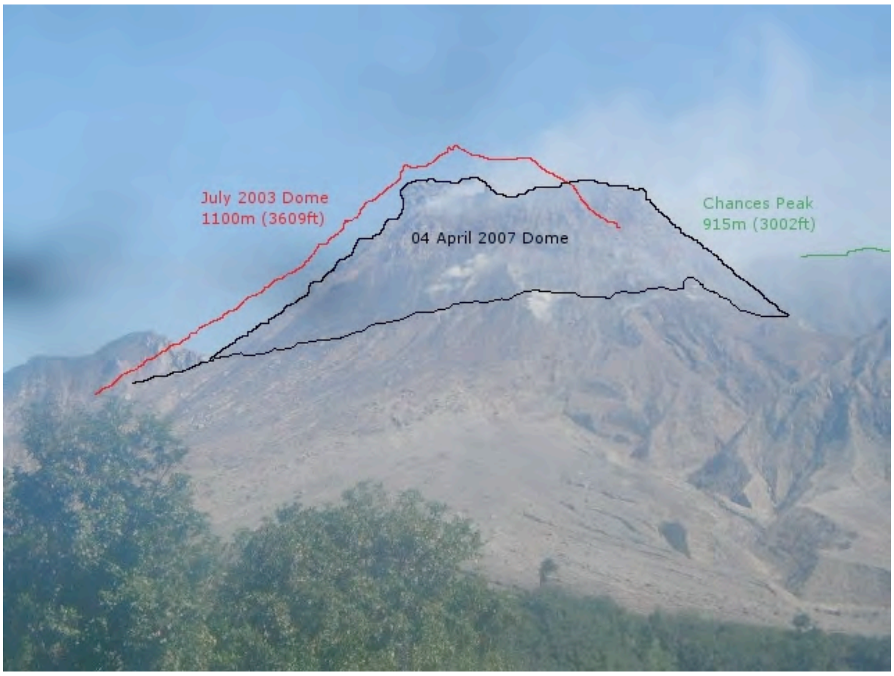
ASSESSMENT OF THE HAZARDS AND RISKS ASSOCIATED WITH THE SOUFRIERE HILLS VOLCANO, MONTSERRAT

Ninth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 1 and 3 October 2007 at the Montserrat Volcano Observatory, Montserrat

Part I: Main Report



Issued on 26 October 2007

Summary

(i) Lava extrusion and dome growth ceased in early April 2007, ending an episode of eighteen months of extrusion at a high average rate. The dome that remains has a height of about 1050 metres above sea level, a volume of about 203 million cubic metres and is situated about 100 metres further to the northwest relative to the dome of mid-2003. There are two main lobes to the dome: one to the east and one to the southwest that just overtops the crater rim next to Galway's Wall and a separate mass to the northwest that spills over into Gage's Valley and Tyre's Ghaut. Since April there have been rockfalls, small pyroclastic flows and lahars, though the first two have been much reduced in frequency.

(ii) The lack of lava extrusion over the past six months indicates that the volcano has entered a paused state, possibly similar in many ways to those of 1998-99 and 2003-05. We have assessed whether this presumed paused state might instead represent the end of the eruption. By this we mean that the eruption will probably end when basalt magma no longer enters the volcanic system at depth to power the extrusion of andesite lava. Using MVO's measurements of sulphur dioxide, surface deformation and long-period earthquake swarms we have tested three criteria that we set up during the 2003-2005 pause in order to make this assessment. We have a high degree of confidence that these measurements currently show that the volcano has not stopped being active, and is in a state of pause in terms of eruption at the surface. Our current estimate is that this pause may continue for many more months, possible 15 months or more.

(iii) Even though no new lava is emerging from the volcano, a large mass of still hot lava sits at a high level above the crater rim. In particular, the northwestern lobe of lava, which was emplaced over two weeks at the beginning of 2007 at very high rates, has sufficient mass, residual heat and gaseous content to produce energetic large pyroclastic flows that could reach the sea to the west or northwest, following a large enough collapse in those directions. The probability of this happening is reduced by the cessation of extrusion and gas loss from the dome rocks. Much more probable (about 40%) is that the next major event over the coming year will be another major collapse of the dome to the east down the Tar River Valley. Almost as likely as that is that there will be no major collapse or renewal of extrusion in the next year.

(iv) Using the same assessment areas north of the Belham Valley as we used in the July 2007 analysis, and taking the new southern boundary to the Exclusion Zone into account (see Fig.1 below), we have estimated the annual risk of death to individuals. For a person living full-time in Area 1, extended to the new boundary, the risk is 1-in-1,700 (3.1 times the background risk of accidental death in the north of Montserrat). In Area 2, immediately to the north as far as Nantes River, the risk is 1-in-21,000 (1.2 times the background risk). Between Nantes River and Lawyers River (Area 3) the risk is 1-in-6 million (1.001 times the background risk). These individual risk levels are much lower than six months ago and slightly lower than our assessment in July 2007. However, because more people have moved back into Area 1, the societal risk of a few people being killed by the volcano has actually increased since July.

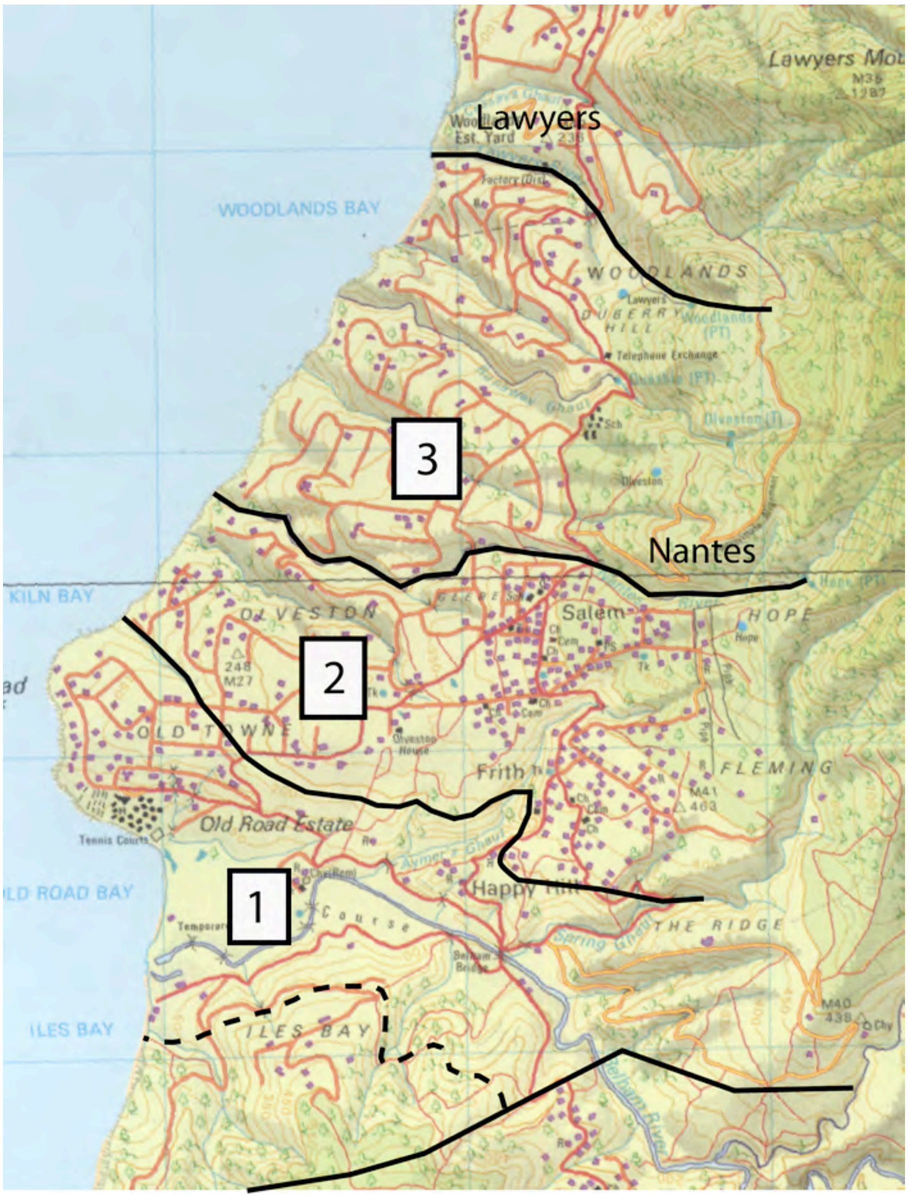


Fig.1 Map showing revised population Areas [1], [2], and [3] following the re-occupation of Iles Bay Hill. The dashed line is the southern boundary of the 20 million cubic metres normal dome collapse pyroclastic flow surge, the northern boundary of which is the the solid line between Areas 1 and 2.

Contents

Introduction

1. The ninth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity took place at the Montserrat Volcano Observatory (MVO) from 1 to 3 October 2007. This report is the main product of that meeting. The Committee was commissioned by the Foreign and Commonwealth Office and operates under the Code of Practice for Scientific Advisory Committees issued by the Office of Science and Technology. The Terms of Reference for the Committee are presented in Appendix 1, and the agenda of the meeting is given in Appendix 2.

2. The meeting was attended by: Professor G. Wadge (SAC Chairman), Dr. W.P. Aspinall (SAC), Ms. V. Bass (MVO), Mr. T. Christopher (MVO), Dr. S. De Angelis (MVO), Dr. V. Hards (MVO), Professor J. Neuberg (SAC), Dr. G. Ryan (MVO), Dr. R.E.A. Robertson (SAC), Mr. T. Syers (MVO) and Professor B. Voight (SAC). Dr K. Rowley (Minister of Housing, Trinidad and Tobago, and former member of the SAC) was present for part of the second and third days. Professor K. Cashman (SAC) was unable to attend but participated remotely in the elicitations. Appendix 3 gives a list of participants and their affiliations.

3. Just after our previous meeting in March 2007 the volcano stopped emitting lava and the resultant lower level of activity coloured this meeting. We have begun to re-consider the criteria for whether the volcano has stopped erupting. The end of the current (2003-2008) management contract for MVO is in sight. This issue and the long-term future of monitoring of the volcano were also matters of considerable debate.

4. There are two parts to this report: Part I contains the main findings and Part II contains the technical aspects of the assessment. Appendix 5 has a glossary of technical terms. In June 2007, after it had become clear that the volcano had entered another "pause", the SAC was asked by the Emergency Policy Group (EPG) to re-assess the volcanic risks. The findings of that study were delivered to government in July 2007 (Appendix 6). A Preliminary Statement from the full SAC meeting was issued on 3 October 2007 (Appendix 4). A two-hour public meeting was held that evening at the Insurance Building in Brades to explain the preliminary findings to the public. That meeting was chaired by Cpt. Horatio Tuitt (Director, DMCA), and the Chief Minister, Dr Lowell Lewis was in the audience. An interview with Wadge that discussed some of the preliminary findings of the risk assessment meeting was broadcast on ZJB Radio that day.

Recent Volcanic Activity

5. During the second half of March 2007 the rate of lava extrusion fell and since 4 April 2007 no new lava appears to have been emitted. Thus we are now six months into the third major pause in lava extrusion since the eruption began. The previous two pauses were from March 1998 to November 1999 (20 months) and from August 2003 to August 2005 (24 months).

6. Although no new lava has been added to the summit there has been some surface activity. This has included rockfalls, pyroclastic flows with runout distances of up to 2-3 kilometres in the Tar River Valley (e.g. 23 August) and a few hundred metres on Farrell's plain and Tyre's Ghaut. There have also been mudflows (lahars) in the Belham Valley.

The original pyroclastic flow deposits from the 8 January 2007 event in the Belham Valley reached to Cork Hill. Subsequent re-mobilisation of these deposits as mudflows has eroded and extended them as far as the sea. A moat between the debris surrounding the dome and the northeastern crater rim has been re-excavated and is being used to channel small pyroclastic flows into the Tar River Valley, for example on 30 July. It is now clear that prior to the cessation of growth, the dome had begun to overtop the Galway's Wall at its westernmost end, but had not succeeded further southeast where a clear moat still exists.

7. Areas of steaming ground in the debris to the northwest and southeast of the dome mark long-lived areas of activity that keep re-asserting themselves. The Gage's Wall vent that formed in early September 2006 is still evident despite burial. It is the source of considerable magmatic gas with high radiant temperatures, and is presumably connected in some direct way to the conduit. During heavy rain, erosion of recent, hot ash deposits in the uppermost part of Tyre's Ghaut and upper Belham River has generated large quantities of steam, and elsewhere on the dome heavy rain triggers roaring noises, presumably as rainwater is flashed to steam.

Monitoring Results

8. A repeat lidar survey from the Perche's Mountain observation site in June 2007 quantified the dimensions of the roughly tri-lobate character of the dome's summit, with distinct eastern and southwestern lobes and a less obvious mass to the northwest above Tyre's Ghaut. Using this new data to re-calculate the volume of this northwestern mass, potentially capable of collapsing into Tyre's Ghaut, gives values of up to 20-30 million cubic metres; in the same range as that used in the previous analyses of the pyroclastic flow hazard.

9. There have been very few earthquakes during the last six months. At the time of the end of lava extrusion in early April 2007 there was a swarm of volcano-tectonic earthquakes and another brief swarm on 1 September, both located beneath the dome itself at a depth of about four kilometres.

10. It is now clear that there was a distinct change in the pattern of surface deformation measured by the GPS network, and the EDM network, around April 2007. The lines that had been shortening since the end of 2005 began to lengthen. This is interpreted as a being caused by a resumption of inflation of the magma reservoir as has happened at the end of previous episodes of lava extrusion. The abruptness of the change is notable.

11. Following the cessation of lava extrusion, MVO has measured a reduction of the ratio of hydrogen chloride to sulphur dioxide gases emitted by the volcano to values of about 0.4, from about 4 during extrusion. This pattern fits previous behaviour that we have interpreted as the loss of the continuous flux of andesite magma through the conduit. The daily emission rates of sulphur dioxide have been generally lower (~300 tonnes per day) than the long-term average (~550 tonnes per day), again, what we would expect when there is still a large lava dome present that has reduced gas permeability. There was a pulse of increased output of sulphur dioxide just after the volcano-tectonic earthquakes at the beginning of April, as noted in paragraph 9, suggesting a fracturing event in the conduit.

Probable Future Behaviour

12. The last six months have shown that the volcano is in a state of pause. As we did during the last pause in 2003-2005, we have posed the question of whether this is a temporary state or whether it represents the end of the twelve-year old eruption. Three criteria, involving MVO's measurements of the emission rate of sulphur dioxide, surface deformation and swarms of long-period earthquakes over the past one-year period, were tested to answer this question. All three tests were indicative, to a high degree of probability, of a pause, and that the eruption cannot be considered to have stopped.

13. We consider that the likelihood of resumption will increase as we approach fifteen months from now, but thereafter the chances of resumption of lava extrusion will start to decrease, albeit very slowly. In other words, we consider that the pause may last 15 months, but recognise that this estimate is highly uncertain. A collapse of the lava dome into the Tar River Valley remains the most likely significant new event during the next year (about 40% probability). The current state of no significant surface activity is considered to be almost as likely. Nevertheless, as long as the current size and position of the dome persists, the much smaller likelihood of a collapse of the dome to the north or west will still exist.

14. As we have pointed out before, this is now one of the longest-lived eruptions of its type in the global record and statistically, the longer it continues the less likely it is to stop soon: we estimate a probability of 80% that it will continue for five years or more. Also the averaged deep magma supply to the volcano over the whole eruption appears to be nearly constant, suggesting long-term stability. Nevertheless, it may be possible for such a system to shut down abruptly.

Assessment of Volcanic Hazards

15. The nature of the hazards posed by the volcano are similar to those faced at the times of the March 2007 SAC8 assessment and, particularly, of the July 2007 interim assessment. The notable reduction in the probability of pyroclastic flows into the lower Belham Valley between these two assessments was a result of the recognition that the lava supply had stopped. This removed the possibility that a major collapse to the northwest could be triggered by lava pushing from the interior of the dome. It also reduced the likelihood of very high pressures within the dome as gas from the slowly crystallising lava there dissipated. Since July, the latter effect has continued but the extra impact on hazards has been less.

16. The hazards from a major dome collapse down the Tar River Valley remain: major pyroclastic flows or surges out to sea (up to about 3 km offshore), hydrovolcanic pyroclastic surges over the evacuated northeastern flanks, minor tsunami waves (up to about 1 metre in populated areas, but higher near Tar River Valley and Spanish Point), rain-generated mudflows, ashfall and rock fall, particularly to the west, high concentrations of sulphur dioxide at ground-level for short periods around the lower

Belham Valley. The wind direction at the time of any collapse is a major factor determining how much ash gets deposited where over inhabited areas. The areas likely to be covered by air fall ash during such a major event can be crudely assessed by using the Puff simulator (http://puff.images.alaska.edu/watch_soufriere_hills.shtml), though the wind data for this model are only updated every six hours. The current dome volume (208 million cubic metres) is about twice that of 20 May 2006, and so some of the effects are likely to be amplified relative to that event should complete collapse of this dome occur.

17. The northwestern position of the current dome (relative to its slightly larger version in July 2003, see front cover photo) means that it still poses a threat to the Belham Valley. A large collapse-derived pyroclastic flow outside of the crater to the west, northwest or northeast could reach the coasts in these directions. The flow volume advancing to the northwest would have to equal or exceed about 10 million cubic metres to reach the coast via the Belham Valley. Models of potential dome collapse volumes show that currently as much as 12 to 30 million cubic metres of dome lava could collapse toward the northwest and enter Tyre's Ghaut and thence into Belham Valley. However, some simulations of such collapses also show that it is very unlikely that more than about 20 million cubic metres could collapse into the Belham Valley from even larger collapse volumes on the north side – the remainder tending to be redirected by topography towards the north (past Windy Hill) and northeast, towards Trants. If one of these large pyroclastic flows moves down the Belham Valley, surges composed of hot ash and gas would spread out laterally up the valley sides. Although such surges would be most marked in the areas nearest the dome they could still be a factor on the populated northern slopes of the lower Belham Valley, from Happy Hill to Frith and Old Towne. In our last report we described how we had simulated such effects from flows with volumes of about 12, 20 and 30 million cubic metres. We do think a net volume of 30 million cubic metres into the Belham Valley is bordering on the unrealistic, but we have calculated its effects as a worst-case reference scenario for this type of event. That surge boundary line also captures conservatively some of the uncertainty involved with calculations for the 20 million cubic metre flow.

18. A lateral blast is a type of horizontally-directed explosion. There has been one clear recorded example at Soufrière Hills Volcano, on Boxing Day 1997, and some explosive phenomena of a related nature may also have occurred during the Tar River Valley collapses on 12 July 2003 and 20 May 2006. The conditions that triggered the Boxing Day event were a large dome banked up over the south crater wall (Galway's Wall) and an adjacent area of weak rock in the soufriere below. A landslide failure then exposed the pressurized dome core, resulting in a blast. A repeat of such conditions could occur conceivably with a collapse of Gage's or Farrell's Walls, but there is little evidence of structural weakness at Gage's Wall and even less at Farrell's Wall. The trigger to the lateral blast is the sudden, sideways exposure of the highly pressurized interior of the dome. It is conceivable that if the dome were big enough, if it were sufficiently pressurized (for example from gas storage) and a sufficiently large "normal" collapse of the dome were to occur, then a lateral blast could ensue. We used, and presented in the SAC8 assessment, computer simulations of the ensuing effects on the lower Belham Valley of pyroclastic flows derived from this type of blast. The physical properties of these effects have not much changed but the probability of such a blast occurring has.

19. If the lava supply to the base of the dome were to resume before any large collapse of the dome, then the lava may intrude within the dome and destabilise it. Again, the likelihood is that any resulting collapse of the dome would be directed relatively harmlessly to the

east, down the Tar River Valley, but it is conceivable that it could initiate a collapse to the northwest. Explosive activity would also likely be part of such a scenario.

Assessment of Risks to People

20. As in previous reports we take each hazardous process identified above, estimate the probability that they will occur and affect a given area of Montserrat and then calculate the risk to which a given number of people in that area will be exposed. We use the numerical divisions of the UK Chief Medical Officer's (CMO) scale (Appendix 8) to convey a qualitative description of the annualised individual risk based on the numerical estimates, but we use letter categories (A, B, etc.) to replace the descriptive terms. We also provide some alternative risk measures to add further perspective. Details of the probability and risk calculations are presented in Part II of this report. These risk estimates have large uncertainties and so the reader should not attribute detailed meaning to small numerical differences in these values. We round-off calculations to two figures. We have also calculated the increased risk faced by individuals from the volcano above the general "background" risk of accidental death thought to be typical for people living in Montserrat.

21. Because lava extrusion has ceased, and the existing dome rocks have had time to cool and lose some of their gas, the probability of pyroclastic flows reaching inhabited areas around the lower Belham Valley has reduced. For individuals living in a particular area the risk of death from such flows has fallen since March 2007 and also, to a lesser extent, since the last Interim assessment in July 2007. However, as a result of the reassignment of the Exclusion Zone boundary to the south of Isles Bay Hill, more people are now living in the more hazardous areas than before. This means that the risk level of sustaining a few (less than ten) casualties has risen slightly since July 2007.

21. *Risks to people living between Isles Bay Hill and Lawyers River*
The individual risk exposure levels are lower than those determined in the July 2007 interim assessment. The individual risk exposure for a person living full-time in Area 1 is marginally lower (down from 1-in-1400 to 1-in-1700 per year). This remains within the CMO's scale category C and represents a risk that is 3.1 times that of the background risk of accidental death in Montserrat. The reduction for Area 2 (from 1-in-8,800, to 1-in-21,000) moves the exposure level down to the next category on the CMO's scale (i.e. D) and is now 1.2 times that of background risk of accidental death. In the case of Area 3, the individual risk exposure is 1-in-6 million, in CMO category F, or 1.001 times the level of background risk of accidental death.

22. *Risks to workers at a Fox's Bay jetty*
At Fox's Bay the protection given by St George's Hill and Garibaldi Hill to inundation by "normal" block-and-ash type pyroclastic flows is considerable, but these two hills afford less protection from energetic, lateral blast-derived flows which can flow above or around obstacles. The assumption is made that safety practices similar to those in place at Trants would also be implemented for any work operations at Fox's Bay, i.e. checks with MVO on activity levels, a dedicated volcano watcher to warn the workers of danger, and formalised evacuation procedures, in place and practised. Because escape from Fox's Bay

involves either a relatively long drive back towards the threat or what must, inevitably, be a relatively slow departure by boat, any risk reduction relating to a finite time to escape is likely to be marginal, and difficult to quantify and justify in the circumstances. This being the case, no additional mitigation on this basis is allowed for in the assessment of this particular scenario. From our latest assessment, we find the likelihood of such an incursion at Fox's Bay to be about 1-in-300 in a year. (This is about one sixth of the likelihood of a similar flow just reaching Belham Bridge, and two-fifths the rate for incursion into Area 1). Allowing for some ability to escape by sea, the risk exposure level for a worker at Fox's Bay is estimated to be equivalent to 1 in 7,900 per annum. This is about 3.5 times higher than the occupational risk level for extractive and utility workers in the U.K (the most directly comparable jobs category for which official data are available).

23. *Risks to workers in Belham Valley*
For workers in the Belham Valley (building the bridge, or extracting sand just below the bridge) we have included in the hazard scenarios a flow/surge of between 5 and 10 million cubic metres from a NW-directed event. Using the new probabilities elicited at SAC9, the range of scenarios with potential to affect the central part of the Belham Valley gives a chance of a flow/surge incursion into that area of about 1-in-47 in a year. This is over twice as great as the likelihood of longer runout into Area 1. For limited working time exposure (i.e. not full-time), the risk exposure for a worker in the Belham Valley is about 1-in-3,100 per annum. In terms of (UK) extractive and utility industries, this exposure is 7.5 times greater than the generic fatality rate for such workers. No allowance is made in this estimate for possible mitigation/escape measures, which could reduce the risk.

24. *Risk to workers at Trants*
Workers extracting sand and gravel from Trant's beach and neighbouring flow deposits are at risk from pyroclastic flows. The likelihood of a pyroclastic flow incursion into the Trants area in one year is 1-in-50 [90% conf. interval: 1-in-94 to 1-in-27]. This is approximately the same as the estimate for a flow incursion to Belham Bridge, mentioned above. We understand that current safety practices at Trants involve checks with MVO on activity levels, a lookout and evacuation practice. Incorporating such mitigatory elements into the Trants workers' situation produces an individual risk exposure level of 1-in-14,000 per annum equivalent, or about 2.5 times higher than the occupational risk level for the (UK) extractive & utility supply industry. If these protection measures fail, or are not implemented for some reason, then the risk level would rise to about 1-in-5000, or about 4 times the equivalent UK occupational risk.

26. *Risks in the Maritime Exclusion Zone*
The Maritime Exclusion Zone was last amended in September 2007 when the zone around Old Road Bay was removed. In our last report we advocated that the area offshore from Spanish Point to Pelican Ghaut be part of the zone. This area of sea is at risk from pyroclastic flows descending to the northeast, particularly in the event of a major collapse of the dome. We make that point again.

The Operation of MVO

27. Despite the extra stress of the 'Review' of scientific advice that was underway at the same time as the SAC meeting, Dr. Hards and the staff of the MVO made us very welcome. The meeting itself benefited greatly from the full scientific input of the staff.

28. MVO staff, currently at full complement, now have contracts to the end of March 2008, the end of the current management contract with BGS. Mr. Mick Strutt had performed well as Acting Director during Dr. Hards period of leave in September. Dr Nico Fournier (Seismic Research Unit, UWI), Mr Lee Jones (BGS) and Dr Brian Baptie (British Geological Survey) had also deputised for Mr Christopher, Dr Ryan and Dr De Angelis respectively. Mr Machel Higgins (software engineer) had resigned and was recently replaced by Mr Michael Allen. Mr. David “Patch” Silcott has indicated his intention to return to Montserrat and make himself available to MVO at the beginning of 2009.

29. The Caribbean Helicopters contract with MVO for two hours per week of flying time has been suspended since 15 August 2007 whilst their twin-engined helicopter awaited replacement parts. During this interval a lot of essential maintenance to the monitoring network has not been done. It is estimated that to clear this backlog would require at least three hours of flying for each of three days. Invitations to tender for the new helicopter contract from October 2007 have been issued. Earlier plans to make MVO’s network maintenance less reliant on the helicopter has not stood this test well and the monitoring network needs to be more resilient in this regard. The demise of Air Montserrat has removed any potential use of fixed-wing aircraft for observation flights.

30. As just noted, the monitoring networks have suffered some degradation as a result of the loss of helicopter-based maintenance. The seismometer network has been robust, but data processing has been highly inefficient because of the recurrent failures of two computers well past their retirement age. Replacement by new machines has been held up by some purchasing issues that need to be resolved with speed. The GPS receivers at White’s Yard, Hermitage and Spring are non-functioning and need to be accessed. The present condition of the South Soufriere GPS receiver means that manual download of data has to be undertaken, and this was last carried out by a visit via the sea, and a climb on foot, on 15 September. The spectrometers for sulphur dioxide measurements have been performing intermittently, with one or other of the two main instruments out of action at different periods. A set of five, newly purchased, spectrometers are due to be deployed to set alongside the old ones at the three current sites and at two additional sites, together with a rover instrument. Help with software for the new network will come from the Cambridge gas group. The wind speed data needed for the emission rate calculations should ideally come from an anemometer mounted on a 10m pole near the height of the dome (e.g. at Galways Mountain). A mast-mounted anemometer at St George’s Hill would at least give a more representative reading than the one at Gerald’s Airport. The FTIR is now working again and showing HCl/SO_2 ratios (~0.4) typical of pauses. Extending the FTIR measurements to other gas species (e.g. H_2S, HF) could yield new insights into the magma dynamics. New automated cameras and software are awaiting installation and a wider-angled photogrammetric camera (to image the larger dome) is on order. EDM measurements on the northeastern flanks have proved their value. The apparent stability of the MVO-Lees Yard line is something of a puzzle and, when access allows, it will be worthwhile installing another reflector on the Farrell’s plain visible from both MVO and Windy Hill to give extra comparable measurements. It is good to hear that 80% of the new capital allowance has been spent or committed, and we await the impact that this new investment should bring to the monitoring data.

31. The Alert Level system is used by MVO to convey to the authorities (EPG) the current perceived state of volcanic hazard with a six-class descriptive scale. A problem with this

system (and others at other volcano observatories) is that hazard does not necessarily present itself in a simple step-wise manner, easily described. The recent re-writing of the Level 4 description to accommodate the changed circumstances illustrates this. Also the direct and automatic matching of these class levels with a specific set of civil actions on the part of the authorities is both inflexible and prone to disparities: volcanic hazard levels can change for different reasons, and on a variety of timescales, from a few hours to years, whereas civil response timescales are usually effected only in periods of weeks to months. Instead, we suggest emphasizing that the levels be used as a framework for discussion (within EPG), that the resultant decisions affecting people should always be modulated by the precise details of the current volcanological situation, and that the levels should not be part of a rigid rubric for action.

32. The Scientific and Management Audit (SMA) of MVO carried out by the Caribbean Consulting Group team (B. Blake, R. Blong, M. Mangan) produced a report that was discussed at the last MVO Board meeting in April 2007. The report did not include any recommendations for the future management of MVO (term of reference 5) and its acceptance was deferred until receipt of these. Unfortunately, partly as a result of the tragic death of Mark Twigg, this appendix to the report was not seen until just before this SAC meeting. There is much valuable commentary in the SMA report and two conclusions stand out. Firstly, they conclude that it is prudent to assume that the eruption will continue for several years and that in order to continue to protect the people of Montserrat, MVO should be funded at a similar level to the current one. Secondly, whilst volcano tourism should be better exploited in Montserrat and that MVO has a part to play in that, volcano tourism must not become one of the primary operational roles of the Observatory.

33. A post-SMA review (Review of the provision of scientific advice on volcanic and related risks to Montserrat) commissioned by the Governor's Office, and to which members of the SAC contributed, was being undertaken (by R. Bellers, N. Petford and J. Kelsick) at the time of this SAC meeting. One of the outcomes of this will be a draft invitation-to-tender document for the new management contract of MVO. Whatever the content of that document, we hope that there will be satisfactory bid(s) sufficient to maintain the quality of MVO in future. Any new regime will have less than six months to take over. In order to maintain continuity of operations across any divide we urge that some form of bridging or extension mechanism be considered.

SAC Matters

34. Between SAC7 (September 2006) and SAC9 (October 2007) there were three interim hazard assessments (January, February and July 2007) in addition to the planned SAC8 meeting. The main responsibilities of the SAC are:

"To carry out regular hazard and risk assessments of the volcano in co-operation with the Montserrat Volcano Observatory (MVO) and to report its findings to HMG and the Government of Montserrat; and

To provide scientific advice at a strategic level to HMG and the Government of Montserrat outside these regular assessments in co-operation with the MVO."

The interim assessments were carried out in response to requests from EPG following changes in volcanic activity. However, such interim assessments are not explicitly covered in the above. Whilst the SAC does not regard the interim requests as unnecessary, far from it, responding to them has stretched our capabilities to respond quickly and as fully as we would have liked – we all have "day jobs" that compete for our time. We would like to re-organise the SAC responses for ad hoc assessments within the new framework that evolves from the latest efforts to manage the evolution of MVO.

35. In whichever way the management of MVO might change in 2008 we see the need for continuity of the SAC's role across that period. We thus propose to meet again in April 2008.

Appendix 1: Constitution of the Scientific Advisory Committee on Montserrat Volcanic Activity

This document outlines the main responsibilities of the Scientific Advisory Committee (SAC) on the Soufriere Hills Volcano, Montserrat. The document includes the terms of reference for the SAC and a membership template. The SAC is to replace the Risk Assessment Panel and is commissioned by the Overseas Territories Department (OTD) of the Foreign and Commonwealth Office (FCO). The SAC will work according to the Office of Science and Technology (OST) Code of Practice for Scientific Advisory Committees.

Terms of Reference

The main responsibilities of the SAC are:

1. to carry out regular hazard and risk assessments of the volcano in co-operation with the Montserrat Volcano Observatory (MVO) and to report its findings to HMG and the Government of Montserrat; and

2. to provide scientific advice at a strategic level to HMG and the Government of Montserrat outside these regular assessments in co-operation with the MVO.

NB: The "Government of Montserrat" will normally mean, in the first instance, the Governor as s/he has the constitutional responsibility for the safety of the Montserrat population. The Governor will be responsible for ensuring appropriate dissemination of SAC assessments or recommendations to the Government and people of Montserrat.

The SAC is also required to perform these additional functions:

3. to provide independent advice on the scientific and technical operations of the MVO to ensure that the work matches the level of risk;

4. to provide scientific advice and assistance to the MVO as required by the MVO Director; and

5. to offer advice on new developments that were not foreseen when the TORs were set up, and if appropriate make recommendations for changes to the TORs.

The SAC will carry out its activities within the OST Code of Practice for Scientific Advisory Committees. The SAC will be responsible to the UK Government through the FCO (OTD). The SAC will not incur expenditure without prior FCO (OTD) authority.

These general terms of reference are supplemented with the following specific points:

(a) The work of the SAC concerns scientific assessment of the volcanic activity and related hazards and risks. This scientific work is an input to decisions made by the HMG and the Government of Montserrat related to the safety of the people of Montserrat (such as evacuation and extent of Exclusion Zones), to issues of planning and sustainable development of Montserrat and to the mitigation of external hazards (e.g. to civil aviation).

(b) The provision of scientific advice to the Governor and Government of Montserrat is the responsibility of the MVO and its Director. The SAC has the function of assisting the MVO in its major missions in all respects of its activities and to assist in matters relating to the provision of long-term and strategic matters.

(c) The MVO Director (or scientific staff designated by the Director) participate in all SAC activities except for ToRs 3 and 4.
(d) The SAC has the function of giving advice and assistance to MVO and the management contractor relating to scientific matters as required by the MVO Director. Such independent advice to the MVO may include appraisal of the technical expertise of staff, evaluation of the monitoring systems, assessment of proposed research projects by external groups, and advice on technical matters.
(e) With respect to ToR 3 the Chair of the SAC will be a member of the MVO Board of Directors and can provide independent advice to the Board as required. The Chair will be expected to attend MVO Board meetings (currently twice a year).
(f) Given the special circumstances of Montserrat as a United Kingdom Overseas Territory, reports of the SAC would be provided for both Governments. Reports would also be given to the MVO Management Board.
(g) The SAC will be required to present its findings in a manner suitable for release to the public. It will also be required to assist the Governments and the MVO in explaining the activity of the volcano and the scientific information pertinent to decision-making by the authorities.
(h) The SAC will liaise with other relevant scientific organisations or committees as required, which might for example include regional scientific institutions and the Department of Health Committee on health hazards from volcanic ash.
(g) The Chair of the SAC will make an annual report to the MVO Board of Directors.

MEMBERSHIP

Membership of the SAC will be at the invitation of the FCO (OTD) and will cover the key areas of expertise required to assess the hazards and risks of erupting volcanoes. Expertise will include such areas as volcanology, volcano geophysics, and hazard analysis. The SAC will continue the approach of the former Risk Assessment Panel that was endorsed by the UK Chief Government Scientist in December 1997. Thus the Committee requires a facilitator as a member for applying expert elicitation methods to estimate volcanic risk. These considerations imply a minimum of four members, excluding the Director of the MVO. Additional experts can be invited to participate as required by the Chair, with prior agreement from the FCO (OTD), if a lack of expertise becomes apparent on a particular issue. As required by the Code the SAC is expected to consider external opinion. The membership will be considered on an annual basis with a view to regular changes and refreshment of membership.

MEMBERSHIP TEMPLATE

Members invited to serve on the SAC for the Montserrat Volcano are expected to attend all hazards and risk assessment meetings and to participate in the formalised elicitation procedure. Members have the responsibility to use their scientific judgement and expertise to meet the Terms of Reference. Opinions of the Members on scientific matters should be expressed through participation in the work of the SAC. Divergences of scientific opinion will normally be reported in terms of scientific uncertainty through the formal expert elicitation procedure. Differences that cannot be incorporated through the elicitation methodology should be included in the reports of the SAC as required by the OST Code. The Chair of the SAC, or his or her delegate from the Committee, will be responsible for presenting the findings of the SAC’s work to the Governments of Montserrat and the United Kingdom and to the public in co-operation with the Director of the MVO. Any disagreement or divergence of opinion with the Director of the MVO that cannot be reconciled or incorporated through the elicitation method should be reported through the MVO Board of Directors.

SECRETARIAT

The FCO (OTD) will provide a Secretariat for the SAC, as set out in the Code of Practice. FCO (OTD) will reimburse premium economy travel costs, reasonable hotel accommodation, meals and professional fees (once agreed) in full. The SAC will not incur additional expenditure without prior FCO (OTD) authority. The Secretariat's main point of contact is Thomas Reagan, Desk Officer for Montserrat in OTD. His contact details are as follows:

Email: Thomas.Reagan@fco.gov.uk

Tel: +44 20 7008 3123
Fax: +44 20 7008 2879

Appendix 2: Scientific Advisory Committee on Montserrat Volcanic Activity, Meeting 9, 1-3 October 2007 : Agenda

1. SAC8 report, July 2007 interim report, this meeting, public meeting
2. MVO Activity Report
    - Petrology
3. The current pause
    - Pyroclastic flows during pauses
    - Propensity for a large collapse
    - End-of-eruption criteria and assessment
4. Centre Hills springs record
5. Long-term prognosis
    - 1-5 years
    - 5-20 years
6. One-year hazard scenarios elicitation
7. Metrics of risk exposure
8. Risks in the Exclusion Zone
    - Lower Belham
9. Risks in the vulnerable zone
10. Work/Visit
    - Trants Bay
    - Foxes Bay/ Belham
    - Plymouth
11. Maritime exclusion zone
12. MVO Matters
    - Staffing
    - Helicopter
    - Monitoring
    - Alert Levels
    - Collaboration
    - Scientific and Management Audit
    - New management contract
13. SAC Matters
    - SAC terms of reference/interim assessments
    - Membership
    - Next meeting

Appendix 3: List of Participants

Chairman

Prof. G. Wadge	ESSC, University of Reading, UK

Committee members

Dr. W.P. Aspinall	Aspinall & Associates, UK
Prof. J. Neuberg	Leeds University, UK
Dr. R.E.A. Robertson	Seismic Research Unit, The University of the West Indies, Trinidad and Tobago
Prof. B. Voight	Penn. State University, USA
(Prof. K.V. Cashman	University of Oregon, USA - absent)

People present in an advisory capacity

Dr. V. Hards (Director, MVO)
Dr. G. Ryan (MVO)
Mr. T. Christopher (MVO)
Dr. S. De Angelis (MVO)
Mr. T. Sayers (MVO)
Ms V.Bass (MVO)
Dr. K.C.Rowley (Govt. of Trinidad and Tobago)

Appendix 4: SAC9 Preliminary Statement, 3 October 2007

Since April 2007, no new lava has been added to the dome. We are now six months into a pause in activity, in many ways similar to those that lasted 20 months in 1998-1999 and 24 months in 2003-2005. We consider it likely that this pause could last a similar period of time. During recent months the MVO data on sulphur dioxide emission rates and ground surface deformation suggests that the volcano is re-charging with new magma at depth. The deep supply that has powered this twelve-year eruption has not yet switched off.

Whilst there is no new lava appearing at the surface, there have been occasional rockfalls, small pyroclastic flows and mudflows. The shape of the dome remains largely unchanged since April and the large mass of hot dome on the northwestern side is capable of generating large pyroclastic flows.

Over the next year we estimate that there is about a 40% likelihood of a major collapse of the dome down the Tar River Valley, and a similar likelihood of no major eruptive activity during this period. The potential for a major collapse of the existing dome into the Belham Valley remains, however, presenting a risk for people living around the Valley. The risks to individuals are similar to that determined by the interim assessment of July 2007.

A full report of the hazards and detailed risk assessment for a year ahead will follow.

Appendix 5: Glossary of Terms

Andesite: The name given to the type of magma erupted in Montserrat.

Basalt: The type of magma entering the magma reservoir below Montserrat.

cGPS: Continuously-measured Global Positioning System for repeated measurement of ground deformation.

Conduit: In a volcano magma flows to the earth's surface along a pathway known as a conduit. The conduit is usually thought to be a cylindrical tube or a long fracture.

EDM: Electronic Distance Measurements made by laser ranging to reflectors gives length changes of a few millimetres accuracy over several kilometres.

Hybrid/LP Seismicity: Varieties of earthquake signal often indicative of magma motion in the upper part of the conduit.

Lava: Once magma gets to earth's surface and extrudes it can be called lava. Below ground it is always called magma.

Lateral Blast: An energetic sideways-directed explosion from a lava dome that can generate highly fluid pyroclastic flows.

Magma: The material that erupts in a volcano is known as magma. It is not simply a liquid, but a mixture of liquid, crystals and volcanic gases. Magma must contain enough liquid to be able to flow.

Magnitude: The magnitude of an explosive eruption is the total mass of material erupted.

Mudflow: A flow of rock debris, ash and mud that occurs on many volcanoes particularly during eruptions and after very heavy rain (same meaning as lahar).

Pyroclastic flow: These are flows of volcanic fragments similar to avalanches of rock in landslides and snow avalanches. They can be formed both by explosions and by parts of an unstable lava dome avalanching.

Pyroclastic surge: These are also flows, but they are dilute clouds rather than dense avalanches. A surge is a rapidly moving mixture of hot particles and hot gas and their behaviour can be compared to a very severe hurricane. Surges can be formed above pyroclastic flows or directly by very violent explosions.

Swarm: A large number of , in this case, earthquakes occurring in rapid succession with characteristics indicating they are generated from a similar region in the earth. Can merge into tremor.

Volcanic ash: Ash particles are defined as less than 4 millimetres in diameter. Respirable ash consists of particles less than 10 microns (a micron is one thousandth of a millimetre) in diameter.

Appendix 6: Interim assessment conducted between 3 and 14 July 2007 by email correspondence

Issued on 19 July 2007

Introduction

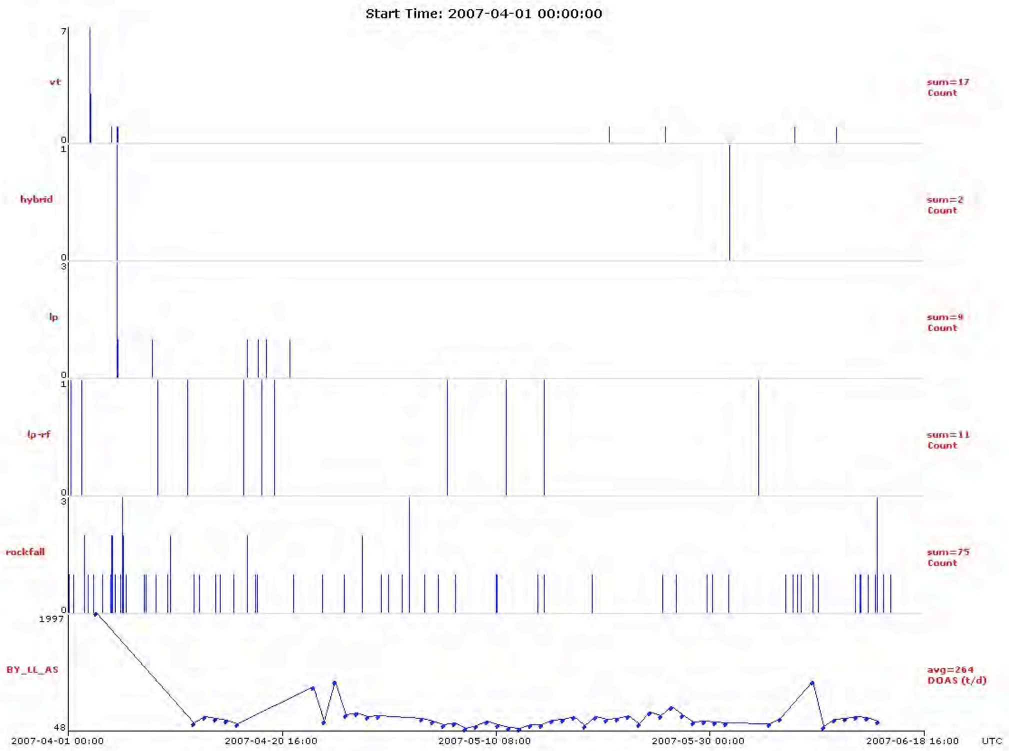
1. This report responds to a request from the Government of Montserrat Emergency Planning Group (EPG) via Mark Twigg on 14 June 2007 for a re-evaluation of the current volcanic risks on Montserrat.

2. Since the last SAC report of 16 April 2007 (SAC 8), there has been no resumption of lava extrusion at Soufrière Hills Volcano. This may well indicate that we are now moving into a major pause in surface activity, the third since the start of the eruption. Given the high risk levels assessed in March-April, it is felt that a re-evaluation now is warranted.

State of Volcanic Activity

3. The next paragraph is MVO's summary (of 18 June 2007) of recent activity followed by plots of the seismic event counts and the SO_2 emission rate since 1 April 2007, and the GPS (MVO1-SOUF line length) plot since 1 Jan. 2006 (Fig.1):

4. "Rockfall activity declined markedly from mid March, and it appears dome growth ceased in early April. There have been no visual changes to the dome structure since. The dome volume has been estimated (from photgrametric methods) to be 208Mm^3. We carried out Lidar scan from Galways just over a week ago, but this data have yet to be processed. All other measurable activity has remained low. See combi-plot attached. GPS data are not included, but has been essentially flat. This trend is confirmed by EDM measurements. No change to line lengths. Pyroclastic activity has been at low level but ongoing, predominantly affecting the east and northeast with occasional flows in Tar river, Tuitts Ghaut and at the top of Farrell's plain. A few small flows have also been observed in Tyres Ghaut. Fresh deposits have also been observed on the southern side of the dome. The largest pyroclastic flows of recent months occurred after a period of heavy rain early on Monday morning in the Tar River valley. Fresh deposits have also been observed on the Tar River fan, but stopping short of the sea. Fumarolic activity is presently observed around the scar from the 08 January collapse where it is currently most vigorous. It can also be observed high on the south eastern side of the dome. The vent behind Gages Wall remains active, and emissions here remain distinctly blue suggesting SO2 venting."



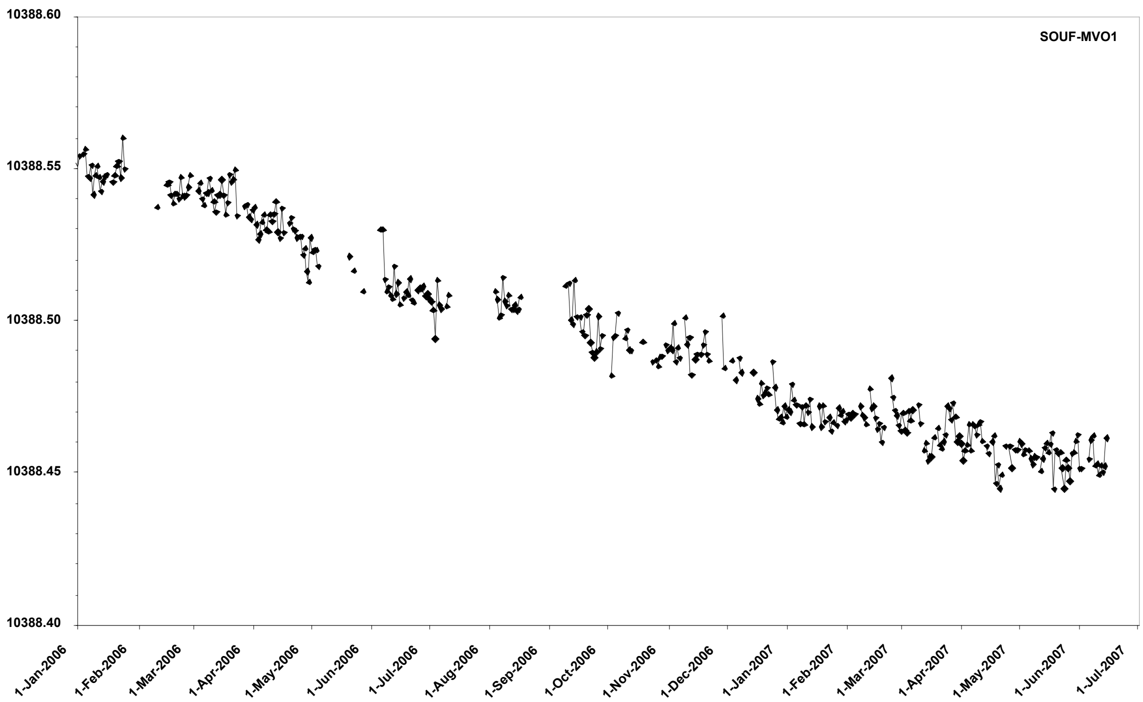


Fig.1 April – June 2007 seismicity and SO_2 emission rate (above), January 2006 – June 2007 GPS line length change (below), data from MVO.

5. During the last 3 months, from a low initial rate, long-period seismic events have almost ceased. Rockfall numbers also fell from April into May, but have increased a little in June. The SO_2 emission rate has averaged 264 t/d, about half the long-term average, and has tended to bump along at about 150 t/d with occasional spikes. The one and a half-year GPS record generally records the line contraction associated with the Episode 3 extrusion. The contraction ceased in about mid-April 2007, with no length change evident since.

6. The potential duration and nature of the current pause was considered briefly in the 1 May 2007 SAC8 report "The April-? 2007 pause in SHV extrusion". In that, besides mention of the long pauses between episodes one and two, and two and three, it was pointed out that there had been two short-lived pauses of 68 and 50 days in 2001 and 2002 respectively during the second episode of lava extrusion. Taking the most conservative (latest) date for the start of the current pause, 4 April, from the earlier discussion, the period of pause is now (19 July, 2007) 108 days long.

7. This, together with the arguments previously advanced:
(i) Episode 3 has resembled Episode 1 in terms of extrusion rate,
(ii) there have been no true intra-episode pauses in Episode 3 before this (unlike episode 2),
(iii) the current cumulative volume of magma extruded from November 1995 to April 2007 reached the average extrusion rate for the whole eruption for the first time since July 2003,
adds to the probability that this current pause will be a major one, lasting many months (e.g. 20 between Episodes 1 and 2).

Current Hazard Factors

8. The cessation of active lava extrusion removes the variability of that process as a forcing agent for lava dome generated pyroclastic flows. Forcing of this type was responsible for the major collapses in Episode 1. However, there is still a large, hot dome, with sufficient mass above Tyre's Ghaut to produce pyroclastic flows in the Belham Valley. The onset of the rainy/hurricane season may provide a trigger for a major collapse of the dome as happened in July 1998, about 4 months after extrusion stopped at the end of Episode 1. That collapse, down the Tar River Valley, with a volume of 17 – 22 Mm^3, removed 230 m from the summit and produced a deep cleft within which extrusion eventually resumed in November 1999. Seemingly, this collapse event also initiated a much higher level of background activity than was present pre-collapse. Such a rain-triggered event now could conceivably involve a north or northwestward-directed collapse. However, there have been **no** major rain-triggered collapse events other than into Tar River valley. This may be to do with the role of the talus in the early stages of collapse, the geometry of the previous collapse amphitheatre, or some aspect of the dome "hydrology". Whatever the reason for this observation, it is felt likely to have a physical, rather than statistical, explanation. If there is no collapse to remove a major portion of the upper dome before the next resumption of extrusion (assuming there is one), then that will represent a situation not seen previously in the eruption – magma forcing its way to the surface through the full 350 m thickness of the largely solidified lava dome. An alternative is magma

forcing its way out laterally, say near the south edge of the current dome. Such scenarios would, presumably, only be relevant in one- to two-years time, should the current pause be similar to the previous major pauses.

9. Has the pre-disposition of the dome to produce a lateral blast changed since March? There is no evidence to suggest that the structural strength of Farrell's or Gage's Walls has been reduced. If anything, the likelihood of structural failure has decreased because there is currently no obvious internal forcing agent to act on the crater walls. The low rate of SO_2 emission to the atmosphere from the dome is consistent with long-term behaviour when the dome is very large and SO_2 is being stored. We had argued that this might contribute to high levels of over-pressure within the dome. One new insight has come from work done with AVTIS measuring the dome growth in March-April 2006. This has shown that at high extrusion rates (~8 m^3s^{-1}) then, the proportion of lava going into talus and pyroclastic flow deposits compared to that remaining (as hot, intact lava) in the dome core was very large, about 9:1. This then means that high effusion rates, seen throughout much of Episode 3, do not guarantee an increased rate of storage of hot, pressurized core rock. However, there have been occasions, for example in December 2006 – January 2007, when large volumes of lava were added exogenously that apparently stayed as lava, and which did add significantly to the core. It is this mass, above Tyre's Ghaut, that we were particularly concerned about, in the previous SAC interim reports for 2007, and the April 2007 SAC8 Report.

10. Since the cessation of magma supply to the dome in early April, the existing core of the dome that is hot, fluid and contains gas will have lost and continue to lose some of those qualities and overall energy content, by cooling, crystallisation and degassing. This will probably affect the outer parts of the dome more strongly than the deep interior. If a major collapse of the dome were to occur now, or over the next year, the energy content of that collapse volume from the dome would be less than in an equivalent volume earlier in 2007, when the dome was being supplied with new magma and when we last considered this possibility. As a result, the mobility of the resultant equivalent-sized pyroclastic flows will probably be less. In the SAC 8 report we considered a dome source volume in the range 12 to 20 million cubic metres capable of entering the Tyre's Ghaut and that a minimum of about 10 million cubic metres of flow volume within the Belham Valley was required for the flow to be capable of reaching the sea. We now consider that with a lower overall energy content to the source dome volume, the source volume that would be required to produce a flow reaching the sea via the Belham could be greater. Unfortunately, we do not have equivalent empirical data on the mobility of pyroclastic flows produced when the dome is not being supplied with magma, as we do for the case of when it is.

11. In summary, the stagnation of lava extrusion through the dome or intrusion into it could be a factor that reduces the instability of the dome, and also reduces stresses on the neighbouring crater walls. Thus far, there has also been a low propensity for rainfall-triggered large collapses to occur on the north or northwest sides of the dome. The thermal energy contained in the dome is decreasing and with it the likely mobility of pyroclastic flows derived from dome collapses. The combination of these factors may reduce the likelihood of a large dome collapse in the first place, and then if one did occur, of it leading to a pyroclastic flow entering the lower Belham Valley and moving near populated areas.

12. We now update our April 2007 SAC8 elicitation from a new position: that is, the Soufrière Hills Volcano is in a condition of "pause". From this point, there are two future courses for the activity at the volcano that are of interest for hazard assessment purposes (it is premature to consider the third – that the present pause represents the end of the eruption). These are (i) continuation of the pause throughout the next year, or (ii) resumption of lava emission from the conduit within one year. The latter, (ii), could happen in one of two different ways: – (a) new lava could break out through the existing large dome, or (b) extrusion could restart, following a large collapse, from a much lower elevation within the collapse scar.
(We treat case (a), using some of the results from the last elicitation, and we treat case (b) as posing no hazard of pyroclastic flow in the Belham River valley).

Elicitation of Probabilities for Hazard Scenarios

13. We summarise the results of the interim elicitation of the SAC members' views on the probabilities of occurrence over the next 12 months of the hazardous events that are inputs to the risk simulation modelling. This elicitation concerned the relative probabilities for the occurrence of what could be the next significant initiating event, its direction and nature. We took into account the progressive loss of energy from the dome lava to estimate the likelihood of the generation of pyroclastic flows in the Belham Valley of equivalent energy and mobility as those that were considered in the SAC8 report. We then used the previous (SAC8) estimates of the likelihood that the resultant flows enter inhabited areas, so this aspect of our procedure has not changed. The following probabilities (expressed as numerical chances), record the elicited relative likelihoods of the different outcomes. For comparative purposes, the corresponding results from SAC8 are also shown, where these were applicable at that time.

P1a GIVEN current condition of a pause in the extrusion, the probability that within ***1 year*** *the next significant development will be the resumption of lava extrusion:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**2 %**	**24 %**	**78 %**

P1b GIVEN current conditions, the probability that for the ***next year*** *the activity will have no major eruptive incidents:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**2 %**	**31 %**	**58 %**

*P1c GIVEN current conditions, the probability that within **1 year** the next significant event will be a major dome disruption event big enough that part of the material avalanching towards the NE (Trants/Bramble) could generate a side flow such that the flow/surge would runout to reach the sea via Belham Valley:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**0.05 %**	**1.1 %**	**25 %**
SAC8	**2.3 %**	**13.8 %**	**34.7 %**

*P1d GIVEN current conditions, the probability that within **1 year** the next significant event will be a major dome disruption event - <u>without a blast</u> - involving enough material avalanching to NW (Tyre's/Belham) to generate a flow/surge runout to reach the sea:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**0.1 %**	**0.8 %**	**17 %**
SAC8	**0.9 %**	**7.3 %**	**32 %**

*P1e GIVEN current conditions, the probability that within **1 year** the next significant event will be a major dome disruption event - <u>with an associated blast</u> - involving enough material avalanching to NW (Tyre's/Belham) to generate a flow/surge runout to reach the sea:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**0.005 %**	**0.14 %**	**4 %**
SAC8	**0.03 %**	**0.9 %**	**6.5 %**

*P1f GIVEN current conditions, the probability that within **1 year** the next significant activity will be a major dome disruption event involving enough material avalanching to W (Gage's), with possible lateral blast and/or explosion column, such that the flow/surge would reach the sea:*
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**0.05 %**	**1.5 %**	**15 %**
SAC8	**0.4 %**	**9.1 %**	**24 %**

P1g GIVEN current conditions, the probability that for the next year the most significant activity will be collapse of the dome (e.g. to Tar River or the south, but not to W; collapses to NW or NE can occur also, but with less mobility than needed to run to sea in the Belham) which takes away the bulk of the dome harmlessly:
Elicited Probability:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
14 July 2007 interim	**10 %**	**41 %**	**77 %**
SAC8	**21 %**	**50 %**	**90 %**

14. The first thing to say is that the net probability of occurrence of any volcanic event, of whatever kind that might be potentially harmful to the present occupied areas, is now estimated to be less than 1-in-25 in the next year (numerically, ~ 4%). The corresponding chance was put at just over 1-in-5 when we assessed hazard levels in April 2007 (probability ~ 22%), so the reduction of threat is about 5*x*, overall.

15. As before, if there is a significant volcanic event within the next year, the most likely anticipated scenario is a big dome collapse into the Tar River or a sizeable collapse in other directions (other than would affect areas to the northwest of the volcano) (*P1g*), with the group's judgement being there is now just over a 1-in-2 chance (41%) of this happening inside twelve months, although this probability is reduced compared to earlier elicitations (it was 50%, at SAC8). This said, there is also judged now to be almost a 1-in-3 chance (31%) that the next year could pass without any major eruptive incidents of any sort (*P1b*). The likelihood that the next (and only) significant development in the next year would be a resumption of lava extrusion at the surface is put at about 1-in-4 (*P1a* = 24%).

16. Moving on to scenarios which could impact populated areas, the possibility of a big collapse to the northeast, towards the old airport and Trants, which might also produce a major secondary derivative flow down the Belham to the sea (P1c), is also considered much less likely than hitherto: the chance of this occurring is put at about 1-in-100.

17. For the scenario of most concern in hazard terms, i.e. a major flow/surge towards the northwest (*P1d*), there is judged to be about a 1-in-125 chance of a significant dome disruption event in the next year, involving enough material to reach the sea via the Belham Valley; this particular scenario assumes no blast component. For a blast-associated event, there is now thought to be about a 1-in-700 chance of such an event happening (*P1e*). *In each case, these likelihoods are factors of nine times and six times lower, respectively, than assessed in March-April 2007.*

18. Given all the various initiating event probability distributions tabulated above, taken together *these equate overall to about a 1-in-130 chance of a flow or surge incursion into Area 1 (Fig.2) over the next year (it was 1-in-14 for SAC 8). The current likelihood is thus a factor of 9x less than when last assessed.* From the distribution spreads provided by the SAC team, the 1-in-130 median probability sits within a 90% confidence interval ranging from 1-in-1060 to 1-in-28; in other words, there is 95% confidence these odds would be no lower than 1-in-28, and a 5% chance they could be as long as 1-in-1060.

19. For Area 2, the elicited probability for a flow or surge incursion stands at about 1-in-350 over the next year [90% conf. interval: 1-in-2200 to 1-in-78]. For the case of a blast reaching the area, there is a 1-in-980 median chance within the year [90% conf. interval: 1-in-4100 to 1-in-120]. *These median values are 8x lower and 3.5x lower than the SAC 8 elicitation findings, respectively.*

20. For Area 3, the median probability of a flow or surge reaching into the area is roughly 1-in-9900 [90% conf. interval: 1-in-69,000 to 1-in-940], or about 6*x* smaller than the SAC 8 estimate, when the dome was still actively growing and the stability of its northwest sector was of heightened concern.

21. For collateral flows (i.e. major flows, directed either to the NE or to the NW, also producing flows in an orthogonal direction because of local topographic divides - in much the same way as happened on 25 June 1997 when the main flow went northeast but a secondary flow separated off and moved towards Cork Hill), the

conditional likelihoods we have used for these entering the different population zones, if they occur, remain unchanged from those arrived at during SAC 8. The same applies to the conditional probabilities of incursion into different areas for the Gages blast scenario (i.e. the specific case of a big dome disruption event directed towards Gage's, in which event a blast component could possibly be involved).

22. As usual, all the ranges of uncertainty (and those associated with other parameters not discussed here) have been each separately defined in the SAC's elicitation procedure by upper and lower bound credible interval quantiles, and the relevant spreads of uncertainty are taken into account in the full Monte Carlo risk assessment methodology. Thus, each event probability, given above, reflects whatever changes there have been between April and now in the elicited distributional spreads associated with the relevant probabilities.

Quantitative Risk Assessment

23. Calculations of volcanic risk are revised by making adjustments to probability and rate estimates in the light of the new developments in the volcano, and on the basis of the committee's current reappraisal of the likelihood of the various associated threats. However, as soon as one of the major events as envisaged here occurs, then the probabilities of all the other scenarios changes too and a full re-appraisal will be required. The risk levels are mainly expressed as potential loss-of-life estimates and as annualised individual risk exposures - that is, the risk of suffering a given number of casualties in the society as a whole, or the risk of an hypothetical individual losing his or her life during one year. Generally, these risk estimates do not include allowance for any reduction in exposure that could be gained from early warnings and civilian mitigation responses. Thus, while the quantitative risk assessment results are not full-blown worst-case scenarios, they do represent conservative estimates for policy-making purposes. The approach and methodology follow those described in the December 1997 MVO Hazards and Risk Assessment report, validated by the UK Government's Chief Scientific Adviser's consultative group.

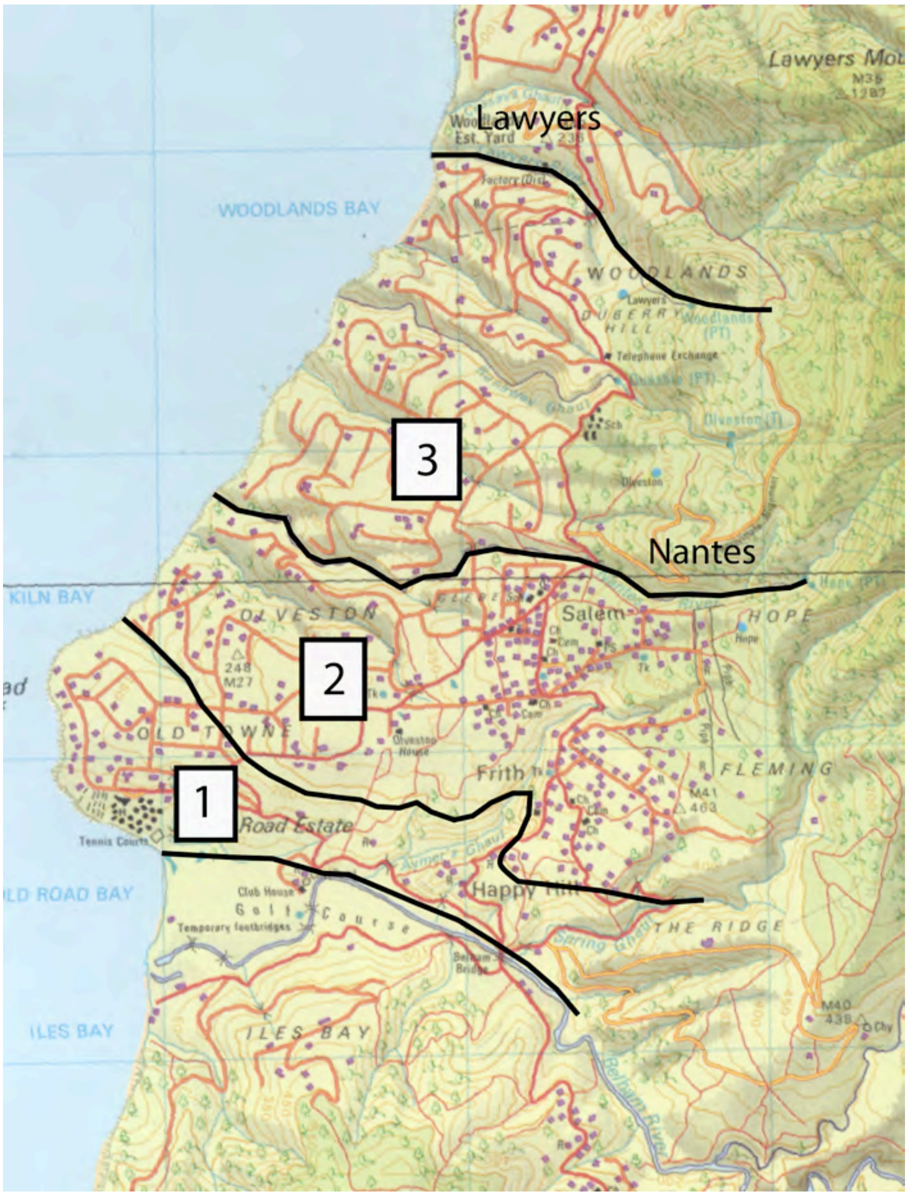


Fig. 2 Map showing revised population Areas [1], [2], and [3], adopted in SAC Interim Report of March 2007

24. The assumed total population on Montserrat is taken to be held at about 4,775 persons, a figure unchanged from previous recent assessments, and the geographic distribution of people (and their day-time entry patterns) are assumed the same as those used for the SAC 8 Risk Assessment.

Societal Risk Levels

25. In order to assess societal risk levels, the impacts of different eruptive scenarios are modelled for the present population of Montserrat, and aggregated according to likelihood of occurrence.

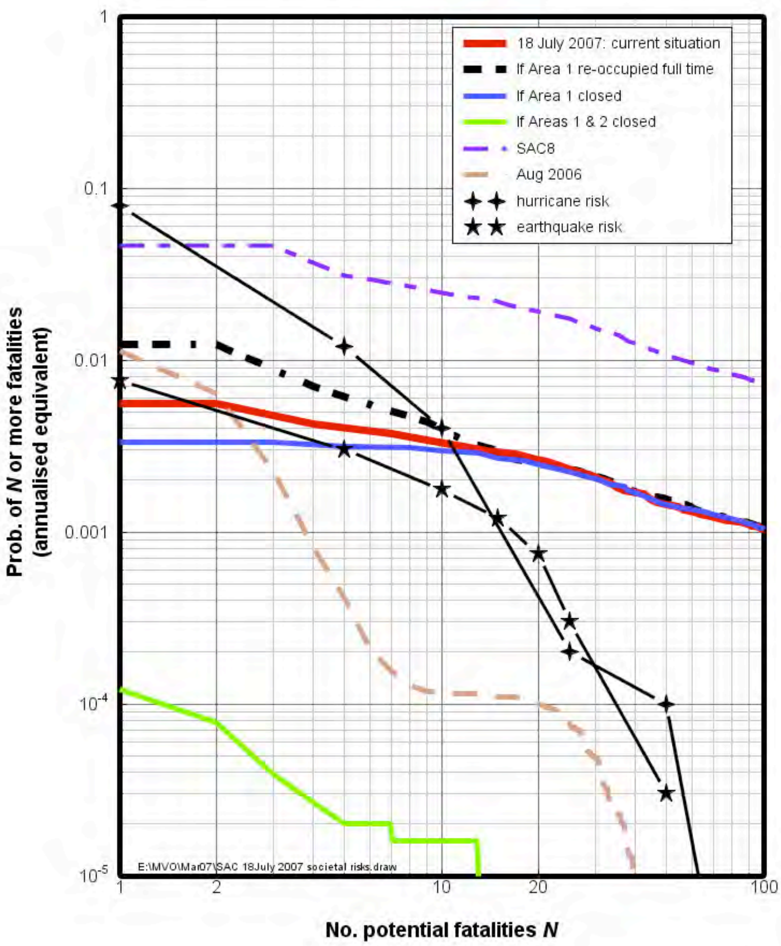


Fig. 3. Societal risk curve (red) for population distribution at present time (July 2007), compared to societal risk levels with alternative exclusion zone configurations (i.e. Area 1 fully re-occupied; Area 1 closed, Areas 1 & 2 closed), the previous full SAC assessment (SAC 8 - April 2007), and risks from other natural hazards in Montserrat.

26. Fig. 3 shows the estimated current annualised societal risk for the present situation on Montserrat (red curve), the corresponding curve from the most recent SAC 8 Report, together with those calculated for three alternative population scenarios (i.e. Area 1 fully re-occupied; no admittance at all to Area 1, and no admittance to both Areas 1 & 2). Also shown is the societal risk curve produced in August 2006, when the dome was re-growing again after a major collapse at the end of May 2006, and curves for risk exposure from hurricanes and earthquakes.

27. The present level of societal risk is about 8 times lower than it was assessed in the April 2007 SAC 8 Report, but the same flat trend in probability when considering relatively high casualty numbers is maintained.

28. The difference in slopes of the curves for hurricane and for current volcano risk curves arises because recent hurricanes have killed at most only a few people at a time - as a result of better warnings and shelter – whereas the volcano is judged capable of causing mass casualties in a severe event. So, although the probability of

one death from a hurricane is greater than that for the volcano in its present state, the probability of several tens of casualties or more from volcanic action is still considered greater than that from a hurricane – even though the current conditions at the volcano are comparatively quiet.

29. The continued inflation of the curve in the present situation for large numbers of casualties (i.e. five or more) - relative to some earlier SAC risk assessments (e.g., Aug 2006) - is mainly due to the non-zero likelihood of a lateral blast – a remote possibility but one that exists because a very large, recently-emplaced and still hot dome is present.

30. The risk curves for alternative population scenarios indicate that, if Area 1 were closed and a substantial portion of the population in Area 2 moved to safer locations further north, then the societal risk exposure to the volcano could be reduced to a level lower than that due to other natural hazards - under the present conditions at the volcano.

Individual Risk Exposure Estimates

31. In terms of individual exposure, *individual risk per annum* estimates (IRPA) for people in different areas are calculated using the probabilities elicited from the SAC committee, coupled with Monte Carlo population impact risk simulation modelling. For the present, the numerical individual risk estimates will continue to be categorised according to the descriptive scale of risk exposure levels devised by the Chief Medical Officer (CMO) of the UK government; however, we also indicate, in numerical terms, the extent to which the active volcano increases an individual's risk over and above the 'background' risk of accidental death for a person living in Montserrat, currently assumed to be 28 in 100,000. Table 1 shows how these current evaluations for residents in different areas compare, according to the two different ways of expressing risk metrics.

32. Thus, on the basis of our quantitative risk modelling, we now consider the level of annualised risk of death (IRPA) due to volcanic hazards for an individual in each population Area:

Area 1 (full-time resident): 1-in-1400, LOW / MODERATE on the Chief Medical Officer's (CMO) scale, 3.5*x* background risk level of accidental death

Area 1 (for a person in day-time entry mode only): 1-in-5600 LOW (CMO), 1.6*x* background risk level

Area 2 (full-time resident): 1-in-8850, LOW (CMO), 1.4*x* background risk level

Area 3 (full-time resident, Woodlands, north of Nantes River): less than 1-in-1,000,000, NEGLIGIBLE (CMO), 1.002*x* background risk level.

Table 1. IRPA estimates and Risk Increase Factors for people living in population Areas (values in brackets show Risk Increase Factors from SAC 8)

Areas	**CMO Risk Scale**	**Probability of Death**	**Risk Increase Factor** (SAC8)	**Occupations**
	HIGH			Soldier at war
		1 in 100	36 *x*	
	MODERATE			Deep sea fishing
		1 in 1000	4.6 *x*	
Area 1 (full-time) **Area 1 (day-time)** **Area 2 (full-time)**	LOW	**1 in 1400** **1 in 5600** **1 in 8850**	**3.5 *x*** *(21 x)* **1.6 *x*** (6 *x)* **1.4 *x*** (4 *x)*	Sand and gravel extraction
		1 in 10000	1.35 *x*	
	VERY LOW			Construction Forestry
		1 in 100000	1.03 *x*	
	MINIMAL			Service industries
		1 in 1000000	1.003 *x*	
 Area 3 (full-time) **N. Montserrat**	NEGLIGIBLE	 1 in 2 million less	 **1.002 *x*** (1.04 *x)*	

33. All these individual risk exposure levels are lower than those determined in SAC 8. The reductions in personal exposures for people in Area 1 (both full-time and day-time entry) and Area 3 translate to corresponding changes to a lower category if the CMO's scale is used. Risks in Area 2 stay as LOW. There is a commensurate reduction in risk increase factors. For full-time occupation of Area 1 under current conditions, the volcanic risk factor is estimated to be 3.5*x* the background risk level of accidental death (reduced from 21*x)*. However, this remains a significant elevation of risk exposure above the background risk of accidental death, similar to that faced by people working in the sand and gravel extraction industry.

34. *Risks to workers*

Whilst the risks to workers at Foxe's Bay, in the Belham Valley and at Trants have not been recomputed in this Interim exercise, the expected reductions in volcanic risk, as an increment over basic occupational risk, may be taken to be similar to the change in Area 1 (day-time entry) risk – that is, probably reduced by a factor of between 2*x* and 3*x*, numerically. This still leaves significant degrees of augmentation above the occupational risks that are allowable for the UK extractive industry workers, in all three scenarios, with Belham Valley workers the most exposed, followed by Foxe's Bay and Trants, respectively.

Conclusions

34. The volcano has paused its lava extrusion (since about 4 April 2007) and there may well be many months before it resumes extrusion, if it does at all. We will address this issue in detail at the next full SAC meeting in October.

35. We still consider that the most likely event on the volcano over the next year is a collapse of the dome down the Tar River Valley. However, we think a year with no major eruptive incidents is almost as likely.

36. The current absence of lava extrusion/intrusion as an agent of dome instability (and crater wall instability), the potentially low propensity for rainfall-triggered large collapses to the west/north , and the probable lowered mobility of resultant pyroclastic flows reduces significantly the likelihood of a large dome collapse leading to a pyroclastic flow entering the lower Belham Valley.

37. Despite these favourable trends, a small chance of a hazardous flow into the lower Belham Valley remains. Overall, we find that the societal risk is about 8 times lower than when we last assessed it for SAC 8 [April 2007].

38. The possibility of multiple casualties from potential volcanic activity in particular still remains elevated, and exceeds that due to hurricane or earthquake risk.

39. The volcanic risk exposure levels faced by individuals living in Areas 1, 2 and 3 are also much reduced. For example, for full-time residents of Area 1 the risk of death from the volcano in a one-year period is now 1-in-1400 or LOW/MODERATE on the CMO scale, compared to 1-in-180 in April. Considered another way, the risk is 3.5*x* the background risk level of accidental death (compared with 21*x* in April).

Appendix 7 Limitations of Risk Assessment

A.1 It should be recognised that there are generic limitations to risk assessments of this kind. The present exercise has been a relatively quick assessment, based on a limited amount of field and observatory information and on a brief review of previous research material. The Foreign & Commonwealth Office, who commissioned the assessment, allocated three days for the formal meeting. Thus the assessment has been undertaken subject to constraints imposed in respect of time and cost allowed for the performance of the work.

A.2 While the outcome of the assessment relies heavily on the judgement and experience of the Committee in evaluating conditions at the volcano and its eruptive behaviour, key decisions were made with the use of a structured opinion elicitation methodology[1], by which means the views of the Committee as a whole were synthesised impartially.

A.3 It is important to be mindful of the intrinsic unpredictability of volcanoes, the inherent uncertainties in the scientific knowledge of their behaviour, and the implications of this uncertainty for probabilistic forecasting and decision-making. There are a number of sources of uncertainty, including:

- Fundamental randomness in the processes that drive volcanoes into eruption, and in the nature and intensities of those eruptions.
- Uncertainties in our understanding of the behaviour of complex volcano systems and eruption processes (for example, the relationships between pyroclastic flow length, channel conditions and topography, and the physics of pyroclastic flows and surges).
- Data and observational uncertainties (e.g. incomplete knowledge of the actual channel and interfluve topography and conditions, material properties inside pyroclastic currents, the uncertain nature of future eruption intensities, dome collapse geometries and volumes etc).
- Simulation uncertainties, arising from limitations or simplifications involved in modelling techniques, and the choices of input parameters.

A.4 These are all factors that are present when contemplating future hazards of any kind in the Earth sciences (e.g. earthquakes, hurricanes, floods etc.) and, in such circumstances, it is conventional to consider the chance of occurrence of such events in probabilistic terms. Volcanic activity is no different. There is, however, a further generic condition that must be understood by anyone using this report, which concerns the concept of validation, verification or confirmation of a hazard assessment model (or the converse, attempts to demonstrate agreement or failure between observations and predicted outcomes). The fact is that such validation, verification or confirmation is logically precluded on non-uniqueness grounds for numerical or probabilistic models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[2].

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[1] Cooke R.M., *Experts in Uncertainty*. Oxford University Press; 1991.
[2] Oreskes, N., Schrader-Frechette, K. and Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the Earth Sciences. *Science*, 263: 641-646.

A.5 This report may contain certain "forward-looking statements" with respect to the contributors' expectations relating to the future behaviour of the volcano. Statements containing the words "believe", "expect" and "anticipate", and words of similar meaning, are forward-looking and, by their nature, all forward-looking statements involve uncertainty because they relate to future events and circumstances most of which are beyond anyone's control. Such future events may result in changes to assumptions used for assessing hazards and risks and, as a consequence, actual future outcomes may differ materially from the expectations set forth in forward-looking statements in this report. The contributors undertake no obligation to update the forward-looking statements contained in this report.

A.6 Given all these factors, the Committee members believe that they have acted honestly and in good faith, and that the information provided in the report is offered, without prejudice, for the purpose of informing the party commissioning the study of the risks that might arise in the near future from volcanic activity in Montserrat. However, the state of the art is such that no technical assessment of this kind can eliminate uncertainties such as, but not limited to, those discussed above. Thus, for the avoidance of doubt, nothing contained in this report shall be construed as representing an express or implied warranty or guarantee on the part of the contributors to the report as to its fitness for purpose or suitability for use, and the commissioning party must assume full responsibility for decisions in this regard. The Committee accepts no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG, GoM, or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor do they accept any responsibility or liability to any third party in any way whatsoever. The responsibility of the contributors is restricted solely to the rectification of factual errors.

A.7 This appendix must be read as part of the whole Report.

Appendix 8: Chief Medical Officer's Risk Scale

Negligible (F)#: an adverse event occurring at a frequency below one per million. This would be of little concern for ordinary living if the issue was an environmental one, or the consequence of a health care intervention. It should be noted, however, that this does not mean that the event is not important – it almost certainly will be to the individual – nor that it is not possible to reduce the risk even further. Other words which can be used in this context are 'remote' or 'insignificant'. If the word 'safe' is to be used it must be seen to mean negligible, but should not import no, or zero, risk.

Minimal (E): a risk of an adverse event occurring in the range of between one in a million and one in 100,000, and that the conduct of normal life is not generally affected as long as reasonable precautions are taken. The possibility of a risk is thus clearly noted and could be described as 'acceptable' or 'very small'. But what is acceptable to one individual may not be to another.

Very low (D): a risk of between one in 100,000 and one in 10,000, and thus begins to describe an event, or a consequence of a health care procedure, occurring more frequently.

Low (C): a risk of between one in 10,000 and one in 1,000. Once again this would fit into many clinical procedures and environmental hazards. Other words which might be used include 'reasonable', 'tolerable' and 'small'. Many risks fall into this very broad category.

Moderate (B): a risk of between one in 1,000 and one in 100. It would cover a wide range of procedures, treatment and environmental events.

High (A): fairly regular events that would occur at a rate greater than one in 100. They may also be described as 'frequent', 'significant' or 'serious'. It may be appropriate further to subdivide this category.

Unknown: when the level of risk is unknown or unquantifiable. This is not uncommon in the early stages of an environmental concern or the beginning of a newly recognised disease process (such as the beginning of the HIV epidemic).

Reference: On the State of Public Health: the Annual Report of the Chief Medical Officer of the Department of Health for the Year 1995. London: HMSO, 1996.

Note: We have added "letter designations" and have used these in our text instead of the descriptive names employed in the original CMO scale.