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

Eighteenth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 29 October and 1 November, 2013 at the Montserrat Volcano Observatory, Montserrat

Part II: Full Report

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Introduction

1. This is the second part of the report resulting from the eighteenth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 29 October to 1 November 2013. Part I of that report, the Summary Report\(^1\), gives the principal findings of the meeting in a non-technical form\(^2\), and this, Part II, gives the technical data and analysis that led to those findings.

2. This meeting took place 12 months since we last met in October 2012. MVO produced a “Report for Volcanic Activity” to the SAC in May 2013 and we discussed this\(^3\) during a teleconference with SAC and MVO members on 21 May 2013, the minutes of which are given as Appendix 2. This meeting took place over four days and involved all six SAC members. The extra time and full attendance resulted in fuller, less rushed, debate and the format should continue.

3. MVO delivered an oral report on the volcanic activity between May and October 2013 that presented the monitoring data and observations collected by MVO between May and October 2013 and considered some of the new developments at MVO.

4. This meeting concerned itself largely with the potential behaviour of the volcano in the longer term. The “doppelganger” study to improve our understanding of the evolution of the Soufrière Hills volcanic system in relation to other volcanoes – work that was introduced by T. Sheldrake (Bristol University) at the previous SAC - was continued with Sheldrake at this meeting and is discussed later. R. Bretton a mature PhD student from Bristol with a legal background was given permission to observe the SAC meeting.

5. At the end of the meeting (see Appendix 3 for an agenda and Appendix 4 for a list of participants) on 1 November we produced a Preliminary Statement (Appendix 5), briefed the Governor on our work and in the evening we held a public meeting at Salem Primary School. This included a review of the SAC’s findings and a talk by Professor Sparks about the recent cruise of the research vessel Nautilus around the seas of Montserrat.

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\(^1\) Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Eighteenth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity, Part I, Summary Report.

\(^2\) 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.

Surface Activity and Observations

Fig. 1  Number of daily seismic events (top), GPS-measured motion radial to the volcano of station MVO1 (middle) and the sulphur dioxide emission rate (bottom) for October 2012 to October 2013: top 3 panels October 2012 – April 2013, bottom 3 panels May 2013 – October 2013. Note scale changes for seismicity and SO$_2$ plots.

6. It is now 45 months since the last phase of lava eruption, the longest pause since the eruption began in 1995. Surface activity has been at a very low level in the last year, with no explosions and only one minor collapse of a slab of rock from
the lava dome into the Tar River valley on 28 March 2013. The fumaroles in the 2010 collapse scar remain stable with measured temperatures up to about 600°C.

7. The 12-month record of seismicity, sulphur dioxide emission and ground deformation is summarised in Fig.1. There has been a slow reduction in seismicity, with only 3 recorded “VT strings”. Minor ash venting may have followed the VT string of 5 February 2013. Following the most recent one on 3-4 August 2013, a very long period (VLP) release of seismic energy on 8 August was recorded, the first since March 2012, but there was no available strain data.

8. The rate of emission of sulphur dioxide during the past year has remained steady but has fallen to values of about 250 tonnes/day in the past few months.

9. There seems to be some correlation between a higher frequency of rockfalls from the dome and lower levels of sulphur dioxide emission, noted over the last 1-2 years. High-level pressurisation by an unknown mechanism in or below the dome may explain this relationship.

Long-term processes at the volcano

10. In the past year a number of papers have been published or are about to be published in Memoir 39 of the Geological Society, London4, that treat various aspects of the long-term processes operating at Soufriere Hills. Some of the key findings are summarised below along with other relevant research and discussion during SAC.

11. The “saw-tooth” pattern of alternating inflation and deflation associated with pause and lava extrusion, respectively, and measured across the whole of Montserrat by the cGPS network is one of the strongest signals of the eruption. This pattern has been frequently modelled and interpreted in terms of pressurisation of a mid-crustal magma reservoir(s). The rapid switch from inflation to deflation at the start of extrusive phases is of the right sign to be explained by reservoir depressurisation or surface loading. Some uncertainties remain and the deformation nearest the volcano fits this pattern least well. Movements at the St George’s Hill site may be associated with local landslides there. The potential effects of surface loading and unloading have recently been modelled by H. Odbert and B. Taisne. The highly variable distribution of the surface load after events such as the collapses of July 2003 and May 2006 must be represented in the surface deformation pattern for this to be a dominant mechanism. During the meeting S. Sparks suggested that a regional pattern of tectonic motion could be responsible for some of the 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, but this cannot readily explain the radial (about the volcano vent) component of the motion, measured by the cGPS network.

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12. The best-fit simple models of the deformation have sources at mid-crustal depths. But there is 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 the upper at about 6 km. The dynamics of magma supply through such a system has been modelled by Melnik and Costa. They show that the ease of magma connectivity between the two chambers plays a vital role in the dynamics, with the upper chamber playing a more passive role when the connecting conduit is large and magma flow relatively easy. Whilst the approximate behaviour of Phases 1-3 can be simulated by the two-chamber model the behaviour does not exclude a single chamber mechanism. Results from the three working dilatometers have also been interpreted in terms of a two-chamber and overlying dyke-cylindrical conduit model by S. Hautmann and colleagues. Interpretation of some Vulcanian explosions calls for very rapid (minutes) strain propagation through the upper crust, with fluids as the only transportation medium that could react on such a timescale. This has its attractions but requires a high degree of contiguous connectivity over ~ 10 km at least. Also it does not explain the observation of lags of several days between the strain transient and surface emission of large sulphur dioxide plumes.

13. T. Christopher and others 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. Time series analysis by Nicholson et al. also of the DOAS record brought out a 50-day periodicity of sulphur dioxide emission. This is similar to that reported from tilt and seismicity and is considered to be driven by an elastically deformable dyke. Interestingly, it also seems to operate sometimes when no lava is extruding. Our view of volatile emission is dominated by sulphur dioxide data. Better knowledge of carbon dioxide emission (from the Multigas instrument) would considerably improve this perspective, given that the melt inclusion systematics indicates carbon dioxide flushing of the system. The cessation of the 2-year pulse cycle following

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the 11 February 2010 collapse to be replaced by a much more steady sulphur dioxide output probably indicates a change of regime in the deep system. For this SAC, W. Aspinall analysed the post-2010 record of DOAS-measured emissions using a log-logistic model sampling at 30-day intervals (Appendix 6). The modelled median strength through time and dispersion about the median shows the former has been notable constant since the last eruptive phase, but dispersion about it has been consistently greater than in previous times. One hypothesis might be that, without perturbations due to active magma extrusion or dome growth, the system has settled to more uniform gas production at depth, while the route to the surface has evolved into a pathway network with short-term modulated flow rate fluctuations.

14. It is increasingly clear that the picture of rather uniform andesite production and extrusion from Soufriere Hills may be less valid than was once thought. The involvement of basalt and andesite magmas within the crust to produce andesite lava with mafic enclaves has long been recognised. Whilst the composition of the basalt shows little change, the andesitic bulk composition of the erupted lavas has changed slightly over the course of the eruption. Evidence for hybridisation mechanisms including incorporation of enclaves, vapour loss disaggregation and assimilation of crystals into the andesite is now stronger. The later Phase 4 and 5 lavas display greater numbers and variety of enclaves relative to those of phase 1, perhaps involving deeper fractionation and higher bulk temperatures. Recent work by M. Plail and colleagues has recognised the presence of cordierite in shear-band facies of the dome rocks. This implies formation at high temperatures (~1000°C) and relatively low pressures, presumably in zones of high frictional heating or strong gas fluxing within the top few kilometres of the conduit/dyke.

15. An alternative view of the magma reservoir beneath Soufriere Hills was proposed by during the meeting by Professor Sparks. At the base of the crust (~30 km), rising basaltic magma becomes trapped by the density contrast and produces waves of upwardly migrating evolved melts within the overlying crust. These andesitic melts or crystal mushes auto-separate into gas-poor lower and gas-rich upper parts. The process of forming melt layers is slow, but as they increase in thickness they move towards instability. Destabilisation of these layers could cause rapid buoyant rise resulting in eruption at the surface and the release of gas that, trapped in the layer, may be quite old. The physical separation of magma produces batches, migrations of which might be responsible for observed longer periodicities in activity observed, either the 2-3 year phases of lava extrusion, or the 30-year intervals between volcano-tectonic crises. The mush destabilisation

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hypothesis is still in its infancy and ways of testing it have yet to appear. However, it can explain important aspects of magmatic systems that are less easy to understand from established models like static magma chamber replenishment.

Geothermal Exploration Drilling

16. MVO has not been directly involved in the geothermal drilling operation, but has been briefed by the project geologist, told of fracture testing, received a duplicate set of downhole chippings (every 3 m) from the two holes drilled between February and November 2013 and had access to the lithological logs. The two holes, ~500m apart, were drilled just east of the main road between St George’s Hill and Garibaldi Hill. The more southerly one ended at a depth of 2298 m (MON-1) and the more northerly one at a depth of 2870 m (MON-2). Temperatures of up to 290°C were reportedly measured in MON-1, and steam was produced there in October-November 2013 (cover photo, MVO). MON-2 was used in two fracture generation experiments, forced by pumping, which produced microseismicity just north of MON-2. These will be the subject of an MVO report\textsuperscript{13}. Fluid injection at pressures of about 4 MPa produced 10 microearthquakes in an area that last saw natural seismicity in 1995. The relatively low fluid pressure suggests these new, induced earthquakes were on an existing fault surface, though not one obvious at the surface. Fault Plane Solution and Joint Hypocentre Determination analysis agree that the moving fault was near vertical, about 1 km in length with a strike of about 30° west of North. This is the clearest evidence for active fault motion on a single plane on Montserrat. Its orientation is similar to that proposed from dilatometer analysis for a dyke between the conduit and the magma reservoir\textsuperscript{14}, but is considerably offset from such a dyke.

The Nautilus cruise

17. The number of research cruises that have recently explored the submerged flanks of Montserrat is considerable. Montserrat now has arguably the best-studied submarine apron of volcanic deposits at any andesite volcano. The part research/part educational Nautilus cruise around Montserrat in late October–early November 2013 was able to inspect the sea floor at centimetric detail and to sample it with a robotic arm, something not achieved previously. One of the distinctive findings was the ubiquity of ~10-cm scale ripples with two orientations: slope-parallel and baroclinic, presumably perpendicular to the commonest gravity current flow directions. Elsewhere, manganese crusts were variably present and may permit a coarse dating method by using isotopes to study their growth rate. Nautilus also visited the “Kahouane” seamounts to the southeast of Montserrat. Morphologically well-preserved summit craters were found and the composition of the rocks are, surprisingly, andesitic.


18. The debris flow and pyroclastic density current deposits (including those from the current eruption) around Montserrat were investigated. Immediately east of Tar River, the hummocky topography of “Deposit 1” identified in previous work proved to consist of large, intact slide blocks that must have slipped readily into place from their origin on land during the formation of English’s Crater. The deposits of the 2003 dome collapse event were notable for the considerable proportion of coral blocks mixed with them, presumably entrained during flow-induced erosion of shallow-water deposits, or simultaneous collapse of the shelf during dome collapse. A big surprise was that, from the evidence of slow-growing whip corals on blocks off the coast at St Patrick’s, we can infer that the lateral blast associated with the Boxing Day 1997 event must have deposited its load in shallow water (< 200m depth, < 1km from shore) whilst the high velocity surge travelled over the sea. Much of the submarine southwestern slopes of Montserrat have a carbonate-cemented carapace that must dominate erosional processes. Off Plymouth there is evidence of pyroclastic deposits that may be the equivalent of the on-land deposits (dated at 16-18 kyr) that underlie much of Plymouth.

**Evolution of Future Behaviour**

19. We would like to better understand how the volcano might evolve in the coming years. In the next section we discuss the “doppelganger” approach to this question, but here we discuss the statistical behaviour of similar volcanoes around the world that we have used in the past. This is much wider group of volcanoes than used in the doppelganger study. The Loughlin et al study\(^\text{15}\) of volcanoes that had built domes since 1800 AD yielded 97 examples worldwide, making Soufriere Hills now 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 (220 months). We obtain an estimate that the statistical probability of it lasting another five or more years is 0.83. For an eruption that has already lasted 220 months, the statistical expectation for total duration (0.50 probability) is 40 years, i.e. a further two decades 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 – without considering any other indicators of activity trends – remains at about 0.04 (i.e. a 1-in-25 chance).

20. For the first time, in SAC 18 we elicited the probability that nothing significant will happen in the next 30 years - i.e. there will be no collapse, no restart of dome growth, or no magmatic explosion > 0.1x ref. The elicited median probability for this eventuality is 16%, or about a 1-in-6 chance; uncertainty on this estimate is wide, the 90% credible range is from 0.3% probability to 74% probability (Appendix 7, question 6), reflecting the difficulty of assessing the long-term future behaviour of the volcano.

21. 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 86% probability of the eruption still continuing now, in October 2013, and a 37% probability of it being on-going in a further 30 years time. The complement of these values would have implied a 14% chance that the eruption might stop in the intervening 45 months, and a 63% chance it could stop in the additional 30 years. Thus, given there has been nearly four years of inactivity, the new elicitation finding of a 16% median probability of no further significant eruptive activity in the next 30 years and an upper confidence bound of 74% probability for this period are congruent with the global data.

Doppelganger Workshop

22. The concept of doppelganger volcanoes is that there may be a set of volcanoes similar in character to Soufriere Hills but with longer historical records that can include several eruptive cycles and so may provide us with insights into the likely future long-term behaviour of our volcano. We discussed this at SAC17 and it was explored fully at this meeting in workshop format run by T. Sheldrake. The document that was used in the workshop is included here as Appendix 7. In addition to that, a summary of observations for each volcano was compiled.

23. There are two main limitations to this approach. Firstly, because silicic volcanic systems tend to have quite long repose periods (hundreds of years in the case of Soufriere Hills), there are relatively few examples globally that are of similar nature (andesitic, Peléean lava dome forming, prone to collapse) and in a state of comparable, current or recent extended eruptive activity. Secondly, the observational record at Soufriere Hills is long, multi-instrumental and generally of good quality. Few of the doppelganger’s records can match it. Hence it is difficult to find close similarities with this volcano across the board, re-inforcing the old adage that every volcano is unique. Nonetheless some more generalised traits of behaviour can be recognised in other volcanoes that can be helpful in understanding behaviour at a particular volcano.

24. Fourteen volcanoes were considered as potential doppelgangers: Augustine, Bezymianny, Colima, Kudryavy, Lascar, Merapi, Mount St. Helens, Pelée, Popocatepetl, Redoubt, Santiaguito, Shiveluch, Tungurahua and Unzen (Appendix 5, Fig.1). Fig.2 shows that there is a wide spread of the rate of extrusion (two orders of magnitude) measured over durations spanning three orders of magnitude. Generally, the shorter the measurement interval, the higher the extrusion rate, as we would expect. Two measures from Soufriere Hills (the 15-year (1995-2010) average and the Phase 3 average (2005-2007) are shown in red in Fig.2. Both are above the average trend of the doppelgangers. This may be because (i) Soufriere Hills is a very vigorous magmatic system of its type, (ii)

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that it’s extrusive to intrusive ratio is high, or (iii) that there is some unknown bias in the measurements of lava flux at Soufriere Hills or across the doppelgangers. In terms of magma flux history, the doppelgangers closest to Soufriere Hills appear to be Pelée, Unzen and Bezymianny.

![Logarithmic plot of average extrusion rate against the duration of the extrusion for (most of) the doppelganger volcanoes. Two values for Soufriere Hills are shown in red for 1995-2010 and 2005-2007 (Phase 3).]

25. A probabilistic approach using a Bayesian Belief Network (BBN) was used because the doppelganger approach is complex, with no unifying theory (a common model that explains behaviour at many volcanoes), the observations partial, many of the processes hidden and the interpretational criteria unclear. For each node of this (10-node) BBN, a prior belief in a condition is sought together with a likelihood of satisfying a particular state given the observations. From the network we also forecast the duration of quiescence and maximum expected explosive activity.

26. The BBN has three main concepts: eruption trend, eruption regime and reservoir eruption potential. The focus is on the state of Soufriere Hills but the evidence from the doppelgangers was used too to inform the interpretations and discussion. The eruption trend is used to capture the process of long-term (>5 yr) changing intensity of the magmatic system via three categories: Escalating, Consistent and Diminishing. The eruption regime captures the degree of continuity of the system
over long periods as Persistent or Discrete. A Persistent regime is one in which magma is erupted semi-continuously, a Discrete regime has long intervals of quiescence before the next, relatively short eruptive phase. The Reservoir Eruption Potential uses the evidence from observables over periods of up to 5 years to capture the probability of renewed lava extrusion. This is rather similar to the 1-year future interval of consideration of seismicity, deformation and degassing used in earlier work, but considers longer intervals, out to more than 30 years ahead.

27. A set of questions were posed to the SAC/MVO group to elicit the group’s belief in the evidential value of these concepts as they applied to Soufriere Hills. The probability distributions rather than the median values were employed. For the eruption trend, the prior probabilities in the three states were based on the eruption history since 1995 and petrological evidence of magma mixing and hybridisation was used to update the probabilities. For the eruption regime the Persistent/Discrete prior probabilities were conditioned on the trends, with the current levels of degassing during the past 3 years of quiescence used to update these values. For reservoir eruption potential the prior probability that the potential is currently increasing was elicited for four intervals: <1, 1-5, 5-30, >30 years and updated using questions about deformation, seismicity and gas. Separate questions on the duration of the current period of quiescence (pause) conditioned on regime and on the maximum explosion magnitude conditioned on trend were also posed. Analysis of the results following the meeting showed evidence of some divergent and some ambiguous thinking in response to some questions. These were re-elicited and paired with their complementary questions.

28. The preliminary results of the elicitation showed slightly more support for the trend in activity to be Diminishing rather than Consistent and that the regime was Persistent rather than Discrete (the relative importance had reversed upon re-elicitation). Only the deformation data were thought to provide evidence of increasing Reservoir Eruption Potential. We thought that the most likely maximum explosive activity given a Diminishing trend would be Vulcanian events with plume heights of less than 5km. Overall, the results did not show strong group support for any one future path of behaviour of Soufriere Hills. This, in part, may reflect the disparity of the Soufriere Hills record with respect to the doppelganger volcanoes in the absence of a stronger theoretical model for their behaviour as a group. The group had diverse feelings about the validity of the doppelganger approach. A survey during the meeting indicated that roughly half of the group considered the evidence from the other volcanoes as important to interpreting the behaviour of Soufriere Hills while the other group gave much lower weight to evidence from other volcanoes.

Volcanic Hazards

29. There was only one significant collapse event in the past year, a minor dome collapse down the Tar River valley that produced a 2 km long pyroclastic flow on 28 March 2013. Rockfall events, too small to affect anyone, continued at a rate of
a few per week. Lahars continued to occasionally disrupt travel across the Belham Valley, with about six major episodes in the past year.

30. The dome is essentially the same size as in the three previous years, though perhaps a little cooler. Hence the types of hazardous events considered then are still relevant: large scale collapse of the dome (especially if forced by new magma entering from below), formation of pyroclastic flows from collapsing existing dome material, even possibly yielding lateral blasts and large Vulcanian explosions producing a rain of ash and blocks. The impact they might have on the northern and western slopes are the most important. Any major change in eruptive state, including relatively mild lava extrusion from the 11 February 2010 amphitheatre, would necessitate a rapid re-evaluation of hazards.

Hazard Scenarios

31. We now summarise the results of the formal elicitation of the SAC and MVO views 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 analyses, and the Expert Opinion Elicitation method that we have used in previous assessments. The questions, explanations of their context and the ranges of uncertainties derived from the group’s responses are presented in detail in Appendix 8. Here, on Table 1, we tabulate the "best estimate” probability values for each of the questions and compare them with the equivalent values obtained a year ago, at SAC17. The series of Question 2a-2i items ask what is the probability that each of these events will be the first significant thing to happen in the next 12 months.

Table 1. Summary of elicited eruption scenario “best estimate” probabilities (SAC17 values shown in brackets)

<table>
<thead>
<tr>
<th>Elicitation Question (summary description)</th>
<th>Probability SAC18 (SAC17)</th>
</tr>
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<tbody>
<tr>
<td>1 At least one criterion for deep magma activity will be met</td>
<td>95% (97)</td>
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<tr>
<td>2a Nothing significant happens</td>
<td>67% (43)</td>
</tr>
<tr>
<td>2b Quiet resumption of lava extrusion</td>
<td>15% (31)</td>
</tr>
<tr>
<td>2c Collapse of most of dome to east (or south)</td>
<td>5% (5)</td>
</tr>
<tr>
<td>2d Major dome collapse to reach the sea to the NE</td>
<td>2% (2)</td>
</tr>
<tr>
<td>2e Major dome collapse to reach Happy Hill to the NW</td>
<td>0.5% (0.3)</td>
</tr>
<tr>
<td>2f Major dome collapse to reach Plymouth to the W</td>
<td>0.8% (2.5)</td>
</tr>
<tr>
<td>2g Blast event to reach Happy Hill to the NW</td>
<td>0.03% (0.01)</td>
</tr>
<tr>
<td>2h Blast event to reach Plymouth to the W</td>
<td>0.08% (0.04)</td>
</tr>
<tr>
<td>2i Vertical explosion (&gt;0.3 million cubic metres)</td>
<td>8% (15)</td>
</tr>
<tr>
<td>3a Next Phase of lava extrusion to be long duration type</td>
<td>30% (37)</td>
</tr>
<tr>
<td>3b Next Phase of lava extrusion to be short duration type</td>
<td>70% (63)</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>0.44% (0.1)</td>
</tr>
</tbody>
</table>
32. Between the elicitations of a year ago (October 2012) and now (October 2013), the assessed median probability that “nothing significant” occurs in the next 12 months is increased substantially, balanced in part by a reduction in the likelihood of a quiet resumption of lava extrusion. Changes in the median probabilities for other scenarios (questions 2c – 2i) are mainly minor; the likelihoods of a major dome collapse to Plymouth (question 2f) and of a vertical explosion (2i) are assessed lower than a year ago. However, there are increases in the assessed probabilities of a major dome collapse without lateral blast to NW (question 2e), of directed blasts from the dome to the NW (question 2g) and to the W (2h), and of a major explosion (question 5).

33. Taken together, these probability changes may express a collective view that, while the present prolonged pause increases the chance of nothing significant happening over the next year, if there is a restart it may be more sudden and violent than previous cases of quiet resumption of lava extrusion. All this said, care is needed when judging these median probabilities at face value. They are only part of the story, and their associated uncertainty distributions (Appendix 8) must be taken into account when quantifying risks to the population; this is the basis for the risk analyses reported in the following sections.

34. The elicitation of complementary probabilities for items 3a, 3b suggest that 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. While the elicited central probability for a moderate vertical explosion (i.e. 2i) has dropped to a half that of the October 2012 assessment, the median chance of a major explosion (item 5) is quadrupled, at 0.4% in 12 months (i.e. 1-in-250 chance). Albeit this is still a relatively low likelihood event, the shift upwards in the probability associated with this scenario is noteworthy. Again, this may be reflecting the view that, given the deep inflation signal and continued sustained gas output, the extended present pause could culminate in a new short duration episode of magma eruption, with some non-zero chance of an associated major explosion.

35. Many of the other probabilities change to minor extents, but not significantly given the range of uncertainties involved and the tentative nature of such hazard estimates.

Quantitative Risk Assessment

36. We make use of the same procedures for quantitative risk assessment that have been used by the SAC since 1997 and are described in the report for SAC16. We used the Hazard Zone boundaries defined by the November 2011 Hazard Level System (Fig.3).
37. 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 that data were not sufficiently detailed to be used fully in the SAC16-17 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\(^ {17} \), 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

\(^ {17} \) 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.
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, relative 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.

38. Other, volcanological, factors relating to renewed lava extrusion, prospective multiple episodes, a less favourable site of outbreak and higher extrusion rate, potentially could increase the threat to the populated areas to the northwest of the volcano. These threats would 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 slightly lower than those from SAC17: for Zone B, the elicited probability of a pyroclastic flow reaching this far within the next year is unchanged at 1-in-230 (SAC17: 1-in-170) and for Zone A the risk is slightly higher 1-in-710 (SAC17: 1-in-660).

39. For the case of a lateral blast-derived surge, the initial elicitation findings were reviewed during the SAC18 meeting, and were then re-elicted post-meeting due to a query from a SAC member. With the updated elicitation findings, the corresponding incursion probabilities are, however, noticeably elevated from those obtained in SAC17: Zone B surge incursion odds are now assessed at 1-in-4,000 (SAC17: 1-in-8,400); Zone A, 1-in-4,500 (SAC17: 1-in-9,300). These sizeable changes reflect mainly the increases 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. However, quantifying the probabilities for unlikely events like this is acutely difficult, so the changes implied from SAC17 to SAC18 should be regarded as indicative, rather than definitive.

40. 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-24,000 for a flow and about 1-in-60,000 for a blast surge – that is, low probability prospects, with odds reduced relative to SAC17 or even SAC16. Again, these numbers should be regarded as indicative rather than definitive. This said, potential consequences for the populations of all these areas could be extreme should such an event occur.

Individual Risk Exposure Estimates

41. 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 10).

42. 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 (the value in the US Virgin Islands). Table 2 shows how the current evaluation compares according to these two measures. In Table 3 we use the same scheme to show the relative risk levels faced by workers in various scenarios. The two types of risk are also displayed in a graphical manner in Figs. 4 and 5, which show the range of risks faced on a vertical logarithmic scale.

43. 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 populated Zones (A and B) of Fig.4 is:

Zone B (full-time resident): 1-in-3,200, C on the CMO* scale,
2.1x background risk level of accidental death.

Zone A (full-time resident): 1-in-35,000, D on the CMO* scale,
1.1x background risk level of accidental death

Due to the changes in the assessed event probabilities, discussed above, the individual risk exposure level in Zone B is fractionally lower than one year ago, while that for Zone A is marginally higher for the reasons discussed in the previous section of this report (SAC17: 1-in-2,800 and 1-in-40,000, respectively); however, the present values remain in CMO* Scale rankings C and D, respectively. Rounding these values from SAC17 and SAC18 to one-significant figure indicates they are essentially identical.

The IRPA for the Woodlands area (and further north) remains negligible; numerically the analysis puts individual risk in Woodlands at about 1-in-4 million, and even lower in the far north.
Table 2  IRPA estimates for volcanic risks to occupants of the populated 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>Zone B (full-time occupation)</td>
<td>C</td>
<td>1 in 3200</td>
<td>2.1x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 10000</td>
<td>1.35x</td>
<td></td>
</tr>
<tr>
<td>Zone C (daily entrant – 8hrs)</td>
<td>D</td>
<td>1 in 20,000</td>
<td>1.2x</td>
<td>Hurricane</td>
</tr>
<tr>
<td>Zone A (full-time occupation)</td>
<td></td>
<td>1 in 35,000</td>
<td>1.1x</td>
<td></td>
</tr>
<tr>
<td>Whole island</td>
<td></td>
<td>1 in 35,000</td>
<td>1.1x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 35,000</td>
<td>1.1x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 100000</td>
<td>1.03x</td>
<td></td>
</tr>
<tr>
<td>Whole island</td>
<td>E</td>
<td>1 in 200,000</td>
<td>1.02x</td>
<td>Earthquake</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 in 1000000</td>
<td>1.003x</td>
<td></td>
</tr>
<tr>
<td>Woodlands (full-time occupation)</td>
<td>F</td>
<td>1 in 4 million</td>
<td>1.001x</td>
<td></td>
</tr>
<tr>
<td>North Montserrat</td>
<td></td>
<td>Much less than 1 in 5 million</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4  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.
44. In the case of Zone C, only short day-time visits are allowed at present. For illustration, a person making regular daily visits of duration about 8 hours\(^{18}\) into Zone C has a risk exposure equivalent to about 1-in-20,000 in annualized terms. For less frequent visits or for visits of shorter duration, the risk is proportionately lower. This risk level is appreciably lower than that assessed in SAC 17, mainly due to the much lower probability ascribed to a dome collapse to the west through Gages.

44. **Risks to workers at Plymouth Jetty and in the Belham Valley**
   We judge that the changes in level of hazard, the working conditions and mitigatory measures in place do not warrant a change in the levels of risk assigned to the Belham Valley workers, as presented a year ago in the SAC17 report. A new IRPA assessment is given for the Plymouth Jetty workers in para. 56.

45. **Risks in the Maritime Exclusion Zone**.
   Risks in the Zone (Fig.3) are assessed to be the same as a year ago.

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\(^{18}\)In the SAC16 Full Report it was presumed Zone C entries were for an interval of 4 hours or less; there is a possibility some people are spending more time than this in Zone C, hence the basis for estimating risk exposure is changed here to 8 hours.
Societal Risk Levels

46. 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. Using 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.

Fig.5 Societal risk curve (red) for the population at the time of SAC 18, and comparisons with SAC17 (blue), other risk assessments and other natural hazards (see text)
47. Fig. 5 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 from a near-simultaneous explosion, both occurring close in time as a restart to eruptive activity (solid red line). Also shown on Fig. 5 is the counterpart societal risk curve produced a year ago (SAC17, blue line), also for the situation of compound restart hazards. The two curves are almost the same, with only secondary differences.

48. Overall, the current societal risk for low numbers of casualties (i.e. less than five) is evaluated marginally below the level assessed in SAC17, reflecting the changes in elicited event probabilities for some limited threat scenarios; however, upward movements in the assessed probabilities for a NW lateral blast and for a major explosion have resulted in increases in the chances of multiple casualties. As a consequence, the calculated risk is about doubled relative to SAC17 for 50-120 casualties (see Fig.5). For comparison, the previous recent highest societal risk curve was that of March 2007 (SAC 8), when the dome was active and still growing vigorously (Fig.6, upper, dashed red line).

49. For limited casualty numbers, i.e. 10 fatalities or less, the present assessment of societal risk from the volcano is comparable with estimated long-term societal risk exposure on Montserrat from earthquakes, and below the corresponding level for hurricanes (Fig.6, black lines with symbols). However, if it produced an extreme eruptive event, the volcano could cause significantly higher casualty numbers than either a hurricane or an earthquake. This said, it should be remembered that volcanic risk could be further reduced by more radical mitigation measures (e.g. moving more people further away) whereas the hurricane and earthquake threats are island-wide.

50. The main conclusions to be drawn from these curves are: (a) overall, current societal risk levels for fatalities are fairly similar, but slightly reduced compared to a year ago; and (b) while societal risk due to the volcano for low casualty tolls is similar to those due to hurricanes or earthquakes, the potential for much larger casualty numbers still remains markedly greater than for those other natural disaster scenarios.

51. Caution should be exercised when using the curves shown on Fig. 5. Any particular curve carries a significant element of uncertainty, up or down, and numerical differences between any two curves may be more apparent than real. Thus the present estimated likelihood of suffering one or more casualties, due to volcanic action, is in the region of a 1-in-150 chance, but could be somewhat higher, or lower. See Appendix 12 for a full explanation of the limitations of risk assessment.
Future Access to Zones C and V

52. If the current pause continues, the case for changing the Hazard Level from 2 to 1 will increase. At Level 1 there is 24-hour access to Zone C and daytime access to some, as yet unspecified, areas of Zone V. The lack of utilities in Zone C will deter full-time occupation at Level 1. However, there is already increasing pressure to allow specific access to Zone V and an increase in permissions to do so. R. Stewart has compiled a list of such recent accesses requested. These include: sand exports (from Plymouth), geothermal drilling, police operations, animal projects, metal reclamation, filming, scattering of ashes, tourist trips. This is likely to increase even more in future and it is best to consider how this should be managed.

53. 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 mitigation 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.

54. 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.

55. As a start to the task of assessing the risk faced by people in Zone V in the future, we have devised a set of scenarios based on four different types of visiting groups which we have called Type1/well-managed (the current jetty operation), Type 2/managed, Type 3/self-managed and Type 4/unmanaged. They have different degrees of contact with MVO and are distributed over different geographical areas (Fig.6). In Fig.6 we also show schematic time lines across a notional hazardous event, at T₀, 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 enters the area.

Fig. 6 Risk framework for entrants to Zone V in the Plymouth area. The map shows the assumed areas of the four entrant types (1-4). The time lines below show the probabilities of MVO alert, entrant awareness, entrant probability of still being in danger area and the time of the pyroclastic flow entering the area.
56. 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.6 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 – 12,000</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 previous SAC 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 – 130,000</td>
<td>1 – in – 90,000</td>
</tr>
<tr>
<td>8 hr every day IRPA</td>
<td>1 – in – 320</td>
<td>–</td>
</tr>
</tbody>
</table>

*Remark: if MVO support is not available, risks levels could be increased by about 45% for visits into Area 2*

**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)
<table>
<thead>
<tr>
<th>Tourist</th>
<th>With MVO contact</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single trip</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 – 1,000</td>
<td>–</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Driver</th>
<th>With MVO contact</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple trip IRPA</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 almost doubled for tourist visits into Area 3 (and 30% higher for regular drivers).

**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>Rogue entrant</th>
<th>–</th>
<th>No MVO contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 4 hr trip</td>
<td>–</td>
<td>1 – in – 110,000</td>
</tr>
<tr>
<td>8 hr every day IRPA</td>
<td>–</td>
<td>1 – in – 160</td>
</tr>
</tbody>
</table>

Remark: 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 – 3000
- Probability of 5 or more persons being killed in 12 months: 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 – 1200
Probability of 5 or more persons being killed in 12 months: 1 – in – 25,000

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 – 1700
Probability of 5 or more persons being killed in 12 months: 1 – in – 6300

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 – 170

Overall fatality number risks in Zone V jointly from all three Type groups:

Probability of 1 or more persons being killed in 12 months: 1 – in – 130
Probability of 5 or more persons being killed in 12 months: 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 other scenarios.

The Operation of MVO

57. Since our last meeting Mr Roderick Stewart succeeded Dr Paul Cole as Director of MVO, following a transitional period as Acting Director. Dr Karen Pascal now occupies the MVO deformation post following the award of her doctorate. Ms Natalie Edgecombe has succeeded Ms Sonja Melander as the Outreach Officer. The volcanology post with responsibilities for quantitative risk assessment will be filled as soon as a suitable applicant can be found.

58. 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 signed.

59. 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 over-running upgrade to the DOAS (SO$_2$) network is still not completed. The instruments supplied by Dr. V.Tsanev of Cambridge have been prone to breakdown under field conditions. He is due out in late 2013. Also 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. Perhaps a dual-instrument (one in the field, one spare) strategy would work better. Certainly the measurement of CO$_2$ would be of great scientific value to assess the long-term behaviour of the volcano. The cGPS network and the Air Studios, Trants and Gerals strainmeters are operational. A lease for the Gerals site. Has been
extended by 5 years. There is a renewed effort to get the strainmeter time series data plotted routinely at MVO. The Windy Hill AVTIS radar worked after repair but is about to be returned to St Andrews again for an overhaul. The thermal camera and ultrasound array are also due for an on-island maintenance by the University of Firenze. The fixed camera at MVO is now installed and the video camera at Harris will soon be. MVO’s FLIR thermal camera will give a calibrated time series of data once corrected for the atmosphere.

60. The capability for MVO to initiate and fund its own petrological and geochemical studies (away from MVO) was discussed. This could be undertaken with internal MVO funds, but also with UWI (campus research and training) funds. Rather more restrictive overseas funding could be sought from CIDA and the Royal Society International Exchange. Ion probe time could be sought via a joint application in the UK.

61. A. Stinton and S. Sparks took part in the Nautilus cruise around Montserrat, just prior to the SAC meeting. The robotic vehicles operating between about 1000 and 200 m sea depth off southern Montserrat discovered many interesting features (www.nautiluslive.com). G. Wadge and colleagues returned in August 2013 to work with K. Pascal using a ground-based interferometric radar (GPRI2) to study the dome and the atmosphere around the volcano. The French muon tomography experiment to image the density structure of the volcano is due in the next few months, as is the US “spider” deployment.

62. Outreach activities with Montserratian school children has included short-story and poetry competitions, with YouTube entries.

63. Archiving the old records of the Observatory has taken off in the last year, in part helped by the efforts of the STREVA project and BGS. Over 3500 paper seismograms from 1995/95 have been digitised by MVO interns. Other sources that will be archived include: observation room notebooks, field notebooks, MVO reports, Montserratian newspaper reports and correspondence. The archive of photographs is huge (80,000 since 1980). David Lea intends to create a chronological archive of activity from his extensive video library. Rose Willock and Bennett Roach have suggested compiling recordings of peoples’ recollections and opinions. Issues of distribution and accessibility have yet to be worked out.

**Benefits of MVO to Montserrat**

64. MVO is a major asset to Montserrat. But the case for that has not been widely made, other than implied by its continued existence as a statutory body of the Government of Montserrat. That case may need to be well made, exercised and strengthened in coming years. R. Stewart provided an initial listing of financial and other benefits (Appendix 9) as a spur to debate. As with all assertions of benefit, the link is best made by specific example, preferably with some valuation. MVO ought to bring increased economic confidence (through consistent assessments of risk) in Montserrat, but it is currently impossible to put a value on that. Other benefits are also difficult to evaluate. For example, it can
be argued that the lessons learned at Montserrat will enable other countries with volcanoes in the region (and globally) to respond more effectively to any future eruption there. Depending on future developments, concepts for managing the post-eruption legacy of Plymouth such as a “geopark” could and should involve a practical role for MVO.

**SAC Matters**

65. The issue of legal indemnity for members of the SAC has concerned us for some time and has been brought into focus by the L’Aquila affair. The defence against the claim of negligence in the provision of scientific advice can only be tested in court and it is the cost of legal representation in such a situation that is of major concern. We asked for and received (on 20 November 2013), from the SAC Partnership/GO Science, draft advice. This is being discussed as this report is being prepared.

66. The SAC is in the process of renewing its membership. Professor Wadge is standing down as Chairman after 11 years in post, as is Professor Voight. Both feel highly privileged to have been able to serve on the SAC. A special Montserrat cake was produced to mark the occasion. Professor Neuberg will become Chairman in 2014.

67. The next meeting of the SAC will take place in September 2013 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 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 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 Lee Davies, Desk Officer for Montserrat in OTD. Her contact details are as follows:

Email: lee.davies@fco.gov.uk
Tel: +44 20 7008 3123
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Appendix 2: Minutes of a teleconference meeting of SAC/MVO members on 21 May 2013

Present
W. Aspinall, J. Barclay, J. Neuberg, S. Sparks, G. Wadge
R. Stewart, P. Smith, T. Christopher, K. Pascal, A. Stinton
V. Bass, R. Syers, C. Williams, F. Dondin
R. Robertson,

Agenda
MVO 6-month report OFR 13-06
Doppelganger update
Timing and agenda for the October SAC meeting
   Increased time on elicitation
   Doppelganger elicitation/discussion
   Geothermal drilling report
AOB

MVO report 13 October 2012 to 30 April 2013

Despite the near complete lack of volcanic activity a full and thorough report had been produced. Discussion focused on a few topics.

The period was characterised by very low levels of seismicity with some VT-strings between November 2012 and February 2013, fairly steady SO2 output and continued inflation but at a declining rate. The VT-strings of 4-5 February 2013 were the most significant during the period. It included the now characteristic elements of a set of events precursory to the main set with hybrid events at the end, minor ash venting and increased SO2 output over an extended period peaking after the seismicity. There was discussion on the origin of the VT-strings. Are they driven by increasing gas pressure in the conduit, or are they a more passive response to tectonic stress? The lengthy seismic hiatus following the much more energetic March 2012 VT-string (Fig. 1.2.3) might suggest a tectonic driver. The VT hypocentral locations (Fig. 1.2.4) are displaced to the northwest of the long-term vent by a distance (~ 0.5 km) that is probably not a measurement artefact. This could be indicative of a fault or dyke. Searching for a common stress tensor across the strings may be worthwhile. The new near-dome seismometers planned will greatly help in future analysis of this. What is the significance of the hybrid events recorded at the end of the string sequence – could they involve magma or another fluid?

The apparent deceleration of the GPS-measured inflation now appears to have begun at least a year ago. The presentation of this is somewhat contradictory in the report. Plots of the MVO1 station motion (Fig. 2.1.2/3 show deceleration, whereas the summary map horizontal vector for MVO1 (Fig. 1.3.4) shows an acceleration of motion over the last 6 months relative to the previous 1.5 years. This apparent deceleration is potentially significant for the evaluation of long-term behaviour, however the role of any intra-island tectonic motion still clouds the issue.

The lengthening of two EDM lines from Brodericks in 2013 is an interesting reversal of longer trends, but is currently unexplained.
Month-scale SO2 emission rates remain stable at about 460 t/d over this period. How will we interpret this high rate if the long-term deformation signal flattens? We will require a deep mechanism of degassing that is effectively decoupled from basaltic magma flux into the andesite. Petrology could help here. Recent ICPMS melt inclusion data hints at a more thoroughly mixed magma with time in the eruption. Thanks to the new IR-camera we now have more accurate fumarole temperature measurements, and they confirm the high temperatures (up to 600C) and long-term stability seen since 2010.

Section 2.4 presents a clear re-partitioning of standard phase-pause subdivision of the eruption, with the periods of seismic/phreatic/transitional activity leading up to most of the phases of lava being assigned to that phase, rather than the pause. Cole et al.’s paper on transitional ash venting in the new memoir gives a similar analysis, and assigns the period in Pause1 from 7 July 1998 to 27 November 1999 to the precursor period to Phase 2.

**Doppelganger Update**

Tom Sheldrake (and Henry Odbert) worked with Wadge, Sparks and Aspinall on the data and analysis of 10 (later 13) andesite, lava dome volcanoes with recent eruptions. On February 19/20 a dummy run exercise (with students) was held at Bristol to populate BBNs for these volcanoes. We now plan a further meeting to refine such a BBN for Soufriere Hills with SAC members plus Stewart and Robertson. This would then be elicited at the October SAC18. Sheldrake would prepare a summary of where we are in the next few weeks. FCO has now agreed in principle to fund the attendance of Voight, Stewart and Robertson. We need to agree a date for this.

**SAC18 agenda**

There was general approval of holding the SAC over 4 days from Tuesday 29 October to Friday 1 November. The extra time available could be spent on:

(i) Doppelganger elicitation
(ii) Fuller briefing for the QRA elicitation
(iii) More detailed discussion of the likelihood of restart of lava extrusion at SHV, including interpretation of evidence for the underlying magma mingling model
(iv) Results of geothermal drilling. There is no available report of the drilling. Funding to allow one of the US-based drilling geologists to attend would be required.

G. Wadge
27 May 2013
1. 21 May 2013 tele-meeting, this meeting, public meeting
2. MVO activity report (R.Stewart)
3. GPS deformation analysis (K.Pascal)
4. Degassing analysis (T.Christopher)
5. Petrological progress (J.Barclay)
6. Mush destabilisation – gas fluxing (S.Sparks)
7. Dilatometer analysis of Vulcanians (S.Sparks)
8. SHV magmatic system summary (G.Wadge)
9. Geothermal drilling (R.Stewart)
10. Nautilus cruise results (S.Sparks/A.Stinton)
11. Doppelganger workshop (T.Sheldrake, W.Aspinall)
12. Doppelganger reprise
13. One-year hazard assessment (W.Aspinall)
   Briefing
   Elicitations
14. Risks in the Hazard Zones
15. Work risks in Plymouth
16. Future access to Zones C and V
17. Financial and other benefits of MVO to Montserrat (R.Stewart)
18. One-year hazard assessment reprise
19. MVO Matters
   Staff
   Monitoring
   Collaboration
   Hazard Level System
   Archive project (STREVA)
20. SAC Matters
   Legal indemnity
   Membership
   Next meeting
Appendix 4: List of Participants

Chairman
Prof. G. Wadge  University of Reading, UK

Committee members
Dr. W.P. Aspinall  Aspinall & Associates & Bristol University, UK
Dr. J. Barclay  University of East Anglia, UK
Prof. J. Neuberg  Leeds University, UK
Prof. B. Voight  Penn. State University, USA
Prof. R.S.J. Sparks  University of Bristol, UK
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. J. Latchman (Seismic Research Centre, UWI)
Dr. E. Joseph (Seismic Research Centre, UWI)
Mr. T. Sheldrake (University of Bristol, observer)
Mr. R. Bretton (University of Bristol, observer)
Over the past year there has been almost no new activity at the surface of the volcano. The dome has remained stable, apart from a large slab of rock that collapsed into the Tar River valley in March 2013 and occasional smaller rockfalls. The dome retains the potential to become unstable. Hot gases from depth, escaping from long-lived fumaroles, have maintained temperatures of about 600°C.

It is now 45 months since the last phase of lava eruption, the longest pause since the eruption began in 1995. Measurements made by MVO of ground movement show a continuing trend of low level inflation of the island. Sulphur dioxide emission rates have remained steady over the past three years. The seismicity has declined during the pause to a low level. Together, these indicate continued activity in the magma deep beneath the volcano. From all these measurements we conclude that the volcano remains able to erupt lava at short notice, but shows no signs that this is imminent.

In order to better understand how the volcano might behave over the coming years we have made a specific study of volcanoes around the world that are similar in character to Soufriere Hills and which are well monitored. While none of these volcanoes show an exact match of behaviour, Soufriere Hills is closest in behaviour to those volcanoes that show persisting activity.

The hazard from pyroclastic flows and surges in the lower Belham Valley that might occur over the next year remains at a similar level to that of one year ago. Pyroclastic flows can occur at any time without warning and consequently a lethal threat to people working in or visiting Plymouth remains.
This note examines long-term temporal fluctuations in the statistical properties of SHV SO₂ 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 SO₂ 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 \(\text{Ln (flux)}\) – i.e. \(\text{Ln(6)} \approx 400\ t/d\), 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[α, β] vary with time throughout the eruption. Uncertainties are calculated for α, β for each 30-day dataset, as a function of number of measurements available.

Figure 3: Time series showing variation through time of the LogLogistic β (median – upper panel) and α (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 β (median) parameter with – unsurprisingly – an overall pattern that is quite similar to that exhibited by plots of the 7-day filtered SO₂ 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 α (shape) parameter are shown in the middle panel, with uncertainties indicated here as bars. There are sections where α and β 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 ongoing 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.

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**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.

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.

![Figure 5 FFT spectral analysis of the LogLogistic $\beta$ (median – upper panel) and $\alpha$ (shape – lower panel) parameters](image-url)
Discussion

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

With the LL $\beta$ 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 loglogistic 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 SO$_2$ 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 loglogistic 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 loglogistic 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 $\beta$ (median), and changes in effective permeability/transmissivity showing up as variations in LL shape factor $\alpha$.

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 $\beta$ (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.
Appendix 7

SAC 18 Doppelganger workshop

Work Schedule

Introduction
1. Rationale for the doppelganger exercise
2. Introduce doppelganger data
3. BBN structure
   a. Eruptive trends
   b. Eruptive regimes
   c. Reservoir eruption potential
   d. BBN sensitivities
   e. Doppelganger data fits to BBN

Inferring the eruption trend at SHV
1. Eruptive history - elicit prior for eruption trend
2. Overview of petrological observations
3. Elicit probability of observing magma mixing and hybridisation
4. Elicit CPT for persistence conditional upon the eruption trend

Inferring the regime at SHV
5. Elicit priors for the probability that SHV is a persistent based upon SO$_2$ observations
6. Calculate likelihood ratios for persistent regime using doppelgangers

Inferring the reservoir eruption potential of the magmatic system at SHV
7. Elicit priors for the probability that the REP is increasing w.r.t seismicity, deformation and gas.
8. Calculate likelihood ratios using doppelgangers for:
   a. Seismicity
   b. Deformation
   c. Gas
9. Elicit CPT for REP conditional upon the duration of quiescence.

Forecasting future activity at SHV
10. Elicit CPT for quiescence continuing conditional upon whether SHV is a persistent or discrete regime
11. Elicit CPT for eruption size, conditional upon the eruption trend

Analyse results

Discussion
Introduction
The eruption at Soufrière Hills volcano (SHV) has been particularly notable for its longevity, having thus far included five distinct phases of extrusive activity over 18 years. As the eruption has progressed, in each of the quiescent phases there has been an increased focus in forecasting if and when activity will restart. In this context, it soon became important for the scientific community to address the issues of how and when it would become possible to identify a long-term cessation of eruptive (and thus potentially hazardous) activity at the volcano (e.g. Loughlin et al., 1998; Aspinall, W. P., Nov 2011). The ‘end of eruption’ issue has been renewed at the end of each eruptive phase and becomes more pressing as quiescence endures. To address the issue, we must consider what observations would be or not be evident in the event that the volcano is entering a long-term (i.e. more than several decades) period of repose. Guidance can be sought by combining what is known about the magmatic processes that favour eruptive activity and, further, by the way those processes are manifested in observations captured through routine volcano monitoring. Here we consider how we can model the state of the eruption probabilistically, using a statistical model and Bayesian inference from uncertain evidence, to represent our understanding of the volcanic system. Because earlier eruptions at SHV preceding 1995 were not observed, which could have provided a historical catalogue of ‘typical’ behaviour; we introduce evidence from other doppelganger volcanoes that can be considered comparable to SHV in order to better constrain interpretation of current observations.

The task at SAC18 is to explore the probability of long-term eruptions at SHV using a Bayesian Belief Network (BBN) informed by the behaviour of SHV and the doppelganger volcanoes. In the following we describe the doppelganger volcano data, the structure of the BBN and the elicitation procedure.

Doppelganger volcanoes
We identified fourteen other dome-building volcanoes for this study (Table 1) to aid the analysis and interpretation of the current situation at SHV. They were partly chosen based on the availability of monitoring data along with well-defined historical records of eruptive activity summarised in Fig.1. It is evident from the doppelgangers that a wide range of activity can be observed at dome-building volcanoes. For each volcano, a synopsis of activity and monitoring observables is prepared as background information (Appendices B-D and the supporting document “Doppelganger Volcano Summaries”). The responses of monitoring observables to a cessation in eruptive activity, the length of repose periods and the general pattern of eruptive activity at the doppelgangers can be used to interpret evidence from SHV, through the BBN concepts, for future long-term behaviour.
Fig. 1: General pattern of extrusive and explosive activity at SHV and each of the doppelganger volcanoes at a yearly resolution. Shaded pink areas represent either extrusive or explosive activity and blue vertical lines, major explosions.
**Table 1 Doppelganger volcanoes**

**Protocol**

The purpose of the rest of this document is to present a methodology to be employed at the SAC 18 meeting in October 2013 (building on a preparatory workshop in Bristol (Appendix A), which will provide a holistic approach to analysing the wide range of evidence available at SHV for the purpose of eruption forecasting, or perhaps more specifically, quiescence forecasting. The method integrates the evidence through the employment of a Bayesian Belief Network (BBN).

The application of a BBN structure provides a systematic approach to inferring the magmatic processes that are occurring and will determine future eruptive activity at SHV. These magmatic processes are hidden and our understanding of them is captured in the model through the application of three ‘unobservable’ (or latent) nodes and relate to either long- or short-term processes. Long-term processes are characterised by the style of activity that is observed at the surface over decadal timescales (1-2) whereas shorter-term processes are characterised by a third node (3).

1. **Eruptive trend**: The purpose of this node is to make inferences about the evolutionary development of future activity at SHV at a decadal scale, with regards to both the eruptive regime (described below) and the intensity of explosive activity. It is characterised by analysing both the past eruptive activity at SHV and petrological evidence of magmatic processes and can take one of three trend states, escalating, consistent or diminishing.
2. **Eruptive regime:** The purpose of this node is to inform forecasts of the continuation of quiescence at SHV. It is characterised by the long-term persistence of magmatic activity and can take one of two regime states, persistent or discrete.

3. **Reservoir eruption potential (REP):** The purpose of this node is to calculate the likelihood of eruptive activity for different forecasting intervals based upon the state of the magmatic reservoir. It acts as a catch-all term for the monitoring observables and is characterised by analysing the cGPS, DOAS and seismic networks to infer whether the REP is increasing or not.

Once the results of the elicitation have been used to populate the BBN, forecasts for both the **duration of quiescence** and **maximum expected explosive activity** can be made, along with inference of whether volcanic activity at SHV is diminishing or not.

To assess the state of each of the ‘unobservable’ nodes described above a range of evidence is used. From this we calculate both the prior belief and likelihood of satisfying a particular state using observations at SHV and interpreting them with respect to both volcanological processes leading to eruptive activity and what is observed at the doppelganger volcanoes. The structure of the BBN is shown in Fig. 2.

![Fig. 2: BBN structure](image)

**Eruption trend**

This unobservable node is used to capture the long-term (> 5 yr) changing intensity of the magmatic system. The eruption trend is inferred by analysing the past eruptive activity at SHV and then updating it by hypothesising how future eruptive activity will develop. The prior belief is elicited based upon analysing the past eruptive activity at SHV in terms of the following three categories:

- **Escalating:** The long-term lava flux is increasing through time and/or there is an increase in the intensity of surface activity through time;
• **Consistent:** Both the long-term lava flux and the intensity of activity remain consistent over time;

• **Diminishing:** The long-term lava flux is decreasing through time and/or there is a decrease in the intensity of surface activity through time.

*Likelihood of eruption trend*

Petrological data can be used to infer the long-term processes of magma mixing and hybridisation in the SHV reservoir. From that, a second inference can be made as to whether increased hybridisation leads to increased magma transport from the reservoir or not. This is expressed here as belief in a long-term trend and used to update the prior beliefs. Thus, the posterior can be interpreted as a belief of the state in the current trend in activity at SHV. Example scenarios for each of the three categories described above are:

- **Escalating:**
  o In the time period over which forecasts will be made, the extrusive flux exceeds the long-term average (c. $2\text{m}^3\text{s}^{-1}$ between 1995-2013) by c. 50%;
  o Some combination of more intense, more frequent or significantly larger explosions than previously observed;
  o Larger footprint for blasts than previously observed.

- **Consistent:**
  o Further periods of dome growth within previous envelope of short and long-term lava fluxes.
  o Vulcanian explosions and blasts broadly within the range of previous activity in terms of column heights, magnitudes and footprints.

- **Diminishing:**
  o Further periods of dome growth with significantly lower (c. 50% or less) long-term extrusive lava flux;
  o Some combination of less intense, less frequent or significantly smaller explosions (i.e. plume heights $\sim <5\text{km}$) than previously observed.
  o May involve no extrusive or explosive activity

The trends of the doppelganger volcanoes are suggested in Appendix B.

**Eruptive regime**

This node captures the degree of continuity of the eruption in terms of two regimes of behaviour. Generally, the activity at dome-building volcanoes allows membership of these regimes to be inferred as either volcanoes that are persistently active over many decades or volcanoes where activity is confined to more discrete intervals. Thus:

(1) **Persistent regime** can be characterised by any of the following:

  a. Continuous magmatic unrest manifested by persistent gas emissions;
  b. Can exhibit a variation in the intensity of activity;
c. Intermittent to continuous activity with intervals of quiescence (i.e. no extrusive or explosive activity) generally lasting months to years (potentially even decades), but with persistent, substantial degassing.

**2) Discrete regime** satisfies both of the following criteria:

a. Phases of activity followed by much longer repose durations;

b. Cessation of gas emissions in the following months to years after extrusive activity has stopped, and thus no significant fumarolic activity throughout periods of quiescence.

The prior belief of what eruptive regime SHV belongs to is conditioned upon the belief in the long-term eruption trend state giving six possible combinations (Fig.3). This is then updated by interpreting current degassing observations that have occurred throughout the current period of quiescence.

![Persistent vs Discrete Eruptive Regimes](image)

**Fig. 3:** Example cartoons of scenarios at volcanoes where the eruptive regime is either persistent or discrete and the trend in eruptive activity can take one of three states; escalating, consistent or diminishing.
Degassing during quiescence
Persistently active systems are almost always characterised by near-continuous fluxes of volcanic gases, of which the most routinely measured is SO$_2$. Therefore, the interpretation of the current situation at SHV (over three years of persistent degassing without extrusive activity) has significant implications for the likelihood of SHV being a persistent regime or not. Consequently the likelihood of SHV being a persistent regime, conditional upon current gas observations is elicited. The doppelganger evidence relevant to this is summarised in Appendix C.

Forecasting the duration of quiescence
Forecasts for the probability of eruptive activity being renewed will be made for three time intervals of interest from the present to 1, 5 and 30 years ahead, representing the traditional SAC forecasting period, short-term political decision making and long-term policy making timescales respectively.

Long-term forecasts of repose duration at volcanoes are traditionally based upon analysing previous phases of activity. However, due to the limited eruptive history at SHV (18 years in total), observations have to be used from other dome-building volcanoes. To account for the varied activity at dome building volcanoes, forecasts for the continuation of quiescence are conditioned upon the belief of the eruptive regime state at SHV. This will be elicited but also has the potential to incorporate the results of statistical models of repose durations and represents the classical approach to ‘long-term’ forecasting.

The prior belief of SHV erupting in each of the three forecasting intervals is updated by the likelihood of observing magmatic processes that lead to renewed extrusive activity. The occurrence of these magmatic processes is inferred by interpreting geophysical and geochemical monitoring observations through an unobservable node, Reservoir eruption potential.

Reservoir eruption potential
In contrast to the other two unobservable nodes, Reservoir Eruption Potential (REP) is meant to capture the probability of renewed lava extrusion up to the next 5 years using the evidence from observables. This is similar to the traditional approach to forecasting activity at one-year future intervals, where assessments are made by interpreting monitoring observables; long-period seismicity, deformation and SO$_2$ degassing. Thus the prior beliefs of extrusive activity being renewed in each of the three time intervals (1, 5 and 30 years) are updated using a likelihood function based on the active state of the shallow magmatic system (<15km). As in the Bristol workshop, the current state of the magmatic system is captured through the application of this unobservable node – Reservoir Eruption Potential. This catchall term aims to incorporate all shallow crustal process (such as magma degassing, crystallisation, mass transfer, etc.) that influence or contribute to eruption potential.

Monitoring observables
Three monitoring observables are employed to infer whether the REP is increasing or not. For each observable the probable level of significance for future eruption potential will be elicited and contribute to the change in REP value. The following
observables are analysed to reflect the influence of specific physical processes occurring in the magmatic system.

- Far-field deformation (either inflation or deflation), measured by cGPS
- Seismicity – all types considered
- $\text{SO}_2$ fluxes measured by DOAS above a background level.

The doppelganger evidence concerning far-field deformation and seismicity is summarised in Appendix D and E respectively.

**Forecasting explosion magnitude**

When the current quiescent period ends, what will be the largest magnitude explosion we might expect during the ensuing activity? Applying the BBN structure described above, probabilistic forecasts of what explosive activity will occur, are based on the belief of whether the trend in eruptive activity at SHV is either escalating, consistent or diminishing. The following four explosion categories have been chosen to present the range of potential activity that could occur at SHV:

- Plinian eruptions
- Vulcanian eruptions and associated blasts
- Smaller Vulcanian eruptions and no associated blasts
- None

The probability that the maximum expected eruption is categorised as one of the above is conditioned upon the belief of the trend in activity observed at SHV except for the ‘none’ state, which is conditioned upon the belief that quiescence will continue for longer than thirty years.
Elicitation procedure

Eruption trend:

Priors – Eruption history:
This is calculated by analysing the eruptive history of SHV since 1995 in terms of variations in the long-term magma flux and the intensity of explosive activity. The probability of past activity being characterised as one of three states is elicited with the probabilities being exhaustive and summing to one (Q.’s 1-3).

Based upon the evolution of extrusive activity since the onset of activity in 1995, what is the probability that the trend in activity is:
1. Escalating
2. Consistent
3. Diminishing

Likelihood – Petrological evidence:
This is based upon petrological data presented by Dr. J Barclay and used to infer whether magma mixing and hybridisation has increased throughout the eruption (Q. 4) and then to update the probability of the three eruption trend states (Q.’s 5-7).

4. Given petrological observations, what is the probability that magma mixing and hybridisation has increased throughout the eruption?

5. Given SHV is in an escalating trend, what is the probability of observing increased mingling or hybridisation?

6. Given SHV is in a consistent trend, what is the probability of observing increased mingling or hybridisation?

7. Given SHV is in a diminishing trend, what is the probability of observing increased mingling or hybridisation?

Eruptive regime
The prior for the eruptive regime is conditioned upon the eruption trend (Q.8-10). For each of the two regime states, persistent and discrete, examples will be provided where eruptive activity has escalated, been consistent or diminished. The likelihood is based on interpreting SO\textsubscript{2} emissions during this latest phase of quiescence, and is based firstly on analysing the degassing behaviour of SHV with regard to volcanic processes (Q.11) and then comparing current gas emissions (persistence, gas fluxes and fumarole temperatures) to volcanoes exhibiting either discrete and persistent regimes (Q.12-13).

Priors – Conditioned upon eruption trend:

8. Given the trend in eruptive activity at SHV is escalating, what is the probability that it is in a persistent regime?

9. Given the trend in eruptive activity at SHV is consistent, what is the probability that it is in a persistent regime?

10. Given the trend in eruptive activity at SHV is diminishing, what is the probability that it is in a persistent regime?

Likelihood – Current (passive) degassing:

11. What is the probability that SHV is in a persistent regime given current levels of degassing at SHV?
12. Assuming SHV is in a persistent regime, what is the probability of observing the current period of quiescence (over 3 years) accompanied by the observed degassing?

13. Assuming SHV is in a discrete regime, what is the probability of observing the current period of quiescence (over 3 years) accompanied by the observed degassing?

Reservoir Eruption Potential (REP)
The REP node is used to calculate the likelihood of quiescence continuing for each of the four forecasting intervals by eliciting the probability that processes leading to an increasing REP are currently occurring given SHV erupts in each of the forecasting intervals (Q.’s 14-18). REP characterises the processes occurring in the magmatic reservoir with an increasing REP assumed to be occurring within the preceding 5 years before renewed extrusive and/or explosive activity. However, although Q’s 16-17 relate to larger timescales than five years, this does necessarily mean the answer is zero to each of these questions. There could potentially be a scenario where the REP is increasing but the volcano never reaches a state of eruptive activity (i.e. what is sometimes considered a ‘failed’ eruption).

The likelihood of the REP increasing is calculated firstly by analysing each of the three monitoring observables (deformation, seismicity and gas). Are they indicative of volcanic processes (e.g. magma degassing, crystallisation, mass transfer, etc.) that will increase the REP (Q.’s 18, 21 & 24)? Secondly, evidence from the doppelganger volcanoes is used to elicit the probability of experiencing the current monitoring observations, given the REP is increasing - i.e. are similar monitoring observations followed by extrusive and explosive activity at the doppelganger volcanoes (Q.’s 19-20; 22-23; 25-26).

Priors – Conditioned upon future eruptive activity

14. Given that SHV has been active for 18 years and will erupt in less than one year, what is the probability that the REP is currently increasing?

15. Given that SHV has been active for 18 years and will erupt between one and five years time, what is the probability that the REP is currently increasing?

16. Given that SHV has been active for 18 years and will erupt between five and thirty years time, what is the probability that the REP is currently increasing?

17. Given that SHV has been active for 18 years and will NOT erupt in the next thirty years, what is the probability that the REP is currently increasing?

Likelihood – Interpreting monitoring observables

Deformation:

18. What is the probability that the REP is increasing given current observations of deformation?

19. Assuming that the REP is increasing, what is the probability of observing the current deformation?

20. Assuming that the REP is NOT increasing, what is the probability of observing the current deformation?

Seismicity:

21. What is the probability that the REP is increasing given current observations of seismicity associated with gas and ash venting?

22. Assuming that the REP is increasing, what is the probability of observing the current levels of seismicity associated with gas and ash venting?
23. Assuming that the REP is NOT increasing, what is the probability of observing the current levels of seismicity associated with gas and ash venting?

Gas:
24. What is the probability that the REP is increasing given the current pattern of volcanic degassing?

25. Assuming that the REP is increasing, what is the probability of observing the current pattern of volcanic degassing?

26. Assuming that the REP is NOT increasing, what is the probability of observing the current pattern of volcanic degassing?

**Forecasting the duration of quiescence**
Forecasts are made conditionally upon whether SHV is in a persistent or discrete regime. Examples of repose intervals are presented for both regime states and probabilities are elicited ensuring they sum to one in each case.

Given SHV is a **persistent** system, what is the probability of quiescence lasting:

- 27. Less than one year
- 28. Between one and five years
- 29. Between five and thirty years
- 30. Greater than thirty years

Given SHV is a **discrete** system, what is the probability of quiescence lasting longer than:

- 31. Less than one year
- 32. Between one and five years
- 33. Between five and thirty years
- 34. Greater than thirty years

**Forecasting the maximum explosion magnitude**
Forecasts are made conditioned upon the belief in the eruption trend. According to the definitions for each of the three states (escalating, consistent and diminishing) all three could be satisfied with similar explosive activity to that which has been observed previously at SHV. However, Plinian activity can only be satisfied by an increasing eruption trend and small Vulcanian explosions (i.e. ~<5km plume heights) satisfied by a diminishing eruption trend. Consequently, the target questions are concerned with eliciting the probability of these two events, conditional on their respective eruption trends. For example, if the eruptive trend is believed to be escalating then the maximum explosive activity in the forecasting period has to be satisfied by at least Vulcanian or Plinian-style activity.

35. Given the eruptive trend at SHV is escalating, what is the probability that the maximum eruptive activity will be classified as Plinian? (small Vulcanian = zero as this satisfies diminishing category)

36. Given the eruptive trend at SHV is diminishing, what is the probability that the maximum eruptive activity will be classified as small Vulcanian or less (i.e. ~<5km plume heights)? (Plinian = zero as this satisfies escalating category)

**Appendix A**
Bristol Review

In February 2013 we held a workshop and expert judgement session over one and a half days in Bristol. The purpose of the meeting was to introduce the doppelganger concept and carry out an elicitation exercise in order to parameterise our model. The participants had a range of experiences with analysing volcanological data for the purposes of hazard assessment involving 5 Post-Docs (including HMO) and 12 PhD students (including TS). Four other scientists from the Foreign Office’s Scientific Advisory Committee for Montserrat (SAC) and MVO were also present (RSJS, WPA, GW and Dr. Paul Cole).

All participants were presented in advance with synopses of eruptive activity at the 12 ‘doppelganger’ volcanoes and some were asked to give short presentations to introduce each of the volcanoes on the day, summarising these synopses. Dr Paul Cole presented an overview of the SHV eruption and explained the current state of the volcano. Following this, an elicitation exercise involving both calibration and target questions, was facilitated by WPA. The elicitation questions had been designed in tandem with a Bayesian Belief Network (BBN) that represented our physical understanding of the SHV system and that may be parameterised via values that can be reasonably constrained through expert judgment. In other words, the target questions in the elicitation must be answerable by an informed expert but must also provide information that usefully constrains the BBN model. Meeting both conditions for this problem is non-trivial, and the Bristol workshop proved to be a valuable exercise and has been particularly helpful in identifying issues with the BBN design, the way inferences are made using the monitoring observables, and how the doppelganger evidence can be exploited effectively in a short time. We identified a number of improvements that were made subsequently:

- Inferences regarding monitoring observables (particularly gas) need to be more directly linked to hypotheses of the long-term trend and patterns in eruptive activity. This means in future elicitation exercises, including with the SAC, the synopses and data for the ‘doppelgangers’ should be presented in terms of whether activity is characterised by persistent degassing of SO$_2$ or not;
- Terms used to hypothesise future activity need to be defined by a series of specific criteria;
- Fewer time intervals are chosen for the forecasting period of 30 years.
Appendix B  Doppelganger Eruption Trends

We are concerned with eliciting three questions that involve trend and regime:

1. Given the trend in eruptive activity at SHV is **escalating**, what is the probability that it is in a **persistent** regime?
2. Given the trend in eruptive activity at SHV is **consistent**, what is the probability that it is in a **persistent** regime?
3. Given the trend in eruptive activity at SHV is **diminishing**, what is the probability that it is in a **persistent** regime?

Examples of eruption trends satisfying one of these three characteristics are provided for volcanoes that exhibit either persistent or discrete eruptive regimes. Further information can be found in each of the volcano profiles in the supporting document “Doppelganger Volcano Summaries”.

<table>
<thead>
<tr>
<th>Eruption Trend</th>
<th>Persistent regime</th>
<th>Discrete regime</th>
</tr>
</thead>
</table>
| **Escalating trend** | Lascar: 1984 - 1993  
Merapi: 2000 - 2010  
Bezymianny: 1975-1985  
| **Consistent trend** | Santiaguito: 1930 - present  
Bezymianny: 2001 - present  
Lascar: 2000 - present  
Merapi: 1900 – 2000  
Popocatepetl: 1994 - present  
| **Diminishing trend** | Santiaguito (each phase):  e.g. 1922-32  
Augustine: 1986, 2006  
Redoubt: 1989, 2009  
Unzen: 1990 – 1995  
Pelée: 1902-1905, 1929-1932  
?Tungurahua: 1912-1916*  
Popocatepetl: 1947* |

* Followed by several years (> 5) of minor ash venting activity  
? Could potentially satisfy the opposing eruptive regime
Appendix C  Doppelganger  SO$_2$ emission

We are concerned with two sets of questions. The first relate to eliciting whether SHV is in a persistent regime and the second the probability of quiescence lasting certain intervals depending upon whether SHV is in a persistent or discrete regime.

- Assuming SHV is in a persistent regime, what is the probability of observing the current period of quiescence (over 3 years) accompanied by the observed degassing?
- Assuming SHV is in a discrete regime, what is the probability of observing the current period of quiescence (over 3 years) accompanied by the observed degassing?

And

Given SHV is in a persistent regime, what is the probability of quiescence lasting:
1. Less than one year
2. Between one and five years
3. Between five and thirty years
4. Greater than thirty years

Given SHV is in a discrete regime, what is the probability of quiescence lasting longer than:
5. Less than one year
6. Between one and five years
7. Between five and thirty years
8. Greater than thirty years

Therefore, in relation to the doppelgangers we are concerned with:

- At volcanoes exhibiting a discrete regime:
  o How long does SO$_2$ fluxes persist after a cessation of extrusive and explosive activity?
  o What is the typical baseline SO$_2$ flux during quiescence?
  o What is the temperature history of fumaroles during quiescence?
- At volcanoes exhibiting a persistent regime:
  o What is the typical baseline SO$_2$ flux during quiescence?
  o What is the temperature history of fumaroles during quiescence?
  o What is the range of repose intervals and extrusive phases at persistently active volcanoes?

Discrete regimes
The following is a series of SO$_2$ flux histories during and following eruptions at Redoubt, Augustine and Mount St. Helens that could be regarded as behaving in a discrete regime. The shaded pink region represents the extrusive and explosive phases with ground based and (if available) satellite based remotely sensed observations.
Augustine 1986 eruption

- SO\(_2\) Flux FL YSPEC (tons/day)
- Date: Jun –86 to Jun –90
- Volume: 0.3 km\(^3\)
- Max. Explosivity: Vulcanian
- Duration: c. 5 months
- Following repose duration: c. 20 yrs

Augustine 2006 eruption

- SO\(_2\) Flux FL YSPEC (tons/day)
- Date: Mar –06 to Mar –10
- Volume: 0.1 km\(^3\)
- Max. Explosivity: Vulcanian
- Duration: 2 months
- Following repose duration: 7yrs +
Redoubt 1989–1990 eruption

Volume = 0.2 km$^3$
Max. Explosivity = Vulcanian
Duration = c. 6 months
Following repose duration = c. 20 yrs

Redoubt 1989–1990 eruption

Volume = 0.1 km$^3$
Max. Explosivity = Vulcanian
Duration = 3 months
Following repose duration = 4yrs +

SO$_2$ Flux \(\text{COSPEC} (\text{tons/day})\)

SO$_2$ Flux \(\text{COSPEC} (\text{tons/day})\)
• The 1980-86 eruption actually consisted of many (20 in total) minor
dome growth phases lasting on the order of days to weeks with
associated elevated SO$_2$ fluxes (as observed above in October 1986).

• Mount St. Helens: In 2004-2008 fluxes were small (< 100 t/d) and only
measured for beginning of the eruption. The total volume of the eruption
was c. 0.1 km$^3$.

• Unzen: SO$_2$ fluxes during the eruption were uniform with an average of
137 tons per day with a maximum value of 230 tons per day. Values
diminished soon after the end of extrusion activity (Hirabayashi, 1995).
  o Fumarole temperatures decreased to 400-500°C in two years
  o Volume: 0.2 km$^3$
  o Explosivity: Vulcanian
  o Duration: c. 5 years
  o Quiescence: 18 years to present

• Pelée: No SO$_2$ fluxes:

<table>
<thead>
<tr>
<th>Date</th>
<th>Volume (km$^3$)</th>
<th>Explosivity</th>
<th>Extrusion duration</th>
<th>Following repose duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1902-1905</td>
<td>0.4</td>
<td>Vulcanian</td>
<td>c. 3 years</td>
<td>c. 24 yrs</td>
</tr>
<tr>
<td>1922-1932</td>
<td>0.2</td>
<td>Vulcanian</td>
<td>c. 3 years</td>
<td>83 years to present</td>
</tr>
</tbody>
</table>
Persistent regimes
Quiescent periods at persistently active volcanoes are characterised by persistent SO\textsubscript{2} emissions. During periods of quiescence fumaroles temperatures remain high between 450°C - 850°C, with some volcanoes exhibiting very high temperature fumaroles greater than 900°C (e.g. Santiaguito (Scott, 2013); Kudryavy (Fischer, 1998)). One or two volcanoes exhibit cooler fumaroles including Lascar where high temperature fumaroles are <500°C and Bezymianny of c.300°C. Thus, rather than present the temporal evolution of SO\textsubscript{2} each of the volcanoes is described using the following features:
- The characteristic explosive SO\textsubscript{2} fluxes
- The passive flux of SO\textsubscript{2}
- Characteristic duration of repose periods
- Characteristic duration of eruptive periods

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Explosive flux (t/d)</th>
<th>Passive flux (t/d)</th>
<th>Repose period duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungurahua</td>
<td>&gt;5000-10000</td>
<td>300-500</td>
<td>Months- Years</td>
</tr>
<tr>
<td>Lascar</td>
<td>&gt;1000-3000</td>
<td>200</td>
<td>Years (c. 2-7)</td>
</tr>
<tr>
<td>Merapi</td>
<td>&gt;400-2000</td>
<td>50-250</td>
<td>Years (c. 1-5)</td>
</tr>
<tr>
<td>Santiaguito</td>
<td>100’s</td>
<td>80-120</td>
<td>Days</td>
</tr>
<tr>
<td>Shiveluch</td>
<td>N/A</td>
<td>N/A</td>
<td>Decades/Years/Months</td>
</tr>
<tr>
<td>Bezymianny</td>
<td>c. 6800</td>
<td>200-300</td>
<td>Months</td>
</tr>
<tr>
<td>Colima</td>
<td>&gt;3000-16000</td>
<td>50-200</td>
<td>Years (2-8)</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>10000’s</td>
<td>1000’s</td>
<td>Years</td>
</tr>
<tr>
<td>Kudryavy</td>
<td>N/A</td>
<td>50-150</td>
<td>Years - Decades</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Characteristic eruptive period duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungurahua</td>
<td>Years &gt;1</td>
</tr>
<tr>
<td>Lascar</td>
<td>Years &gt;1</td>
</tr>
<tr>
<td>Merapi</td>
<td>Years (1-2)</td>
</tr>
<tr>
<td>Santiaguito</td>
<td>Near continuous</td>
</tr>
<tr>
<td>Shiveluch</td>
<td>Years (1-2) to near-continuous</td>
</tr>
<tr>
<td>Bezymianny</td>
<td>Months – Years (1-2)</td>
</tr>
<tr>
<td>Colima</td>
<td>Years &gt;1</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>Years &gt;1</td>
</tr>
<tr>
<td>Kudryavy</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Appendix D  Doppelganger far-field deformation

We are concerned with two questions:

1. Assuming the Reservoir eruption potential (REP) is increasing, what is the probability of observing the current rate of inflation?
2. Assuming that the REP is NOT increasing, what is the probability of observing the current rate of inflation?

Therefore, in relation to both SHV and the doppelganger volcanoes we are concerned with:

- How common is inter-eruptive inflation? – i.e. inflation following the end of the previous eruption followed by deflation once the eruption has started.
- How common is pre-eruptive inflation following significant periods of quiescence?
- How common is post-eruptive inflation followed by no significant extrusive or explosive activity for a period on the order of 5 years or greater?

The collation of data for the doppelganger volcanoes yields only a few circumstances where cGPS is employed in the far field (~ 5-20 km from the vent) as a monitoring tool. Many of the volcanoes that are persistently active employ near field techniques such as tilt meters in an effort to focus on short-term forecasting. Volcanoes where far-field deformation monitoring exists present discrete eruptive regimes and are perhaps coincidentally found in countries where monitoring resources are much greater, including the USA and Japan.

1. Mount St. Helens:
   - Using a station 8km to the north – JRO. 1
   - No precursory deformation before 2004
   - North component is reflective of radial deformation
2. Redoubt 2009:
   - Stations RGBY and DUMM 11.5 and 12km respectively from the volcano.
   - Radial inflation during pre-eruptive phase and deflation during eruption
   - No clear deformation signal following the eruption

Fig. 3 Top: daily north time-series (aligned to the fixed-MSH local tectonic reference frame; 95% confidence indicated by grey bars) of JRO1 station. The three time intervals investigated (1, 2 and 3; see text for details) are labelled. Bottom: temporal histogram of daily located earthquakes ($M_L > 1.0$) (http://earthquake.usgs.gov/regional/neic/) and cumulative seismic moment ($M_b$).

Taken from Palano et al., 2012
3. Unzen:
   • Precursory inflation followed by deflation
• No monitoring after the eruption
• Re occupation of far field baseline in 2010 shows no deformation

![Map of Bezymianny showing horizontal displacement vectors with 1σ ellipses and the location of the estimated pressure source.](image)

Fig. 4. Horizontal displacement vectors with 1σ ellipses and the location of the estimated pressure source (solid circle). (a) Inflation stage by magma intrusion. (b) Deflation stage by lava discharge. Solid triangle: Fugendake peak.

Taken from Nishi et al., 1999.

4. Bezymianny
• More recently, a GPS network has been installed around the persistently active Bezymianny volcano, but no far field deformation is associated with either quiescent or eruptive phases.
Appendix E  Doppelganger seismicity

We are concerned with two questions:
1. Assuming that the REP is increasing, what is the probability of observing the current levels of seismicity associated with gas and ash venting?
2. Assuming that the REP is NOT increasing, what is the probability of observing the current levels of seismicity associated with gas and ash venting?

Therefore, in relation to both SHV and the doppelganger volcanoes we are concerned with:
• How common is the occurrence of extrusive or explosive activity at persistently active volcanoes with levels of seismicity similar or lower than currently observed at SHV?
• How common is it to observe ash venting and associated seismicity following extrusive activity and in the early stages of prolonged periods of quiescence?
• How common is the occurrence of swarms of seismicity in prolonged periods of quiescence?

The following table provides examples of two scenarios:
1. Volcanoes exhibiting persistent regimes where repose periods are less than ~5 yrs.
2. Volcanoes exhibiting persistent or discrete regimes, where repose periods are longer ~5yrs

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shiveluch 1990 – present</td>
<td>Augustine 1986, 2006</td>
</tr>
<tr>
<td>Santiaguito 1922 – present</td>
<td>Unzen 1995</td>
</tr>
<tr>
<td>Bezymianny 1955 – present</td>
<td>Pelée 1905, 1932</td>
</tr>
<tr>
<td></td>
<td>Tungurahua 1926 – 1999</td>
</tr>
<tr>
<td></td>
<td>Popocatepetl 1945 - 1995</td>
</tr>
</tbody>
</table>

* Orange colours represent persistent regimes and blue colours discrete regimes; black represent uncertainty about the eruptive regime. Further details where relevant can be found in each of the volcano profiles in the supporting document “Doppelganger Volcano Summaries”.

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Appendix 8: 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 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>

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>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

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>
<th></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<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>
</thead>
<tbody>
<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 $\sim 10^{5}$ M $m^3$):

<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 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 $\sim$ 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 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 $\sim$ 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 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 $\sim$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 18**</td>
<td>0.0002%</td>
<td>0.03%</td>
<td>0.5%</td>
</tr>
<tr>
<td>SAC 18</td>
<td>0.0002%</td>
<td>0.08%</td>
<td>1.5%</td>
</tr>
<tr>
<td>SAC17*</td>
<td>0.0001%</td>
<td>0.012%</td>
<td>0.75%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.0002%</td>
<td>0.013%</td>
<td>0.3%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0%</td>
<td>0.03%</td>
<td>3%</td>
</tr>
</tbody>
</table>

* re-elicited following 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></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 18</td>
<td>0.0008%</td>
<td>0.08%</td>
<td>1.3%</td>
</tr>
<tr>
<td>SAC 17*</td>
<td>0.0006%</td>
<td>0.044%</td>
<td>1.3%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.0005%</td>
<td>0.046%</td>
<td>1.4%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.0002%</td>
<td>0.03%</td>
<td>3%</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>
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<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 18</td>
<td>0.5%</td>
<td>8%</td>
<td>61%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.2%</td>
<td>15%</td>
<td>68%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.5%</td>
<td>24%</td>
<td>68%</td>
</tr>
</tbody>
</table>

3. GIVEN a resumption of lava extrusion what is the probability that it will be part of a “long duration” pattern?

<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 18</td>
<td>6%</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>9%</td>
<td>37%</td>
<td>60%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>15%</td>
<td>44%</td>
<td>81%</td>
</tr>
</tbody>
</table>

3b. GIVEN a *resumption* of lava extrusion, what is the probability it will follow the short-sharp episodic on-off extrusion pattern, similar to Phases 4 & 5

<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 18</td>
<td>21%</td>
<td>70%</td>
<td>90%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>18%</td>
<td>63%</td>
<td>88%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>16%</td>
<td>56%</td>
<td>83%</td>
</tr>
</tbody>
</table>
4. GIVEN magma extrusion resumes within the next year, what will be the monthly average extrusion rate (in cu m/sec)?

<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 18</td>
<td>0.5</td>
<td>5.5</td>
<td>15.3</td>
</tr>
<tr>
<td>SAC 17</td>
<td>1.0</td>
<td>5.4</td>
<td>16.8</td>
</tr>
<tr>
<td>SAC 16 Long 3a</td>
<td>0.3</td>
<td>4.2</td>
<td>12.6</td>
</tr>
<tr>
<td>SAC 16 Short 3b</td>
<td>0.3</td>
<td>6.9</td>
<td>18.8</td>
</tr>
</tbody>
</table>

5. IF activity resumes, what is the probability of experiencing 9 million cu m (3x reference; twice 8 January) explosion(s) or greater in next year?

<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 18</td>
<td>0.01%</td>
<td>0.44%</td>
<td>12%</td>
</tr>
<tr>
<td>SAC 17</td>
<td>0.01%</td>
<td>0.12%</td>
<td>6%</td>
</tr>
<tr>
<td>SAC 16</td>
<td>0.006%</td>
<td>0.6%</td>
<td>12%</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></th>
<th>Credible interval lower bound</th>
<th>Best estimate</th>
<th>Credible interval upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC 18§</td>
<td>0.3%</td>
<td>16%</td>
<td>74%</td>
</tr>
</tbody>
</table>

§ This question has not been elicited in previous SAC meetings
Appendix 9: Benefits of MVO to Montserrat

Volcano Monitoring, Hazards and Safety

1. Advice about volcanic activity to GoM, FCO, DFID.
2. Advice and education to general public on Montserrat.
3. Deal with requests for information from the press and public worldwide.
4. Maintenance of a stable hazard level system boosting social confidence.
5. Advice on ash movements to air-traffic control in Montserrat, Antigua and further afield.
6. Provide advice to DMCA on applications for access to restricted areas.
7. Advice, monitoring and support for operations in restricted areas
   - Sand mining exports at Plymouth Jetty
   - Geothermal Project
   - Police and GoM departments
   - Sand mining in Trants and Belham Valley

Non-Volcano Monitoring, Hazards and Safety

8. Microseismic monitoring of geothermal project
9. Landslide monitoring (St George’s Hill)
10. Earthquakes and tsunamis (with SRC)

Outreach, Education, Employment and Training

11. Provide advice on earthquake, volcano and tsunami safety in schools
12. Science education in schools
13. Major supporter of Science Week
14. Work-experience programme from MSS
15. Volunteer Scientist programme with MCC
16. Intern programme
17. Close cooperation with National Trust and Montserrat Library

Geological / Geophysical / Geotechnical Advice

18. Geothermal project
19. PWD construction projects

Visitors / Tourism

20. Brings money-spenders to Montserrat
   - Tourists
   - Visiting scientists and volunteers
   - Attendees at conferences and training courses
21. Tax revenues
   - Books and souvenirs sold by MVO
   - Carribbean Helicopter’s tours from Antigua (US$60 per flight)
Government of Montserrat and its Departments

22. Active member of NDPRAC
23. Innovator of IT projects on Montserrat
24. Working with government departments on non-volcano matters
   - Disaster planning and exercises
   - Strategic planning
   - Education scholarships
25. Provision of helicopter time at reduced (no positioning charges) or no cost
Appendix 10: 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.

**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 11: 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 12  Limitations of Risk Assessment

A12.1  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.

A12.2  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, by which means the views of the Committee as a whole were synthesised impartially.

A12.3  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.

A12.4  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

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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{21}.

A12.5 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.

A12.6
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.

A11.7 This appendix must be read as part of the whole Report.