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

Report of the 19th Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between September 22nd and 25th, 2014, at the Montserrat Volcano Observatory, Montserrat

Part II: Full Report

Issued on November 4th, 2014
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Introduction

1. This is Part II of the report resulting from the 19th meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at Olveston House and the Montserrat Volcano Observatory from 22nd September to 25th September, 2014. Part I of that report, the Summary Report1, gives the principal findings of the meeting in a non-technical form2, and Part II gives the underlying technical data and analysis in more detail, including several appendices, that led to those findings.

2. The meeting took place 11 months after we last met, at the end of October 2013. It took place over four days and involved five SAC members, including two new members, Dr Eleonora Rivalta and Dr Eliza Calder, and the new chairman, Prof Jurgen Neuberg. Apologies for absence were received from Prof Steve Sparks. A list of all participants and their affiliations is given in Appendix 3. The MVO produced a “Report of Volcanic Activity” to the SAC3 which was distributed to all SAC members prior to the meeting.

3. One of our main agenda items was the proposed plan for tourist visits into Zone V and the associated risk. In order to get a first-hand impression of the conditions in the areas to be visited, all SAC members spent a couple of hours on the ground in Zone V assessing current conditions at Plymouth Jetty and the northern part of Plymouth, as well as the look-out on St George’s Hill.

4. Based on their volcanic activity report, MVO staff delivered several oral presentations on the monitoring data and observations covering the period between May 2013 and August 2014; their report and presentations included latest developments at MVO, the geothermal site and changes in the alert level system.

5. Discussions during this meeting dealt mainly with (i) the ongoing volcanic activity, (ii) the potential behaviour of the volcano in the longer term and a review of the three ‘end-of-eruption criteria’, and (iii) the hazard and risk levels for the population of Montserrat in different zones for the next year, including the risk to tourists visiting different places in Zone V.

2 The information provided in both parts of this Report is advisory. It 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, and has been prepared subject to constraints imposed on the performance of the work. While Committee members believe that they have acted honestly and in good faith, they accept no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can they accept any liability to any third party in any way whatsoever. See also Appendix 1.
6. As outlined in the Terms of Reference (see Appendix 1), the SAC is also requested to provide independent advice on the scientific and technical operations of the MVO to ensure that the work matches the level of risk; accordingly, a considerable amount of time was spent discussing different monitoring procedures and the role of the SAC in its scientific advisory capacity to MVO. Direct, verbal feed-back including recommendations were given to MVO staff, a summary of which is part of this report.

7. As usual, a Preliminary Statement (Appendix 4) was issued and presented to the Governor, the FCO and the Premier. Given the apparently quiet state of volcanic activity and the subsequent, noticeably low attendance of the general public in a public meeting, as undertaken at previous SAC meetings, we decided to substitute such a meeting with a radio interview with ZJB. This featured the new SAC members and the new chairman, and was recorded and later broadcast.

**Surface Activity and Observations**

8. The volcanic surface activity in the reporting period has been low and remained at the same level as for the last four and a half years. This is the longest pause since the eruption began in 1995. Monitoring data over the last 18 months are depicted in Fig 1 while an overview of the entire eruption is given in Figure 2.

9. Temperatures of volcanic gases that escape through fractures and fumaroles in the lava dome have remained high, with the hottest fumaroles maintaining 600°C over the last four and a half years since the last major activity. Although the dome material is slowly cooling, two processes are acting to maintain these high temperatures: (i) further outgassing of the huge amount of material accumulated in the dome, the entire edifice and the deep magma reservoir provides a steady supply of hot volatiles which has kept the temperatures of the dome and fumaroles in particular at constant, high temperatures, and (ii) a certain amount of heat is produced due to the crystallisation (latent heat) of lava. These conditions might continue for several years, even without any new magma influx.

![Fig.1 Number of seismic events per day (top), ground motion of GPS station MVO1 relative to the volcano (centre), and SO₂ emission rate (bottom) for May 2013 to August 2014.](image)
10. With fewer rock-fall events than before, overall seismicity is further declining as the dome appears to stabilise. No low-frequency seismic swarms, usually associated with magma movement at depth, have been recorded. The only significant seismic signals observed were so-called VT strings, a series of volcano-tectonic earthquakes at a depth of 3 to 5 km which occurred sometimes simultaneously with elevated SO$_2$ emission rates. These events are thought to indicate gas release from depth through the brittle fracturing and opening of cracks within the volcanic edifice.

11. Since the last surface activity in February 2010, sulphur dioxide emissions have converged to an average rate of about 300 tonnes per day, with peaks of about 1400 and 1200 tonnes per day in March and May 2014, respectively.

Fig. 2 Overview of monitoring data throughout the eruption: Daily number of seismic events (top), ground motion of GPS station MVO1 relative to the volcano (centre), and SO$_2$ outgassing (bottom); all in relative amplitudes.

12. Ground deformation on Montserrat continues to show a radial extension away from the volcano. Fig 2, centre panel, shows the linear motion of the GPS station MVO1 compared to previous pauses.

**Long-term processes at the volcano**

13. The “saw-tooth” pattern of ground motion measured across the whole of Montserrat (Fig 2) was previously interpreted as alternating inflation and deflation associated with pause and lava extrusion, respectively. This pattern has been frequently modelled and interpreted in terms of pressurisation of a mid-
crustal magma reservoir. Together with petrological and seismic tomographic evidence for melt at about 5-6 km depth, this has led to a hypothesis of dual chambers, the lower at about 15 km and the upper at about 6 km (Melnik & Costa, 2014).  

**Fig. 3** Horizontal deformation velocities measured at the MVO continuous GPS Stations and corrected for plate motion. Velocities vectors in red represent the ground motion between May 2013 and August 2014, in black for the entire Pause 5.

14. The ground motion depicted in Fig. 3 corresponds to the average motion observed during several pauses and remains more complex than a simple model can explain. Topographic effects as well as loading effects studied by Odbert & Taisne need to be accounted for. In addition, Sparks suggested that a regional pattern of tectonic motion could be responsible for some of the intra-island deformation. The case for left-lateral strike slip motion distributed widely across the northern half of the island can be made from the evidence of offshore sediment displacement, however this model cannot explain all features of the observed ground motion either. More sophisticated models need to be tested and fitted to the data. K. Pascal (MVO) and several SAC members will co-operate on

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this task and will report their findings to the SAC at the next meeting. For the time being we interpret the ground motion as at least partly caused by inflation and, therefore, by continuing accumulation of magma at depth. It is the aim to obtain an upper and lower bound estimate of magma accumulation rate in the near future.

15. T. Christopher and others\(^5\) have analysed multi-year periodicity in sulphur dioxide emissions. Including two early episodes from the COSPEC record there now seem to have been five, approximately two-year long, pulses of elevated sulphur dioxide emission from 1995 to 2010. These pulses do not coincide with the phases of lava extrusion, indicating that at this timescale volatile exsolution is dissociated from magma flux through the system. The cessation of pulse cycles following the 11 February 2010 collapse to be replaced by a much more steady sulphur dioxide emission clearly indicates a change of regime in the deep magma reservoir. T. Christopher (MVO) with various SAC members and other international experts will collaborate to look into possible mechanisms to explain the average sulphur dioxide emission rate of 300 tonnes per day, which could be compared to and constrained by magma accumulation rates derived from the inversion of deformation data.

16. Following a statistical approach, W. Aspinall analysed for SAC 18 the post-2010 record of DOAS-measured emissions using a log-logistic model sampling at 30-day intervals, and updated this with new measurements to end August 2014 (Appendix 5). Since the last eruptive phase, the monthly flux statistics median value has been notably constant through time, but conversely the dispersion on these rates is consistently greater than in previous times. One hypothesis to explain this statistical variability might be that, without major perturbations to the system, for instance due to active magma extrusion or dome growth, the volcano has settled into more uniform gas production at depth, while the route(s) to the surface has evolved into a pathway network with short-term modulated flow rate fluctuations.

Evolution of Future Behaviour

17. We would like to better understand how the volcano might evolve in the coming years. Here we discuss the statistical behaviour of similar volcanoes around the world, based on information from the Loughlin et al MVO study\(^6\) of volcanoes that had built domes since 1800 AD. The dataset comprises 97 examples worldwide, of which Soufriere Hills is the fifth longest-lived. On the basis of these cases, we can calculate a statistical distribution function for the duration of a typical eruption which has been going on as long as the present Montserrat eruption (228 months). We obtain an estimate that the statistical probability of it lasting another five or more years is 85%. For an eruption that has already lasted


228 months, the statistical expectation for total duration (50% probability) is 43 years, i.e. a further twenty-four years or so, in the present case. On the basis of the same global data, the statistical probability of an eruption like this one stopping within one year – if it has not already stopped and without considering any evidence for a declining activity trend – remains at about 4% (i.e. a 1-in-25 chance).

18. For the first time, at SAC18 we elicited the probability that nothing significant will happen in the next 30 years - i.e. there will be no significant collapse, no restart of dome growth, or no magmatic explosion > 0.1x ref. Then, the elicited median probability for this eventuality was 16%, or about a 1-in-6 chance. At SAC19 the elicitation was repeated, and produced a new, higher probability of 32%; in other words, the odds against this scenario are shortened. However, uncertainty on this estimate remains wide, the ninety-percent credible range is from 8% probability to 85% probability (Appendix 6, question 6), reflecting the difficulty of assessing the long-term future behaviour of the volcano in the absence of compelling evidence on its own trend and pattern of activity.

19. However, if we revert to the global statistics of dome-building eruption durations used above, and go back to the point in time of last eruptive activity in February 2010, a recalculation of the Generalized Pareto distribution survivor function at that instant would have indicated an 84% probability of the eruption still continuing now, in September 2014, and a 35% probability of it being on-going in a further 30 years time. The complement of these values would have implied a 16% chance that the eruption might stop in the intervening 54 months, and a 65% chance it could stop in the additional 30 years. Thus, given there has been nearly five years of inactivity, the new elicitation finding of a 32% median probability of no further significant eruptive activity in the next 30 years and an upper confidence bound of 85% probability for this period are not incongruent with the global data.

20. The recent advent of a new extensive dome eruption database (Ogburn et al., 2013)⁷, with more data than that used here, offers the prospect of updating the analysis of the statistical properties of dome building eruptions and, in particular, how they finish. This would be valuable additional information for assessing the eventual evolution of the Soufrière Hills eruption.

**Hazard Scenarios**

21. We now summarise the results of the formal elicitation of the views of the SAC members and MVO staff on the probabilities of occurrence over the next year of the hazardous events that are inputs to the risk simulation modelling. In order to assign quantitative estimates to these probabilities, we use our knowledge of the factors that influence specific hazard scenarios, results of any available modelling

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analyses, and the expert elicitation method that we have used in previous SAC assessments. The questions, explanations of their context and the ranges of uncertainties derived from the group’s responses are presented in detail in Appendix 6. Here, on Table 1, we tabulate the ‘best estimate’ probability values for each of the questions and compare them with the equivalent values obtained previously, at SAC18. The series of query Items 2a-2i ask what is the probability that each of these events will be the first significant thing to happen in the next 12 months. Note that these probabilities are only valid under current conditions and have to be re-evaluated in case current conditions change.

**Table 1. Summary of SAC19 elicited eruption scenario central value estimates of scenario probabilities (items marked * were not re-considered)**

<table>
<thead>
<tr>
<th>Elicitation Question (summary description)</th>
<th>Probability SAC19 (SAC18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  At least one criterion for deep magma activity will be met</td>
<td>98% (95)</td>
</tr>
<tr>
<td>2a Nothing significant happens</td>
<td>64% (67%)</td>
</tr>
<tr>
<td>2b Quiet resumption of lava extrusion</td>
<td>32% (15%)</td>
</tr>
<tr>
<td>2c Collapse of most of dome to east (or south)</td>
<td>1% (5%)</td>
</tr>
<tr>
<td>2d Major dome collapse to reach the sea to the NE</td>
<td>0.3% (2%)</td>
</tr>
<tr>
<td>2e Major dome collapse to reach Happy Hill to the NW</td>
<td>0.03% (0.5%)</td>
</tr>
<tr>
<td>2f Major dome collapse to reach Plymouth to the W</td>
<td>0.06% (0.8%)</td>
</tr>
<tr>
<td>2g Blast event to reach Happy Hill to the NW</td>
<td>0.001% (0.03%)</td>
</tr>
<tr>
<td>2h Blast event to reach Plymouth to the W</td>
<td>0.003% (0.08%)</td>
</tr>
<tr>
<td>2i Vertical explosion (&gt;0.3 million cubic metres)</td>
<td>2% (8%)</td>
</tr>
<tr>
<td>3a Next Phase of lava extrusion to be long duration type</td>
<td>(30%)*</td>
</tr>
<tr>
<td>3b Next Phase of lava extrusion to be short duration type</td>
<td>(70%)*</td>
</tr>
<tr>
<td>4 Extrusion rate on re-start</td>
<td>(5.5 cu m/sec)*</td>
</tr>
<tr>
<td>5 Major explosion (&gt; 9 million cubic metres)</td>
<td>(0.4%)*</td>
</tr>
</tbody>
</table>

22. Between the elicitations of SAC18 (October 2013) and now (September 2014), the assessed median probability that “nothing significant” occurs in the next 12 months is almost unchanged (the small drop is well within the uncertainty associated with such probabilistic enumeration and should not be ascribed significance). There is an apparent and notable increase in the assessed likelihood of a quiet resumption of lava extrusion; however, this is, in effect, offsetting systematic reductions in the median probabilities for all the other, more energetic, magmatic restart scenarios (i.e. questions 2c – 2i).

23. Taken together, the probability changes may express a collective view that, while the chance of nothing significant happening over the next year is judged to have not increased, the chances of any of the sudden and violent restart scenarios occurring are now much reduced relative to the scenario of a quiet resumption of lava extrusion. This said, the ‘nothing significant happens’ scenario is, at 2-to-1 on in betting odds terms, judged four times more likely than the next most likely scenario – ‘quiet resumption of lava extrusion’ (2-to-1 against).

24. **Care is needed when judging these median probabilities at face value.** They are only part of the picture of scenario likelihoods because their associated
uncertainty distributions (Appendix 6) must be taken into account when quantifying risks to the population; full uncertainty quantification is essential in formulating a basis for a risk analysis, the findings of which are reported in following sections.

25. Given there has been no new activity and no substantive new insights into related volcanological factors, the previous (SAC18) elicitations of complementary probabilities for items 3a, 3b are retained here unchanged – that is, a new phase of lava extrusion, if it occurs, is more than twice as likely to be of the “short duration” type experienced in Phases 4 and 5, rather than reverting to the earlier, long duration extrusion behaviour.

26. Similarly, we accept, unrevised, the SAC18 elicited central probability for a major explosion (item 5), held at 0.4% in 12 months (i.e. 1-in-250 chance). It was noted in the SAC18 Report that this probability might have reflected a view at the time, that given the deep inflation signal and continued sustained gas output, the present long pause could culminate in a new short duration episode of magma eruption, with a small, non-zero chance of an associated major explosion. The probability of this particular scenario should be re-considered at the next SAC, especially if there is a new appraisal of possible non-magmatic causal elements contributing to the deformation signals that have been inferred, thus far, to indicate deep inflation under the volcano.

27. Many of the other probabilities also appear to change to minor extents, but these variations are not significant given the range of uncertainties involved and the tentative nature of such hazard estimates.
Quantitative Risk Assessment

28. We make use of the same procedures for quantitative risk assessment that have been used by the SAC since 1997 (described in detail in the report from SAC16). For continuity and comparability, we continue to use the on-land Hazard Level System (HLS) zone boundaries that were defined in the November 2011 version of the HLS (which remain essentially the same in the latest version, promulgated in August 2014 - see Fig. 4).

29. The issue of population numbers is fundamental to the estimation of societal risk levels (but not individual risk estimates). A census of Montserrat was taken in May 2011 but those data were insufficiently detailed to be used fully in the SAC risk assessments. In SAC18 we used population numbers, based partly on information from the 2011 census, which indicated that 583 people were in the area south of Nantes River (the northern boundary of Zone A) in May 2011,
during the low season for visitors to the island\(^8\), and partly on an MVO estimate that the number of people who were living full-time in Zone B was about 33. Thus we inferred a population of about 550 in Zone A. We further assumed that there could be a 50% increase in the numbers in Zone A during high season (presumed to be November to March inclusive), whilst the numbers in Zone B could be doubled. Similarly, we assumed a potential increase of 25% in the population of Woodlands during the high season period. These were central estimates so, for risk assessment, purposes, we also assumed suitable variations about these numbers. In running the risk model, the higher holiday numbers are activated if the initiating hazard event is simulated as occurring in one of the high season months (this was a modelling refinement, in comparison to previous analyses). For continuity, and in the absence of newer information, these population numbers and seasonal variations are retained for the present risk assessment.

30. Other uncertain volcanological factors, for instance relating to lava extrusion restart, prospective multiple episodes, a less favourable site of outbreak in the crater or higher extrusion rate, potentially would increase the threat to the populated areas to the northwest of the volcano. These threats could involve incursion into areas by pyroclastic flows or surges or, more dangerously, by lateral blasts. Given the present conditions, the median values for probabilities of flow incursions are estimated to be lower than those from SAC18: for Zone B, the elicited probability of a pyroclastic flow reaching this far within the next year is about 1–in–300 (SAC18 1-in-230), almost halved when compared to SAC17 (1-in-170). For Zone A the risk can be viewed as substantially reduced now, at 1–in–1900 (SAC18: 1-in-710; SAC17: 1-in-660).

31. For the case of a lateral blast-derived surge, the corresponding incursion probabilities from the latest elicitation findings are, however, noticeably reduced from those obtained in SAC18, and lower even than the preceding values from two years ago at SAC17. Zone B surge incursion odds are now assessed at 1-in-9200 (SAC18: 1-in-4000; SAC17: 1-in-8400); Zone A, 1-in-10,200 (SAC18: 1-in-4500; SAC17: 1-in-9300). In other words, the risk of incursion in Zone B is now judged equivalent to what it was for the safer Zone A, two years ago. These sizeable changes reflect the latest revisions in the elicited central value for the probability (Item 2g on Table 1) of a major dome disruption event with an associated blast avalanching to the NW, capable of generating a surge that reaches Happy Hill and beyond.

32. Although the area between Nantes and Lawyers Rivers (Woodlands) is not a Hazard Zone under the HLS, for consistency with previous SAC analyses we have calculated the likelihoods of pyroclastic flow or blast surge reaching this area in the next year. These now stand at about 1-in-32,000 (SAC18: 1-in-24,000) for a flow and about 1-in-140,000 (SAC18: 1-in-60,000) for a blast surge – these are very low probability prospects, with much longer odds against occurrence relative to those estimated for SAC17, or even SAC16.

\(^8\) The area north of Nantes River lies outside of the MVO Hazard Level System defined Zones; however, in line with previous assessments we continue to assess the contribution of this area to the overall societal risk estimation.
33. Some variation in such assessed probability values, from one SAC meeting to the next, is due to the acute difficulty of quantifying probabilities for unlikely events, so the quoted numbers should be regarded as indicative, rather than definitive. This said, and the very low likelihoods notwithstanding, potential consequences for the populations of each these areas could be extreme should a blast surge event occur in their direction.

**Individual Risk Exposure Estimates**

34. In terms of individual exposure, *individual risk per annum* estimates (IRPA) for people in different Hazard Zones are calculated using the probabilities elicited from the SAC committee, coupled with Monte Carlo population impact risk modelling. We have categorised the levels of risk exposure using the six-point risk divisions of the scale of the Chief Medical Officer of the UK government in which we have replaced the labelling of these factor-of-ten divisions with an alphabetical ordering, which we term the Modified Chief Medical Officer’s scale (CMO*) (see Appendix 8).

35. We also indicate, in numerical terms, the extent to which the 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 (a value taken from statistics for the US Virgin Islands). Table 2 shows how the current evaluation compares according to these two measures. The two types of risk are also displayed in a graphical manner in Figs. 5 and 6, which show the range of risks faced, displayed on a vertical logarithmic scale.

36. On the basis of our assessment of the volcano’s future behaviour – including possible re-start of lava extrusion and accompanying hazards - our quantitative risk modelling indicates the annualised risk of death (IRPA) due to volcanic hazards for an individual in each of the open or populated Zones of Fig. 5 is:

- **Zone C (full-time resident):** 1-in-29,000; *D* on the CMO* scale, 1.1x background risk level of accidental death.
- **Zone B (full-time resident):** 1-in-95,000; *D* on the CMO* scale, 1.03x background risk level of accidental death.
- **Zone A (full-time resident):** 1-in-950,000; *E* on the CMO* scale, 1.003x background risk level of accidental death.

In the case of Zone C, under the August 2014 revised Montserrat HLS (see MVO Open File Report OFR-14-02) day-time only entry restrictions are lifted at Hazard Level 1. Whereas previously individual risk in Zone C was estimated on the basis of a person making limited visits of duration about 8 hours, the risk exposure is calculated here for full-time occupation; it comes out at about 1-in-29,000 for a hypothetical individual resident in annualized terms. This risk level is very similar to, but marginally lower than that assessed in SAC18 for this Zone.
Table 2  IRPA estimates for volcanic risks to occupants of populated or open areas

<table>
<thead>
<tr>
<th>Residential Area</th>
<th>CMO* Risk Scale#</th>
<th>Annualised Probability of Death</th>
<th>Risk Increase Factor</th>
<th>Other Natural Hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td>1 in 100</td>
<td>36x</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>1 in 1000</td>
<td>4.6x</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>1 in 10000</td>
<td>1.35x</td>
<td></td>
</tr>
<tr>
<td>Zone D (full-time)</td>
<td></td>
<td>1 in 29,000</td>
<td>1.1x</td>
<td>Hurricane</td>
</tr>
<tr>
<td>Zone B (full-time occupation)</td>
<td></td>
<td>1 in 95000</td>
<td>1.03x</td>
<td></td>
</tr>
<tr>
<td>Zone A (full-time occupation)</td>
<td></td>
<td>1 in 950,000</td>
<td>1.003x</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Whole island</td>
<td>1 in 200,000</td>
<td>1.02x</td>
<td>Earthquake</td>
</tr>
<tr>
<td>Zone A (full-time occupation)</td>
<td></td>
<td>1 in 950,000</td>
<td>1.003x</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Woodlands (full-time occupation North Montserrat)</td>
<td>Less than 1 in 10 million</td>
<td>1.0001x</td>
<td></td>
</tr>
</tbody>
</table>

but under different circumstances (i.e. restricted entry) and volcanic conditions; the change in assessed risk is indicative of the current reduction of assessed hazard levels, overall. The corresponding CMO* Scale for this Zone is D, with the risk falling in the upper range of this ranking.
Fig. 5 Relative individual annual risk from the volcano for full-time Montserrat residents compared with other non-volcanic risks in Montserrat and everyday risks in the UK.
Due to the changes in the assessed event probabilities, discussed earlier, the individual risk exposure levels in Zones B and A are each substantially lower than one year ago (i.e. SAC18: 1-in-3,200 and 1-in-35,000, respectively). The present risk value for Zone B remains in CMO® Scale ranking D, but now sits at the extreme lower end of that range. Zone A is ranked in E, and sits at the very lowest end of that risk range.

The IRPA for the Woodlands area (and further north) remains negligible. While the exact risk is very difficult to determine numerically with any confidence, our tentative analysis puts individual risk from the volcano in Woodlands and in the far north of the island in the same ballpark of the risk of an individual being killed by lightning (see Fig. 5).

**Proposed Plymouth Visitor Tours - access risks**

37. An update to the SAC18 IRPA assessment for Plymouth Jetty and Belham Valley workers is provided in a separate, more detailed Assessment Paper, covering the risk in more detail for persons entering Zone V (Appendix 7). Here, we summarize the main issues and findings.

38. The Montserrat Governor’s Office has prepared a “Plymouth Tour Concept Note” which outlines preliminary aspects of a proposal to institute excursion tours into Plymouth by cruise ship passengers, stay-over visitors, day ferry trippers and local residents. Using the information in that Note, a scoping calculation has been undertaken to estimate the volcanic risk levels to which tourists and bus drivers could be exposed whilst transiting Zone C and visiting Zone V, according to the tentative timetable outlined in the Note. For this, risk model probability parameters are updated with the latest volcanic event probabilities elicited during SAC19.

39. If there is continuing presence of a fully-functioning MVO, providing monitoring and alert back-up to the bus convoys, the estimated individual risk of death per annum (IRPA) for a tourist making a single visit is about 1-in-20 million, roughly the same likelihood as a person being killed by lightning in the UK in the next year. Without the MVO, the risk for a tourist would rise to about 1-in-200,000; hence the risk would increase by two orders of magnitude.

40. Assuming one hundred days with three fully-subscribed tours each day, with MVO support, the probability of having one or more tourists killed by volcanic activity in the next year is estimated to be about 1-in-34,000; without the MVO support, this risk could rise to 1-in-3,200. Based on current conditions, the probability of mass casualties in Montserrat terms (i.e. about five victims) is very similar, and only marginally lower for fifty or more casualties - reflecting the truism that, with large numbers of persons present in a zone that may be impacted by a violent volcanic hazard, the likelihood of suffering a high proportion of casualties is not significantly less for many than for a few.
41. For bus drivers making 100 trips in a year, the corresponding IRPA values are: 1-in-170,000 (with MVO), and 1-in-2,000 (without MVO). The former is below the range of typical occupational risks reported in the UK, whereas the latter is much greater (see, e.g., Figure 5 in SAC17 Report Part II).

42. The comparative risk estimates given above, with and without an MVO, demonstrate the critical importance of a fully-functioning monitoring service, even though it cannot be assumed that MVO will be able to give adequate early warnings on every occasion a volcanic event takes place once a tour has entered Zone C or Zone V (see description of jetty workers risk assessment in the SAC 18 Report Part II).

Societal Risk Levels

43. 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. Taking the elicitation results reported above, the risk assessment analysis uses Monte Carlo re-sampling to explore possible outcomes from a range of scenarios relating to dome collapse, lateral blast, and from relative likelihoods of their occurrence. Our assessment represents a one-year risk outlook.

44. Fig. 6 shows the calculated current annualised societal risk curves for Montserrat using the assumed population numbers for the situation where there might be a rapid combination of hazards from, say, a major dome collapse and a near-simultaneous explosion, both occurring close in time as a restart to eruptive activity (solid red line). Also shown on Fig. 6 is the counterpart societal risk curve produced a year ago (SAC18, blue line), also for the situation of compound restart hazards.

45. Overall, the current societal risk – expressed as different total numbers of casualties – is evaluated now well below the level assessed in SAC18, reflecting the reduction in elicited event probabilities for the greater threat scenarios. For comparison, the highest societal risk curve in recent years was that of March 2007 (SAC8), when the dome was very active and still growing vigorously (Fig. 6, upper, dashed red line).

46. For the first time since the eruption started in 1995, the projected chances of casualty numbers, due to volcanic hazards, are significantly below the estimated long-term societal risk exposure on Montserrat from earthquake or from hurricane (Fig. 6, black lines with symbols). Even though this clear gap has now opened between volcanic risk levels and those of other natural hazards, it should be remembered that hurricane and earthquake threats are island-wide, hence independent of location, whereas volcanic risk could be reduced, if desired, by additional mitigation measures (e.g. moving more people further away from the volcano).
47. The main conclusion to be drawn from these curves is that, overall, current societal risk levels for fatalities are assessed significantly reduced compared to those estimated about a year ago. This said, some caution should be exercised when using the information implied by the curves shown on Fig. 6. Each curve carries a significant element of uncertainty, up or down, and numerical differences between any two curves may be less than indicated by these central tendency (median) calculations. Thus the present estimated likelihood of suffering one or more casualties in the next year due to volcanic action is in the region of a 1-in-2000 chance, but could be somewhat higher, or lower, under different assumptions.
The Operation of MVO

48. The next 5-year contract for the management of MVO has been awarded to the Seismic Research Centre (SRC) of the University of the West Indies, but has not yet been ratified.

49. Most of the cGPS network and the Air Studios, Trants and Gerals strainmeters are operational. MVO1 was flooded on August 25, 2014, and is down since. Calipso equipment was recycled in Dec 2013. Under the new contract there is provision for a general upgrade of the seismic network including new seismometers at Galways, Hermitage, South Soufriere Hills and Rendezvous and abundant spare capacity. The upgrade to the DOAS (SO$_2$) network with instruments supplied by Dr. V.Tsanev of Cambridge is still not completed. The set supplied does not seem to be fit for purpose on an operational level. The INGV (Italy) Multigas instrument has also proven to be insufficiently robust for use long-term in the plume (beyond a few weeks). The instrument was taken back to Italy in August 2013. The infra-sonic network near the helipad is down and awaiting maintenance through the University of Florence led by M. Ripepe. The ground-based radar instrument AVTIS 3 is not operational awaiting replacement of a gimbal.

50. The US spider deployment is underway and the additional stations in the near field of the seismic sources have demonstrated already their usefulness through improved depth location.

51. MVO is now better integrated in the operations regarding the Geothermal Drilling Project on Montserrat. The director R. Stewart is a full member of the project’s operational board.

52. Given the proficiency, competence and high motivation of the scientific and technical staff, the overall monitoring capacity of MVO regarding the measurements of ground deformation, gas and seismicity can be considered as adequate to the current level of volcanic risk. We note that any attempt to relax any restrictions to enter Zone V is entirely dependent on the MVO’s capability to detect even the slightest changes in volcanic activity in a timely manner.

53. Before the new seismic network will be ready for installation, the SAC recommend performing a vulnerability analysis of the network including all back-ups, relays and radio links. It has been demonstrated on many volcanoes worldwide, and on Montserrat during the run-up to the Boxing Day event in 1997, that in case of increased volcanic activity major parts of networks can fail and leave the observatories with insufficient monitoring capacity once the eruption is under way.

54. VT-strings are at present the most significant seismic signals sometimes accompanied by increased gas emission and the occurrence of VLP events. To utilise the full capability of seismic broadband equipment we recommend integrating (velocity to displacement) the signals of at least one seismic station in
order to detect more easily VLP events. This should be done on a routinely base
together with the display of the filtered traces.

55. A webpage is nowadays an important communication tool as well as the public
façade of an organisation. We feel that the current webpage does not represent the
MVO properly, as it does not reflect the wider scope of all MVO operations, nor
the profiles of MVO scientific and technical staff. We recommend focussing on
the re-build of the webpages as a matter of urgency, even though the new
software engineer might not be in place yet.

56. We understand that the loss of the previous webpages was caused by computer
problems completely out of MVO’s hands. This situation reveals the importance
for MVO to be computationally more independent and not to have to rely on a
network manager who is not fully integrated in MVO operations. We recommend
an analysis of this unsatisfactory situation to prevent similar problems in the
future.

SAC Matters

57. The SAC has undergone a renewing process of membership with two new
members and change in chairmanship. To keep the right balance between
renewing the membership and maintaining important experience the next changes
in personnel will be carried out at a slower pace than envisaged previously. Prof
Sparks agreed to stay on the SAC for another year. Prof Aspinall will hand over
the role of elicitation facilitator to Dr Calder at the next meeting, allowing a
smooth transition of this vital role. According to the Code of Practice for SACs
we will define a job description for the SAC member replacing Prof Sparks and
advertise the position in co-operation with the FCO.

58. The next meeting of the SAC will take place in September 2015 unless a
significant event on the volcano brings that forward.
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 Soufrière 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 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 was Helen MacLeod, Desk Officer for Montserrat in OTD. Her contact details are as follows:

Email: helen.macleod@fco.gov.uk
Tel:   +44 20 7008 3123
Fax:   +44 20 7008 2879
Appendix 2: Agenda SAC19

September 21st – 24th, 2014

Sunday, 21st, 2014 (Olveston House, SAC)

Introduction to new SAC members

14:00h
- Modus operandi, past – future
- SAC 19 Agenda
- SAC Terms of Reference (ToR)
- Code of Practice for SACs
- Role of SAC

Monday, 22nd, 2014 (SAC & MVO staff)

09:00h MVO

09:30h Start of Meeting
(i) Meeting agenda & plan, TOR
(ii) Volcanic activity report, presentations (MVO)
(iii) Change of Alert Level System
(iv) Geothermal project
(v) Analysis of volcanic activity
(vi) Comparison with Doppelgänger study
(vii) Identification of future hazard scenarios
(viii) End of eruption criteria

Tuesday, 23rd, 2014 (SAC & MVO staff)

09:00h Visit to Plymouth & St George’s Hill

11:00h Meeting
(ix) One-year hazard assessment
    - Briefing
    - Elicitation

(x) Tourist visits to Plymouth & St George’s Hill

14:30h Meeting with Governor & Premier (Gov’s Office)

(x) (continued…)

(xi) Number crunching/preparation of report
Wednesday, 24th, 2014 (SAC & MVO staff)

09:00h Meeting

(xii) Health check of elicitation results

(xiii) MVO matters
  - Communication with MVO
  - MVO website
  - Monitoring issues
  - Co-operations/knowledge exchange to/from MVO
  - Expectations re SAC

(xiv) SAC matters (SAC only)
  - SAC membership
  - Role of SAC
  - Performance of MVO

Thursday, 25th, 2014

09:00h Meeting

(xv) Feed-back to MVO (SAC & MVO staff)

(xvi) Preliminary statement (SAC)

(xvii) Preparation of SAC statement re ‘Plymouth & St George’s tourist visit’
Appendix 3: List of Participants

Chairman
Prof. J W Neuberg  University of Leeds, UK

Committee members
Prof. W.P. Aspinall  Aspinall & Associates & Bristol University, UK
Prof. J. Barclay  University of East Anglia, UK
Dr. E. Calder  University of Edinburgh, UK
Dr. E Rivalta  GFZ-Potsdam, Germany
Mr R. Stewart  Director, MVO; University of the West Indies

Dr. T. Christopher (MVO)
Dr. A. Stinton (MVO)
Dr. P. Smith (MVO)
Dr. K. Pascal (MVO)
Ms V. Bass (MVO)
Mr R. Syers (MVO)
Mr. Pyiko Williams (MVO)
Ms N. Edgecombe (MVO)
Dr. E. Joseph (Seismic Research Centre, UWI)
Appendix 4: Preliminary Statement SAC 19

September 25th, 2014

During the past year Soufriere Hills volcano showed no significant changes in its behaviour. While the major part of the lava dome remains stable and rockfall activity continues to decline, the dome has still the potential to become unstable. Temperatures of volcanic gases that escape through fractures and fumaroles have remained high with the hottest fumaroles maintaining 600°C over the 54 months since the last major activity.

Measurements by the MVO show a steady rate of sulphur dioxide emission of about 300t/day over the 54 months. Seismicity overall has declined to a low level except for occasional short bursts of volcano tectonic events that occur, sometimes accompanied by elevated degassing. Measurements of ground deformation indicate a slow but continuous lengthening trend over the island, interpreted as due to inflation of the volcano. In the past, this has been taken as a sign of continuing replenishment of a deep magma reservoir. When these observations and measurements are taken together we conclude that the volcano remains in a state in which lava extrusion is still possible at short notice; however, there is no indication that this is imminent.

We interpret the absence of pyroclastic flows or major rockfalls in the last year as an indication that the lava dome continues to stabilise. While the hazard from pyroclastic flows and surges into the lower Belham Valley and Plymouth remains we estimate the chance that such an event occurs within the next year is now less likely than one year ago. However, the volcano remains a source of hazards, some of which could occur at any time with little or no warning, and consequently could pose a threat to people working in or visiting Zone V.
Appendix 5: Soufriere Hills volcano: long-term statistical trends in measured SO$_2$ flux

Willy Aspinall
29 October 2013; updated 14 October 2014

This note examines long-term temporal fluctuations in the statistical properties of SHV SO$_2$ flux measurements in terms of the parameters of a LogLogistic (LL) distribution. Over the length of the eruption, the LL is found to be as good a fit to random sub-groups of SO$_2$ data as any other distributional form, and so a series of LLs are sequentially obtained by fitting to contiguous 30-day sets of daily measurements (where the period has at least ten values).

The version of the LL adopted here has two parameters: LL$[\alpha, \beta]$ where $\alpha$ is a shape factor, and $\beta$ is a scaling factor which, in the case of an LL distribution, is equal to the median value of the variable samples. A high value of $\beta$ indicates a high median value, while high $\alpha$ indicates a narrow, concentrated spread in the distribution. Two pairs of examples from the SHV dataset illustrate these attributes in Figures 1 & 2:

**Figure 1:** In the first case, the two samples have very similar median values (expressed as Ln (flux) – i.e. Ln(6) ≈ 400 t/d), but the 20/05/2013 data are much more tightly clustered around their median than are the 02/12/2010 samples (dates are the mid-points of the respective 30-day intervals).

**Figure 2:** In this panel, the distributional spreads are similar, but the 30-day medians ($\beta$) differ substantially, being equivalent to daily fluxes of 900 t/d (16/02/2008) and 135 t/d (21/02/2007).
Next we examine how fitted parameter values for $LL[\alpha, \beta]$ vary with time throughout the eruption. Uncertainties are calculated for $\alpha, \beta$ for each 30-day dataset, as a function of number of measurements available.

**Figure 3:** Time series showing variation through time of the LogLogistic $\beta$ (median – upper panel) and $\alpha$ (shape – middle panel) parameters, with uncertainty estimates; the lower panel shows long-period trends for both parameters, by Kalman filter analysis.

The upper panel depicts variation with time of the LL $\beta$ (median) parameter with – unsurprisingly – an overall pattern that is quite similar to that exhibited by plots of the 7-day filtered SO$_2$ data in MVO/SAC reports (see below). The boxes indicate $+1$ and $-1$ sd uncertainties on each 30-day estimate. The absence of obvious association with extrusion phases or pauses up to Phase 5 is again manifest; however a different regime appears to set in for the current Pause. In addition, there are no obvious annual or seasonal patterns, although to be confirmed this requires a more detailed time series analysis than is deployed here.
Temporal variations in the LL $\alpha$ (shape) parameter are shown in the middle panel, with uncertainties indicated here as bars. There are sections where $\alpha$ and $\beta$ appear to increase in unison (e.g. latter part of Phase 2), as one might expect if the number or size of the largest flux episodes is elevated, but at other times that pattern is absent.

In the lower panel, the two datasets are smoothed by a Kalman filter, and their fundamental low-pass normalized trend components are shown jointly (tests indicate individual datapoint residuals are uniformly and normally distributed). As just remarked, inspection suggests there may be correlated changes in $\alpha$ and $\beta$ from the latter part of Phase 2 through to Phase 5. Ignoring data prior to 2001/01/01 because of data sparseness, the correlation between $\alpha$ and $\beta$ from 2001 to present is statistically meaningful, but not high (+0.30); for the restricted period from 2001/01/01 to 2010/02/10 the correlation is greater: +0.54. In other words, in that nine-year period about 30% of the variability in one parameter may be associated with variations in the other, in the interval encompassing Phases 2 to 5 and intervening Pauses.

This modest positive correlation suggests that as $SO_2$ median flux levels increased there was also a tendency for the spread of 30-day measurements to tighten around the median value. The raw data will need to be scrutinized to determine whether this is due to reductions in the numbers/values of low observations, or high ones, or both.

In the current pause, since Phase 5, an opposite pattern is manifest: long-term LL $\beta$ (median) values have become stabilized at a moderate level (upper panel): typically ~350 t/d equivalent – or slightly lower than the corresponding current long-term average (mean) of 460 t/d (MVO OFR 13-06), commensurate with a skewed distribution with longer upper tail. But, at the same time, the LL shape parameter $\alpha$ has gone high, and even carries a hint of an on-going increase during the current year (2013). In other words, fluctuations in the daily measurements are getting smaller compared to previous times in the eruption when flux rates were similar.

Figure 4: Figure 2.1.1 from MVO OFR 13-06 (2013)
**Frequency spectra**

Next we examine frequency components in the time series of the two loglogistic parameters, $\beta$ (median) and $\alpha$ (shape), using a standard fast Fourier transform (FFT) technique.

For $\beta$ (median), the FFT amplitude spectrum shows several peaks (figure 5), but no dominant single frequency. There are long-period peaks (e.g., a double peak at about 343/480 days and another at around 800 days) which correspond to the sustained periods of high gas output, shown in the upper panel of Fig 3, above. Other, minor peaks are present for $\beta$ indicating periods of about 83, 100 and 133 days; it may be possible to identify when these were present in terms of their timing during the eruption by FFT analysis of shorter sections of the time series.

![FFT spectral analysis of the LogLogistic $\beta$ (median – upper panel) and $\alpha$ (shape – lower panel) parameters](image)

For $\alpha$ (shape), there are two long-period peaks (i.e., 343 and 800 days) which are the same as two of the three in the $\beta$ (median) spectrum, and another strong peak at 96 days.

Again, it may be possible to determine when, during the eruption, this latter periodicity was happening, and relate it to conditions at the time.
Discussion (October 2013)

In terms of representative 30-day samples (i.e. 10 data points or more), these time series are satisfactorily complete from mid-2002 onwards, with plentiful observations for distribution fitting.

With the LL β median flux rate data, the most obvious long-term features are the previously-recognized three episodes of waxing then waning output levels between 2002 and 2010, followed by a near constant trend, since Phase 5 ended. In this logistic statistical representation of the data, the episodes have more saw-toothed appearance than the 7-day averaged data from MVO, and this attack-decay pattern is more evident in the low-pass Kalman filtered version (lower panel). What also seems clear is that the temporal pattern of SO₂ production from SHV is currently in a different regime, with observed fluxes that are much more constant and more uniform than before during the eruption.

Various reasons can be conjectured for these patterns: at the SHV, the logistic distribution has been found to summarize interval patterns in the 1997 series of vulcanian explosions, with explanation adduced in terms of the net effect of two competing processes (Connor et al., 2003), and to characterize rockfall frequencies in relation to dome-building extrusion rate (Calder et al., 2005).

In contrast to those two, relatively short-term cases, where a single logistic distribution is determined, the present analysis of gas flux observations shows the existence of significant long-term variations in the parameters of distribution fits. A possibility is that here also there are two contributing – and time-varying – processes: one might be deep production rate, and the other conduit/dome throughput, with changes in the former manifest in the level of the LL β (median), and changes in effective permeability/transmissivity showing up as variations in LL shape factor α.

In considering the pattern since Phase 5 and what the future holds at SHV, one speculative hypothesis might be that, without perturbations due to active magma extrusion or dome growth, the system has settled into more uniform gas production at depth, and the route(s) to the surface has evolved into a pathway network with modulated flow fluctuations. The current long-term trend in LL β (median gas flux rate) shows no sign of diminishing, so constancy of deep production might be inferred. One might go further and suggest something major and dynamic would be required to engender a game-changing disturbance of the present flow path.

This said, the application of more detailed time series analysis techniques might reveal other features, especially in relation to short-term patterns.

Update (October 2014)

Courtesy Thomas Christopher (MVO), the dataset used in this analysis has been updated by the addition of SO₂ flux data from September 2013 to end of August 2014.

Figure 6 shows the time series of the value of the Loglogistic β value (scale parameter: i.e. median), together with estimates of the corresponding 30-day LL distribution 5th and 95th percentiles using the corresponding α (shape) values (these percentiles were not plotted above, in the earlier version of this Note).
Figure 6  Timeline plot of the LogLogistic β value (median 30-day SO₂ flux: central markers with line), and LL distribution 5th and 95th percentile values.

As noted above in the Discussion, there appears to have been a definite change in the gross statistical properties of this time series from March 2010 onwards (a gap in this dataset extends from 21 Oct 2009 to 17 Mar 2010), which has persisted throughout the most recent 12 months. In particular, the median 30-day flux and the lower bound (5th percentile) values have remained notably stable, without the long period variations exhibited before early 2010; short-term excursions of the upper tail of the distribution continue, but with a hint of an overall slow decline in amplitude.
Appendix 6: SAC 19 Elicitation of Probabilities for Hazard Scenarios

**Target questions**

1. GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that at least one of the criteria for continuing activity will be sustained over the next 12 months.

<table>
<thead>
<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>69%</td>
<td>98%</td>
<td>99.99%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>56%</td>
<td>95%</td>
<td>99.9%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>53%</td>
<td>97%</td>
<td>99.9%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>51%</td>
<td>95%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

*1. GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that the criteria for cessation of eruption will start to be met (even though we can’t confirm it according to 1 year test period) in the next 12 months.

2a. GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that **nothing** significant will happen (i.e. no collapse, no restart of dome growth, no magmatic explosion > 0.1x ref) in the next 12 months.

<table>
<thead>
<tr>
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<th>Credible interval lower bound</th>
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<th>Credible interval upper bound</th>
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<td>64%</td>
<td>91%</td>
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<tr>
<td>SAC 18</td>
<td>20%</td>
<td>67%</td>
<td>94%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>9%</td>
<td>43%</td>
<td>82%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>1%</td>
<td>30%</td>
<td>73%</td>
</tr>
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2b. GIVEN current conditions, what is the probability that within the next year the **first** significant development will be a **resumption** of lava extrusion.

<table>
<thead>
<tr>
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<th>Credible interval lower bound</th>
<th>Best estimate</th>
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<tr>
<td>SAC 18</td>
<td>1%</td>
<td>15%</td>
<td>53%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>6%</td>
<td>31%</td>
<td>60%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>6%</td>
<td>43%</td>
<td>78%</td>
</tr>
</tbody>
</table>

2c. GIVEN current conditions, what is the probability that in the next year the **first** significant activity will be collapse of the dome (e.g. to Tar River or the south, but not to W, NW) which takes away the bulk of the remaining dome:

<table>
<thead>
<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
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<tbody>
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<td>SAC 19</td>
<td>0.01%</td>
<td>0.7%</td>
<td>10%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.1%</td>
<td>5%</td>
<td>28%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.2%</td>
<td>5%</td>
<td>33%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.01%</td>
<td>2%</td>
<td>28%</td>
</tr>
</tbody>
</table>
2d. GIVEN current conditions, what is the probability that within the next year the **first** significant event will be another major dome collapse with sufficient material avalanching towards the NE (Trants/Bramble) that it would reach the sea (available volume ~ 10's M m$^3$):

<table>
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<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.005%</td>
<td>0.3%</td>
<td>2%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.06%</td>
<td>2%</td>
<td>9%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.1%</td>
<td>2%</td>
<td>15%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.01%</td>
<td>1%</td>
<td>25%</td>
</tr>
</tbody>
</table>

2e. GIVEN current conditions, what is the probability that within next year the **first** significant event will be a major dome collapse event - without blast - involving enough material avalanching to the NW (Tyre’s/Belham) to generate a flow/surge runout to reach ~ Happy Hill:

<table>
<thead>
<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.0005%</td>
<td>0.03%</td>
<td>2%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.01%</td>
<td>0.5%</td>
<td>6%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.001%</td>
<td>0.3%</td>
<td>6%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.002%</td>
<td>0.2%</td>
<td>12%</td>
</tr>
</tbody>
</table>

2f. GIVEN current conditions, what is the probability that within next year the **first** significant event will be a major dome collapse event - without a blast - involving enough material avalanching to W through Gage’s to generate a flow/surge runout to reach close to or beyond ~Dagenham?:

<table>
<thead>
<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.001%</td>
<td>0.06%</td>
<td>3%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.03%</td>
<td>0.8%</td>
<td>7%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.1%</td>
<td>2.5%</td>
<td>24%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.05%</td>
<td>1%</td>
<td>24%</td>
</tr>
</tbody>
</table>

2g. GIVEN current conditions, what is the probability that within next year the **first** significant event will be a major dome disruption event - with an associated blast - involving enough material avalanching to the NW (Tyre’s/Belham) to generate a flow/surge runout to reach ~Happy Hill:

<table>
<thead>
<tr>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.0002%</td>
<td>0.001%</td>
<td>0.6%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.0002%</td>
<td>0.003%</td>
<td>0.5%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.0002%</td>
<td>0.008%</td>
<td>1.5%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.0002%</td>
<td>0.013%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

** re-elicited post meeting
* re-elicited following review and further discussion at the meeting
2h. GIVEN current conditions, what is the probability that within next year the **first** significant activity will be a major dome disruption event involving enough material avalanching to the W (Gage’s), *with lateral blast*, such that the flow/surge would reach to or beyond ~Dagenham:

<table>
<thead>
<tr>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.001%</td>
<td>0.003%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.0008%</td>
<td>0.08%</td>
</tr>
<tr>
<td>SAC17*</td>
<td>0.0006%</td>
<td>0.044%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.0005%</td>
<td>0.046%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.0002%</td>
<td>0.03%</td>
</tr>
</tbody>
</table>

* re-elicited following review and further discussion at the meeting

2i. GIVEN current conditions, what is the probability that the **first** significant event will be a vertical explosion of 0.1x reference size or greater (with limited associated dome disruption):

<table>
<thead>
<tr>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>0.02%</td>
<td>2%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.5%</td>
<td>8%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.2%</td>
<td>15%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.5%</td>
<td>24%</td>
</tr>
</tbody>
</table>

6. Supplementary Question: GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that nothing significant will happen (i.e. no collapse, no restart of dome growth, no magmatic explosion > 0.1x ref) in the next 30 years?

<table>
<thead>
<tr>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 19</td>
<td>8%</td>
<td>32%</td>
</tr>
<tr>
<td>SAC 18§</td>
<td>0.3%</td>
<td>16%</td>
</tr>
</tbody>
</table>

§ This question has not been elicited in previous SAC meetings
Appendix 7: Future Access to Zone V

A7.1 With the Hazard Level now at 1 on the revised system there is the possibility for more general daytime access to designated areas within Zone V. Recent accesses that have been requested and allowed include: sand exports (from Plymouth), geothermal drilling, police operations, animal projects, metal reclamation, filming, scattering of ashes, and tourist trips. This is likely to increase even more in future and it is best to consider how this should be managed.

A7.2 NDPRAC devolves responsibility for approval of requests for Zone V access to a collective DMCA/MVO/police decision. DMCA require a health and safety plan and signed indemnities, distributing applications to MVO and the police for comments or objections. Problems have arisen because the protocols are not written down and so the process can become opaque and decisions and reasons are not justified or properly recorded. The other issue with this is that the risks faced by people in Zone V, with the specific exceptions of the Plymouth Jetty sand mining operations, have not been assessed. So although people may look at the risk levels as calculated by us for the jetty work and judge them acceptable for their purposes, this may not be the case. For example, a visit to Plymouth may be in an area further inland and hence inherently more dangerous, it may not have the same mitigatory measures in place such as radio links to MVO or a fast escape route. It could be envisaged that multiple groups of people could be in Plymouth at the same time placing a major monitoring burden on MVO and raising the group level of risk considerably.

A7.3 A safe way forward would be to organise a more robust and transparent process of visit request processing, assessment, approval and recording. This should include a protocol of how to go about this from the user and manager perspectives. It should include access to the application forms, who approved it, together with justification, notification of decision and filing and archival of the cases.

A7.4 For SAC18, in an initial assessment of the risks faced by people entering Zone V, we devised a set of scenarios based on four different types of visiting groups which we called: Type1/well-managed (e.g. the current jetty operation); Type 2/managed; Type 3/self-managed, and Type 4/unmanaged. In these scenarios, there are different degrees of contact with MVO and the visits are distributed over different geographical areas (Fig. A7.1). In Fig. A7.1 we also show schematic time lines across a notional hazardous event, at T<sub>n</sub>, that would affect the Plymouth area: the probabilities of MVO issuing an alert, an entrant being aware of the alert/activity, an entrant still being in the danger area and the time the pyroclastic flow or other hazard enters the area.
Fig. A7.1 Risk framework for entrants to Zone V. The map shows the assumed areas of the four entrant types (1-4). The time lines below show schematically the probabilities of: (upper) MVO alert; (middle) entrant awareness; and (lower) entrant probability of still being in danger area and the time of the pyroclastic flow entering the area.
We consider five types of (hypothetical) person at risk when entering four different parts of Zone V, under different circumstances and assumptions regarding alerts, alert timings and response speeds.

**Individual risk levels**

**Type 1**
Well-managed, e.g. jetty workers (Area 1 on Fig A7.1 map): at coast (furthest from danger), known to MVO and work in MVO hours only, sea and land fast escape routes, radio contact, mitigation part of daily routine.

Risk exposure: working 8hr x 3 days x 50 weeks

<table>
<thead>
<tr>
<th>Jetty worker</th>
<th>With MVO contact</th>
<th>Without MVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work hours IRPA</td>
<td>1 – in – 21,000</td>
<td>1 – in – 11,000</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 12,500</td>
<td>1 – in – 6,500</td>
</tr>
</tbody>
</table>

Remark: if MVO support is not available, risks levels would be approximately doubled for Jetty workers (n.b. jetty worker risk estimates in SAC17 and earlier reports were “worst case” scenarios and did not include mitigation and time-to-escape factors).

**Type 2**
Managed, e.g. film crew: going into different locations (Area 2 on map), including closer to volcano away from roads; radio contact with MVO, but individuals not appreciative of local conditions.

Risk exposure: one 8 hr trip into Area 2 (and equivalent risk for 8 hr visit every day of year)

<table>
<thead>
<tr>
<th>Managed entrant</th>
<th>With MVO contact</th>
<th>Without MVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 8 hr trip</td>
<td>1 – in – 155,000</td>
<td>1 – in – 100,000</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 130,000</td>
<td>1 – in – 86,000</td>
</tr>
<tr>
<td>8 hr every day IRPA</td>
<td>1 – in – 420</td>
<td>1 – in – 280</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 320</td>
<td>1 – in – 240</td>
</tr>
</tbody>
</table>

**Type 3**
Self-managed (e.g. taxied tourist party): into "downtown" Plymouth (Area 3), led by experienced taxi driver; straying no more than 100 m from vehicle; with contact to MVO, but also reliant on own eyes and ears to spot activity starting.

Tourist’s risk exposure: one 2hr trip into Plymouth (and equivalent risk for 8 hr visit every day of year)
### Tourist

<table>
<thead>
<tr>
<th></th>
<th>With MVO contact</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single trip</td>
<td>1 – in – 5 million</td>
<td>1 – in – 1.2 million</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 1.5 million</td>
<td>1 – in – 780,000</td>
</tr>
<tr>
<td>8 hr every day IRPA</td>
<td>1 – in – 64,000</td>
<td>1 – in – 13,000</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 16,000</td>
<td>1 – in – 8,000</td>
</tr>
</tbody>
</table>

Remark: these figures emphasize the importance of the active presence of the MVO, even though adequate warning time cannot be assured for every event.

Driver’s risk exposure, one hundred repeat 2hr trips into Plymouth over 12 months

<table>
<thead>
<tr>
<th></th>
<th>With MVO contact</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple trip IRPA</td>
<td>1 – in – 25,000</td>
<td>1 – in – 18,000</td>
</tr>
<tr>
<td>SAC18</td>
<td>1 – in – 15,000</td>
<td>1 – in – 11,000</td>
</tr>
</tbody>
</table>

Remark: if MVO radio contact is not available, risks levels would be quadrupled for tourist visits into Area 3 (and 40% higher for regular drivers), given the current of event probabilities.

### Type 4

Unmanaged individuals or group who decide to visit Zone V telling no one (e.g. rogue hikers): individuals dispersed anywhere, even up to dome; not known to MVO; no external contact; on foot considerable distance from fast vehicle/road.

Entrant’s risk exposure: one 4 hr visit anywhere into Area 4 on map Plymouth (and equivalent risk for 8 hr visit to Area 4 every day of year)

<table>
<thead>
<tr>
<th></th>
<th>–</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 4 hr trip</td>
<td>–</td>
<td>1 – in – 300,000</td>
</tr>
<tr>
<td>SAC18</td>
<td></td>
<td>1 – in – 110,000</td>
</tr>
<tr>
<td>8 hr every day IRPA</td>
<td>–</td>
<td>1 – in – 1700</td>
</tr>
<tr>
<td>SAC18</td>
<td></td>
<td>1 – in – 650</td>
</tr>
</tbody>
</table>

Remark: by definition, this case does not involve direct contact with MVO

### Fatality risks

Type 1 Scenario: between two and twenty well-managed workers at the jetty (Area 1 on map), typically five persons, working an 8hr day, three days a week for fifty weeks (n.b. does not include truck drivers moving to and from the jetty).

Probability of 1 or more persons being killed in 12 months: 1 – in – 7000
(SAC18: 1 – in – 3000)

Probability of 5 or more persons being killed in 12 months: 1 – in – 14,000
(SAC18: 1 – in – 6300)
For the following hypothetical scenarios, the total number of persons occasionally in Zone V of different Types (excluding jetty workers) is modelled as ranging from zero (almost all the time) to a possible maximum of 20 at any one time.

Type 2 Scenario: one film-crew group enters Area 2 and work for two 8-hour days (Mon-Fri) per month, involving 5 ± 1 persons.

*Probability of 1 or more persons being killed in 12 months: 1 – in – 5500*

(SAC18: 1 – in – 1200)

*Probability of 5 or more persons being killed in 12 months: 1 – in – 200,000*

(SAC18: 1 – in – 25,000)

Type 3 Scenario: one 2-hour tourist bus trip to Area 3 each day (Mon to Fri) over a year, involving 7 ± 3 people per trip.

*Probability of 1 or more persons being killed in 12 months: 1 – in – 6900*

(SAC18: 1 – in – 1700)

*Probability of 5 or more persons being killed in 12 months: 1 – in – 33,300*

(SAC18: 1 – in – 6300)

Type 4 Scenario: two trips per week (Mon-Sun) by unauthorized hikers into Area 4, involving 2, 3 or 4 persons spending 8 hours in area.

*Probability of 1 or more persons being killed in 12 months: 1 – in – 660*

(SAC18: 1 – in – 170)

Overall expected fatality risks in Zone V from Type groups 2, 3, 4 combined:

*Probability of 1 or more persons being killed in 12 months: 1 – in – 480*

(SAC18: 1 – in – 130)

*Probability of 5 or more persons being killed in 12 months: 1 – in – 11,000*

(SAC18: 1 – in – 3200)

These results are scenario dependent and can be modified to suit other conditions of overall hazard on the west side of the volcano and to reflect other scenarios.
Appendix 8: Modified Chief Medical Officer’s Risk Scale (CMO*)

**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).

Appendix 9: 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.

**eGPS**: 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.

**Dyke**: Vertical, tabular body of magma within a fracture below the volcano that can act as the conduit for flow to the surface.

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

**Fumarole**: A vent in the surface of the dome where hot gases exit.

**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.

**Lidar**: A laser-based surveying tool that measures the distance to surfaces using pulses of light.

**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 (equivalent to “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.

**Simulation**: Use of a computer program to mimic (or model) the behaviour of a physical process.

**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.

**Talus**: A pile of cool lava blocks and ash that accumulate by rockfall around the core of the hot lava dome.

**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 10: Limitations of Risk Assessment

A10.1 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.

A10.2 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 methodology9, by which means the views of the Committee as a whole were synthesised impartially.

A10.3 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.

A10.4 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

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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.\textsuperscript{10}

A10.5 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.

A10.6 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.

A10.7 This appendix must be read as part of the whole Report.