subsisdence, degassing and explosive eruption. *Bull. Volcanology* **59**, 72–82.

Melnik, O. & Sparks, R. S. J. 1999 Nonlinear dynamics of lava extrusion. *Nature* **402**, 37–41.

Sparks, R. S. J. 1997 Causes and consequences of pressurisation in lava dome eruptions. *Earth Planet. Sci. Lett.* **150**, 177–189.

Taylor, G. A. M. 1958 The 1951 eruption of Mount Lamington, Papua. *Aust. Bureau Mineral Resources Aust. Geol. Geophys. Bull.* **38**, 1–117.

Voight, B. (and 24 others) 1999 Magma flow instability and cyclic activity at Soufrière Hills Voclano, Montserrat, British West Indies. *Science* **283**, 1138–1142.

Wadge, G. & Isaacs, M. C. 1988 Mapping the volcanic hazards from Soufrière Hills volcano, Montserrat, West Indies using an image processor. *J. Geological Soc.* **145**, 541–551.

Woods, A. W. & Koyaguchi, T. 1994 Transitions between explosive and effusive volcanic eruptions. *Nature* **370**, 641–644.