Geological Society, London, Memoirs

Chapter 22 Evaluating the respiratory health risks of volcanic ash at the eruption of the Soufrière Hills Volcano, Montserrat, 1995 to 2010

P. J. Baxter, A. S. Searl, H. A. Cowie, D. Jarvis and C. J. Horwell

Geological Society, London, Memoirs 2014, v.39; p407-425.
doi: 10.1144/M39.22

Chapter 22

Evaluating the respiratory health risks of volcanic ash at the eruption of the Soufrière Hills Volcano, Montserrat, 1995 to 2010

P. J. BAXTER[1]*, A. S. SEARL[2], H. A. COWIE[2], D. JARVIS[3] & C. J. HORWELL[4]

[1]*Department of Public Health & Primary Care, Institute of Public Health, University of Cambridge, Cambridge CB2 2SR, UK*

[2]*Institute of Occupational Medicine (IOM) Consulting Ltd, Research Avenue North, Riccarton, Edinburgh EH14 4AP, UK*

[3]*Respiratory Epidemiology and Public Health Group, Imperial College London, National Heart & Lung Institute, 1B Manresa Road, London SW3 6LR, UK*

[4]*Department of Earth Sciences, Institute of Hazard, Risk and Resilience, Durham University, Science Labs, South Road, Durham DH1 3LE, UK*

**Corresponding author (e-mail: pjb21@medschl.cam.ac.uk)*

Abstract: The management and outcomes of the volcanic crisis on Montserrat, which began with the onset of activity at the Soufrière Hills Volcano (SHV) on 18 July 1995, might have been very different without the scientific precedents set by the Mount St Helens eruption, USA, on 18 May 1980, and the research advances that followed. This narrative is intended to show the steps taken by health scientists in response to the unfolding developments at the volcano to characterize the hazard presented by the volcanic ash and to devise mitigation measures to prevent the development of irreversible lung disease in the island population. Initial assessments of the health risk for silicosis were deterministic and based on industry exposure limits derived from published epidemiological and clinical studies of workers exposed to dusts containing free crystalline silica. However, by 2003, new research findings on the ash enabled the risk to be updated with a probabilistic approach incorporating the expertise of scientists from a wide range of disciplines including toxicology, volcanology and statistical modelling. The main outcome has been to provide reassurance to the islanders and policy makers that the chances of developing silicosis on Montserrat are very small given the preventive measures that were adopted during 1995–2010 and the change in style of the eruption.

The scientific narrative behind the identification and eventual elucidation of the risks to human health of the ash emissions in the different phases of the eruption of the Soufrière Hills Volcano (SHV) warrants a place in this Memoir alongside the other scientific challenges faced by volcanologists and the population of Montserrat, which have slowly but steadily unfolded since the first eruptive activity manifested itself on 18 July 1995. No one could have envisaged then how long the eruption on this small Caribbean island would last, nor its consequences; that it would astonish scientists with its showcase of natural phenomena and, yet, would ultimately frustrate, leaving an island abandoned by most of its population and an uncertain future for those who remained.

This chapter describes how the elucidation of the health threat of silicosis from inhaling volcanic ash containing raised levels of the mineral cristobalite became a multi-disciplinary research effort and an integral part of the volcanic risk assessment. The goal of this extensive work was to prevent the development of irreversible lung disease in the population of the island.

After an introductory section on the Mount St Helens (MSH) eruption in 1980, which set the precedent for the health concerns on the ash at SHV, we follow the chronology of the major eruptive events at the SHV lava dome that were responsible for the frequent ashfalls, and later the major ashfalls due to dome collapses, and their health impacts. We refer to key publications and unpublished reports commissioned by the UK government for the Government of Montserrat (see the Appendix). We divide the time periods of activity into the same phases of the lava-dome growth as have the volcanologists, and we recommend readers to refer to the accompanying overview paper (Wadge *et al.* 2014) to learn much more about the volcanology behind our brief summaries.

We have focused almost entirely on respiratory health for this Memoir, in full awareness that this is only one part of a spectrum of health issues and life changes that the volcanic crisis inflicted on the islanders. But the ash was a major contributor to, at times, traumatic psychological stress in the way it invaded every part of people's homes, as well as all aspects of their lives, to become an inseparable part of the small decisions they and their families made every day, and also the overwhelming ones as they were uprooted from their homes. At every eruption around the world there is fear that the ash will permanently affect the lungs, especially of children, and it is very hard to reassure people otherwise when they are also afraid for their businesses and their physical safety. Eruptions like this are fortunately uncommon, but the experience in the United States of the people impacted by MSH was very similar, with the same hopes and fears. A large research effort was mounted at the MSH eruption to ensure that the risk of a potentially disabling and fatal lung disease, silicosis, was not being overlooked in over a million people living in the area impacted by the widespread ashfall.

This paper is, above all, intended to be a published record of the steps taken by scientists and medical doctors with the support of the British and Montserratian governments to evaluate the health effects of the ash in the successive phases of the eruption over the 15 year period to 2010. As those who were children on the island when the eruption started have grown into adulthood, and they and their elders get older, health problems will inevitably arise over time and sometimes questions will be asked on whether they have anything to do with the ash exposure received years before on Montserrat. Furthermore, many will forget the work that was done and recorded in these pages to safeguard the future health of Montserratians; and they, or their advisors, may need a reminder of what was done, when and why. We hope this paper will enlighten all readers who are looking for such a record for whatever purpose.

From: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) 2014. *The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010*. Geological Society, London, Memoirs, **39**, 407–425. http://dx.doi.org/10.1144/M39.22

Background to silicosis

Silicate minerals, with quartz, make up more than 99% of all volcanic rocks and are the commonest rock-forming minerals in the world. Despite the abundance of free crystalline silica (sometimes just referred to as 'silica') in such forms as sand and dust, clinically significant silicosis is rarely found outside dusty workplaces. Two volcanoes have been extensively studied for the environmental health hazard presented by their erupted ash containing free crystalline silica, namely MSH and the SHV, Montserrat, as will be explained later (Horwell & Baxter 2006). The hazard from both volcanoes to the general population, as well as to outdoor workers, lay mainly in the high exposures to suspended ash immediately following eruptions, and the re-suspension of the ash deposits in the weeks and months afterwards. The thicker layers of compacted ash become future soils, with the possibility of significant exposure to workers quarrying ash for aggregate in subsequent years.

Manual workers in industries such as mining, quarrying and civil engineering are at risk of developing silicosis, which took on epidemic forms during the Industrial Revolution in Britain and in all industrialized nations between the two world wars with the spread of mechanization that led to high exposures among workers to quantities of fine dust when drilling or handling rock containing crystalline silica. One of the major achievements of occupational health in economically developed countries in the twentieth century was the dramatic reduction in silicosis and other scourges, such as coal miner's pneumoconiosis and asbestosis, by preventive measures to reduce exposure in the workplace, although globally they remain serious and prevalent causes of morbidity and mortality in rapidly industrializing nations (Baxter *et al.* 2010).

Silicosis is a preventable occupational lung disease caused by inhaling dust containing one of three crystalline forms of silicon dioxide, usually over several decades (Leung *et al.* 2012). (Silica exposure is associated with an increased risk of developing tuberculosis even without silicosis (Leung *et al.* 2012). There were no cases of tuberculosis reported on Montserrat. The chances of developing lung cancer in the absence of silicosis are low, as it is a weak lung carcinogen. Chronic obstructive pulmonary disease (COPD) is associated with silica exposure, independent of smoking. There are reports of rheumatoid arthritis, scleroderma and chronic kidney disease being more common in persons suffering from silicosis. These quite common conditions in the general population are not expected to arise as a result of living on Montserrat. Two patients with a confirmed diagnosis of pulmonary sarcoidosis were identified in the lung survey and both had worked in the Salem police station in 1997. This disease has been reported as having a possible link with long-term exposure to silica (Rafnsson *et al.* 1998), but there is no other evidence to support this assertion. Quartz is the most common form, the other two being cristobalite and tridymite. In the worst exposure conditions, quartz dust can cause fatal disease after exposure for only a few months (acute silicosis). No effective treatment for silicosis is available, and the condition is irreversible and may progress even after exposure to crystalline silica has ceased. Many mixed dusts produce disease due to their quartz content; any of them inhaled at levels above the lung clearance capacity for long enough may ultimately cause serious disease. Despite much research, the mechanism by which inhaled fine dust particles containing crystalline silica cause disease at the cellular level in the lung remains unresolved, but a reasonable amount of epidemiological data have accumulated over the years to support occupational exposure limits that can be legally enforced in workplaces. The important role of toxicological tests in helping to clarify the bioreactivity of crystalline silica present in dusts will be referred to in later sections.

Mount St Helens: the birth of modern volcanology

The story begins, though, with the eruption on 18 May 1980, at MSH, USA, a cataclysmic event that triggered an unprecedented disaster response and signalled the birth of modern volcanology. Ash fell in at least 10 states, but hardest hit were over a million people in the State of Washington, where road and rail transport was paralysed, and other outdoor activities were restricted by the clouds of ash that remained suspended until the air was cleared by unseasonal rainfall on 26 May.

On 19 May, the Centers for Disease Control and Prevention (CDC), Atlanta, USA was contacted by the Idaho State Health Department who were seeking advice on the health effects of volcanic ash. Hospitals in the affected areas were being bombarded by patients asking for information which none could confidently provide. At CDC, a rapid trawl through the medical literature and US national library resources found hardly any information on the subject at all. In effect, the eruption of a volcano on this scale was beyond the experience of almost any government agency in the United States (including the US Geological Survey, which was monitoring the volcano) and government departments in Washington, DC were temporarily paralysed as they scrambled to find a response.

One of us (P.J. Baxter) flew to Seattle from Atlanta at the request for CDC assistance from the Washington State Health Department, the plane taking a wide detour to avoid the volcano, and landed on 21 May, just after President Carter had visited the area and declared a national disaster. His declaration enabled the other federal agencies that were not already involved to move into action, and CDC established its operational base in the State health department offices for its team of investigators to work closely with the US Geological Survey and other agencies, such as the newly established Federal Emergency Management Agency (FEMA) and the Environmental Protection Agency (EPA). CDC and its sister agency NIOSH (National Institute of Occupational Safety and Health) are mandated as the lead US government agencies in public health and occupational health, respectively, and CDC's prompt response to the emergency confirmed its role to be the most authoritative source of advice on the health impacts of the volcano, on which so little was known at the time. The US Congress subsequently provided a tranche of funding to enable CDC to have a coordinating role and commission work by other research groups, which also proved crucial to the eventual effectiveness of the health sector response, in which an important part was played by Sonia Buist MD, a respiratory clinician and epidemiologist at the Oregon Health Sciences University, Portland, Oregon. This background detail is necessary to explain how this unprecedented multi-disciplinary effort, the outcome of which filled a special volume of the *American Journal of Public Health* (Buist & Bernstein 1986), became the foundation for all subsequent studies on volcanic ash from eruptions around the world, including on Montserrat.

The region around MSH had been prepared for an eruption, but not a fall of ash on this scale. Geologists define volcanic ash as the solid silicate fragments of 2 mm or less in diameter ejected in an eruption, but the most striking thing about the MSH ash was just how fine it was – over 90% (18 wt%) of the ash particles were less than 10 μm in diameter and able to enter the lungs (Olsen & Fruchter 1986). Few geologists routinely examined this fine fraction of ash, and even air pollution monitors in the USA at that time were not calibrated to measure it in the air. Instead, they collected particles of 100 μm and less in diameter (total suspended particles, TSP) for air-quality measurement, which corresponds to the largest size range of particles that can remain suspended in the air for any length of time. The metrics of most interest for human health are the thoracic and respirable fractions (10 and 4 μm or less in aerodynamic diameter, respectively), but these then were mainly of special interest for complying with standards in the workplace and then mainly for dusts containing asbestos fibres or crystalline silica. The mind-set of the time dictated that most ordinary mineral dust particles, however fine they may be, were not especially harmful to breathe at current levels in the air compared to concentrations of particulate matter in the 1950s and 1960s, and the adverse effects of air pollution in cities could be mainly put down to gases such as sulphur dioxide and ozone in the gas–particle mix. (Lawther and Waller, pioneers of air pollution studies in the UK after the London Smog in 1952, investigated sulphur dioxide and 'black smoke' (particles in the respirable range measured with a specific method) (see Advisory Group on the Medical Aspects of Air Pollution Episodes 1992).) Over 10 years later this concept had begun to shift, as epidemiological research began to show that the adverse effects of air pollution are most strongly associated with the fine particle fraction. This led to the introduction of air monitors measuring PM_{10} and $PM_{2.5}$ (mass concentration of particulate matter less than 10 and 2.5 μm in aerodynamic diameter, respectively) during the 1990s.

The next mineralogical question to answer at MSH was whether the respirable ash could contain asbestiform fibres or crystalline silica. Both materials are capable of causing fibrosis or scarring of the lungs (pneumoconiosis – literally, dust in the lung disease) and lung cancer. This required laboratory skills commonly applied to evaluating exposure of workers in industry, and the expertise of NIOSH was brought to bear. A local laboratory had first reported an alarming level of 20 wt% of free crystalline silica, which had to be rapidly repeated for confirmation. By that time, almost any laboratory in the ash-fall areas felt able to analyse ash samples for crystalline silica and publicize their widely variant results (from none at all to over 20 wt%) regardless of their expertise to conduct such a specialized analysis. Newhall & Fruchter (1986) deliciously quoted a Spanish landowner after an eruption in the Philippines in 1814, which reflects well the mayhem the mineral analytical work provoked in May–June 1980:

> [I]t was at once heard that several analyses [on the ash] had been done . . . that some had extracted lead, some iron, and others gold; there were even some who were not sure whether they had extracted pearls or diamonds.

Some physicians began drawing blood samples from their patients, looking for toxic minerals listed in the mineralogical analyses of the rock or their own fancied exotic metals. Many 'experts' confused the conventional reporting of the 'SiO_2 content' (60–70 wt%) for classifying volcanic rock as being the same as the free crystalline silica content (eventually confirmed as 3–8 wt%: Dollberg *et al.* 1986). Not surprisingly, some families worrying about the risk of developing silicosis thought reassurances were just a cover up and moved away during this period, while many small businesses were pushed into closing.

The main health outcomes at MSH for summary here in relation to the future Montserrat eruption are as follows:

- During the period of severe air pollution in the first 2 weeks after the major ashfall there was a detectable increase in the numbers of people attending hospitals for acute respiratory symptoms, mainly amongst people with pre-existing asthma or lung problems, but there were no significant increases in hospital admissions or a rise in the numbers of deaths reported in the affected areas (Baxter *et al.* 1981, 1983).
- The symptoms of patients with chronic respiratory diseases when they moved around outside were exacerbated, whilst ash continued to be resuspended in the air for months after (Baxter *et al.* 1983).
- The main group of outdoor workers exposed to ash from the deposits lingering in the environment for many months were loggers working for the Weyerhauser company. A 4 year follow-up study of a cohort of loggers conducted by NIOSH found no substantial acute or long-term effects on lung function and the study was stopped (Buist *et al.* 1986). The risk of silicosis was viewed as remote because the measured exposure to silica had been low and the ash did not persist for long enough in the environment to pose a long-term risk, since there had been no repeat heavy ashfalls. Whether a subgroup of men would go on later to develop COPD from the ash exposure they had received could not be answered without a longer study, which was not planned.

Further details, including the results of laboratory toxicological testing, can be found in Buist & Bernstein (1986) and Horwell & Baxter (2006). Martin *et al.* (1986) concluded that the published results of the toxicological tests were indicative that the MSH ash caused less toxicity to lung cells *in vitro* and *in vivo* compared with the effects of crystalline silica alone.

By 1985, a line had been drawn under the long-term health risk of exposure to the ash and the concern over silicosis: the crystalline silica (3–8 wt%) was mainly in the form of cristobalite and quartz, but exposure to ash after the MSH eruption had not been high enough, and had not continued for long enough, to induce the disease. A very thorough characterization of the ash for health purposes had been undertaken which was to form the basis for all future work at other volcanoes. In particular, any controversy over the crystalline silica composition of the ash was laid to rest by a round-robin, multi-laboratory study (Dollberg *et al.* 1986) – a forerunner of what was carried out over Montserrat. Finally, the very high proportion of sub-10 μm particles in the ash (by count) could exacerbate acute symptoms in persons with common pre-existing lung diseases, whether they were the young or elderly with asthma or older patients with COPD.

The overall conclusions over MSH (Buist & Bernstein 1986) were mostly reassuring, but left open were what severe acute health impacts might occur at future eruptions in different socio-economic settings, especially in low-income countries with inadequate health care and with poor housing that was unable to keep out fine ash, compared to the United States, and where infectious diseases such as childhood pneumonia and tuberculosis were common. Most volcanic eruptions occur in such countries where epidemiological studies are also much more difficult to carry out, yet where the need for further research is greatest. Some work had already been done on comparing the characterization and laboratory toxicity of ash from the El Chichón, Mexico, and Galungungg, Indonesia, eruptions (Vallyathan *et al.* 1984), but a big question remained over the range of potential toxicity and health impacts from future eruptions around the world which might not be reflected in the findings at MSH.

Moreover, Buist *et al.* (1986) made some further important points in summing up the outcome of the health research sparked off by MSH:

- The effects of both short- and long term exposures to 'the relatively low levels of airborne ash that are typical following such a volcanic eruption' (p. 74) were minor, and related more to the irritant effects of the ash on the airways than to the potential of the ash to initiate a fibrotic response.
- But questions remained on whether a subset of the population was more susceptible to develop pulmonary-related problems, like COPD and asthma, from the exacerbation of airflow obstruction when exposed for a short- or long-term period to inhaled ash.
- In addition, could the exposure to ash have been high enough to trigger airways sensitivity in previously well individuals, and could long-term exposure to ash contribute towards the development of COPD, as with certain other occupational dusts? Those at special risk might include children and the elderly, and groups with unusually high exposure.

These issues could only be resolved by continued surveillance of population groups living and working for many years in ash-fall areas, but no plans or funding for such work had existed at MSH. Until a suitable major eruption occurred where this work on ash could be rapidly progressed all over again with major funding, we would have to wait before the next substantial advance in our knowledge. Quite unexpectedly, the opportunity arose 15 years after the MSH eruption in one of the British Overseas Territories – the Caribbean island of Montserrat.

Soufrière Hills Volcano, Montserrat: the path-breaking volcano

On the afternoon of 18 July 1995, the SHV began to stir, lazily at first, with a quiet roaring sound, distant like an aeroplane, but persistent and unsettling. Next day, wet ash was falling in Plymouth and tremors were being felt when a scientific team from the Seismic Research Unit (SRU) in Trinidad arrived, called in to monitor for signs of volcanic activity. The 13 000 or so inhabitants (the exact number was never officially clarified) were accustomed to the natural threats of hurricanes, and having to board up their homes and temporarily move to shelters when the warnings during the hurricane season came. In 1989, Hurricane Hugo had inflicted the worst disaster for decades, when almost every building on the island was either destroyed or badly damaged, miraculously with barely any loss of life. The memory of this crisis was fading and the economy of the island was growing, when, for the first time in over 400 years, volcanic disaster began to loom over the island.

After an initial rush of people going overseas, the life of the residents continued as normal, while the volcano remained under scientific monitoring, which was soon augmented by a team from the US Geological Survey Volcanic Disaster Assistance Programme. An evacuation to the northern half of the island was being planned should a threat develop near the volcano. Minor episodes of ash venting and occasional felt earth tremors added to the island's sense of unease. Then, during the day of 21 August – nicknamed 'Ash Monday' – a cool cloud of ash generated by a phreatic explosion swept down the flank of the volcano without warning and briefly enveloped Plymouth in darkness, triggering widespread panic. People spontaneously drove out to the north, with a full-scale official evacuation (including Glendon Hospital patients) following in the next 2 days. Two and a half weeks later, after hurricane Luis had passed, people returned to their homes and daily activities resumed. On 11 November, Plymouth and its surrounding communities experienced their first fine layer of ashfall, which penetrated homes and offices, and hung suspended in the air for days by wind and vehicle traffic.

Eruption Phase 1: 15 November 1995–10 March 1998

The beginning and ending of the major episodes of extrusion of lava and the formation of the lava dome in the summit crater marks the five phases of the SHV eruption up to the time of the preparation of this Memoir. It is also convenient to frame the main milestones of the volcanic ash health hazard within these phases of the growth of the dome and its eruptive activity, which is the main driver of ash emissions in this eruption (Fig. 22.1). Ash clouds arise from the surface of the dome itself (Fig. 22.2) or when the dome material forms pyroclastic flows. Explosions, Vulcanian and sub-Plinian events with associated ashfalls have also been part of the volcanic behaviour. The growth of the dome has been so substantial at times that it has threatened to collapse and send pyroclastic flows down the Belham Valley, with possible lethal consequences for people living in the vicinity.

With the recognition by the end of November that the lava dome was growing in the crater, the eruption began to visibly get underway. No one at the time had any thought that the eruption would last long or that it would involve successive phases of lava dome growth. The volcano has since gone on to extrude lava for a total aggregate period of only 8.5 years out of 16 (Wadge *et al.* 2014), but there has been no overall decline in discharge rates over the 15 years. No one can fathom when it will stop, let alone predict the future behaviour with any certainty. And throughout Phase 1, scientists had much to learn, taking each day at a time, anxiously observing the volcano.

Fig. 22.1. Soufrière Hills Volcano, 1996, seen from the NE showing the first lava dome growing in the old crater.

The second evacuation of the southern half of the island took place on the weekend of 2–3 December 1995 and lasted until 1 January 1996. It was a precaution when the lava dome was confirmed to be growing in the crater, with incandescent lava seen for the first time, which might presage a violent explosion. The gas emissions had also increased as trees on the summit and down the flank towards Plymouth were noticed to be dying or losing leaves. In February, health concerns over gases arose again when a haze persistently hovered around the volcano, and the leaves of plants in the Gages and Amersham areas were reported to have turned brown. The first volcanic health study to be undertaken on Montserrat on 10–18 March 1996 was also the first to investigate the gas emissions from the volcano (Allen *et al.* 2000). The main gases (SO_2 and HCl) and particle concentrations were found to be too low in the ambient air for them to present an acute health hazard under typical weather conditions, but, as the predominant gas in the plume was HCl, this gas was most likely to have been responsible for damaging trees and plants through its wet (acid rain) and dry deposition.

It was also during this survey that new photographs of the crater alerted volcanologists to how rapidly the lava dome had grown, and that it was now threatening to spill out of the crater at its lowest point and send pyroclastic flows into the Tar River

Fig. 22.2. Surface of the early dome, showing how the rock formed from the extruded lava auto-fragments into fine particles: gases passing out of the dome lift off the fine ash particles into the plume. For scale, see the trees on the ridge to the left of the picture.

Valley. During March, small ash plumes were visible over Plymouth, and these increased with minor pyroclastic flow activity, which began on 27 March, and rock falls and avalanches on the dome. On 3 April, the first pyroclastic flow occurred, prompting the third and final evacuation of the southern and eastern areas, including Plymouth, but about 500 people remained in the newly designated hazard zone against official advice. The villages along the Central Corridor road that skirted past the north flank of the volcano were included in the evacuation: Harris, Streatham, Molyneux and Lees.

From then on, the pyroclastic flows became more frequent, with the wind sending the ash clouds produced by these in a northwesterly direction towards inhabited areas south of the Belham River, which were still being regarded as safe from volcanic hazard: Cork Hill, Richmond Hill, Foxes Bay, and St George's Hill. By May, coping with the ash became the norm for people in these areas, with two of the largest events on 12 and 19 May. On the 28 and 29 July, the largest ash clouds so far were accompanied by thunder and lightning, and marked an escalation of the pyroclastic flow activity. Another large plume deposited wet ash over Salem, Olveston and Old Towne on 30 July, heralding a new phase with the widening of the area impacted by ashfalls to include the homes and businesses NW of the Belham River.

Further dome collapses in August and the beginning of September were followed by a lull in activity until 15 September, when activity at the dome stepped up and culminated in the landmark first explosive eruption on 17 September 1996. There was the heaviest fallout of ash so far in Plymouth and the non-evacuated Richmond Hill, Fox's Bay, St George's Hill and Cork Hill areas. Many residents now had to face clearing ash off their house roofs and the surrounding ground areas (including the empty houses in the evacuated zone), and dealing with the ash safely and efficiently became a major priority. The much raised exposure of the population to ash and the effects this might have on health started to add fuel to the anxieties of the islanders over the volcano and their future.

First investigations of the ash hazard to health

The ash deposits looked and felt like talcum powder, alerting scientists who could see the potential acute and chronic health hazard it was going to present (subsequent study would confirm that the SHV ash comprised a substantial fine, respirable-sized fraction similar to MSH ash). Initially, as at MSH, the focus was on analysing the ash for the crystalline silica content, while keeping the island's fully stretched Chief Medical Officer (CMO) and health workers informed on the potential health effects of the ash. The in- and out-patients functions of the Glendon Hospital in Plymouth had by now been transferred to make-do facilities at St John's in the north of the island.

On 22 August 1996, the British Geological Survey (BGS) Analytical Geochemistry Laboratory reported that a fine ash sample (sub-10 μm fraction) collected from the deposit of the fallout from the first major pyroclastic flow on 3 April contained 25 wt% of crystalline silica in the form of cristobalite and tridymite. Following this, ash samples from fallout from two other pyroclastic flows were collected, and split samples were sent to the BGS and the Institute of Occupational Medicine (IOM), which was highly experienced in measuring dusts for crystalline silica in workplaces. The BGS reported their previous result again, but the IOM appeared to refute this by reporting only 10 wt%. These results were reported to the Foreign and Commonwealth Office and the Overseas Development Administration (later DFID) in early September with the recommendation that the exposure of the population to ash should be urgently studied and the ash analyses should continue to be repeated to monitor the concentration of silica over time; investigations would also proceed to understand the reasons for the interlaboratory differences found in measuring the cristobalite in the ash. The work was agreed and a survey team was able to start work only 4 days after the 17 September ashfall when the adverse exposure conditions were important to capture.

These early laboratory results on the cristobalite concentration were a stark warning to the investigators in the light of the growing activity of the volcano and the increasing frequency of the ashfalls in the most southerly populated areas. Good exposure data were going to be vital to base estimates of the risk to the population of developing silicosis, and the preventive measures needed to reduce the exposure, and, hence, the risk, all of which was becoming a high priority for the authorities. Ash deposits could remain in the environment for months and, when conditions were dry, the fine ash could be readily suspended by human activity of all kinds, as well as by the strong prevailing winds on Montserrat.

First exposure surveys and silicosis risk assessment, September 1997

For the next few months after the 18 September 1996 event, ash continued to fall intermittently in Cork Hill and the Salem area, including Frith, Old Towne and Olveston, but then the emissions started to build up again as the dome grew relentlessly and pyroclastic flow activity increased, culminating in the major dome collapses on 25 June 1997 and the deaths of 19 people in pyroclastic flows and surges.

This tragic episode marked a new turning point, with the growing volcanic threat leading to Cork Hill being hastily evacuated on 27 June and people in the central area, including Salem, Frith, Olde Town and Olveston, were sent northwards on 16 August. For many of those displaced, there was nowhere left to go other than shelters, or to sleep in their own cars, and many opted to leave the island under the assisted passage scheme provided by the UK government. The numbers of people and families leaving the island now rose dramatically.

Exposure assessment. The exposure of the residents to ash in these threatened central areas was already becoming intolerable as their tropical houses were designed to allow for the free flow of air from outside keeping the inside cool, and they provided little resistance to the ingress of ash. A cumulative deposit of several centimetres of ash had blanketed the village of Cork Hill (Fig. 22.3). Being forced to leave their houses by the threat of pyroclastic flows had the benefit of reducing residents' exposure to the ash emissions, which were getting worse as the ghauts on the northern and eastern flanks of SHV had filled up with pyroclastic flow deposits, making it more likely that even larger clouds of ash

Fig. 22.3. View of Cork Hill, Montserrat, at the foot of the SHV, showing deep ash layer around houses. The village had been recently evacuated in June 1997.

would be formed and blown by the prevailing winds towards the Cork Hill and Salem areas, and even further northwards to Woodlands. The north of the island had still escaped significant ash fallout. A new survey of exposure of the population to ash at this time was completed, and it was possible to use the results of the two surveys in September 1996 and June 1997 as a basis of the first formal health-risk assessment for silicosis.

These two exposure surveys used personal samplers worn by individuals for up to 8 h at a time while they were working or moving around performing a range of activities (Fig. 22.4), and hand-held monitors were left in locations to give background readings. The exposure levels to cristobalite in a variety of locations, exposure conditions and human activities, as measured in the two IOM surveys, were undertaken using a direct-reading (TSI) DustTrak monitoring instrument that was set to measure PM_{10}, as well as a cyclone sampler with filters for gravimetric analyses back in the laboratory, which could also be used to determine the mass of the respiratory fraction (sub-4 μm) and its cristobalite content. The technology in the Montserrat exposure surveys was to change further over time, but the DustTrak measuring PM_{10} became the convenient workhorse on Montserrat for background air measurements thereafter and for assessing local air quality in terms of guideline levels. PM_{10} was used in preference to $PM_{2.5}$ because relatively inexpensive handheld equipment was available

Fig. 22.4. Personal monitoring of exposure on a port worker, September 1996. He is hosing the ground to suppress ash being mobilized by traffic. His DIY mask is inadequate and respiratory protection was later upgraded on the island. A. Nicholl, occupational hygienist, is monitoring his exposure to dust: note the cyclone sampler attached to the worker's shirt. The old port stayed open for a while after Plymouth had been evacuated.

to measure this parameter and the UK Expert Panel on Air Quality Standards had produced an air-quality standard for PM_{10} in 1995 (EPAQS 1995).

Particles in the respirable fraction are fine enough to enter the alveoli (small air sacs deep inside the lung) and it is the cristobalite in this fraction that is of most importance in the development of silicosis. Cristobalite can only be reliably measured using gravimetric methods; that is, wearing a pump that draws air through a filter paper inside a sample head attached to the clothing near the breathing zone of an individual (Fig. 22.4), the filter paper is later removed and weighed and analysed in the laboratory.

This exposure assessment was to become the first of several performed by the team over the following years which were funded by ODA, and the results with recommendations were reported to ODA and Governor of Montserrat. Searl *et al.* (2002) subsequently collated the findings for December 1996– April 2000 for a report and paper, which highlighted the risk of the islanders developing silicosis based on these. This will be discussed further below.

Risk assessment. The main points of the health-risk assessment by Baxter & Seaton in 1997 are as follows:

- The intensity of exposure to cristobalite in the affected general population was excessive by occupational health standards (the 24 h exposure levels in the affected communities regularly exceed the equivalent NIOSH occupational standard in the United States).
- The toxicity of the crystalline silica as cristobalite had not been established and it was very dependent on the surface activity of the crystal. This is affected by other minerals, particularly silicates, present in the dust and it may be wrong to assume that exposure to a given concentration of cristobalite is the same when the mineral is alone or when it forms only 10–20% of the inhaled dust.
- The duration of exposure to the cristobalite in the ash at the recorded levels in the impacted communities had not been long enough to lead to the development of silicosis, and it would be very unlikely that anyone would be adversely affected if their exposure were now to cease.
- If exposure to the increased levels continued for approximately 6 years or more, silicosis in the form of fine nodules seen on chest X-ray could develop in approximately 10% of the population. In a small proportion of these individuals, the condition may become progressive and lead to a reduction in lung capacity, but it is unlikely to be fatal. There is a risk that pulmonary tuberculosis could be reactivated in some individuals and more evidence points to silicosis being associated with a small increase in lung cancer risk (very small in relation to cigarette smoking).
- More severe silicosis, leading to impairment of lung capacity and symptoms of breathlessness, could develop in individuals exposed regularly to cristobalite concentrations of around 0.5 mg m^{-3} over 24 h in a matter of only 2–3 years. Exposure to the lower concentrations (*c.* 0.1 mg m^{-3}) estimated for workers in the central area might be anticipated to lead to the same consequences if exposure were to continue for a further 8–10 years. This assumed that cristobalite is twice as toxic as quartz, and that cristobalite in a mixed dust is as toxic as pure cristobalite at the same concentration. In the longer term, some subjects who developed severe silicosis could die as a consequence.
- In a small proportion of the population, including children, the consequences of frequent, high exposures may be less predictable and some could develop enlargement of the hilar lymph glands detectable on a chest X-ray after only 2 or 3 years, a condition that could lead to a raised susceptibility of developing silicosis on exposure to lower levels of crystalline silica in the future.

The recommendations that followed these uncomfortable warnings in the report included the need to relocate from areas impacted by heavy and frequent ashfalls, especially families with young children, if there was no immediate expectation of a decline in volcanic activity and its accompanying ashfalls, as experienced in June 1997. The report also advised on other measures to reduce exposure to the ash, such as wearing appropriate masks in dusty conditions or when doing dusty jobs. This stern advice for people to relocate to protect themselves against the development of a serious lung disease that would take years of repeated exposure to develop, and was shrouded in uncertainty, at least until further toxicological testing was done, could have provoked resistance amongst at least certain sectors of the population, but the widening of the volcano Exclusion Zone to guard against the more immediate and growing pyroclastic flow threat described above had the same effect of moving people from the areas with the highest exposure to the ashfalls. This fortuitous correspondence between the two main volcanic hazards raised no doubts in the population at the time, and helped to consolidate the essential on-going collaboration between the health scientists and the Montserrat Volcano Observatory (MVO), particularly in advising the population over safe and unsafe areas.

Constantly, people wished for the eruption to show signs of stopping, but science had no power or foresight to bolster that hope. The dome kept on growing and showed no signs of respite. At least the northern part of the island, which had received little ash, remained habitable and the core of the island's life could continue. Even this tenet, though, was going to be tested before the year was out.

Visit to Montserrat by the British Government's Chief Medical Officer

As an Overseas Territory, HM Governor of the island was also, de facto, ultimately responsible for the population's health and safety, and the island's own government looked to Britain for life support in the crisis. The island had its own CMO and Minister of Health, but an erupting volcano had not been a regular part of the Minister's portfolio. At the request of the Government of Montserrat, the British Government's CMO, Sir Kenneth Calman, led a team of senior health professionals and specialists to the island between 20 and 25 September 1997. The purpose of the visit was to examine and report on public health and health-service provision in the light of the volcanic activity. Amongst other important health-care issues, the CMO's report noted that the airborne ash levels in the evacuated central area had remained exceptionally high since the 25 June eruption; the team's visit also coincided with the major eruption on 21 September that added to the ash deposits in the central area and Woodlands. A second period of Vulcanian explosions lasted from 21 September to 24 October (the first had been on 3–12 August).

The report was adamant on the need to control the risk to health from the ash. It recommended there should be regular dust monitoring in the central area, extended to other areas further north as necessary, and to keep the health risks under close review. All means, it said, should be taken to prevent further excessive exposure of the population to ash. A much wider use of masks by the population was needed. Epidemiological studies on the effects of exposure to the ash should begin as soon as possible; exposed groups of Montserratians should have long-term follow up. The sequel to the visit was the formation of the CMO's Montserrat Advisory Group within the Department of Health in London, which had the role of overseeing the full range of recommendations on improving the resilience of the island's health services, including further studies on health effects of the ash. (Members of the CMO's Advisory Group on Montserrat were: Dr Robert Maynard CBE, Dr Ross Anderson, Dr Peter Baxter, Professor Anthony Seaton CBE, and Dr Bill Kirkup CBE. The CMO was Sir Kenneth Calman.)

Alerted to the immediate dangers of the crisis by the eruption in the night on 21 September, and shaken by a dramatic dome explosion during their visit to the MVO, the CMO's team had noted that no adequate risk assessment for the safety of the central zone (including Woodlands) had been undertaken and they queried the recommendations on the occupancy of the area. The risk assessment was later requested by the UK government on the whole range of hazards of the volcano, and was conducted by a team of British and international scientists in Antigua in December 1997.

The landmark assessment of volcanic hazard and risk on Montserrat, December 1997

One of the terms of reference of the Antigua scientific meeting was to complete a risk analysis of the volcano based on the best available geo-scientific and health information. In the run-up to the meeting, a very detailed evaluation co-ordinated by the Department of Earth Sciences, University of Bristol (R.S.J. Sparks), affirmed the cristobalite content of 10–24 wt% in the sub-10 μm portion (Baxter *et al.* 1999). The hazard and risk report contained very little change to the view expressed in the Baxter & Seaton statement published in September, but was updated to say that the erupted ash from the regular Vulcanian explosions contained substantially less cristobalite (3–6 wt%).

The UK Chief Scientist, Sir Robert May, convened a meeting in London on 16 December with a subgroup of scientists and officials, including the CMO and the main author (P.J. Baxter), to discuss the Antigua report. May acknowledged the wide uncertainties inherent in the volcanology and predictions of future eruptive activity, which he opined in his report (unpublished) were based on expert judgement and not on statistical evidence of risk. Thus, the scientists' assessment could only offer 'distributions of probability, whose shapes and magnitudes are themselves uncertain' and 'our understanding of both the short term and the longer term effects of the ash on humans is largely speculative'. These frank statements did not, in the end, deter him from concurring with the main thrust of the advice that there was no need to evacuate the island as a precaution, although he was initially unconvinced that the north of the island would be always safe in a major eruption. He concluded, in regard to the latter, that we should recommend in the strongest terms that people should leave area 4 (Woodlands), as well as areas already in the Exclusion Zone.

Thus, it was that the seal was set on the area of the island north of the Nantes River, and shielded by Lawyers Mountain, being at low risk from major eruptive activity or falling ash. A high level of activity at the volcano was to continue until March 1998, when magma extrusion and dome growth temporarily ceased, marking the end of Phase 1 of the eruption.

A study of respiratory symptoms in children living in Montserrat, February 1998

Before the end of the first phase, the opportunity was taken to investigate the 'irritant' effects that high levels of fine particulate ash (as PM10 and PM2.5) could have on the airways of the lungs, which was one of the priorities at MSH. As in that eruption, the natural group to target was children and the condition, asthma and related symptoms.

Planning for this study on schoolchildren had begun following the CMO's team visit. By the time it was enacted in 16–20 February 1998, the population of the island had fallen to 3500, or slightly more than a quarter it had been before the eruption started. Many families had recorded on their exit forms that a reason for leaving was a member of the family suffered from asthma. It seemed likely from the outset that a self-selected, possibly less symptomatic, group of families remained and we might underestimate the extent of asthma-related problems in a study designed to measure the prevalence of respiratory symptoms in children who were living, or had lived, in the areas most affected by ashfall compared with children from less exposed areas. The method used a standardized international (ISAAC) questionnaire and lung function tests. Classifying exposure to ash according to residence was based on cumulative deposit depth (isopach) data (Fig. 22.5). The methodology and the results were later published in Forbes *et al.* (2003).

Anecdotally, expatriate adults on the island who had a diagnosis of asthma found the ash aggravated their symptoms: they could remedy this by staying out of the ash or by wearing an effective mask in dusty conditions – and, in addition, increasing their medication. Some Montserratians had left the island early on in the crisis because of the ash and having a child with asthma. But when the hospital and clinic attendances were checked, and from the accounts of the doctors and nurses and the pharmacists at the hospital, and the private dispensing chemists, it was not possible to identify more than a very few asthma sufferers on the island and even these were not affected badly enough to attend hospital in an attack after a heavy ashfall.

Yet, what the survey of 440 schoolchildren showed (questionnaire information on 80%) was that the prevalence of wheeze symptoms in the previous 12 months was 18% in children aged 12 years and under, and 16% in children aged 13 years and over. In the former group, the prevalence of wheeze was three to four times greater in those who had ever been heavily or moderately exposed to volcanic ash compared to the group who had only been exposed to low levels; and the prevalence of exercise-induced bronchoconstriction (an objective test with a fall in lung function after exercise that mimics an asthma-type response) in 8–12 year olds was about four times higher in those currently heavily exposed to volcanic ash compared to those currently exposed to low levels. The prevalence of symptoms found (16–18%) was in line with that which had been reported from Barbados.

Studies at MSH in children found little evidence for an effect of ash on lung function in the weeks after the 18 May ashfall (Buist *et al.* 1986), but, in the Montserrat children, the high levels of ash in the ambient air had been experienced by the high exposure group for 2 years.

None of the Montserratian children who had reported wheeze in the preceding 12 months used a corticosteroid inhaler and only four reported use of a ß-agonist inhaler. Clearly, asthma was being grossly underdiagnosed on Montserrat, especially during the crisis years of 1995–1997 when the population and health services on the island were being so highly disrupted.

Other reasons why the condition was so elusive were that some people sought medical treatment in Antigua, while most Montserratians, it seemed, tolerated and controlled the condition without seeking medical assistance. Underdiagnosis of asthma is regrettably common in many countries with limited health-service provision.

Waiting to reoccupy Salem, April 1998–October 1999

With the lull in activity in March 1998, many of the people who had been moved north in June and July and had stayed on island sought to re-occupy their homes and businesses in the Salem, Frith, Old Towne and Olveston areas, but the decision by the authorities to delay re-entry until October 1998 was based on health grounds and on the need to wait until much of the ash had been removed by public works from houses and roads, and the ash in grassy and wooded areas had been eroded by rain.

The NIOSH recommended limit for cristobalite in the workplace (50 $\mu g\ m^{-3}$) was used as a working guide for assessing environmental exposure. Dividing the limit by five would allow for the difference between workplace exposure over the 8 h day and 5 day working week, and the inescapable 24 hour/day exposure to the ambient air in homes and shops and workplaces. This reduced the NIOSH limit value to 10 $\mu g\ m^{-3}$ over 24 h to compensate for the added number of hours of exposure. A further adjustment was made for those days in the dry season when significant resuspension of ash occurred 1 day in 3 ($\times 1.5$), for night time when exposure was minimal ($\times 1.5$) and for possible susceptibility in children (divide by 10). Exposure to volcanic ash up to that time on Montserrat had been at most only 3–4 years compared with 40 years allowed for by the occupational exposure limit ($\times 10$). Finally, the cristobalite concentration in the ash was taken as about 20% of the PM_{10}. A background reference level of 100 $\mu g\ m^{-3}$ PM_{10} measured using a DustTrak was adopted to be used in conjunction with a list of criteria for adequate clear-up around houses and roads to decide on the suitability of areas for reoccupation. (Although not stated, the fraction of most significance for the development of silicosis was the respirable or sub-4 μm, which was known to contain a similar proportion of silica as the sub-10 μm (Horwell *et al.* 2003). The actual exposure to silica over 24 h would therefore be approximately 10 and not 20 $\mu g\ m^{-3}$ if the reference level was adhered to.)

An extensive programme of dust monitoring over the island in March–August 1998 involved members of the MVO and was led by the IOM, followed by the IOM survey in September 1988 of the Salem area. Reoccupation of Salem, Frith and Happy Hill was found acceptable, but further clean up in Old Towne was required along the small roads and in the unoccupied villas. Advice on clean-up measures and the results of an exposure study in clean-up workers were included in the IOM report. The clean-up measures and criteria for clean-up would, it was noted, be important in helping asthma sufferers amongst the schoolchildren studied in February 1998.

The move back to Salem was welcomed, but the area did not fully regain its vitality, while the threat of further ashfalls remained. Businesses moved further north away from the areas that had seen the heaviest of the ashfall up to then. Even though dome growth had stopped, explosions, ash venting or dome collapse occurred on average every 2 days. The regular ash emissions continued at an usually high level, and an ash monitoring programme was established in the Isles Bay–Belham Valley area to evaluate the ash in air levels using a network of DustTrak instruments during 7 May–9 July 1999. For particular study was the effect on air quality of the strong winds raising ash from the deposits around the volcano and blowing particles towards Salem and Old Towne. The air levels of PM_{10} were often higher than the UK air-quality standard but not excessively high despite the on-going ash emissions. Analysis of ash samples collected at this time showed high cristobalite levels, including the highest in Cork Hill at 30 wt% cristobalite in the sub-10 μm fraction.

Eruption phase 2: 27 November 1999–28 July 2003

A new dome was observed to be growing in the bottom of the crater by a passing MVO helicopter on 27 November 1999 and a new period of uncertainty for the islanders began once again. Volcanologists stated that there was a reasonable chance of the hazard and ash conditions returning to resemble those at the height of activity in 1997. This concern led to the IOM planning a chest X-ray study of all workers who had been regularly exposed to ash, to exclude the development of silicosis. The MVO (C. Bonadonna and R.S.J. Sparks) began work on modelling the dispersal of tephra fallout incorporating data from all the activity since 1995. Scientists were beginning to acknowledge that there was an increasing chance that the volcano could become persistently active.

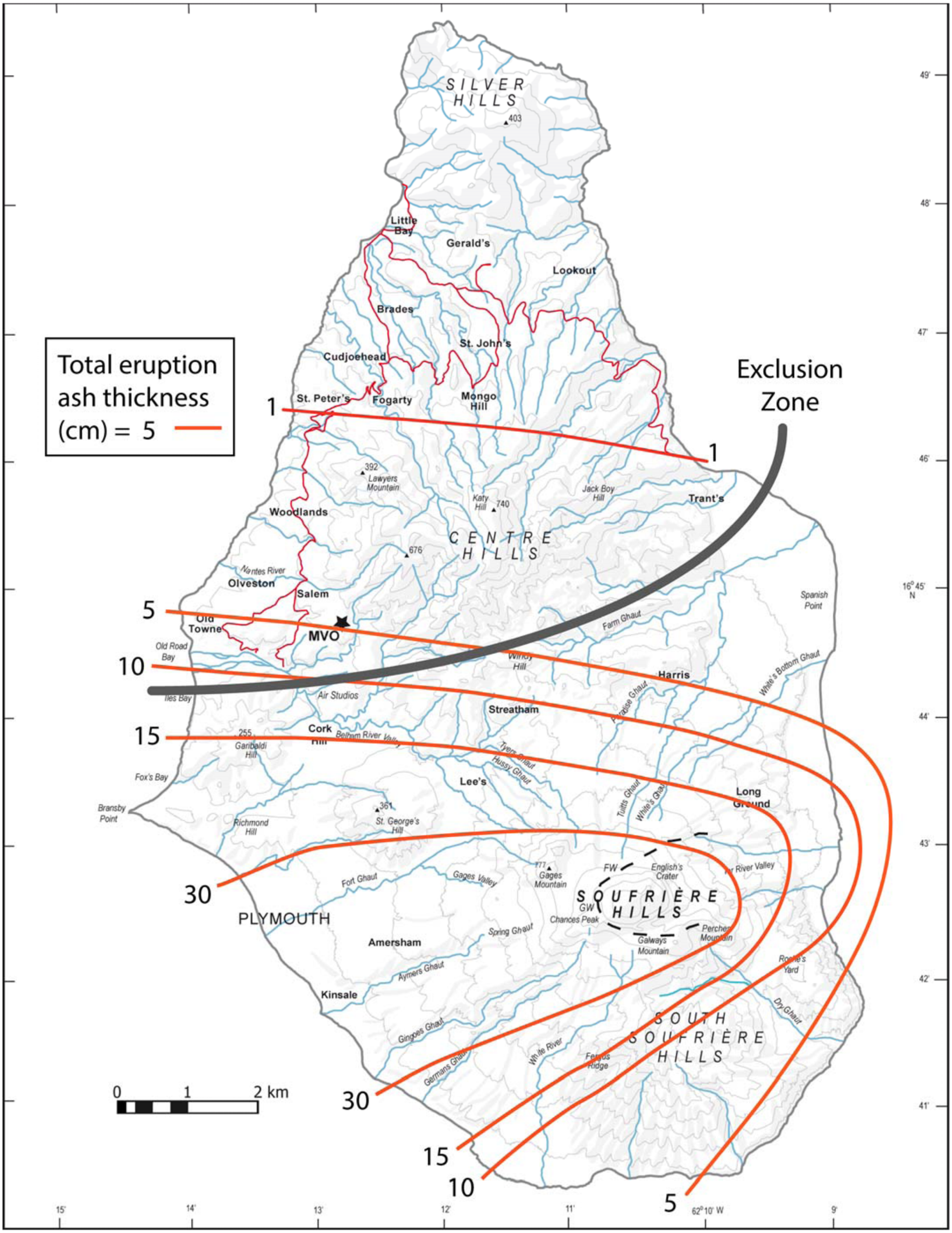

Fig. 22.5. Soufrière Hills Volcano, Montserrat. Cumulative depths of ash (isopachs) by March 1999 (BGS).

Ashfall on 20 March 2000

The next large ashfall was after a dome collapse on 20 March, when most of the ash went out to sea. A new survey of exposure to ash in selected groups of workers and the general population was conducted on 31 March–6 April 2000. There had been frequent rains before the survey and the ashfall had not been very substantial in central areas – in fact, conditions and exposure to dust in Salem and Old Towne had improved markedly since the end of the previous year. Remaining ash deposits that had resisted weathering were being covered and stabilized in new growths of grass, and the air monitoring confirmed the reduction in ambient air levels.

Ashfall on 29 July 2001

No further significant ashfalls occurred while the dome was growing until the dome collapse of 29 July 2001, which in one day reversed the gains that had been made in the clearance and weathering of the old ash deposits. The dome had grown to an estimated volume of $162 \times 10^6 \times m^3$, and $45 \times 10^6 \times m^3$ was lost in the collapse; fortunately for the inhabitants, most of the ash fell in the Exclusion Zone. About 3–4 cm fell in Salem/Old Towne/Isles Bay (the maximum depth of compacted ash in the inhabited areas up to that date), while 6–7 cm fell in Fox's Bay and Cork Hill, with 10–12 cm in the Richmond Hill area. Frequent rainfall since the collapse had consolidated the ash and kept ambient air levels low. A major clean up had been rapidly co-ordinated in Salem/Old Towne/Isles Bay immediately after the event and this had followed the criteria previously laid down for the reoccupation of Salem in October 1998. Many householders had also removed the ash around their properties. The rain had played an important role in reworking ash as well.

A further exposure assessment in 27 August–1 September 2001 found that the ambient air quality was satisfactory. The first reaction of the islanders to the large event on 29 July had been a mixture of fear and despair, but morale rose when the clean up operations got underway, with conditions returning to near normal by the time the survey team had arrived. According to the IOM, the cristobalite in three samples of the new ash was 24–29 wt% in both the bulk and the sub-10 μm fractions, and there was no change in the fine-ash-size distribution. The exposure assessment highlighted the high exposure of ash to gardeners after this ashfall as a result of the ash deposits lodging in lawns and on hedges.

The effective clean up and rapid improvement had been greatly assisted by the wet weather, but it showed what could be achieved by an effective clean up by public works and it bode well for the island in the future. However, this event did raise the serious doubt about what conditions would be like in a similar-sized dome collapse during drought conditions in the future, such that the wind direction resulted in 10–12 cm depth of fallout in the central areas rather than in Richmond Hill on this occasion. The ash would also affect the areas further north and would be a 'worst scenario'. The 'dust bowl' conditions might be so bad that people would not be able to tolerate them and normal daily activities would grind to a halt as happened in central Washington State after the 18 May 1980 eruption described above. This type of event, with periods of low activity during dome growth followed by large collapses when the dome has grown massively, could ultimately be as testing for the island's resilience as were the regular showers of ash and slowly accumulating ash deposits in 1996–1998. The survey report recommended that planning for the worst-case scenario should be undertaken, with special attention given to the equipment needed to be on standby to effectively remove the ash as rapidly as possible from the inhabited areas.

The MVO study by Bonadonna and Sparks on the tephra fallout hazard and risk modelled the impact of frequent dome collapse and recurrent dome growth over a 3 year period with frequent ashfalls. A report was produced by the MVO in April 2002 (see also Bonadonna *et al.* 2002*a*, *b*), which was to be used in the probabilistic risk assessment of 2003. It showed again how vulnerable the area north of the Belham Valley was to ashfall from future dome growth and collapse, but the chances of major tephra accumulation in the north were considered to be quite low. The study used data on tephra fallout through the eruptive period 1995–1998 and did not include the probability of the infrequent but very large ashfall (as on 29 July 2001).

Ashfall on 12 July 2003

Dome growth continued with minor collapses and pyroclastic flow formation after the shock fallout on 29 July 2001. Had not the winds over many months been kind and changed direction to blow most of the ash out to sea, the conditions would have resembled the worst time in the 1995–1998 period, and the probabilistic predictions of Bonadonna and Sparks would have been fulfilled.

Instead, the volcano and weather conspired to produce a double whammy on 12 July 2003 – the largest ashfall in residential areas to date, as predicted in the 2001 report, but accompanied by heavy rain, which so effectively soaked the ash that the feared 'dust bowl' conditions did not form. The small army of road workers with mechanical diggers, and the residents with their shovels, were able to effectively shift the huge quantities of rain-compacted and hardened ash from the Isles Bay/Salem/Olveston/Old Towne and Woodlands areas in the largest and longest clean-up campaign mounted on the island that was to last for 6 months. Regular rainfall kept the ash consolidated. Thus, contrary to all expectations, a 10 cm layer of consolidated ash in Olveston supported the weight of an adult when previously residents were used to sinking into ash that provided no resistance at all. Diggers were able to scoop up ash from gardens on an unprecedented scale (Fig. 22.6), and some queried whether such a costly clearance operation was even necessary, but in the end it was highly successful, showing once again what could be achieved against such odds, in returning the island to proper functioning.

About $45 \times 10^6 \times m^3$, or 25%, of the mass of the dome at the time collapsed on 29 July 2001 compared with $\sim 200 \times 10^6 \times m^3$ on 12 July 2003. Prior to the collapse the dome had grown to its largest size up to then (Fig. 22.7). The north of the island had a fallout of 0.3–2.0 cm., which did create very dusty conditions

Fig. 22.6. Ash being removed by a mechanical digger from a villa garden in Olveston after the July 2003 ashfall. The compacted depth of ash was up to 14 cm, the largest recorded in Olveston during the eruption.

Fig. 22.7. Soufrière Hills Volcano lava dome in 2003. The dome was growing to its maximum height before collapsing in July 2003. Note the gas plume mixing with the ash as it becomes airborne (photograph courtesy of the MVO).

for some days, until regular rainfall helped to settle and remove much of the ash.

In contrast to previous events, the rain-soaked ash had stripped vegetation of its leaves when it fell and it also had a substantial corrosive effect that was visible on any leaves that had remained. As a result, the vegetation did not act as a reservoir for wind-blown dust as seen in previous ashfalls, and the frequent rainfall subsequently prevented the new leaves from becoming covered in a layer of ash, as well as dramatically reducing the amount of wind-blown dust from existing deposits. The rain produced a firm but breakable crust on the deposit surface, which also reduced the potential for ash to be easily resuspended by wind. This type of crust commonly forms on fine-grained materials that contain some soluble salts and similar crusts formed on the MSH ash when the initially dry deposits were consolidated by rain that fell days later.

The results of the air monitoring and exposure assessment of various workers – police, gardeners, Public Works Department personnel, cleaners, domestic staff and drivers – during 25–29 August provided objective confirmation of this optimistic view of the aftermath of the largest ashfall on the island to date (Figs 22.8 & 22.9). Exposure levels were not excessively high, but our visit did coincide with rainfall and so did not reflect the very dry conditions that could occur at any time and lead to much worse exposures. Accordingly, advice was focused on adequately protecting the workers involved in the clean up of the Old Towne, Salem, Happy Hill and Frith areas which was going to take months to complete. This included not only the provision of masks, but a list of working methods to reduce the suspension of clouds of ash during its removal and its transport, including its disposal at the selected collection sites. The operations would give rise to raised exposures in residents as well as workers unless undertaken with adherence to strict working protocols. The report also recommended repeating exposure measurements on the road workers at intervals to check the levels were not becoming excessive as the work progressed.

A medical survey of outdoor workers exposed to ash was undertaken by the IOM in 2000 and was planned to be followed up by another survey that would ensure the inclusion of the workers involved in the above clean-up operations as well. In the event, it took place in March 2005 and the results were reported to the CMO's Montserrat Advisory Group. The two surveys comprised a respiratory symptoms questionnaire, lung function tests and chest X-ray. The results of the two studies were consistent and were reassuring for the heavily exposed workers. Ordinary residents were not included, but the absence of radiological abnormalities in workers who through their jobs were most exposed would also serve as a reassurance for the lesser exposed general population.

Quantifying the silicosis risk on Montserrat – the probabilistic (predictive) risk assessment (2003)

The need for a more rigorous assessment of the silicosis risk of the ash became apparent in 2002, at a time when scientists were foreseeing that the eruption could continue for at least another 10 years, with a return at times to periods of moderate to heavy, frequent ashfalls as had occurred in 1997–1998. Very high exposures to the population and outdoor workers could also follow the infrequent but major dome collapses and very heavy ashfalls that had been a recent feature of the volcanic activity. The clearance of ash after these events presented the road workers involved with potentially the highest exposures of all (Fig. 22.9).

Fig. 22.8. A villa cleaner wearing a personal air sampler (CIP10). Cleaning indoors with a brush leads to clouds of dust: she is wearing a recommended type of mask. August 2003.

Fig. 22.9. A road sweeper in a gang cleaning ash from roads after the July 2003 ashfall. Clouds of ash are generated by sweeping under dry conditions as here. Wearing a respirator is uncomfortable in the tropics and they are not likely to be worn constantly. Wetting down the roads first before sweeping was recommended.

Several surveys of exposure in groups of islanders (mainly workers) using cyclone and CIP10 samplers (Figs 22.8 & 22.9) and direct reading DustTrak instruments had been undertaken for DFID between September 1996 and April 2000 (Searl *et al.* 2002). Survey data were used to estimate the cumulative exposures to cristobalite up to 2000 in most of the 4500 people left living on island and who had been exposed since the eruption began. We compared these values with the NIOSH Recommended Exposure Limit for crystalline silica limit as the exposure criterion. Nearly all islanders came below this, the main exception being about 12–20 gardeners whose exposure had been the highest of all the groups studied and who were considered to be at potential risk of developing at least minimal radiographic evidence of silicosis (Searl *et al.* 2002).

The limitations of using the US and UK government-approved (NIOSH, American Conference of Governmental Industrial Hygienists (ACGIH) and Health and Safety Executive (HSE)) occupational exposure limits include the limited number of epidemiological surveys on which they are based. The available studies provided widely disparate exposure–response curves (Fig. 22.10), the variation being due to methodological limitations, as well as other factors to do with the mineralogy of the dusts. For example, particle size, variability between freshly fractured and 'aged' surfaces, and the presence of other types of minerals, including the way they may coat the surfaces of ash particles, will all play an important part, but the effects of these on toxicity cannot be predicted on the basis of the mineralogical composition alone (HSE 2002; NIOSH 2002).

A rigorous follow up involving toxicological testing to overcome this limitation, as was progressed by scientists over the SHV ash to be described below, is not routinely undertaken in epidemiological studies, which also makes it difficult to confidently benchmark between the studies published by different groups. Occupational exposure limits are a best estimate given the health data available, and those produced by government committees are not always only health based, but may be set on economic grounds as well (what industry can reasonably afford), further blurring their usefulness in novel exposure situations like Montserrat. This was true of the limits set by the UK HSE at the time which adopted a maximum exposure limit (MEL) for industry to operate well below, but they did not specify how low, except it should be as low as reasonably practicable.

This was the reason for adopting the NIOSH recommended limit of 50 $\mu g\ m^{-3}$, which was the most health-based limit then available; it was also the lowest (most precautionary) for applying to exposure of a general population, as opposed to exposure in the workplace for which it was intended. It is important to note that most occupational exposure limits are not guarantees of safety either – the only guarantee comes with having no exposure to a toxic substance at all, which, in the case of Montserrat, was not an option unless you left the island. In practice, the proferred medical guidance was attempting to ensure that people did not live in any areas where the risk of developing silicosis was higher than expected in comparison with other, more typical background environmental risks to health that people generally accept (and much less than, e.g., the risk of smoking).

A further difficulty arises as the exposure limits do not enable a quantification of the risk of an individual developing silicosis if the limit values are exceeded on a regular basis, as had already occurred to our knowledge in some gardeners, and could apply to many more people on Montserrat if the ashfalls continued into the foreseeable future, as was now being openly discussed. The question being asked was what would be the risk of developing silicosis if the volcanic activity and further exposure to ash from this lasted for 20 years?

We also needed a way of incorporating expert judgements on the results of the toxicology studies that had become available by now and were directed at the key question of how toxic was the cristobalite when it was part of the volcanic ash mineral matrix compared with when it was in the form of crystals by itself. This issue had been raised in the first risk assessment in 1998. Had the risk been overestimated then, and would the toxicology tests confirm this and point to a new basis for quantifying the risk?

These questions were not academic: the UK government was also interested in the answer before committing new financial resources into the island's long-term future.

A meeting of UK experts took place on 28 March 2002 at the IOM in Edinburgh to plan a quantified (probabilistic) risk assessment and to arrive at some conclusions on the main inputs into the mathematical modelling that would be required. Members of the Risk Assessment meeting in Edinburgh included: W. Aspinall, P. Baxter, J. Cherrie, H. Cowie, K. Donaldson, F. Hurley, B. Miller, M. Meldrum, A. Searl and A. Seaton.

(1) The cristobalite concentration of volcanic ash in its respirable fraction (<4 μm). A joint study was undertaken by the IOM, Edinburgh, the BGS, Nottingham, the Department of Earth Sciences, Bristol University and the Department of Public Health and Primary Care, Cambridge University to confirm the crystalline silica content of the ash and the best analytical methods available. The sub-10 μm fraction of ash generated by pyroclastic flows formed by lava-dome collapse contained, on average, 10–24 wt% crystalline silica, an enrichment of 2–5 relative to the magma due to selective crushing of the groundmass (Baxter *et al.* 1999). The same fraction of ash generated by explosive eruptions had a much lower content, which closely reflected the magma composition (3–6 wt%). Most of the crystalline silica was in the form of cristobalite, with small amounts of tridymite and quartz. The respirable fraction (sub-4 μm) – as sampled at head height from the air in areas with ash resuspended

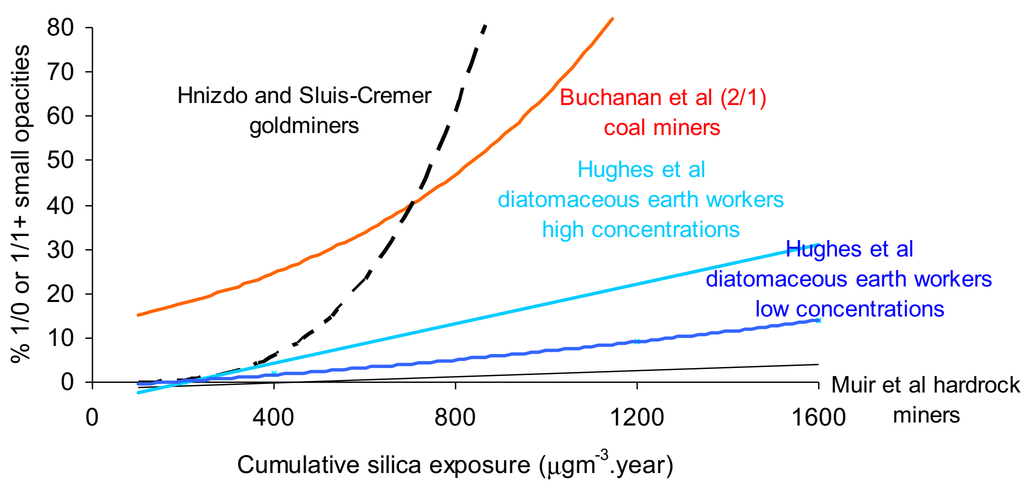

Fig. 22.10. Exposure–response curves from selected epidemiological studies of groups of workers exposed to dusts containing crystalline silica. The initial risk assessment by Baxter & Seaton was based on the Muir *et al.* (1989) curve (see text). Expert judgement for providing inputs into the probabilistic risk assessment adopted the Hughes *et al.* (1998) (low concentration) curve as the one most suitable on the basis of the results of the toxicological studies. Note that if any of the other curves had been chosen the risk estimates would be much greater.

from ground deposits – contained at least the same proportion (10–24 wt%) of crystalline silica as the sub-10 μm fraction overall (Horwell *et al.* 2003).

(2) A numerical model for human exposure to the ash and cristobalite. The exposure data later published in Searl *et al.* (2002) were used to estimate in future years the likely exposures (and ranges) at different depths of ground deposits in different locations around the island and under different weather conditions (rainfall), including estimates of erosion rates for the deposits. Police, gardeners and Public Works Department were the workers most exposed. For children (up to the age of 10 years), additional exposure factors were added to allow for greater deposition of dust in children's lungs and, as a precautionary measure, another safety factor for possible sensitivity of the growing lung to crystalline silica. An individual's exposure in relation to the ashfalls depended on their place of residence, their job and their other daily activities, much of which could already be linked from the results of the previous exposure surveys. The model was run for scenarios with the cristobalite concentrations of ash varying from 10 to 24 wt%.

(3) A model for eruptive activity, ashfalls and ash dispersion. Prediction of ground deposits and their depths based on previous eruptive activity of the volcano depended on the modelling of stochastic volcanic events, including dome growth rates, the variability of dome collapses and the probability of explosions. Inputs on ash dispersion and depth were obtained from a standard model for ash plumes (HAZMAP) incorporating local rainfall and wind data that had been previously developed for the SHV (Bonadonna *et al.* 2002*a*, *b*). Future rainfall, as a determinant of exposure, was also modelled separately. A critical (and limiting) assumption of the model was that volcanic activity would continue at rates similar to the previous 8 years.

(4) A toxicological model for the Soufrière Hills ash. After modelling the exposure to the ash and integrating it over time in relation to the behaviour of the volcano, the question then becomes: which exposure–response curve should be used to quantify the risk? If the NIOSH and other published exposure limits were inadequate, and could only give a cut-off for the presence or absence of risk, what other basis is there for quantifying the probability of developing disease at different levels of exposure?

The UK experts (listed earlier) were asked to review all of the toxicological data on the ash that had become available since the eruption started. The main studies were:

- Cullen & Searl (1998) performed *in vitro* testing on human epithelial cells and rat alveolar macrophages.
- Wilson *et al.* (2000) examined the competence of human epithelial cells and the ability of volcanic ash to induce sheep blood haemolysis (destruction of red blood cells).
- Cullen *et al.* (2002) performed an inhalation study and an instillation study in two groups of rats and further *in vitro* studies.
- Housley *et al.* (2002) studied the effects of ash on the lungs of rats in an instillation study.
- Lee & Richards (2004) undertook the most detailed *in vivo* work involving instillation in groups of rats sacrificed at intervals up to 49 weeks.

The meeting concluded that according to the results of these studies the ash could be best regarded as a mixed dust of low–moderate toxicity, analagous to the toxicological findings seen with coalmine dust in which crystalline silica is found in a mixture of other minerals and carbon particles. This 'mixed dust' comparison implied that the toxicity of the cristobalite in the SHV ash was being masked by the mineral matrix of the particles and so was significantly less than the bioreactivity expected using the concentration of cristobalite in a pure dust, which was the precautionary stance taken until now. The most comparable published study in which workers were deemed to have a similar pattern of exposure to dust containing cristobalite as the islanders was that by Hughes *et al.* (1998) of a group of diatomaceous earth workers in California exposed, in their study, to low concentrations of cristobalite (Fig. 22.10).

The first risk assessment in 1998 was a judgement based (not probabilistically) on the exposure–response curve from the Muir *et al.* (1989) study (see Fig. 22.10), which is not very different in slope from the California study (Fig. 22.10). However, the September 1997 assessment used a higher estimate of exposure derived from the ash conditions in places like Cork Hill when they were still occupied and assuming continuing exposure to these levels of ash with a cristobalite concentration of 10–20 wt%. It did assume that the toxicity of cristobalite in the lung was twice that of quartz, a view widely held at the time, and its bioreactivity was not being masked by other minerals that were present in the ash.

(5) Monte Carlo simulations. Probability distributions of all the inputs to the model were used to capture the model uncertainties by adopting this standard and widely used method. The code was run for periods of 5, 10 and 20 years, with 10 000 runs per simulation. Full details of the modelling approach is found in Hincks *et al.* (2006).

Main findings of the risk assessment. The disease endpoint commonly used in occupational epidemiological studies of silicosis is a radiological one – in this case the ILO International Classification of radiographs for pneumoconiosis – and their category 1/0–1/1 small opacities. This is a sensitive cut-off point – that is, the earliest indication of changes suggestive of silicosis – and is not associated with symptoms of silicosis, although the disease can progress to a more severe stage over time, even in the absence of further exposure; however, the risk of this was regarded by the experts as small. This cut-off was adopted as the most conservative approach for risk assessment purposes, rather than clinically manifest disease.

The risks in the north of the island (Fogarty), where most of the population lives, as computed by the model, were so small and uncertain that they could be ignored.

The estimated exposures and risks in the inhabited areas in the central part of the island (Salem and Woodlands), which receives the most ashfall and where the minority of the population lives, are summarized in Tables 22.1 & 22.2 and Figure 22.11a, b:

- The 'best estimate' probability of developing early radiological evidence of silicosis in the general population is less than 1 per 1000 after 5 years of volcanic activity, reaching 4 per 1000 after 10 years of activity and 12 per 1000 after 20 years. If the highest likely personal exposures are assumed to occur throughout the period of volcanic activity, the risks are double these.
- The occupational group with the highest exposure to ash is the gardeners: the 'best estimate' risk is around 8 per 1000 after 5 years, and, if the volcano remained active for 20 years, the estimated risks would rise to 2–3 per 100. The risks using maximum likely personal exposures would be higher than this – 1 per 100 after 5 years, 4 per 100 after 10 years and up to 10 per 100 after 20 years.
- The estimates for children were less than 5 per 1000 after 5 years of volcanic activity, 2 per 100 after 10 years and up to 4 per 100 after 20 years. If maximum exposures were assumed these risks were approximately doubled.

Main implications. The findings indicated that a significant risk (approximately >1%) of developing early radiological signs of silicosis exists for some sectors of the population already exposed since 1995 (especially children and outdoor workers, such as gardeners) and living in the central inhabited areas most impacted by ashfalls *if* the volcanic activity continued as

Table 22.1. *Percentage risk of silicosis category 1 or more by location and population group*

Population group	Location			
	Cork Hill	**Salem**	**Woodlands**	**Fogarty**
Average adult	0.62 (*0.3*, *1.2*)	0.27 (*0.2*, *0.5*)	0.19 (*0.1*, *0.3*)	0.17 (*0.1*, *0.2*)
Dusty adult	0.79 (*0.4*, *1.6*)	0.34 (*0.2*, *0.7*)	0.24 (*0.2*, *0.4*)	0.22 (*0.1*, *0.3*)
Gardener	1.36 (*0.9*, *2.2*)	0.81 (*0.6*, *1.2*)	0.68 (*0.5*, *0.9*)	0.62 (*0.4*, *0.8*)
Police	0.82 (*0.4*, *1.6*)	0.34 (*0.2*, *0.7*)	0.24 (*0.2*, *0.4*)	0.22 (*0.1*, *0.3*)
Public Works Department	0.86 (*0.4*, *1.7*)	0.35 (*0.2*, *0.7*)	0.24 (*0.2*, *0.4*)	0.22 (*0.1*, *0.3*)
Child	2.92 (*1.5*, *5.4*)	1.36 (*1.0*, *2.5*)	1.01 (*0.7*, *1.5*)	0.92 (*0.6*, *1.2*)

Assuming 10 years of volcanic activity. Variable personal exposure. Each cell contains median value (5th percentile, 95th percentile, given in italics).

in 1996–2000 for a further 10 years or more. However, the risk would be substantially reduced by measures to reduce occupational and community exposure, which had already been adopted on the island.

A population-based strategy for limiting exposure to ash would be essential, as well as focusing on high-risk outdoor workers. Since 1997, recommendations have been made on routinely minimizing exposure to ash across all groups on the island, including insisting on the active clean up of roads and dwelling areas after heavy ashfalls, a policy that has high-cost implications for the authorities. Ash clearance can potentially overexpose the workers and home owners involved, and measures such as dampening down ash before clearance, or only clearing it after rainfall (which is usually frequent on Montserrat), as well as wearing masks, needed to be followed.

Gardeners and other outdoor workers needed to be adequately protected using standard approaches of occupational hygiene: reducing exposure as far as practicable, routine wearing of appropriate respiratory protection and ensuring it is properly used, monitoring exposure and regular medical examinations, including 5 yearly chest X-rays.

The exposure of children should be minimized: play areas should be kept clear of ash and children should not be involved in clearing ash from houses and gardens. Schools and houses in the central area could be made more 'ash proof'.

The CMO's Montserrat Advisory Group reviewed the findings and concluded that, with an appropriate island-wide strategy to minimize exposure of the population to ash, the health risk could be controlled at tolerable or even minimal levels. Most importantly, there has not been a return to the frequent ashfalls of the earlier years on which the risk assessment was based, which also substantially reduces the predicted risks.

Eruption phase 3: 1 August 2005–20 April 2007

A pause in lava extrusion of 2 years followed the collapse of July 2003. This lengthy break in activity led to some scientists raising hopes that the eruption had, in fact, ended. An exhibition of stunning photographs of Montserrat in London coincided with tourist publicity and newspaper articles that Montserrat was open for business and tourism again. The 'Soufrère Hills Volcano – Ten Years On' scientific conference was held on Montserrat, and it was opened on a wave of optimism on 24 July 2005, but sadly, as international scientists debated whether the eruption had ended or not, a small plume of ash rose from the volcano to announce it was not yet over. A newly extruded lava dome was first seen on 8 August after a period of cloud cover had lifted, and growth was assumed to have begun on 1 August.

Catastrophic dome collapse on 20 May 2006

This was the first major dome event in which volcanic gases played a more important part in the health impact than ash, and it is included for completeness. All through the eruption, the prevailing wind only occasionally blew over the north of the island and even then in an inconstant way. Although people sometimes smelt gases, these occasions were short lived. A small network of gas diffusion tubes that measured sulphur dioxide downwind of the volcano for year after year indicated that major fumigation of the ground by the plume did not, or only rarely, occur.

According to the MVO, sulphur dioxide emission rates remained close to, or slightly above, a 500 t/day average, but the hydrogen chloride–sulphur dioxide ratio rose from just below 1 in September 2005 to 2–3 in February and March 2006, with a peak of 5.89 just before the collapse in May. The MVO considered that this represented an increase in the overall emission of hydrogen chloride in recent months. Coinciding with this increase, the MVO helicopter pilot reported seeing new vegetation damage near Plymouth and around White Ghaut. During the week following 29 April, farmers and others reported widespread damage to vegetation which they attributed to acid rain. On 1 May, there was a strong smell of gas in the Olveston area. Prior to the 20 May event, vegetation damage was also occurring on the Central Hills close to the MVO, and at Fox's Bay and Richmond Hill. The plume appeared to have been affecting the

Table 22.2. *Percentage risk of silicosis category 1 or more by location and population group*

Population group	Location			
	Cork Hill	**Salem**	**Woodlands**	**Fogarty**
Average adult	1.99 (*1.2*, *3.2*)	0.89 (*0.6*, *1.4*)	0.58 (*0.5*, *0.8*)	0.52 (*0.4*, *0.7*)
Dusty adult	2.52 (*1.5*, *4.0*)	1.13 (*0.8*, *1.8*)	0.75 (*0.6*, *1.1*)	0.67 (*0.5*, *0.8*)
Gardener	4.25 (*3.0*, *5.9*)	2.60 (*2.1*, *3.4*)	2.08 (*1.6*, *2.6*)	1.91 (*1.4*, *2.3*)
Police	2.60 (*1.6*, *4.2*)	1.15 (*0.8*, *1.8*)	0.75 (*0.6*, *1.1*)	0.67 (*0.5*, *0.8*)
Public Works Department	2.74 (*1.6*, *4.4*)	1.19 (*0.8*, *1.9*)	0.76 (*0.6*, *1.1*)	0.67 (*0.5*, *0.9*)
Child	8.87 (*5.7*, *13.3*)	4.41 (*3.3*, *6.5*)	3.10 (*2.4*, *4.2*)	2.79 (*2.1*, *3.5*)

Assuming 20 years of volcanic activity. Variable personal exposure. Each cell contains median value (5th percentile, 95th percentile, given in italics).

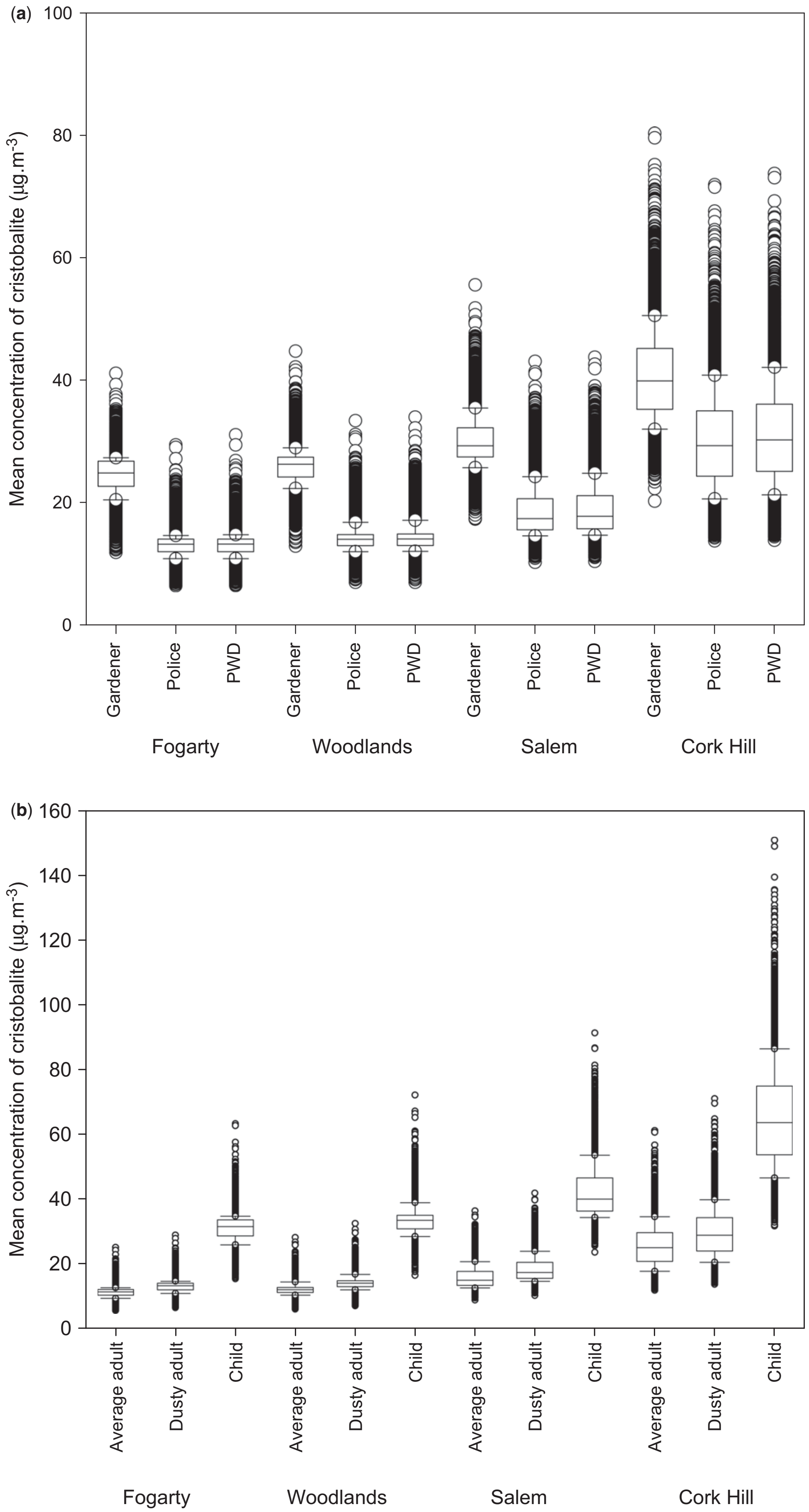

Fig. 22.11. (a) & (b) Box-and-whisker plots of exposure estimates to ash based on eruption (ash fallout) modelling from the last 8 years of volcanic activity and collected survey data (see text) in Fogarty, Woodlands, Salem and Cork Hill for (**a**) gardeners, police and the Public Works Department; (**b**) average adults, 'dusty' adults and children.

inhabited areas to a more significant degree than previously due to the unusual northerly-directed winds. From mid-March, the volcano was seen to be frequently venting steam and light amounts of fine ash, which formed thin and frequent deposits on the ground and might have added to the irritancy of the plume where it polluted at ground level.

The extent to which the general population was troubled by the plume is not known, but there was no clinically discernible increase in the numbers of patients attending clinics or the hospital for asthma, and no increase in the severity of asthma attacks. Inhalers are supplied by the island's central pharmacy at the hospital and sold at a private chemist, but the demand from patients had remained static.

The supposition at the MVO is that the gas output increased in line with the rise in the rate of growth of the lava dome from February 2006 onwards, with a disproportionate rise in hydrogen chloride emission. Hydrogen chloride, which dissolves readily in clouds and precipitation, is the main cause of acid rain around volcanoes. A modest increase in acid rainfall in inhabited areas was observed, whilst a much greater impact has occurred in the main direction of the prevailing winds to the areas west of the volcano, namely St George's Hill, Richmond Hill and Fox's Bay.

On 20 May 2006, the lava dome volume was of the order of $90 \times 10^6 \times m^3$ and most of its collapse was over a period of less than 3 h, but the most intense phase lasted only 30–40 min. Activity, which had commenced 2 h before, began to wane after 08:15, and a high-amplitude seismic signal remained until 09:00. It was during this time that people in the Lower Belham area began to be exposed to volcanic gases in sufficient concentrations to frighten people and provoke mild asthma attacks in susceptible individuals. One 13 year-old child in Hope, with a history of mild, untreated asthma, and a worker at the Vue Pointe Hotel, both developed an attack of asthma that lasted about 15–20 min., at about the time the gas was present in the ambient air. Both individuals rested indoors until the attacks passed off and they did not seek hospital or clinic treatment. Others reported a pungent or burning smell affecting their noses and throats, akin to catching breath in a cloud of chemicals or strong acid vapour, and some became very frightened. Difficulty in breathing and a sulphur or acid smell, or a smell like swimming-pool chlorine chemicals, were all reported by others. A diving instructor made his wife, who was pregnant, breath through a mask connected to a compressed air diving tank; their house was open to the outside. He and another person in the house got relief by breathing through ash masks. In another house, a person reported having to breath through a damp cloth as protection. No systematic survey was carried out, but these adverse effects of gases had not been recorded before on Montserrat.

The symptoms were compatible with brief exposure to about 1–2 ppm sulphur dioxide, enough to trigger bronchospasm (asthma attack) in the two subjects with asthma (asthma sufferers are more susceptible to this gas than normal people) and to cause the frightening feeling of tightness in the chest in the other people. Exposure to other acid gases such as hydrogen chloride would have also contributed to the overall impact of the plume on respiratory symptoms.

Ashfall to the north of the Belham Valley was narrowly averted by the wind direction. The main axis of the ash plume was towards Garibaldi Hill. About 5 cm deposit of ash was found here, but at St George's Hill it was 23.5 and 17 cm at Cork Hill. At Lee's Estate the deposit was 31.5 cm. The populated areas, surprisingly, remained unaffected. A flock of 65 sheep were being kept at Lee's Yard near the bottom of Gage's Mountain at the foot of the volcano and the farmer got to them next day. Forty animals died by being buried under up to 60 cm of ash and 15 were dug out alive. Five of these had blue appearances to the front of the eyes instead of the normal brown, and copious ash had to be removed from their eyes as they were rescued. Most of the dead sheep had been in a pen and so had little space to manoeuvre during the ashfall. Ash continued to fall on and off until 23 May, forming thin layers on top of the main deposit.

The appearances of the eyes of two surviving goats were considered compatible with resolving corneal damage due to mechanical or acid injury to the front of the eye (the blue discoloration of the front of the eyes, as reported when the sheep were rescued, is corneal oedema; the residual, diffuse corneal opacity is due to injury to the deeper layers of the cornea).

The partial mixing of the plume at ground level is to be expected in unusual atmospheric conditions, but the adverse effects of the plume on people on 20 May is a new hazard that needs to be considered in future dome collapses. The episode shows how readily gases can infiltrate the houses on Montserrat, even when all the windows and other openings had been closed to prevent the ingress of ash when the people realized that another major eruptive event was occurring. The need for housing and schools in the Salem–Old Towne area to be adapted to make the windows and other openings much more resistant to their penetration by fine ash (to reduce the silicosis risk: e.g. Hincks *et al.* 2006) becomes all the more necessary to reduce the infiltration of gases as well. At least a single room in each house could be adapted so that all the occupants could stay there until an eruptive event dies down and the ashfall stops. Since this unusual event, no new problems with gases have been reported.

Second study of the respiratory health of children, September 2007

The impetus grew after the risk assessment was over for another study of school children to update the conclusions of the first study in 1998. It was hoped this would confirm that the impact of the heavy ashfalls in 2001 and 2003 had been minimal in terms of persistent respiratory effects, but the need for reassurance on the health of children became more compelling after the gas events of 2006 and the impacts on vegetation, indicating that hydrogen chloride output had increased and could even have been blown with other gases northwards where families lived and on a scale that had not knowingly occurred before.

As in 1998, the purpose of the study was to determine whether those schoolchildren who had ever been exposed to moderate and high levels of volcanic ash during their lives had more respiratory disease than those who had not. The methodology was also along the same lines. Parents of children under the age of 12 years completed questionnaires asking about symptoms, and children over the age of 12 completed questionnaires themselves in the classroom. Children aged between 8 and 12 years were tested for allergy to common allergens (house dust mites, grasses and animals), lung function and for their response to exercise.

The results suggested that about 10% of children had symptoms suggestive of asthma and that there was a high rate of allergy to common allergens.

About half of the children were born overseas. This group of children was, therefore, different from the one surveyed in 1998, in that half belonged to families who had migrated to Montserrat from other islands since the exodus of Montserratians in 1997.

There was no evidence that children who had ever been or who were currently living in areas of moderate/high exposure to ash had more symptoms of asthma, allergies or worse lung function than those who had never lived in such areas (as defined by isopach maps of cumulative ashfall).

The results were reassuring, but could not be interpreted that the volcanic ash poses no health risk – it was some time since the children had been exposed to ashfall, in contrast to children in the study in 1998: the findings then suggested that there were acute effects of ash on the lungs. Overall, the prevalence of symptoms suggestive of asthma is similar to or even lower than when the study was conducted in 1998, but an increase in the prevalence of exercise-induced bronchoconstriction was noted and it could be due to an increase in asthma-like conditions on the island. As in 1998, a relatively low proportion of children with asthma reported that they received conventional regular medication.

Thirty-seven children were identified who had received the highest exposures by having lived or moved around for 3 years or more in heavily ash-impacted areas (e.g. Salem, Friths, Olveston, Cork Hill) and were given chest X-rays. All chest X-rays were normal and showed no evidence of silicosis.

The results of this study were reviewed by the CMO's Montserrat Advisory Group and the reassuring conclusions were communicated in an official visit to the island on March 2008. The risk assessment in 2003, which was published in 2006, had provided an important context in which the children's study was undertaken – and it reinforced the view that the ash was of low risk to health provided that the precautions adopted over the years on the island to minimize exposure to ash were maintained for as long as the eruption continued.

Eruption phase 4: 29 July 2008–3 January 2009

This short period of dome growth was marked by a high degree of explosivity and some pyroclastic flow production, but no substantial ashfall in the populated areas. In December 2008, a pyroclastic flow from an explosion nearly overtopped the SE flank of St George's Hill.

Eruption phase 5: 9 October 2009–11 February 2010

Activity picked up again with moderate ashfalls from pyroclastic flows beginning in October 2009. On 8 January 2010, a Vulcanian explosion sent a plume to about 8 km altitude and produced pyroclastic flows in several valleys, including one that entered the Belham Valley with a runout of 6 km, further than the previous longest flows of 8 January 2007. Phase 5 ended with a massive dome collapse on 11 February, the largest to occur on the northern flank. High-energy surges destroyed much of the abandoned villages of Harris and Streatham. The ash plume reached an altitude of 15 km, but dispersed away from Montserrat towards Guadeloupe, Dominica and St Lucia.

This phase was characterized by an unexpected sharp fall in the cristobalite concentration of the ash deposits generated by pyroclastic flow activity. Instead of the consistently raised levels found on analysis of ash samples conducted throughout the eruption, bulk ash samples from this phase contained only 4–7 wt%. In the context of the 2003 risk assessment, such values would not be regarded as presenting much of a hazard to health, but they are in the same range as the free crystalline silica content of the ash at MSH.

Discussion

The settings of the eruptions of MSH and SHV could not have been more different – the vast spaces of the American Pacific NW and an island only 17 km long and 10 km wide. In the one, over a million people were affected by a single large ashfall, with a decline in exposure to the ash over months; in the other, a few thousand, who were to face repeated ashfalls and high exposures to respirable-sized particles containing much higher levels of free crystalline silica in an eruption lasting over 15 years and beyond. The two eruptions were without scientific precedent in recent times, and triggered a large and urgent response to evaluate the health hazards they both presented.

In both eruptions it took at least 5 years of research before scientific opinion became increasingly confident over the lower risk of the ash to respiratory health than was at first envisaged. The very high levels of TSP measured by air monitors in the first few days after 18 May in the semi-arid conditions in Central Washington State recalled the very high black smoke levels of the London smog in December 1952 (see earlier in this chapter) when there were at least 4000 extra deaths (Anderson 1999). So on this basis alone, there were fears that severe health problems might arise in vulnerable persons, such as children, the chronic sick with cardio-respiratory disorders and the elderly. Once this concern was seen to be unfounded (and rapidly confirmed by the hospital surveillance studies conducted by CDC: Baxter *et al.* 1981), attention immediately switched to the free crystalline silica content of the respirable fraction of the ash, and its implication for the health of children and groups of the most exposed adults.

It is fully understandable that clinicians with experience of conditions such as silicosis will express alarm over the potential risk of this disease developing in a general population living 24 h/day under such high exposures when stringent precautions are taken, and demanded by regulators, in industry to protect workers against fine, silica-bearing dusts and the potentially fatal consequences of inhaling them over a long-term basis. Indeed, the relaxing of health concerns after an eruption should only follow the evidence from expert analysis of the ash composition, exposure studies of workers and people living in the ashfall areas, clinical and toxicological investigations, and epidemiological surveys. On Montserrat, the finding of rapidly increasing exposures to ash in the 1996 and 1997 field surveys as the activity of SHV increased led to the anxious warnings of the first risk assessment in 1997, even though it was not clear how long the eruption would last. In retrospect, the precautionary approach taken was fully justified as the eruption has lasted well beyond any expectations at that time, and the cumulative exposure over 15 years would have been sufficient to have led to early cases of silicosis if those initial concerns over the silica in the ash had also turned out to be supported by further research. By 2003, the risk assessment had down-graded the silicosis risk in the light of the toxicological studies showing that the toxicity of the silica was most probably being masked to at least some extent by other minerals in the ash matrix. A similar view had been given by toxicologists on the MSH ash, where significant exposure had, in any case, been for probably less than 2–3 years (Martin *et al.* 1986).

Uncertainty will remain in the absence of comprehensive epidemiological studies, both in the immediate post-eruption period and over years of follow-up of large exposed populations. In many locations, the conditions surrounding the disaster or the local infrastructure of the region may make such studies either too difficult or too costly to undertake. In theory, the long eruption on Montserrat should become a valuable source of information on the health effects of volcanic ash. However, the small population involved and the disruption to the island, with most of the population being forced to leave by the volcanic activity, does not lend itself to establishing short- or long-term epidemiological studies, which could provide, for example, confirmation of the low risk to the general population of developing silicosis according to the risk assessment. The findings of toxicological studies on which the risk assessment was partly based may also have questionable or limited applicability to the actual exposures and susceptibility to respiratory diseases in humans.

There is no doubt that the very high particle levels achieved in eruptions in explosive volcanoes will continue to cause widespread alarm in populations wherever they occur, and reassurance based on rigorous enquiries and investigation will be needed in these relatively rare events. Today, clinical investigators would be as much interested in the effects on the cardio-respiratory system of the ash particles per se, as the free crystalline silica content and the risk of silicosis. There has been a notable shift in the understanding of the health effects of particles in the last 15 years that would now be applicable to volcanic crises. The continuous, open-vent eruption of the Eyjafjallajökull Volcano in Iceland in 2010 covered a swathe of farmland in southern Iceland with ash on a regular basis for 6 weeks: the ash did not contain free crystalline silica, but was as fine as the ash at MSH and SHV. This is a newly appreciated form of eruption, although examples in the past have included the 2 year eruption of Irazu, Costa Rica, 1983–1985, which resulted in almost daily fallout of fine ash in

San José, the country's capital. Indeed, the high levels of ash particles in ambient air in the form of PM_{10} and $PM_{2.5}$ may resemble particles in the air pollution in our towns and cities, and have short- and long-term effects on cardio-respiratory health that have nothing to do with silica (WHO 2006), but the risks are too small to easily detect in epidemiological studies in the small population on Montserrat. It is likely, however, that volcanic ash and other natural mineral particles are less toxic than the particles found in urban air, but there is presently uncertainty over this issue too.

The following limitations of doing epidemiological studies include:

- Massive and variable outwards migration – leading to a particular subgroup staying who may be particularly vulnerable for a variety of reasons, and also a loss to follow-up of some of those who have moved being those most likely to have suffered acute symptoms, such as exacerbation of asthma.
- Conducting surveys on anxious populations (objective measures of health needed and not just relying on self-reported questionnaire information), in conditions with anxious officials (independence essential), and without strong local infrastructure in terms of expertise and facilities. A considerable commitment may be required from 'brought in' expertise, optimal training of local experts to provide ongoing surveillance and the need for the authorities to be committed to supporting and funding such studies.
- Modelling of exposure is essential and requires field surveys and modelling work (as undertaken at SHV).
- Long-term follow-up – major commitment is required and is fraught with difficulties, such as cost and feasibility, but with increasing access to mobile communications it may not be impossible in the future.

These difficulties lay behind the decisions on the types of epidemiological studies that were undertaken at MSH and SHV. In future eruptions on this scale, early commitment for undertaking epidemiological studies should be sought wherever possible, and recent advances in epidemiological methods adopted to provide information on acute and long-term health effects in adults and children.

Unstinting support for this work was forthcoming from successive representatives of the UK and Montserrat governments following the onset of the eruption, as well as from the Montserrat people. Funding was provided through the Department for International Development in London. We thank the many scientists who worked at the MVO over the years for their technical support and advice as the volcanic activity waxed and waned, including the notable contributions of S. Sparks and S. Young. We acknowledge the invaluable collaboration of colleagues on the CMO's Montserrat Advisory Group, particularly the constancy of expert advice from A. Seaton and R. Maynard over the entire period of this study. It is also a pleasure to thank W. Aspinall who was an unfailing source of sound advice on SHV's activity and who also carefully reviewed an early draft of this chapter. R. Maynard made valuable suggestions on a previous draft. C. Buffong's island chronicle 'Volcano! 1995–96' informed our description of the first months of activity at SHV.

Appendix

Unpublished reports to government in chronological order

(See also the References for reports cited in the text.)

Baxter, P. J. *Medical Aspects of the Activity of the Soufrière Hills Volcano: Report on a Visit to Montserrat*. 23 November–2 December 1995.

Baxter, P. J. & Nicholl, A. *Montserrat Volcanic Crisis: Preliminary Results of Air Sampling of Volcanic Ash*. 21–28 September, 1996.

Baxter, P. J. *Report on the Medical Aspects of the Activity at the Soufrière Hills Volcano: Visit to Montserrat*. 21 September–1 October 1996.

Baxter, P. J. & Seaton, A. *A Health Risk Assessment of Exposure to Ash Emissions from the Soufrière Hills Volcano, Montserrat*. 1997.

Searl, A. S. & Nicholl, A. *Assessment of the Exposure of the Population of Montserrat to the Volcanic ash Containing Cristobalite*. Report **P752**. Institute of Occupational Medicine, Edinburgh. September 1997.

Duffle, H. *Air Quality Monitoring Programme*. Montserrat Volcano Observatory, Flemmings, Montserrat. 3 January–6 March 1998.

Searl, A S. *Air Quality Monitoring on Montserrat*. Report 752-400. Institute of Occupational Medicine, Edinburgh. March–August 1998.

Baxter, P. J. & Maynard, R. L. *Health Criteria for Reoccupation of Ashfall Areas in Montserrat*. Report to the Department for International Development, London. 3 October 1998.

Baxter, P. J. & Maynard, R. L. *Montserrat: Provisional Report on Conditions in Salem, Frith and Old Towne*. 29 September 1998.

Cullen, R. T. & Searl, A. 1998. *Preliminary Toxicological Hazard Assessment of Montserrat Volcanic Ash:* in Vitro *Cytotoxicity*. Report **P752/200**. Institute of Occupational Medicine, Edinburgh.

Horwell, C. *Montserrat Dust Monitoring Programme (8.5.99–9.7.99)*. Montserrat Volcano Observatory, Flemmings, Montserrat,

Baxter, P. J. *Health Hazards of Volcanic Ash South of the Belham Valley, Montserrat*. First Report. 7 May–9 July 1999.

Baxter, P. J. *Health Hazards of Volcanic ash South of the Belham Valley: Volcanic Impact Assessment*. Second Report. 7 May–9 July 1999.

Baxter, P. J. *Report on a Visit to Montserrat to Reassess the Health Impacts of the Volcanic Activity*. 31 March–6 April 2000.

Baxter, P. J. *Air Monitoring Programme at the Soufrière Hills Volcano, Montserrat. Health Impact Assessment Following the Dome Collapse on 29 July 2001*.

Cowie, H. A., Graham, M. K. *et al.* 2002. *A Health Survey of Workers on the Island of Montserrat*. IOM TM/02/02. Institute of Occupational Medicine, Edinburgh.

Baxter, P. J. & Searl, A. S. *Preliminary Report on a Health Impact Assessment of the 12 July 2003 Ash Fall-out in Montserrat*. 25–29 August, 2003.

Baxter, P. J. & Searl, A. *Final Report on a Health Impact Assessment of the 12 July 2003 Ash Fall-out in Montserrat*. 25–29 August, 2003.

Searl, A. S. & Nicholl, A. *Report on Trials to Aid the Prevention of Exposure to Airborne Dust During Operation Clean-Up. Montserrat, 1998*. Institute of Occupational Medicine, Edinburgh. 2003.

Cowie, H. A., Hutchison, P. A., Graham, M. K., Cattermole, T. J., Dempsey, S. & Russell, M. *Study of Workers on the Island of Montserrat. Follow up to Survey in 2000*. IOM Report TM/06/02. Institute of Occupational Medicine, Edinburgh. March 2006.

Baxter, P. J. *Soufrière Hills Volcano, Montserrat: Human and Animal Impacts of the Catastrophic Dome Collapse on 20 May 2006*. July 2006.

Jarvis, D., Baxter, P., Hooper, R., Bakolis, I., Cullinan, P. & Hansell, A. *Study of Respiratory Health in Children on Montserrat*. 5 February 2008.

References

ADVISORY GROUP ON THE MEDICAL ASPECTS OF AIR POLLUTION EPISODES 1992. *Sulphur Dioxide, Acid Aerosols, and Particulates*. Second Report. Department of Health, HMSO, London.

Allen, A. G., Baxter, P. J. & Ottley, C. J. 2000. Gas and particle emissions from Soufrière Hills volcano, Montserrat, West Indies: characterization and health hazard assessment. *Bulletin of Volcanology*, **62**, 8–19.

Anderson, H. R. 1999. Health effects of air pollution episodes. *In*: Holgate, S. T., Samet, J. M., Koren, H. S. & Maynard, R. L. (eds) *Air Pollution and Health*. Academic Press, London, 461–482.

Baxter, P. J., Ing, R. *et al.* 1981. Mount St Helens eruptions, May 18 to June 12 1980: an overview of the health hazard. *JAMA*, **246**, 2585–2589.

Baxter, P. J., Ing, R., Falk, H. & Plikaytis, B. 1983. Mount St. Helens eruptions: the acute respiratory effects of volcanic ash in a North American community. *Archives of Environmental Health*, **38**, 138–143.

Baxter, P. J., Bonadonna, C. *et al.* 1999. Cristobalite in volcanic ash of the Soufrière Hills Volcano, Montserrat, British West Indies. *Science*, **283**, 1142–1145.

Baxter, P. J., Aw, T. C., Cockroft, A., Durrington, P. & Harrington, J. M. (eds) 2010. *Hunter's Diseases of Occupations*, 10th edn. Hodder Arnold, London.

Bonadonna, C., Macedonio, G. & Sparks, R. S. J. 2002*a*. Numerical modelling of tephra fallout associated with dome collapses and

Vulcanian explosions: application to hazard assessment in Montserrat. *In*: Druitt, T. H. & Kokelaar, B. P. (eds) *The Eruption of the Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 517–537.

Bonadonna, C., Mayberry, G. C. *et al.* 2002*b*. Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. *In*: Druitt, T. H. & Kokelaar, B. P. (eds) *The Eruption of the Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 483–516.

Buchanan, D., Miller, B. G. & Soutar, C. A. 2003. Quantitative relations between exposure to respirable quartz and risk of silicosis. *Journal of Occupational and Environmental Medicine*, **60**, 159–164.

Buist, A. S. & Bernstein, R. S. (eds) 1986. Health effects of volcanoes: an approach to evaluating the health effects of an environmental hazard. *American Journal of Public Health*, **76**, 1–90.

Buist, A. S., Bernstein, R. S., Johnson, L. R. & Vollmer, W. M. 1986. Evaluation of physical effects due to volcanic hazards: human studies. *In*: Buist, A. S. & Bernstein, R. S. (eds) *Health Effects of Volcanoes: An Approach to Evaluating the Health Effects of An Environmental Hazard. American Journal of Public Health*, **76**, 66–75.

Cullen, R. T. & Searl, A. 1998. *Preliminary Toxicological Hazard Assessment of Montserrat Volcanic Ash: in Vitro Cytotoxicity*. P752/200. Institute of Occupational Medicine, Edinburgh.

Cullen, R. T., Jones, A. D., Miller, B. G., Donaldson, K., Davis, J. M. G., Wilson, M. & Tran, C. L. 2002. *Toxicity of Volcanic Ash from Montserrat*. IOM TM/02/01. Institute of Occupational Medicine, Edinburgh.

Dollberg, D. D., Bolyard, M. L. & Smith, D. L. 1986. Evaluation of physical health effects due to volcanic hazards: crystalline silica in Mount St. Helens volcanic ash. *In*: Buist, A. S. & Bernstein, R. S. (eds) *Health Effects of Volcanoes: An Approach to Evaluating the Health Effects of An Environmental Hazard. American Journal of Public Health*, **76**, 53–58.

EPAQS 1995. *Particles*. Expert Panel on Air Quality Standards. Department of the Environment, HMSO, London.

Forbes, L., Jarvis, D., Potts, J. & Baxter, P. J. 2003. Volcanic ash and respiratory symptoms in children on the island of Montserrat, British West Indies. *Occupational and Environmental Medicine*, **60**, 207–211.

HSE 2002. *Respirable Crystalline Silica – Phase 1. Variability in Fibrogenic Potency and Exposure–Response Relationships for Silicosis*. EH75/4. Health and Safety Executive, Sudbury.

Hincks, T. K., Aspinall, W. P., Baxter, P. J., Searl, A., Sparks, R. S. J. & Woo, G. 2006. Long term exposure to respirable volcanic ash on Montserrat: a time series simulation. *Bulletin of Volcanology*, **68**, 166–284.

Hnizdo, E. & Sluis-Cremer, G. K. 1993. Risk of silicosis in a cohort of white South African gold miners. *American Journal of Industrial Medicine*, **24**, 447–457.

Horwell, C. J. & Baxter, P. J. 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology*, **69**, 1–24.

Horwell, C. J., Sparks, R. S. J., Brewer, T. S., Llewellin, E. W. & Williamson, B. J. 2003. The characterisation of respirable volcanic ash from the Soufrière Hills Volcano, Montserrat, with implications for health hazard. *Bulletin of Volcanology*, **65**, 346–362.

Housley, D. G., Berube, K. A., Jones, T. P., Anderson, S., Pooley, F. D. & Richards, R. J. 2002. Pulmonary epithelial response in the rat lung to instilled Montserrat respirable dusts and their major mineral components. *Occupational and Environmental Medicine*, **59**, 466–472.

Hughes, J. M., Weill, H. *et al.* 1998. Radiographic evidence of silicosis risk in the diatomaceous earth industry. *Americal Journal of Respiratory and Critical Care Medicine*, **158**, 807–814.

Lee, S. H. & Richards, R. J. 2004. Montserrat volcanic ash induces lymph node granuloma and delayed lung inflammation. *Toxicology*, **195**, 155–165.

Leung, C. C., Yu, I. T. S. & Chen, W. 2012. Silicosis. *Lancet*, **379**, 2008–2018.

Martin, T. R., Wehner, A. P. & Butler, J. 1986. Evaluation of physical health effects due to volcanic hazards: the use of experimental systems to estimate the pulmonary toxicity of volcanic ash. *In*: Buist, A. S. & Bernstein, R. S. (eds) *Health Effects of Volcanoes: An Approach to Evaluating the Health Effects of An Environmental Hazard. American Journal of Public Health*, **76**, 59–65.

Muir, D. F. C., Julian, J. A., Shannon, H. S., Verma, D. K., Sebestyen, A. & Berholtz, C. D. 1989. Silica exposure and silicosis among Ontario hardrock miners: III. Analysis and risk estimates. *American Journal of Industrial Medicine*, **16**, 29–43.

Newhall, C. J. & Fruchter, J. S. 1986. Volcanic activity: a review for health professionals. *In*: Buist, A. S. & Bernstein, R. S. (eds) *Health Effects of Volcanoes: An Approach to Evaluating the Health Effects of An Environmental Hazard. American Journal of Public Health*, **76**, 10–24.

NIOSH 2002. *Hazard Review. Health Effects of Exposure to Respirable Crystalline Silica*. Department of Health and Human Services, National Institute of Occupational Safety and Health, Cincinnati, OH.

Olsen, K. B. & Fruchter, J. S. 1986. Identification of the physical and chemical characteristics of volcanic hazards. *In*: Buist, A. S. & Bernstein, R. S. (eds) *Health Effects of Volcanoes: An Approach to Evaluating the Health Effects of An Environmental Hazard. American Journal of Public Health*, **76**, 45–52.

Rafnsson, V., Ingimarsson, O., Hjalmarsson, I. & Gunnarsdottir, H. 1998. Association between exposure to crystalline silica and sarcoidosis. *Occupational and Environmental Medicine*, **55**, 657–660.

Searl, A., Nicholl, A. & Baxter, P. J. 2002. Assessment of the exposure of islanders to ash from the Soufrière Hills volcano, Montserrat, West Indies. *Occupational and Environmental Medicine*, **59**, 523–531.

Vallyathan, V., Robinson, V., Reasor, M., Stettler, L. & Bernstein, R. 1984. Comparative in vitro cytotoxicity of volcanic ashes from Mount St Helens, El Chichon, and Galanggung. *Toxicology and Environmental Health*, **14**, 641–654.

Wadge, G., Voight, B., Sparks, R. S. J., Cole, P. D., Loughlin, S. C. & Robertson, R. E. A. 2014. An overview of the eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. *In*: Wadge, G., Robertson, R. E. A. & Voight, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010*. Geological Society, London, Memoirs, **39**, 1–39, http://dx.doi.org/10.1144/M39.1

Wilson, M. R., Stone, V., Cullen, R. T., Searl, A., Maynard, R. L. & Donaldson, K. 2000. In vitro toxicology of respirable Montserrat volcanic ash. *Occupational and Environmental Medicine*, **57**, 727–733.

WHO 2006. *Air Quality Guidelines: Global Update 2005*. World Health Organization (Europe), Copenhagen.