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

Ninth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

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

Part II: Technical Report

Issued on 26 October 2007

Contents

Introduction

1. This is the second part of the report resulting from the ninth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 1 to 3 October 2007. Part I of that report, the Main Report[1], gives the principal findings of the meeting [2], and this, Part II, gives the technical data and analysis that led to those findings.

2. For this meeting MVO produced Open File Report 07/03[3], which synthesised the monitoring data and observations collected by MVO between September 2006 and March 2007 and considers some of the new developments at MVO during the last seven months. In addition we considered a number of short presentations and papers generated within the SAC membership on scientific and hazard analysis topics.

3. By June 2007 the likelihood that the volcano had entered a paused state was recognised and the SAC was asked to produce another interim risk assessment – the third such one in 2007 alone. It was not possible to involve all the SAC members in this because of other commitments, but the task was completed in July. The results of this were summarised in an interim report[4] that is appended to Part I of this report.

Activity and Observations since March 2007

4. From mid-March 2007 the extrusion rate of lava declined, until by 4 April, a day of excellent visibility, no further change to the shape of the lava dome could be seen. Thus 4 April 2007 is taken to be the end of the third episode of lava extrusion that had begun on 1 August 2005, a total of about twenty months.

5. Two notable changes in measured activity occurred around the beginning of April 2007. On 3 April five volcano-tectonic earthquakes were recorded, with none recorded for a month after 6 April. On 4 April an SO_2 emission rate of about 2000 tonnes/day was recorded followed on 10 April by a 3-day episode of high SO_2 output. This latter episode was only measured by one spectrometer (Lover's Lane), so the measured emission rate of about 7000 tonnes/day has higher

[1] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Ninth report of the Scientific Advisory Committee on Montserrat Volcanic Activity, Part I, Main 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.

[3] Hards, V., Strutt, M., De Angelis, S., Ryan, G., Christopher, T., Syers, T., Bass, V. Report to the Scientific Advisory Committee Montserrat, 9th meeting, 1-3 October 2007. MVO Open File Report 07/03, 26 September 2007(freely available from MVO).

[4] Interim assessment conducted between 3 and 14 July 2007 by email correspondence.(Issued 19 July 2007l).

uncertainties. The combination of a small swarm of volcano-tectonic activity at the end of a period of inferred deceleration of magma flux up the conduit, followed by two pulses of increased SO_2 emission suggests a re-adjustment of conduit stresses that perhaps involved the opening of a fracture(s), thus causing increased permeability to gas flux.

6. Since early April surface manifestations of volcanic activity have been at a very low level. There have been occasional rockfalls, small pyroclastic flows and mudflows/lahars, usually in response to heavy rainfall on the dome. The pyroclastic flows have been restricted to the eastern side of the dome and the "moat" between the crater wall and the talus has been partially re-excavated by them. Lahars originating in the Tyre's Ghaut catchment produced vigorous steaming as they eroded into the hot deposits produced there earlier in the year. Steaming also occurs due to rain infiltration. The now-buried vent behind the Gage's Wall continues to vent hot magmatic gases, indicating its connection to the magma conduit at depth.

7. The summit of the lava dome is at a height of about 1050 m above sea level. The upper part of the dome comprises three main components: an eastern lobe, a southwestern lobe and a northwestern mass. It is the northwestern mass that was formed very rapidly, probably by more fluid lava, during the last week of December 2006 and the first week of 2007 and poses the main threat of flows into the Belham Valley. Calculations of the volume of lava in the northwestern mass capable of collapsing in this way into Tyre's Ghaut, based on the lidar survey of 15 June 2007, suggest a volume of up to 20-30 million cubic metres. This is similar to the volumes estimated in March 2007 on which the earlier hazard assessments were based. There have been no signs of any changes to the structural integrity of either Gage's or Farrell's Walls. However, it is now clear that the westernmost part of Galway's Wall is now, just, overtopped by talus from the southwestern lobe. Overall, the centre of mass of the current dome is about 100 metres further northwest than that of the slightly larger dome of July 2003 (see front cover of the Main Report).

8. Seismicity has been at very low levels since April with no long period earthquake swarms and few rockfall events (Fig.1). The only notable seismic event was a small swarm of volcano-tectonic earthquakes on 1 September 2007. Since the beginning of July the SO_2 emission rate has been measured by the Broderick's spectrometer only and the values show a clear positive bias relative to the twin-spectrometer period. The pre-July average rate of 316 tonnes/day (about half the long-term rate, but similar to that in the preceding six months) is probably a more accurate representation of the general degassing rate than the average rate calculated from data after early July.

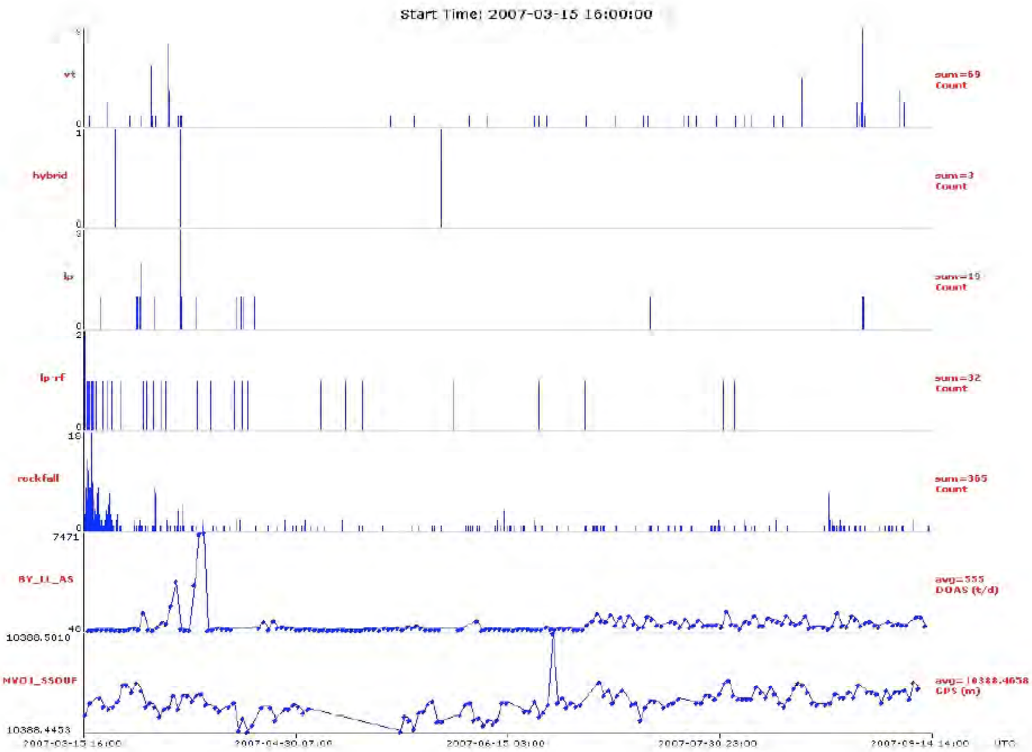

Fig.1 Integrated MVO monitoring data for the period mid-March 2007 to mid-September 2007. Variables plotted from top to bottom are numbers of volcano-tectonic seismic events, hybrid seismic events, long period seismic events, rockfall seismic events, daily sulphur dioxide emission rates (tonnes/day), length of baseline between MVO1 and SOUF cGPS stations (metres).

9. The cessation of lava extrusion at the beginning of April 2007 also correlates well with a change in the behaviour of ground motion measured by GPS and EDM techniques. Measurements show that baselines between survey stations began to increase in length during the month of April after at least 16 months of baseline shortening. As before, we interpret this change in surface deformation to be caused by increased pressure in the magma reservoir as basalt magma continues to enter but no andesite magma leaves via the conduit to the lava dome.

A Pause or the End of the Eruption?

10. There has been no new lava extrusion for about six months. Twice before during the twelve-year eruption lava has stopped extruding for many months: March 1998 – November 1999 (20 months) and August 2003 – August 2005 (24 months). This current behaviour may therefore represent either a new “pause” – to be followed by a resumption of lava extrusion, or it may represent the end of the eruption.

11. During the last pause we devised a set of criteria to test the question of whether the volcano had reached the end of the eruption. The last time we used these criteria (SAC4) they were:

Criterion 1. The SO_2 daily emission rate averages less than 50 tonnes per day.
Criterion 2. An absence of low frequency seismic swarms and tremors associated with the magmatic system.
Criterion 3. No significant surface deformation from a demonstrably deep source.

The reasoning behind these criteria is that once basalt magma stops entering the crustal magma reservoir and exchanging its heat with the resident andesite magma, then SO_2 flux through the volcano will fall considerably (criterion 1), there will no longer be any magma reservoir pressure fluctuations causing surface deformation (criterion 3), and magma will not be driven through the conduit causing long-period earthquakes (criterion 2). All three criteria should be met and tested retrospectively against the MVO measurements made over the previous one-year period. We will use these criteria again in this report and future assessments until we see a reasoned need to modify them.

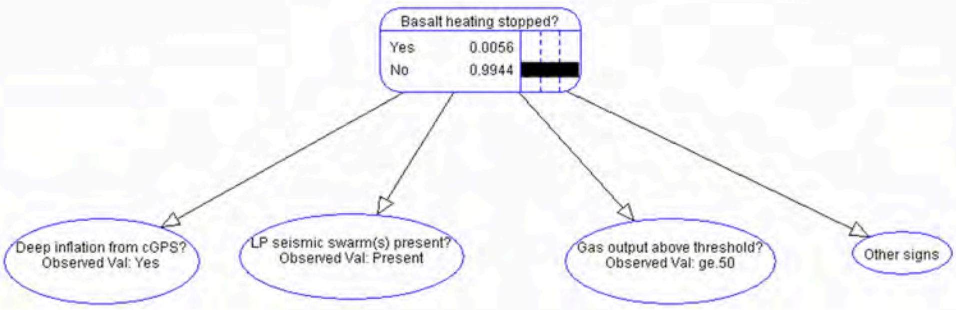

Fig. 2. Bayesian Belief Network illustrating inference about the probability of the deep internal state of the volcano (i.e. has basalt heating stopped?) based on observations of deep deformation, LP activity and gas output criteria.

12. Our confidence in the outcome of such a test with these criteria depends on the correctness of our interpretation of the process powering the eruption, the sensitivity of the measurements to that process and the quality of the measurements themselves. In order to assess the degree of confidence in our decision as to whether the eruption has stopped we have used a Bayesian Belief

Network (BBN) method[5]. This tests the combined effects all the criteria expressed as both positive and negative outcomes for the cases in which the process (of basalt entering the reservoir) is and is not occurring. Fig. 2 shows the network used. The values used in the network for the conditional probabilities of seeing the different data matching the three criteria, when (a) basalt heating is continuing and (b) when it has stopped, were elicited during the meeting.

13. In order to use the three criteria as tests for whether basalt influx and heating has stopped, or not, we need to assess their diagnostic powers. In other words, it is essential to estimate how often each gives a true positive indication of the internal state of the volcano or a false positive indication, a true negative indication or a false negative indication. To do this, the SAC discussed the properties and shortcomings of each observational technique, and elicited for each a pair of indicative values that enable the four (2*x*2) contingency probabilities to be defined (for any given test, the probability of the alternative outcome is the complement of the probability of the other).

    The following items summarise the questions used for this elicitation, and the weighted outcomes from the SAC team (the credible intervals enable sensitivity testing, if desired).

    For deep deformation:
    IF basalt input at depth has stopped (say, within last 6 months), what is the probability we would be seeing cGPS evidence for line-lengthening within that period (in other words, what is the probability that a line-lengthening trend is a false positive for test: basalt = NOT stopped?):

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
3%	**14%**	**57%**

    IF basalt input at depth has NOT stopped up to now, what is the probability we would see cGPS line-lengthening evidence during last six months (i.e. the present evidence is a true positive for test: basalt = NOT stopped?):

[5] A Bayesian Belief Network (BBN) is a graphical formalism for inference and decision-making in problems that involve uncertainty and probabilistic reasoning. A BBN is a directed graph, like the one shown in Figure 2. The nodes represent variables (that may or may not be observable) and the arrows ("arcs") represent causal or influence relationships between variables. Associated with each node is a Node Probability Table (NPT), which expresses the conditional probability of each state of that node GIVEN each combination of values that may exist in the causal node or nodes. With a BBN we can enter observations for any node in order to update the probability distributions on all unknown variables in the light of that piece of new information. This process, called propagation, uses Bayes' Theorem and basic probability calculus to compute the various probabilistic interplays that can exist between different nodes. The principles of Bayesian updating and the numerical rules for implementation are quite simple and theoretically confirmed, but become unwieldy and calculationally burdensome when more than two or three variables are involved. A modern BBN formulation is a graphical computer-based aid for managing complex inference problems with many strands of evidence or data, and for performing the necessary calculations when there are these multiple combinations of states on multiple different nodes. The full range of possible inference outcomes from all alternative sets of uncertain observations can be explored with a BBN. An important attribute of the BBN technique for risk assessment work is that it provides a formalised means of checking such probability calculations, and the graphical structure helps ensure all relevant factors are included and evaluated.

Credible interval lower bound	Best estimate	Credible interval upper bound
28%	**75%**	**98%**

Thus the sensitivity of this deep deformation evidence in a diagnostic test is 0.75, and its specificity is 0.86 (i.e. the complement of the false positive rate elicited above, converted from percentages). That is, a negative observation is, superficially, better at indicating basalt heating has stopped than is a positive observation that it is continuing.

However, it is necessary to also take into account false positives and false negatives. This is done by estimating the Positive Likelihood Ratio LR+ for this type of observation, and the Negative Likelihood Ratio LR-, where each Likelihood Ratio expresses the relative frequency of true indications to false, for the presence or absence of the state being tested for, respectively (for further information on likelihood ratios and their use in diagnostic tests, see for example: http://www.cebm.net/index.asp?o=1043). In this case, LR+ = 5.4 and LR- = 0.29 (i.e. 3.4x), thus positive indications of continuing basalt heating should carry more weight than negative indications would for heating stopped because they are slightly less compromised by false results.

For SO_2 gas output:
IF basalt input at depth has already STOPPED, what is the probability we would be seeing > 50 tonnes/day SO_2 output levels over, say, last two months of measurements (i.e. a false negative for test: basalt = stopped?):

Credible interval lower bound	Best estimate	Credible interval upper bound
16%	**43%**	**79%**

IF basalt input at depth has NOT stopped, what is the probability we would see AVERAGE SO_2 output levels drop consistently below 50 tonnes/day over, say, last two months (i.e. a false negative for test: basalt = NOT stopped?):

Credible interval lower bound	Best estimate	Credible interval upper bound
3%	**39%**	**86%**

For gas output observations, the Positive Likelihood Ratio LR+ = 1.4, and the Negative Likelihood Ratio LR- = 0.66 (i.e. 1.5x). In this case, negative indications of basalt heating having stopped would carry fractionally more weight than positive indications that it continues.

For LP seismic activity:
Given the basalt influx has STOPPED, what is the probability to observe seismic low frequency events in swarms (i.e. a false negative for test Basalt = stopped):

Credible interval lower bound	Best estimate	Credible interval upper bound
1%	**21%**	**77%**

GIVEN the basalt influx is CONTINUING, what is the probability NOT to observe any low frequency swarm events (over, say, retrospective 2 months?) i.e. false positive for test basalt = stopped):

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
11%	**55%**	**94%**

For observations of seismic LP swarms, the Positive Likelihood Ratio LR+ = 2.6, and the Negative Likelihood Ratio LR- = 0.6 (i.e. 1.8x). In this case, positive indications of magma movement – by way of LP swarms – and hence continuing basalt heating, would carry more weight than would an absence of such swarms as evidence for a cessation.

Summing up the criteria individually, it is clear that deformation is thought to be the strongest diagnostic of the three – whether for inferring that basalt heating is continuing or has stopped - whilst gas output is the weakest, in both situations. None represents conclusive evidence, on its own. However, if all three criteria point the same way, then their associated Likelihood Ratios are compounded. Thus, $LR+_{ALL}$ = 19.7 or $LR-_{ALL}$ = 9.2, when all three agree in their positive or negative senses, respectively (i.e. 5.4 *x* 1.4 *x* 2.6 = 19.7, and 3.4 *x* 1.5 *x* 1.8 = 8.2, respectively). In the first instance, all three indicators are positive for on-going basalt heating, and taken jointly this represents "strong" evidence (in the evidential worth terminology of Jeffreys[6]) for the inference, whilst all three showing negative would be "substantial" evidence for a stoppage.

Based on this evidence-weighing concept, confidence in the outcome of applying the criteria tests jointly can be quantified in probabilistic terms, using the BBN analysis technique. In a BBN, the 2x2 contingency tables derived above are ascribed each to its own observational node, and an inference about the parent (causative) node state is made on the strength of the evidence (see Fig. 2). The parent node has two states, in this case basalt heating continues or basalt heating stopped, and the relative prior probability of each is required (prior to the acquisition of observations). In the case where there is total ignorance about the internal state of the volcano, probabilities of 0.5 would be appropriate for the two alternative priors. Updating these probabilities by setting the three observation nodes all to positive indications for on-going basalt heating changes the probability of that state from 0.5 to 0.952 - in other words, there is perhaps a 1 in 20 chance the observations are misleading and basalt heating has actually stopped.

However, we are not in a position of total ignorance - we can be fairly sure that basalt heating was still going on up until April 2007, and had been doing so for more than twelve years before that. In these circumstances one might conjecture that there is a much smaller chance than 0.5 that it has since stopped, implying a higher prior probability than 0.5 that basalt heating is on-going. If this is true and, for illustration, a value of 0.9 is used as the probability for on-going heating, then concurrent observations of deformation, high gas output and occasional LP activity would, together, update this prior probability of 0.9 to 0.994 – given the observations we currently have. In other words, there should be less than a 1 in

[6] Jeffreys, H. (1961) *Theory of Probability*. Third Edition (reprinted 1985), Oxford University Press, 459pp - at Appendix B.

100 chance these data are misleading. This provides the measure of the confidence that we can invest in our interpretation that processes at depth are on-going, notwithstanding apparent inactivity at the surface, and the grounds for arguing that the likelihood for a potential restart is quite high.
If, or when, any of the observation bases change, the probability of a cessation or continuation of basalt heating can be re-evaluated with the BBN.

14. Thus we find that over the past year none of the criteria have been met, and believe that basalt heating at depth continues. This confirms that the volcano is in a paused state and that, on the basis of likely on-going heating at depth, we expect it to resume extruding lava at some stage in the future. While, by elicitation of opinions, we think this is "most likely" to happen in about fifteen months time (i.e. around the end of 2008), our credible interval until restart ranges from as little as one-and-a-half months (i.e. mid-November 2007) to as much as thirty months (i.e. March 2010). There is the possibility that it may never resume but we have not yet started to see or recognise any indications of that.

Pyroclastic Flows during Pauses

15. The July 2007 interim assessment recognised that although the northwestern mass of lava still constitutes the main threat to the inhabited areas around the lower Belham Valley, the end of active extrusion reduced the possibility of internal forces triggering a major collapse in this direction, and cooling and gas loss may reduce the mobility of any subsequent flows. However, we had not looked closely at the earlier records of pyroclastic flows produced during pauses in extrusion to add further insights to the hazards posed. We have now done so.

16. During the pause of 1998-1999 a large lava dome occupied the crater, similar to the current pause, whilst in the 2003-2005 pause there was essentially no dome left, with the crater empty. The elevation of the dome in March 1998 when extrusion stopped was about 1030 m asl (spine summit). The volumes of the 1998 and 2007 domes were 113 and 210 million cubic metres respectively. The difference between these two figures is produced by a combination of the lower basal topography of the 2007 dome (the 1998 dome was underlain by the Castle Peak dome) and the higher surface of the 2007 dome. Both domes had been largely built by extrusion at high rates (5-10 cubic metres per second) in the previous year. One difference between the domes is that the latest extrusion of the 1998 dome had been in the southern part of the crater, infilling the collapse scar of the Boxing Day 1997 event and spilling over the crater to the south. In contrast, the 2007 dome has more mass towards the northwest. About four months into the first pause, on 3 July 1998, a large (~ 25 million cubic metre), rain-triggered collapse of the dome on the southeastern side of the 1998 dome occurred. This left a large scar and appeared to initiate increased mass wasting and activity over subsequent months[7].

[7] Norton, G.E and 15 others.(2002) Pyroclastic flow and explosive activity at Soufriere Hills Volcano, Montserrat, during a period of virtually no magma extrusion (March 1998 to November 1999). In.

17. Fig. 3 shows the daily record of pyroclastic flow runout distances throughout the eruption. We are mainly interested in pyroclastic flows outside of the crater (i.e. those not originating in the Tar River Valley: "non-TR"). The true runout distances of flows entering the sea is unknown, which means that a lot of flows through the Tar River Valley, particularly those associated with large collapses of the dome are not represented. Multiple flows in one day are not counted. During the first pause non-TR flows only occurred after the 3 July 1998 collapse. The largest and most mobile of these occurred on 5 and 12 November 1998 at the peak of the rainy season.

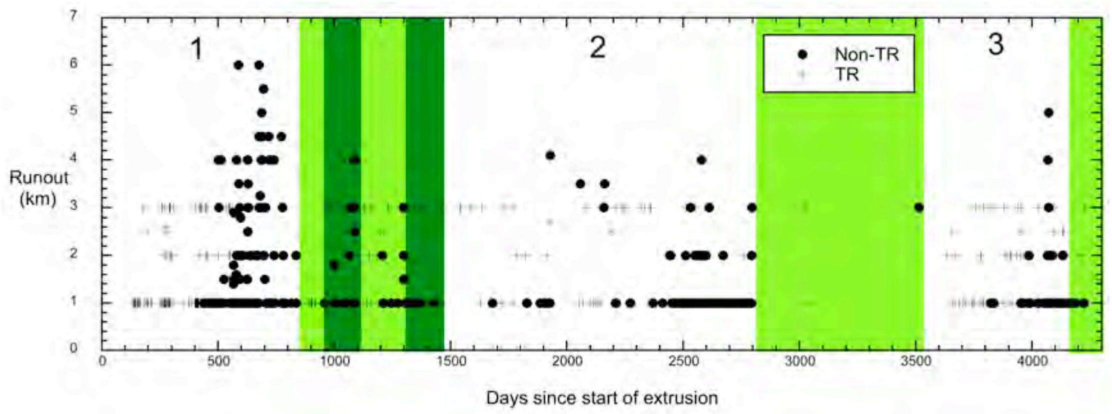

Fig.3 Pyroclastic flow runout distances achieved during the course of the eruption (to July 2007) segregated into those flows down the Tar River Valley (TR) and those outside (Non-TR). 1, 2 and 3 represent the three episodes of lava extrusion and the green bars the intervening pauses. The dark green bars during Pause 1-2 denote the July-December rainy season on Montserrat.

18. Table 1 presents two measures of the vigour of pyroclastic flows throughout the eruption derived from the above data: the daily rate and the average runout. The rate of occurrence of pyroclastic flows, particularly non-TR flows, is notably less during pauses than during lava extrusion by a factor of about 3. However, the average runouts are nearly the same across all intervals. This implies that the mobility of flows is similar irrespective of continued extrusion. Because of the relative small numbers of samples and the 1-km binning, the absolute values of the runout statistics should not be given too much weight.

Druitt, T.H. and Kokelaar, B.P. (eds.) The eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999. Geological Society , London, memoirs, 21, 467-481.

Table 1 Daily rates and average runouts of pyroclastuc flows for each episode and pause

	Episode 1	Pause 1-2	Episode 2	Pause 2-3	Episode 3	Pause 3-4?
PF days/all days[1]	0.39	0.14	0.24	-	0.23	0.12
Non-TR	0.21	0.056	0.18	-	0.10	0.040
Av. Runout all[2] **(km)**	1.63	1.73	1.26	-	1.44	1.47
Non-TR	1.86	1.57	1.17	-	1.24	1.0
Non-TR > 1 km	3.0	2.7	2.7	-	2.7	-

1. The number of days on which a pyroclastic flow was recorded divided by the total number of days in that interval.
2. The total aggregate runout distances for that interval divided by the number of days on which a pyroclastic flow was recorded.

19. From the above it would appear that we can expect pyroclastic flows during the current pause to be about one third as frequent as during periods of lava extrusion, that is about 0.05/day for flows outside the crater. But when they do occur the likelihood is that they will travel as far outside the crater during either situation. The latter finding is quite surprising, because the physical processes during lava extrusion provide a different set of initial conditions for dome collapse from those during the paused state (e.g. shear intrusion, over-steepening), though both can share external forcing from heavy rainfall. One of the key features of Pause 1-2, from which most of the data on pauses derive, was that the partial collapse of 3 July 1998 created a deep gash into the heart of the dome that presumably made the surrounding still-pressurized core lava more likely to collapse and produce substantial pyroclastic flows. It may be that if such a partial collapse does not happen during the current pause then this will prevent the same history of mobile pyroclastic flows, particularly outside the crater, from developing.

20. With time, the internal temperature and gas content of the core lava of the dome will decrease. Analysis by Dr. M. Humphreys (who has succeeded Dr J. Devine as MVO petrological consultant) of two samples from the 8 January 2007 event indicates melt fractions in the ranges 40-25% and 30-15% for magma that rose rapidly from the reservoir; these melts containing 2-3.2 wt% gas. The total lava volume that was emplaced on the northwestern side of the dome between 24 December 2006 and 8 January 2007 at rate of perhaps 20 cubic metres per second (MVO estimate from Windy Hill camera data) was about 26 million cubic metres. It is the fraction of gas within this mass that determines its ability to provide the source conditions for a lateral blast-type of pyroclastic flow down the Belham Valley. Crystallization of the melt fraction releases the gas and causes overpressure to develop which can then be relieved by diffusion or via fractures. The bulk permeability of the dome determines how quickly this gas is lost, but its value is not known. The inferred mass emission rate of all volatiles through the dome, based on measurements of the flux of individual species such as SO_2, is of

the order of 10,000 tonnes/day[8]. If the source of this flux were the northwestern mass of lava alone then it would have lost all its volatile content in roughly three months. However, that is very unlikely to be the case and most of the measured gas emission is thought to be transported from the magma reservoir, because of the relative constancy of the SO_2 flux and the measured reduction in HCl flux by an order of magnitude when lava extrusion stops[9]. Thus the lava on the northwestern part of the dome may still contain a significant fraction of its original exsolved magmatic gas and some liquid capable of producing vigorous pyroclastic flows.

Long Term Prognosis

21. As we discussed in the SAC8 report (Fig.6), the cumulative volume curve for the eruption in March sits close to a line based on a rate of 2.2 cubic metres per second. One way to view this is that this rate is representative of the Soufrière Hills system in a steady state of supply by basaltic magma from depth at time scales of the order of tens of years (the length of the eruption). Of course we will continue to test this with data in future. Were the system to depart from this steady state, perhaps ahead of it shutting down, then we might detect it as a deceleration of magma output over more than one cycle of extrusion and pause.

22. Now over twelve years long, this eruption remains the fifth longest-lived eruption of its type in a global catalogue of 97 examples. As in the last report we use the Generalised Pareto distribution derived from this catalogue to calculate the survivor function for this eruption. Given that it has now lasted 146 months, we obtain the statistical probability of it lasting another five years or more as 0.8 (i.e. an 80% chance), and a probability of 0.5 (i.e. a "50-50" chance) that it will last another thirty-three years or more. On this simple statistical basis, however, there is a small probability (0.05, or 5% chance) that the remaining duration of this eruption could be as little as 1 year.

Assessment of Volcanic Hazards

23. Since the last interim assessment in July 2007 little has changed in terms of the main volcanic hazards posed. They remain as:

    Pyroclastic flow from dome collapse;
    Pyroclastic flow from explosive vertical or lateral blasts;
    Vulcanian explosions with rock and ash fallout.

24. Triggering of a dome collapse by heavy rainfall could yet occur during this ongoing rainy season but, anecdotally at least, this season has not been a

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[8] Edmonds, M., Pyle, D.M. and Oppenheimer, C. (2002) HCl emissions at Soufriere Hills Volcano, Montserrat, West Indies, during a second phase of dome building: November 1999 to October 2000. *Bull. Volcanol.*, 64, 21-30.

[9] Edmonds, M., Oppenheimer, C., Pyle, D.M., Herd, R.A. and Thompson, G. (2003) SO_2 emissions from Soufriere Hills Volcano and their relationship to conduit permeability, hydrothermal interaction and degassing regime. *J. Volcanol. Geotherm. Res.*, 124, 23-43.

particularly wet one. As before, we regard the likelihood of a large collapse to the east down the Tar River Valley as the most likely "major" event over the next year. Depending on the winds at the time of such an event, a significant covering (several centimetres) of ash, including gravel-sized clasts, on the western inhabited areas is possible, as happened during the July 2003 collapse.

25. As the dome cools and the magma in the conduit increasingly solidifies, then the resistance to any future rise of new magma from the reservoir will increase. This will probably result in increased seismicity at strengths considerably above that currently experienced, including the resumption of long-period swarms, precursory to resumption of lava extrusion at the surface. If there is no large collapse of the dome then the extra "head" of overpressure required to lift the magma to the current summit at 1050 m asl will be about 9 million Pascals more than it was to restart the last extrusion episode in August 2005. We have not experienced this, restart-through-a–large-dome, scenario at Soufrière Hills Volcano before. One possibility is that the intrusive efforts of the rising magma once it enters the base of the dome may trigger a major collapse. Another possibility is that it the higher overpressures may encourage stronger explosive activity.

26. The threat from a lateral blast sending highly mobile pyroclastic flows into the Belham Valley remains, but diminishes gradually as the dome cools[10]. The triggering mechanisms for such an event, the source volumes of lava, and the dynamics of flow outlined in the SAC8 report are essentially unchanged, but the gas pressure gradients within the lava mass have probably been reduced during the past six months. Our downward revision of the likelihood of such an event being initiated and the anticipation of a decrease in mobility of the resultant flows, made in the July 2007 interim assessment, also holds. Neither Farrell's Wall (to the north), nor Gage's Wall (to the west) show any new signs of structural deterioration leading to collapse that might generate such a blast. The hazards of a lateral blast from either source would threaten not only the lower Belham Valley but also the whole coast from Plymouth to Olveston, including Fox's Bay.

Elicitation of Probabilities for Hazard Scenarios

27. Here we summarise the results of the formal elicitation of the SAC members' 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.

[10] Belousov,A., Voight, B., Belousova, M., 2007. Directed blasts and blast-generated pyroclastic density currents: a comparison of the Bezymianny 1956, Mount St. Helens 1980 and Soufriere Hills, Montserrat 1997 eruptions and deposits. *Bull. Volcanol.* 69, 701-740.

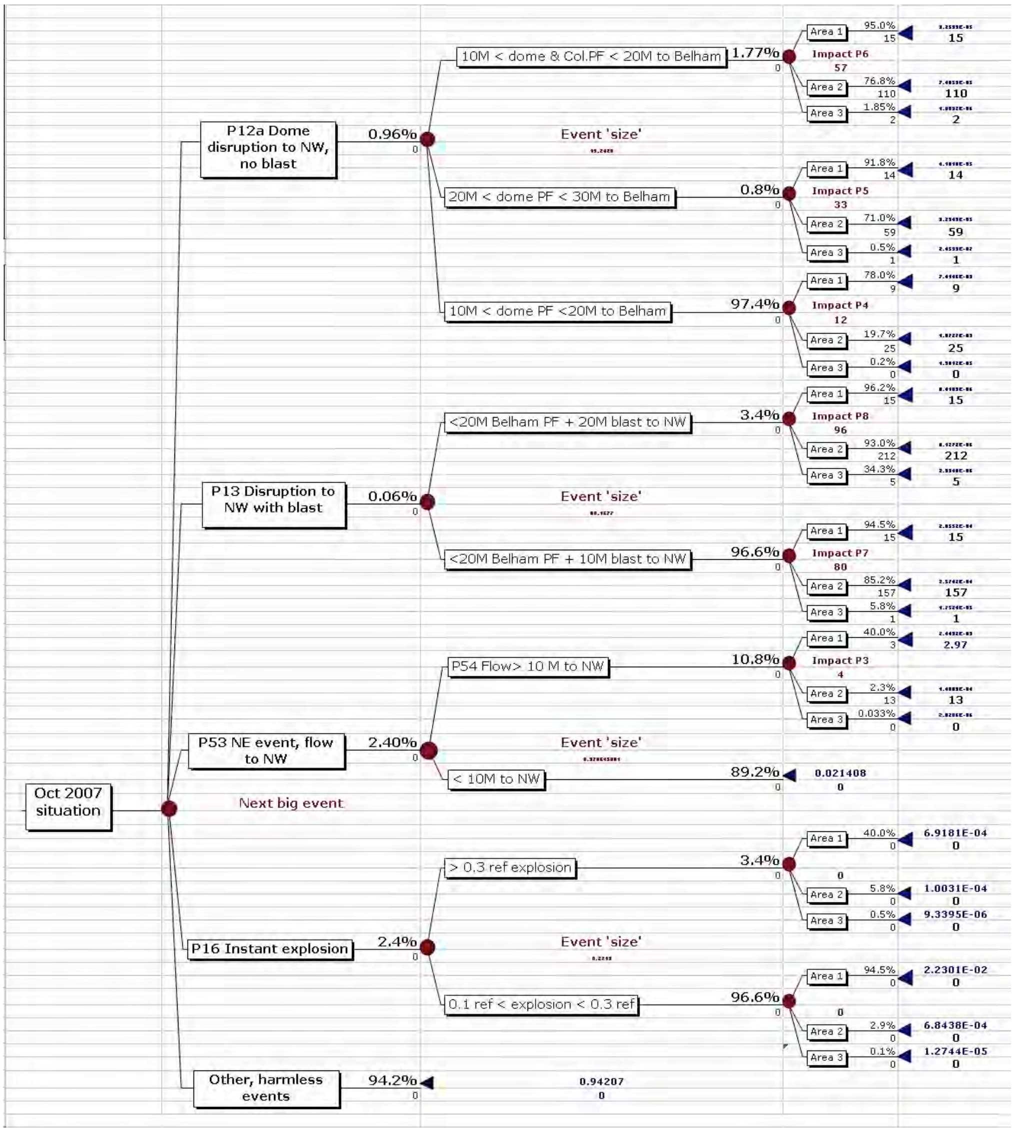

Fig.4 Event tree for hazard scenarios populated with typical probability values shown (in the Monte Carlo analysis for risks, each branch carries a distribution of probability values to represent the scientific uncertainty associated with each).

28. We follow the general framework of questions used in SAC8 and the July 2007 Interim assessments. Any event that could give rise to hazards in and beyond the Belham Valley margins is termed an initiating event on the revised event tree (Fig. 4) and denoted generically as a “major dome disruption”. This initiating event scenario, which could involve a flow of 10 million cubic metres or more of material going down the Belham Valley, is then developed on subsequent branches in terms of a number of representative ‘size’ classes and styles of flow, surge or blast activity. Similarly, the three areas (1-3, Area 1 now modified) designated in SAC8, and the previously determined percentages of each that might be affected by each type of flow were re-used (Fig. 5). This latter part of

the scenarios is unchanged from the SAC8 analysis. The only significant modification to the event tree from the July 2007 exercise is the addition of a branch representing an instantaneous vertical explosion from the volcano. This would inevitably involve some disruption of the dome (if it remains), but could take the form of a chimney through the centre of the dome, with most of the displaced dome material being likely to be directed into Tar River.

The following boxes summarise the results of the SAC elicitation for the identified scenarios.

GIVEN present conditions and a big dome, what is the probability of **nothing** significant happening (i.e. no collapse, no restart of dome growth, no magmatic explosion > 0.1x ref) in the next 12 months.

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
5%	**36%**	**87%**

GIVEN current conditions, what is the probability that within the next year the **first** significant development will be the resumption of quiet lava extrusion.

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.03%	**12%**	**48%**

GIVEN current conditions, the probability that within the next year the **first** significant event will be a major dome disruption with sufficient material avalanching towards the **NE (Trants/Bramble)** that it would reach the sea *(available volume = 30 – 50 M* m^3*)*:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.07%	**2%**	**24%**

IF there is a big collapse **to the NE** that would reach the sea at Trants, what is the **conditional probability** this will also involve enough material (i.e. at least 10 M m^3) spreading to N / NW to generate a flow/surge with runout to reach the sea **down the Belham**:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.4%	**10.5%**	**63%**

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

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.02%	**0.9%**	**13%**

GIVEN current conditions, the probability that within next year the **first** significant event will be a major dome disruption event - without a blast - involving enough material avalanching to **W through Gage's** to generate a flow/surge runout to reach the sea at **Plymouth**:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.02%	**3%**	**30%**

GIVEN current conditions, 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 the sea:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.0001%	**0.06%**	**6%**

GIVEN current conditions, 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 and/or explosion column, such that the flow/surge would reach the sea at Plymouth:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.0001%	**0.08%**	**11%**

GIVEN current conditions, 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 or NE) which takes away the bulk of the dome harmlessly:

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
12%	**46%**	**92%**

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 associated dome failure):

Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
0.007%	**2%**	**24%**

As noted in the description of each case, the particular scenario relates solely to the **first** occurrence of any significant event that happens in the next year. If such an eruptive event occurs, all scenario-associated probabilities will need to be updated in the light of the new conditions.

29. The most likely scenario over the next year is a major dome collapse into the Tar River Valley with a very similar percentage probability (46%) as in the July Interim assessment. The next most likely outcome – no new major activity or collapse (36%) – is judged almost as likely as major collapse. The resumption of normal lava extrusion within the next year without any preceding "event" is thought to have a probability of 12%. The balance of probability (6%) is split between a number of explosive and dome collapse scenarios that could threaten the lower Belham Valley and adjacent areas nearby.

30. Given all the various initiating event probability distributions tabulated above, taken together these equate overall to about a 1-in-120 chance of a flow or surge incursion into Area 1 (Fig.5) over the next year (it was put at about 1-in-130 for the July Interim Assessment – that assessment was done off-island and without the full involvement of all the SAC, and in any case the difference is not judged meaningful). From the distribution spreads provided by eliciting the SAC team, the present 1-in-120 median probability sits within a 90% confidence interval ranging from 1-in-165 to 1-in-80; in other words, there is 95% confidence these odds would be no lower than 1-in-80, and a 5% chance they could be as long as 1-in-165.

31. For Area 2, the elicited probability for a flow or surge incursion stands at about 1-in-410 over the next year [90% conf. interval: 1-in-600 to 1-in-370]. For the case of a blast reaching the area, there is a 1-in-2100 median chance within the year [90% conf. interval: 1-in-3000 to 1-in-1400]. These median values for probabilities of incursion represent slightly lower likelihoods of incursion than those of the July 2007 Interim Assessment elicitation.

32. For Area 3, the median probability of a flow or surge reaching into the area in the next twelve months is now judged to be roughly 1-in-17,000 [90% conf. Interval: 1-in-25,000 to 1-in-11,000]. This likelihood is about half that assessed in the July Interim Assessment estimate.

In all four cases just discussed, the ranges of uncertainty about the median probability are considerably narrower - in both directions around the respective medians - than those associated with the July Interim Assessment, when fewer SAC members were available to participate, and those who did were working with reduced information.

Quantitative Risk Assessment

33. We make use of the same procedures for quantitative risk assessment that have been used since 1997. Our previous calculations of volcanic risk are revised by making adjustments to probability and rate estimates in the light of the new developments in the volcano, new datasets and on the basis of the committee's reappraisal of the likelihood of the various associated threats. The risk levels are mainly expressed as potential loss-of-life estimates and as annualised individual risk exposures - that is, the risk of suffering a given number of casualties in the society as a whole, or the risk of an hypothetical individual losing his or her life during one year. Except where noted, these risk estimates do not include allowance for any reduction in exposure that could be gained from early warnings and civilian mitigation responses. Thus, while the quantitative risk assessment results are not full-blown worst-case scenarios, they do represent conservative estimates for policy-making purposes. The approach and methodology follow those described in the December 1997 MVO Hazards and Risk Assessment report, validated by the UK Government's Chief Scientific Advisor's consultative group

34. For present purposes, and for consistency with earlier assessments, the total population of Montserrat is assumed to be 4,775 persons (this number will be reviewed in future assessments when updates on official population figures are confirmed). On 13 September 2007, the EPG re-drew the boundary of the Exclusion Zone as a dog-leg across the Belham River Valley and around to the south of Isles Bay Hill. As a result, whilst we retain the three area designations of the last assessments, we now extend Area 1 to this new boundary in the south (Fig.5). The peak population in Area 2 at any time is taken to be about 1020 persons, and that of Area 3 about 315 persons.

35. The provisional number of people in Area 1 is taken, currently, to be about 22 persons, i.e. those who have returned following the re-opening of the closed area, according to information from the police. However, Area 1 in our model covers a wider area than that evacuated, so a larger population figure (55 persons) is also examined here; this number is still significantly lower than the number used in the August 2006 assessment, when about 150 persons were assumed to be present. The issue of population numbers is critical to the estimation of societal risk levels, and would benefit from improved corroboration.

Societal Risk Levels

36. Estimates of the potential numbers of persons that might be injured by volcanic action are not included here – for emergency planning purposes, medical and volcano emergency specialists can infer casualty numbers from the probable loss-of-life estimates.

37. 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 associated explosive activity that might develop within the next twelve months. The potential impacts of each scenario are weighted according to the elicited relative likelihoods of their occurrence. As before in full SAC meetings, our estimates of risk are based on one year ahead, effectively from October 2007 onwards.

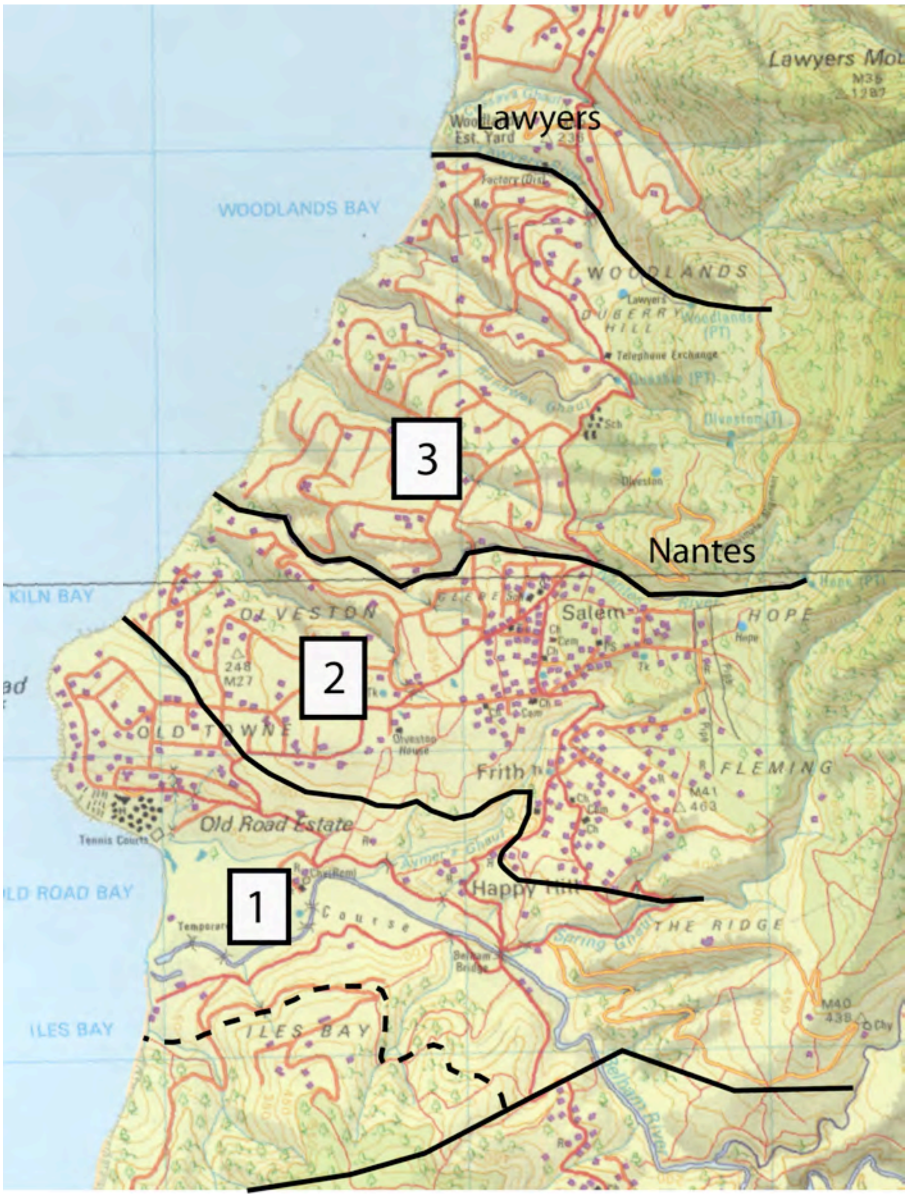

Fig. 5 Map showing revised population Areas [1], [2], and [3] following the re-occupation of Iles Bay Hill. The dashed line is the southern boundary of the 20 million cubic metres normal dome collapse pyroclastic flow surge, the northern boundary of which is the the solid line between Areas 1 and 2.

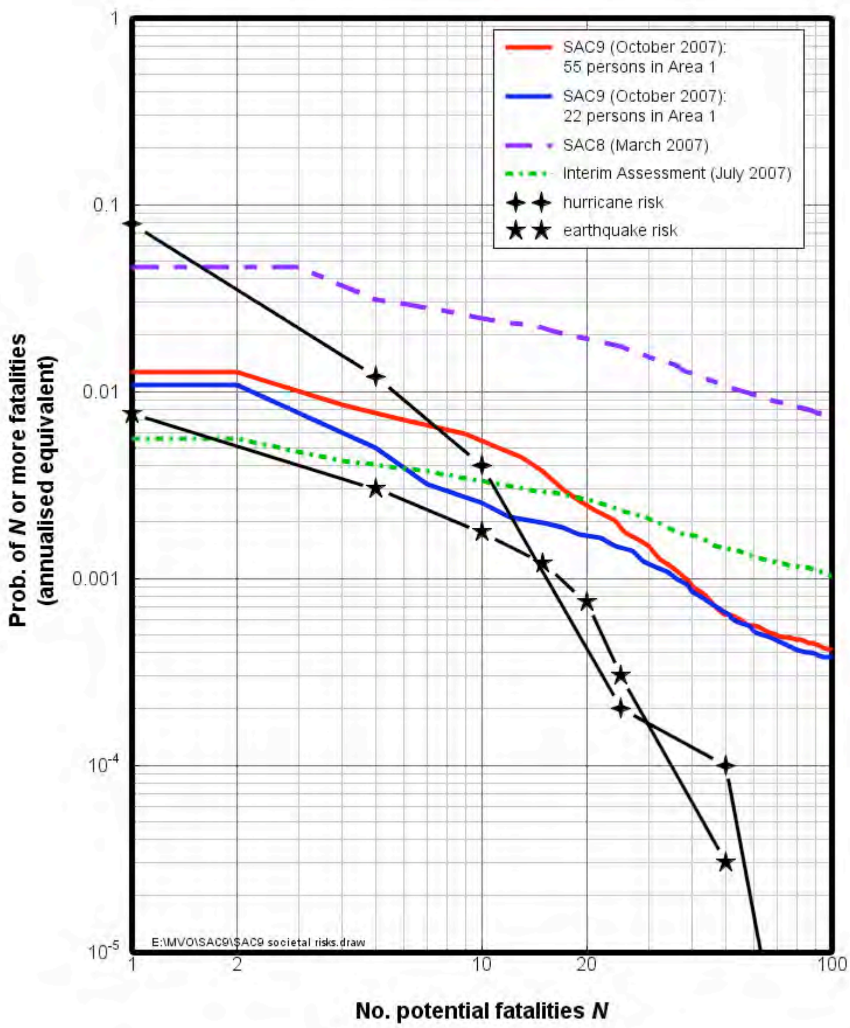

Fig. 6. Societal risk curves for current October 2007 assessment under different assumptions of the number of persons in Area 1 (blue and red). Also shown are the risk curves for the last SAC8 (violet) and July 2007 Interim (dashed green) assessments, and risks from other natural hazards in Montserrat.

On the assumption that perhaps 55 people now currently reside full-time in Area 1 (this zone is extended here to include Isles Bay and parts of Garibaldi Hill), the *overall* societal risk level is little changed from the July 2007 interim assessment. There is a slight increase in the likelihood of suffering a few casualties (up to five) - because more people are now present in the more exposed areas, but the curve for higher numbers of casualties is depressed below that of the July Interim Assessment, reflecting a lower elicited probability of the crucial NW-directed blast scenario.

If a smaller resident population, say only 22 persons, is actually present in Area 1, the societal risk level is slightly lower than that estimated for 55 people (see Fig. 6). If, however, the resident population of Area 1 is much greater, then societal risk levels would be significantly more elevated.
It should be noted that these relative reductions to societal risk appear much smaller than those derived for individual risk exposure (see below). This is because societal risk is sensitive to the numbers exposed, and hence how many people live where, whereas individual risk estimates deal solely with the threat to a hypothetical individual in a given situation, and are not influenced by how many other people are in the same situation.

Individual Risk Exposure Estimates

38. In terms of individual exposure, *individual risk per annum* estimates (IRPA) for people in different areas are calculated using the probabilities elicited from the SAC committee, coupled with Monte Carlo population impact risk simulation modelling. 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 (see Appendix 2). In Table 2, however, 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*). We will also indicate, in numerical terms, the extent to which the active volcano increases an individual's risk over and above the 'background' risk of accidental death for a person living in Montserrat, currently assumed to be 28 in 100,000 (the value in the US Virgin islands). Table 2 shows how the current evaluation compares according to these two measures.

39. Thus, on the basis of our quantitative risk modelling, we now consider the level of annualised risk of death (IRPA) due to volcanic hazards for an individual in each Area of Fig. 8:

    Area 1 (full-time resident): 1 in 1700, C on the CMO* scale, 3.1*x* background risk level of accidental death

    Area 2 (full-time resident): 1 in 21,000, C on the CMO* scale, 1.2*x* background risk level

    Area 3 (full-time resident, Woodlands, north of Nantes River): 1 in 6 million, F on the CMO* scale, 1.001*x* background risk level.

Table 2. SAC9 Individual Risk Per Annum (IRPA) estimates for volcanic risks to occupants in the lower Belham Areas

Residential Area	**CMO* Risk Scale#**	**Annualised Probability of Death**	**Risk Increase Factor**	**Other Natural Hazards**
	A			
		1 in 100	36x	
	B			
		1 in 1000	4.6x	
Area 1 (full-time occupation)	C	**1 in 1700**	**3.1x**	
		1 in 10000	1.35x	
Area 2 (full-time occupation) Whole island	D	**1 in 21,000** 1 in 35,000	**1.2x** 1.1x	 Hurricane hit on Montserrat
		1 in 100000	1.03x	
Whole island	E	1 in 200,000	1.02x	Earthquake striking Montserrat
		1 in 1000000	1.003x	
Area 3 (full-time occupation) N. Montserrat	F	**1 in 6 million** **less**	**1.001x**	

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

40. These individual risk exposure levels are lower than those determined in the July 2007 interim assessment. The individual risk exposure for a person living full-time in Area 1 is marginally lower (down from 1 in 1400 to 1 in 1700), while the reduction of the IRPA for Area 2 (from 1 in 8,800, to 1 in 21,000) moves the exposure level down to the next category on the CMO's scale (i.e. D). However, this change is less striking in terms of the net effect on risk over background (i.e. it moves from a 40% increment to a 20% increment). In the case of Area 3, the IRPA is reduced from the July 2007 assessment by a factor of about 3*x*; the corresponding individual's risk increment above background levels – due to the volcano - is now estimated to be about 0.1%.

In Table 2, we have added, for comparison purposes, some very crude estimates of the IRPAs for people living (island-wide) on Montserrat due to long-term hurricane and earthquake risks. Residing in Area 1 or Area 2, with the present volcano threat, involves a higher exposure to life-and-limb than that due to hurricane dangers. For people living in Area 3 and in the far north of Montserrat, the volcano poses a lesser threat than either hurricanes or earthquakes.

41. Residents of Isles Bay Hill are calculated as being in Area 1 for risk estimation purposes, but those at the highest elevations, south of the dashed line in Fig. 5, effectively fall into the same risk zone as Area 2 to the north of the Belham River. However, this does not take into account the extra risk associated with more frequent crossings of the Belham Valley. Without more information, a more detailed analysis is not possible. A suggested floating jetty at the southern end of Isles Bay beach would help with evacuation from Isles Bay if the Belham Valley was not navigable, but sea journeys in such circumstances could themselves encounter volcanic and other hazards.

42. *Risks to workers at Fox's Bay jetty*
At Fox's Bay while the protection given by St George's Hill and Garibaldi Hill to inundation by "normal" block-and-ash type pyroclastic flows is considerable, these two hills afford much less protection from lateral blast-derived flows which can flow above or around obstacles. The assumption is made that safety practices similar to those in place at Trants would also be implemented for any work operations at Fox's Bay, i.e. checks with MVO on activity levels, a dedicated volcano watcher to warn the workers of danger, and formalised evacuation procedures, in place and practised. Because escape from Fox's Bay involves either a relatively long drive back towards the threat or what must, inevitably, be a relatively slow departure by boat, any risk reduction relating to a finite time to escape is likely to be marginal, and difficult to quantify and justify in the circumstances. This being the case, no additional mitigation on this basis is allowed for in the assessment of this particular scenario. From our latest assessment, we find the likelihood of such an incursion at Fox's Bay to be about 1-in-300 in a year. (This is about one sixth of the likelihood of a similar flow reaching Belham Bridge and two-fifths the rate for incursion into Area 1). Allowing for some ability to escape to sea, the IRPA for a worker is estimated at 1 in 7,900. This is about 3.5x higher than the occupational risk level for extractive and utility workers in the U.K.[11] (Table 3).

43. *Risks to workers in the Belham Valley*
For workers in the Belham Valley (building the bridge, or extracting sand just below the bridge) we have included in the hazard scenarios a flow/surge of between 5 and 10 million cubic metres from a NW-directed event. Using the new probabilities elicited at SAC9, the range of scenarios with potential to affect the central part of the Belham Valley gives a chance of a flow/surge incursion into that area of about 1 in 47 in a year. This is roughly two-and-a-half times what is obtained for the likelihood of incursion into Area 1. For limited working time

[11] Health & Safety Executive (2001) *Reducing Risks, Protecting People: HSE's decision-making process*. HSE Books. Appendix 4.

exposure (i.e. not full time occupation), the IRPA for a worker in the Belham Valley is about 1 in 3,100. In terms of (UK) extractive and utility industries, this exposure is 7.5x greater than the generic fatality rate for such workers (Table 3). No allowance is made in this estimate for possible mitigation/escape measures, which could reduce the risk.

Table 3 SAC 9 Individual Risk Per Annum (IRPA) estimates for volcanic risks to workers in specific locations

Activity	**CMO* Risk Scale**	**Annualised Probability of Death at Work**	**Volcanic risk relative to Extractive industries risk**	**Occupations**[11]
	A			Soldier at war
		1 in 100		
	B			Deep sea fishing
		1 in 1000		
Belham work[1] **Fox's Bay work**[1]	C	**1 in 3100** **1 in 7900**	**7.5x** **3.5x**	Mining & quarrying
		1 in 10000		
Trant's work[1]	D	**1 in 13,600**	**2.5x**	Construction Forestry **Extractive & utility supply industries**
		1 in 100000		
	E			Services
		1 in 1000000		
	F			

[1] workers' risk estimates take account of limited time of exposure

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

44. *Risks to workers at Trants*

Workers extracting sand and gravel from Trant's beach and neighbouring flow deposits are at risk from pyroclastic flows. The likelihood of a pyroclastic flow incursion into the Trants area in one year is 1-in-50 [90% conf. interval: 1-in-94 to 1-in-27]. This is approximately the same as the estimate for a flow incursion to Belham Bridge above. We understand that current safety practices at Trants involve checks with MVO on activity levels, a lookout and evacuation practice.

Incorporating such mitigatory elements into the Trants workers' situation produces an IRPA of 1 in 14,000, or about 2.5x higher than the occupational risk level for the (UK) extractive & utility supply industry. If these protection measures fail, or are not implemented, then the IRPA would rise to about 1-in-5000, or about 4x the equivalent UK occupational risk (Table 3).

45. *Risks to visitors in Plymouth*

The main risk for visitors to Plymouth comes from pyroclastic flows, surges or blasts coming down the Gage's Valley. The loss of a road into Plymouth now necessitates a detour through Richmond Hill and a walk through Sturge's Park, a round trip of about 3-4 hours. For a tourist or person who makes a single short visit into the middle of Plymouth of about this duration, their limited time at exposure would correspond to an annualised individual risk of death of less than 1 in 1 million. However, it should also be recognised that whereas the risk levels involved are insignificant for any one individual tourist, who is exposed just the once, the chances of suffering two or more casualties in a 12-month period from repeated multiple visits by different groups involving several persons may be non-negligible.

For taxi drivers or others who make regular short-term visits to Plymouth, week-by-week, the chances of becoming a casualty are higher, the exact risk level depending on all the circumstances involved (i.e. number of trips made, and total time spent in Plymouth). For the case of a driver who makes two such 2-hour visits per week (i.e. 100 in a year), the individual risk is judged to be about 1 in 16,000 per annum. In occupational risk terms, this is closely similar to official UK statistics for the Construction Industry, or for Agriculture, Forestry, and Fishing (other than deep sea).

46. *Risks in the Maritime Exclusion Zone*

The Maritime Exclusion Zone was last amended in September 2007 when the zone around Old Roads Bay was removed. In our last report we advocated that the area offshore from Spanish Point to Pelican Ghaut be part of the zone. This area of sea is at risk from pyroclastic flows descending to the northeast, particularly in the event of a major collapse of the dome. We make that point again and show in Fig. 7 the zone decreasing from 4 kilometres off Spanish Point to 2 kilometres off Pelican Ghaut.

Fig.7 Suggested extension to the September 2007 Maritime Exclusion Zone – black lined area between Spanish Point and Pelican Ghaut.

Appendix 1 Limitations of Risk Assessment

A1.1 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.

A1.2 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[12], by which means the views of the Committee as a whole were synthesised impartially.

A1.3 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.

A1.4 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

[12] Cooke R.M., *Experts in Uncertainty*. Oxford University Press; 1991.

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[13].

A1.5 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.

A1.6 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.

A1.7 This appendix must be read as part of the whole Report.

[13] Oreskes, N., Schrader-Frechette, K. and Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the Earth Sciences. *Science*, 263: 641-646.

Appendix 2: Chief Medical Officer's Risk Scale

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

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

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

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

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

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

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

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