The Eruption of Soufrière Hills Volcano, Montserrat, From 1995 to 1999

Dedicated to Peter Francis

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The Eruption of Soufrière Hills Volcano, Montserrat From 1995 to 1999

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Foreword

Volcanoes are the most violent surface expression of the Earth's internal energy. Only impacts of large extra-terrestrial bodies can match the explosive release and devastation of the largest volcanoes. Indeed for some of the most dramatic events the Earth has seen – the large terrestrial extinctions of animal life – the jury is still out as to whether they were brought about by meteoritic impact or by wide-scale effects of volcanic activity. Volcanoes have it too when it comes to sustained visual impact. Earthquakes, tsunamis and avalanches all cause massive devastation, but it is accomplished in the blink of an eye, and floods rise with a progressive and depressing inevitability. Volcanoes are simply the most spectacular of the destructive natural hazards to life on Earth.

To those who are far enough away to view them in safety, volcanoes can offer a truly awe-inspiring pyrotechnic display of the Earth's innate power – a natural, spectacular son et lumière. For this reason from time immemorial they have exerted a siren-like attraction for geologists, photographers, filmmakers and many others. And, like the sirens of ancient fable, they have lured to their death all too many of those who dared to get too close. Indeed volcanoes inspired such awe in the ancient world that their own mythology sprang up about them. Cyclops, the one-eyed giant who all-unprovoked threw rocks great distances to kill shepherds tending their flocks, we know today as Mount Etna. The giant was also able to cause springs to flow where he struck the ground – it is not uncommon for groundwater flows to be disrupted during volcanic episodes.

Like its neighbouring islands in the Caribbean, Montserrat exists solely because of volcanic activity. It is a volcanic island formed by the progressive accumulation of layers of lava and debris erupted on the sea floor. It is a small Caribbean island, which, along with a host of others, is located close to where the slowly moving crust of the Atlantic takes leave of the surface and plunges down into the Earth's interior. All life forms, humans included, are so eager to find new habitats that as soon as a volcano has been inactive for a hundred years or so, and sometimes sooner, it is colonized by a flora and fauna. Montserrat had long been inactive and, besides being well situated for fishing and tourism, and a little agriculture, it supported a resident population of over ten thousand.

The art of volcanic prediction is still too poorly developed to be very useful and when in 1995 the volcano showed signs of renewed activity the population simply hoped that it would soon die down. It had been quiescent for about 350 years. Understandably, people who in their own lifetime have known only a gently steaming mountain are not inclined to believe that things are about to change. But change they did. Devastating pyroclastic flows overwhelmed the southern half of the island with its villages and smallholdings. In the north, the infrastructure of life was disrupted and part buried by settling ash.

The people had no experience of active volcanoes and could not imagine how rapidly the behaviour of the volcano could change and how unpredictable it was. The inescapable speed and heat of flows of incandescent ash were beyond their comprehension. Although they were warned, many were reluctant to abandon their homes on official advice and chose to take the risk. Sadly some paid the ultimate price. And when this happened in spite of their best efforts, some on the ground had to live with the nagging doubt as to whether, had they tried just one more time, they could have persuaded the farmers to leave.

In the world league of volcanic eruptions the ongoing Montserrat eruption does not rate very high. What was unusual, indeed unique, about Montserrat was the combination of two special circumstances. First, because of the risk to life and the presence of an indigenous population with no escape other than to leave the island, resources were available to monitor the volcano that would simply not have been there for a purely scientific study. Whether those resources were really adequate is another matter. Second, there has been no recent opportunity anywhere in the world to study an oceanic island arc volcano during eruption. Different kinds of recent volcanic activity have been studied elsewhere in Iceland, in Hawaii, in Washington State, in southern Italy and in Japan, but Montserrat offered a unique opportunity to study this kind of oceanic eruption with modern techniques.

This combination of circumstances has made it possible to document the behaviour of the volcano in considerable detail and to do so with the collaboration of geologists from a wide range of organizations and from many countries. Intriguingly, there is one important feature of the Montserrat eruption that is little known elsewhere. The fine ash that is common in many eruptions and which buried buildings on Montserrat to depths of three metres or more is very unusual: it contains, and in places largely comprises, very fine particles of silica in an unusual crystalline form – minute particles of the mineral cristobalite. These are uncomfortably similar in their characteristics to other fine particles that damage the respiratory system, and were regarded as potentially a significant health hazard on the island.

Occurrences such as this present governments with major moral dilemmas. Montserrat is a British dependency many thousands of kilometres from the UK and therefore difficult, not to say very expensive, to support. In the early years of the renewed eruption, the infrastructure and much of the farming land was destroyed. Resettlement was offered to the inhabitants and eventually the majority of them accepted the offer. But what are our obligations to the others? The economy of the island is now extraordinarily tenuous and life there can continue only if external support is maintained. It looks as if the northern part of the island will be relatively safe from the direct products of eruption for the foreseeable future. But it will be decades before soils develop and before agriculture can be re-established in the south. The eruption is still in progress and has now lasted for more than six years, longer than in virtually all similar lava-dome eruptions around the world. It seems that Soufrière Hill Volcano is evolving into a persistently active state that could continue for decades.

And so, alongside the scientific investigations, a complex human drama was playing as well, and geoscientists, for whom volcanology had been their somewhat esoteric and rather academic specialization, suddenly found themselves at the frontline of its practical application where life at times had much in common with a war-zone.

There are other lessons to be learned as well. Volcanology has been very much a minority discipline within UK Earth Sciences. It has been kept alive by the efforts of a few outstanding and energetic individuals of real academic distinction. No value for money or relevance criteria would have suggested that volcanology was worthy of more than peripheral support. But without this infrastructure of knowledge and experience the UK would have had no indigenous capability to cope with the events on Montserrat.

Many of the results of the scientific studies at Montserrat are presented in this volume. They represent an unparaleled suite of detailed observations that will add significantly to the understanding of volcanic hazards. In due course, they will lead to a better understanding of how volcanoes work and to a better ability to predict their behaviour. I am proud that the Geological Society is the publisher of this volume.

Ron Oxburgh
President of the
Geological Society of London

Preface

The andesitic dome-building eruption of Soufrière Hills Volcano has wreaked havoc on the small Caribbean island of Montserrat. About half of this 'Emerald Isle' has been rendered barren and uninhabitable, almost two-thirds of the original population has left, and 19 lives have been lost, all as a direct result of the volcanic activity. Many Montserratians have suffered multiple evacuations and displacements from their homes, and the economy has been severely affected by the loss of infrastructure and farmland, and by the adverse impact on tourism. The centre of the former capital, Plymouth, today lies partially buried under metres of volcanic debris, and several villages have been swept away by catastrophic flows of incandescent ash. As this book goes to press, the eruption continues and as yet shows no signs of abating. The still-populated northern half of the island is to some extent recovering and the people are learning to live with the volcano. Nevertheless, fine airborne ash from intermittent major events continues to penetrate into many homes and to pose a health hazard, while boulder-laden floods following the torrential rains of all-too-frequent hurricanes impede recovery of property.

This Memoir presents results of monitoring and associated research over a five-year period, from the onset of the eruption in July 1995 until November 1999. Scientists on active volcanoes need to balance their essential activities in monitoring, assessing hazards, advising local and national authorities, and informing the public, with programmes of basic research into causes, mechanisms and consequences of the volcanic activity under scrutiny. Mitigation of volcanic hazards is most effective when there exists good understanding of the physical and chemical processes controlling the system. Monitoring and research on Montserrat evolved from mainly remote surveillance by the Seismic Research Unit of the University of the West Indies in Trinidad, before the eruption, to establishment of a multinational and multidisciplinary team at the Montserrat Volcano Observatory (MVO). The observatory, which moved its location three times as the eruption slowly escalated between July 1995 and September 1997, developed enhanced capabilities over the period as funding and technical assistance became available. The slow escalation of the crisis gave the scientists time to build effective monitoring infrastructures and team management before the most devastating phases of the eruption in 1997. Monitoring included use of short-period and broadband seismometers to detect and locate all types of earthquakes, Global Positioning Satellite (GPS) and Electronic Distance Measurement networks to detect upheaval of the volcano, measurements by Correlation Spectrometer and Fourier Transform Infra-red spectroscopy to monitor gas exhalations, and photogrammetry and GPS-based methods to determine magma extrusion rates and volumes. Petrological and geochemical studies of magmatic products were carried out as the eruption progressed. Monitoring was initially aided by the close proximity to the volcano of the MVO, which until September 1997 benefited from line-of-sight observations. Analysis and cross-correlation of emerging multi-parameter data sets, together with the development and application of physical models of magma ascent, degassing and extrusion, led to greatly increased understanding of the system dynamics and origin of the various signals being monitored as the eruption unfolded. This in turn influenced subsequent monitoring strategies. The large numbers of visiting scientists, who undertook diverse studies at the MVO, greatly enhanced the effectiveness and innovation of the work of the core teams.

Many diverse phenomena related to the ascent and extrusion of andesitic magma have now been studied at close quarters. These include phreatic explosions, dome collapses with formation of pyroclastic flows and surges, dispersal of ash plumes, vertically directed explosions with fountain collapse, sector collapse followed by debris avalanche, lateral blast and violent pyroclastic density current, and a remarkable period of disintegration of a lava dome with little or no accompanying magma extrusion or precursory seismic activity. Cyclic activity, registered in seismic and deformation data, in compositions and fluxes of magmatic gases, and in rates of magma extrusion, has been attributed to interactive physical processes in the conduit and extruding lava dome. Cycles with timescales ranging from several weeks to several hours are now understood in terms of the ascent, degassing, rheological stiffening and pressurization of crystal-rich andesitic magma, with complex feedback effects and multiple regimes of behaviour. The eruption has permitted detailed documentation and better understanding of processes and associated signals that lead to lava dome instability and to explosive decompression, and of the physical behaviour and characteristics of associated pyroclastic currents. It has also provided the opportunity for development of different methods in hazards assessment and zonation, including formal elicitations of international scientific expertise and statistical treatments of eruption-scenario models and associated uncertainties. The eruption and its consequences constitute an important case of volcanic crisis management and of the interactions between scientists, authorities and populace on a small island, with significant lessons for the future.

The decision was taken to publish as much as possible of the material pertaining to the 1995–1999 eruptive period in one book. Previous notable benchmark eruptions, such as of Mount St Helens in 1980 and Mount Pinatubo in 1991, have been similarly followed by scientific monographs that are the main repositories of data and interpretations concerning those eruptions. The books constitute an invaluable resource for those researchers, volcano observatories and government agencies concerned with volcanic risk minimization. Two series of short reports on the Montserrat eruption up to August 1997 were published during 1998 in *Geophysical Research Letters*. This Memoir contains 30 papers, many of which address the chronology, dynamics, products and associated hazards of the eruption. It also includes papers specifically on the associated geophysics and geochemistry, although geophysical aspects in particular constitute significant parts of many of the other papers. Four introductory papers provide overviews of the eruption chronology and consequences, of the scientific results, of the evolution, organization, role and activities of the Montserrat Volcano Observatory, and of the volcanic development of Montserrat through time. A large photographic record of the 1995–1999 eruptive period is included.

Using author consensus, we have adopted certain conventions for clarity and consistency throughout the Memoir. We consider the recent events to represent a single eruption of Soufrière Hills Volcano, which, following six years of increased seismicity, started on 18 July 1995 and continues at the time of publication. We use the convention that there have been two lava domes to date during the eruption. One grew intermittently from mid-November 1995 to mid-March 1998, undergoing multiple collapses as it did so. This was followed by a twenty-month interval during which sectors of the first dome collapsed with little or no associated extrusion and commonly without seismic precursors. The second dome started growing in mid-November 1999. This Memoir concerns only that period of the eruption up to the resumption of magma discharge in mid-November 1999. Individual lava extrusions during dome growth are referred to as shear lobes, or, for brevity, lobes. Lobes are referred to by the date of their first appearance (e.g. 17 July 1996 Lobe).

We have also tried, for the benefit of non-specialist readers, to simplify the terminology used in the Memoir, particularly that concerning pyroclastic density currents. In most cases during the 1995–1999 period it was possible to distinguish fairly clearly, using conventional criteria, between pyroclastic density currents predominantly of high-concentration and those predominantly of low-concentration, and also between their respective deposits. We have retained the terms *pyroclastic flow* and *pyroclastic surge* respectively for these phenomena. We distinguish genetically between *dome-collapse*, *fountain-collapse* and *surge-derived pyroclastic flows*. The descriptive terms *block-and-ash flow* and *pumice-and-ash flow* are also used respectively for the former two phenomena. Only in one case, the catastrophic collapse of 26 December 1997, have we retained the general term *pyroclastic density current*, because significant vertical and lateral gradients in particle size and concentration are inferred to have been present in the moving current so that neither pyroclastic flow nor pyroclastic surge seems appropriate.

Monitoring the eruption from 1995 to 1999 was the work of more than 120 people, including Montserratian scientific, technical and clerical staff along with scientists and technicians from the British Geological Survey, the Seismic Research Unit on Trinidad, the US Geological Survey Volcanic Crisis Assistance Team, and universities in the UK and other countries including the USA, Puerto Rico and France. Many were graduate students in volcanology or young, MVO-trained staff and much of the collection and analysis of data from the eruption was accomplished by these young people, who also participated in the daily jobs of hazards assessment and public education. Although tragic in so many ways, the eruption has served as a training ground for a large cohort of young volcanologists who are now well prepared to deal with future volcanic crises around the globe. It is a tribute to all of the people involved that, after more than five years of volcanic activity and with constant changing of observatory personnel, the vast amount of information collected is in such good order that it could be compiled and analysed for the papers in this Memoir.

A hundred years ago, on 8 May 1902, a cloud of hot gas and pyroclastic debris from a lava dome on Montagne Pelée swept over the town of St Pierre on the French Caribbean island of Martinique and claimed about 28 000 lives. Many of the processes that drove that eruption probably resembled those at Soufrière Hills. This Memoir registers the enormous advances made since that time, both in our understanding of lava-dome eruptions and in the sophistication of the tools we use to monitor them. Much, however, remains to be learned. Nature will not reveal many secrets in one go.

Tim Druitt & Peter Kokelaar
Editors

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