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

Fourth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 4 - 6 April 2005 at the Montserrat Volcano Observatory, Montserrat

Part II: Technical Report

Contents

Introduction

1. This is the second part of the report resulting from the fourth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 4 - 6 April, 2005. 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 03/05[3], which synthesises the monitoring data and observations collected by MVO between October 2004 and April 2005 and considers some of the new developments during the last six months. The SAC also considered a new draft report on GPS deformation modelling at MVO[4] and a draft report on thermal monitoring[5]. In addition we considered a number of short presentations and papers generated within the SAC membership on hazard analysis topics.

Activity since October 2004

3. Up to the time of the SAC meeting in the first week of April 2005, there had been very little surface activity during the previous six months. The exceptions were mudflows in the Belham River valley, and two periods of higher than normal degassing between 1 and 15 October 2004, and between 9 February and 10 March 2005, the latter being both visible and smelt on other islands. Seismicity was low with some VTs and hybrids with dominant 2Hz signals. The hybrids seemed to correlate with rainfall, which led to the suggestion that the seismicity represented energy released during fumarolic activity. In addition, occasional seismic events recorded first on Garibaldi and then on St George's Hill and at Brodericks suggest a source between Garibaldi and St. George's Hills; more precise locations of this activity could be provided by deployment of another seismometer.

4. In the last six months, as noted, seismicity associated with the volcano has been remarkably low (Fig.1). Although there have been very few low frequency earthquakes, small numbers still occur after heavy or intense rainfall. An episode of small earthquakes, classified as VT type, was recorded on 6-7 March 2005 in the middle of the high gas output episode; these were located at shallow depths (<5km) directly beneath the volcano.

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[1] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Fourth report of the Scientific Advisory Committee on Montserrat Volcanic Activity, 4 – 6 April 2005: Part I, Main Report, issued May 2005.

[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 Panel 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] Bass, V., Hards, V., Loughlin, S., Luckett, R., Norton, G., Ryan, G.A., and Strutt, M. Report to the Scientific Advisory Committee Montserrat, April 2005. MVO Open File Report 03/05, 2005.

[4] Ryan, G.A. Odbert, H. M. and Strutt, M.H. Mogi modelling of the SHV continuous GPS deformation data: How well does it work?, 2005.

[5] Ryan, G.A. and Lowe, C. Thermal monitoring. MVO Open File Report 02/05, 2005.

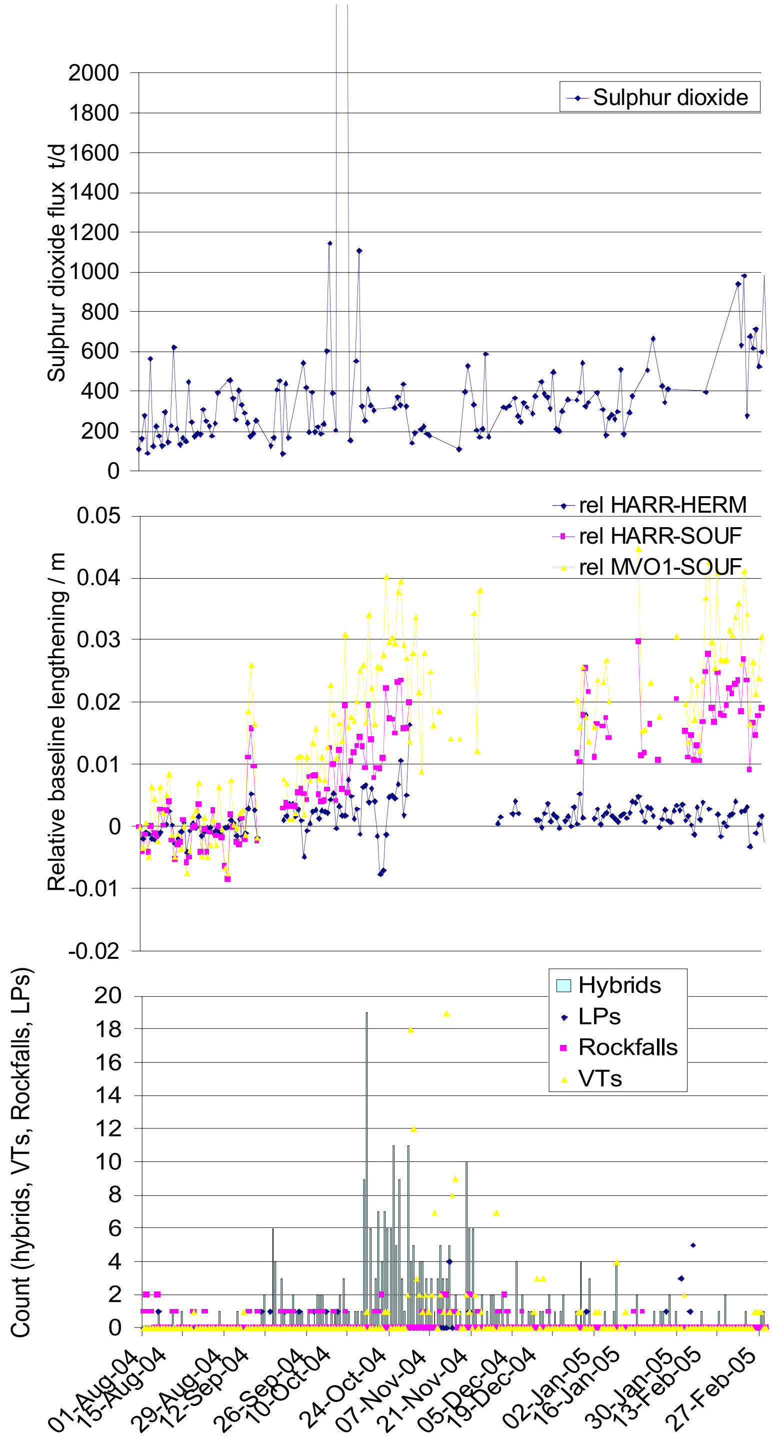

Fig.1 MVO plot of gas, deformation and seismicity data for Oct. 2004 to Mar. 2005

5. Whilst seismicity was at low levels until the mid-April 2005 episode, the average emission rate of sulphur dioxide of 300-400 t/d was close to the long-term rate for the eruption and showed two periods of raised rates from 1 to 15 October 2004, and from 9 February to 10 March 2005 (Fig.1). An exceptional rate of about 13,000 t/d was measured on 8 October 2004, and rates around 1000 t/d in the second period. Such episodes may reflect short-term buffering of gas release within the volcanic system. Although the long-term trend since the collapse events of 12 July 2003 is for reduced gas output, this has not been manifest as gradual decay. Rather, the pattern seems to be of step changes in general flux rate (in November 2003, April 2004 and February 2005).

6. Over the last several months, the near-surface hydrothermal system was clearly re-establishing itself and although this may not have a significant effect on the magmatic system it probably does affect the composition of the gas plume. The smell of hydrogen sulphide seemed to be unusually intense during February - March 2005, when there was a marked increase in gas flux, and this may be due to the interaction of hot water with the abundant sulphur deposits in the crater. It remains the presumption, however, that the variations in SO_2 flux are largely unaffected by conditions in the hydrothermal system. The phreatic activity that began on 15 April 2005 (after the SAC meeting had concluded) was the most vigorous since March 2004.

7. The GPS-based observations of surface deformation since June 2003 have shown a pattern of generally increasing line lengths and inflation. However, superimposed on this have been periods of reversed motion. Soon after the last SAC meeting, in September 2004, the inflationary trend appeared to ease off, and since November 2004 there has been little apparent change in the surface deformation, although gaps affect the data available (Fig.1). Inflation may have been present in early February, corresponding with the three-week long peak in gas flux in February - March 2005. In the case of the short episode of very high gas flux in early October 2004, however, the intensification in gas flux was not clearly associated with any changes in deformation trend. To sum up, whilst the tendency for deformation movements appears to have become more neutral in 2005, it is too early to claim a genuine change in the long-term trend: loss of data due to equipment malfunction makes the most recent (2005) data difficult to interpret with confidence.

8. Dr Ryan has begun analysing the current monitoring data time series in terms of change-points using the CUSUM approach. This approach shows encouraging results and may help identify significant changes in the behaviour of the volcanic system, perhaps in response to forcing agents. Independently, another SAC study of the 2000-2004 period, indicates that the inflections in the GPS data have a bi-annual period and may be driven by the global hydrological cycle operating locally. The significance of this needs careful analysis. On one hand it could be treated as a periodic noise term, whilst on the other it could be a significant external forcing agent whose effect can be of varying criticality to the issue of the resumption of lava effusion.

9. Between September and December 2004, intense rainfall sometimes caused mudflows that affected the Belham valley. As noted above, these episodes of heavy rainfall were commonly associated with swarms of small, shallow hybrid earthquakes.

10. Shortly after the April 2005 meeting, there was a strong steam venting episode on the volcano: nineteen small VT-like earthquakes were recorded between midnight and 10am on Friday 15 April, and at 8am!low level tremor began to be recorded on St George's Hill seismometer, but by 11am this had died away. These seismic events were small and difficult to locate, but several originated at shallow depths!under and around!Gages Mountain, with a distinct cluster around 1km depth. At 1pm the tremor began again and then from 4pm the volcano could be heard making the classic 'jet engine' sound associated with strong steam venting. High gas emissions and light ash fall were reported by MVO staff collecting sampling tubes in Plymouth. The venting noises continued until about 2 am on 16 April and contained very clear pulses varying from every minute to two minutes, to four minutes in the early morning. The main new vent for the steam release was later observed to be just inside the NW rim of the current crater – while another, second vent had formed on the outside of the crater, although that one had become less vigorous with time. After Monday 18 April the seismic tremor had ceased, and venting has been less vigorous, although gas output was still higher than average (about 900 t/d). A first analysis of ash samples collected from this episode indicates that there was apparently no juvenile magmatic material in the ash, and the most likely interpretation is that the material in the recovered deposits probably originated from shallow parts of the conduit. Our preliminary interpretation of this episode is that it was caused by the release of a build-up of gas pressure at shallow depths. The cause of this build-up of pressure was probably either steam derived from groundwater gaining access to new areas of hot rock around the upper conduit, or to magmatic gas collecting within the upper part of the (blocked) conduit. !

Magma influx - is the eruption over?

11. The first SAC technical report made the case that the current eruption of Soufrière Hills Volcano is driven by the influx at intermediate levels in the crust of basaltic magma into a large reservoir filled with andesitic magma. One consequence of this is that if the influx of basalt from depth stops, then this should also eventually stop the eruption of andesite at the surface and hence end the eruption. This is the best current model for what powers the Soufrière Hills eruption. Its qualitative consequences allow us to assess whether the eruption is over.

12. It is now over twenty-one months since the last lava reached the surface at the volcano. This makes the current pause in activity longer than the previous longest pause of twenty months (March 1998 – November 1999). As we pointed out in the last report, the present pause has also shown weaker manifestations of surface activity than that of 1998 – 1999. Thus, whilst this current pause looks more like what we might expect to mark the end of the eruption than the earlier long pause, it does not yet convince. At Unzen volcano, Japan, the end of the 1991-1995 eruption was marked by a quite abrupt cessation of seismicity, surface deformation and SO_2 flux, which we have not yet seen.

13. At the second SAC meeting, we proposed a set of quantitative criteria that can be tested using measurements and observations made by MVO. The three criteria are associated with the main areas of observation that inform us about the internal state of the volcano: gas, seismicity, and surface deformation; details are to be found in the Second SAC Report (March 2004). If, together, all three conditions are met for a suitable period of time (we choose one

year) then that scientific evidence would be consistent with the cessation of basaltic magma supply.

14. The three criteria, unchanged since September 2004, are:

Criterion 1. The SO_2 daily emission rate averages less than 50 t/d
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

Criterion 2 is concerned with the evidence for andesite magma movement in the conduit, whilst the other two are essentially driven by processes within the magma reservoir at greater than 5km depth. To be met, all three criteria effectively require the absence of signals. There is another possible observable effect of the cessation of basalt supply that might involve the manifestation of new signals. This is the occurrence of diffuse volcano-tectonic earthquakes caused by the adjustment of the rocks around the reservoir and conduit to the regional crustal stress field as the upper volcanic system shuts down, such as has been observed after eruptions at other volcanoes. We do not know if this is sure to occur at Soufrière Hills Volcano and hence we suggest its use with caution, but it could be helpful evidence to support the three main criteria.

15. There is always a possibility that other evidence may emerge that is informative about the eruptive state of the volcano, which should not be excluded from consideration. We need to incorporate, with appropriate weight, such possibilities into a structured inference about the state of magma supply.

16. The data acquired by MVO over the year to April 2005 allow us to retest the behaviour of the volcano against the three criteria. Criterion 2 comes closest to being met. Discounting the 15 April 2005 activity, the last episode of increased long-period and hybrid seismicity ended in May 2004. Although the emission rates of SO_2 during the last year were a little lower than the long-term average (500 t/d), it is substantially above the 50 t/d threshold, and deep-seated deformation of several centimetres has occurred on the GPS network during the last year. Thus none of the criteria are met.

17. We will continue to review these criteria, their underpinning scientific basis and the ways in which they can be best used to decide whether or not the magma supply at depth has ceased.

18. As discussed in the last SAC Meeting Technical Report (at paras. 17-18), there are two different ways in which such criteria can be employed in the present circumstances: they may be stated as straightforward decision conditions, to be met or not, as described above; or, they can be considered as strands of evidence for scientific inference. As a basis for direct decision-making, the criteria have significant limitations in practice. In the context of deducing ‘latent’ or ‘hidden’ states of the volcano, the issue is one of scientific reasoning in the face of uncertainty, and an alternative framework was proposed in which the influence of the different strands of observational evidence can be weighed together to express scientific belief in whether or not the magma influx at depth has stopped.

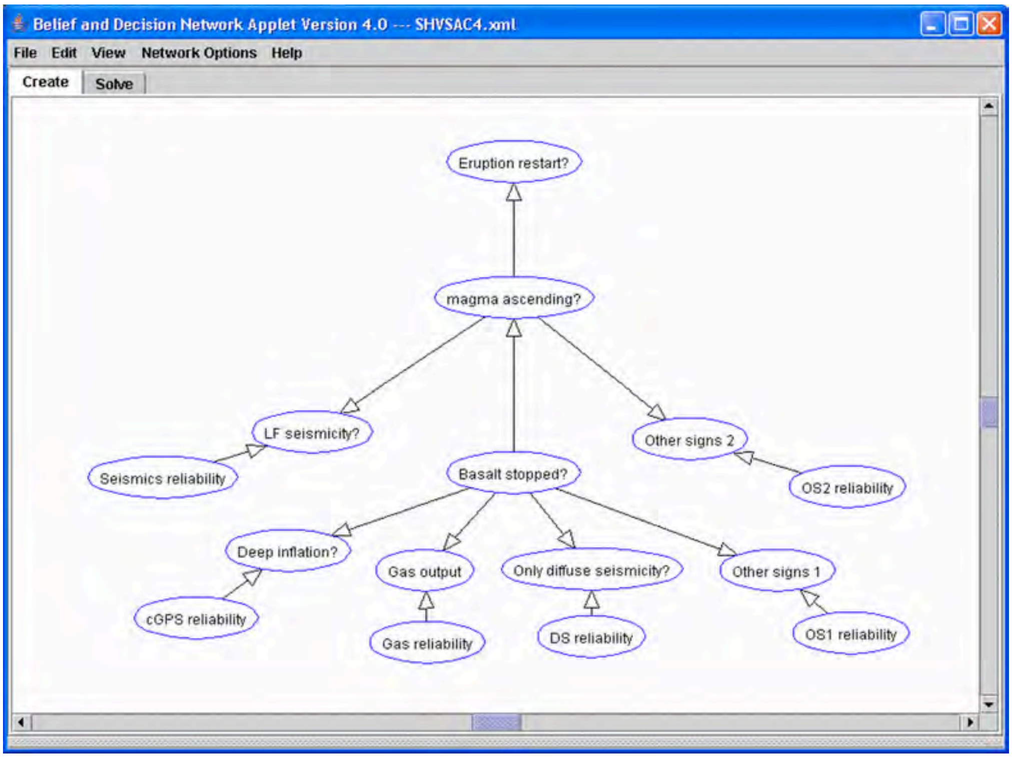

Fig. 2. The basic Bayesian Belief Network (BBN) for inference about the basalt influx – magma ascent – eruption states (see text)

19. For situations where multiple factors are involved, each with its own degree of uncertainty, graphical implementation of a Bayesian Belief Network (BBN) provides a convenient way to take care of the calculational aspects of the problem[6]. In the case of the cessation of activity in the Soufrière Hills volcano, the problem was summarised in the last report by a simple BBN (SAC September 2004 Technical Report, Fig. 3), in which the basalt influx state at depth could influence the various observables (deformation; LP seismicity; gas output, and other signs). However, as recognised in para. 14 above, shallow focus LP seismicity is believed to be more indicative of conditions and processes in the mid- to upper conduit and, for the Soufrière Hills volcano, not symptomatic of what is going on in the deep storage region. This difference calls for a modification to the BBN model. In the new version, adopted by the present meeting and shown in Fig. 2, separate latent nodes are used for basalt supply ('Basalt stopped?') and for magma movement in the conduit ('Magma ascending?'). In this scheme, magma movement in the conduit is presumed to be conditioned (i.e. dependent in some way) on a continued basalt supply, and evidence about one can influence inferences about the other.

20. Another refinement is the addition of a further node ('Eruption restart?') to reflect the fact that even though there may be evidence of magma movement within the conduit, there is no

[6] Here we use the Belief Network applet from The CIspace Web site URL http://www.cs.ubc.ca/labs/lci/CIspace/ at The Department of Computer Science at the University of British Columbia, authored by the CIspace Group © 1999-2003 S. Amershi, N. Arksey, M. Cline, W. Coelho, C. Conati, P. Gorniak, H. Hoos, A. Mackworth, K. O'Neill, M. Pavlin, J. Santos, D. Poole, S. Sueda, L. Tung, and A. Yap.

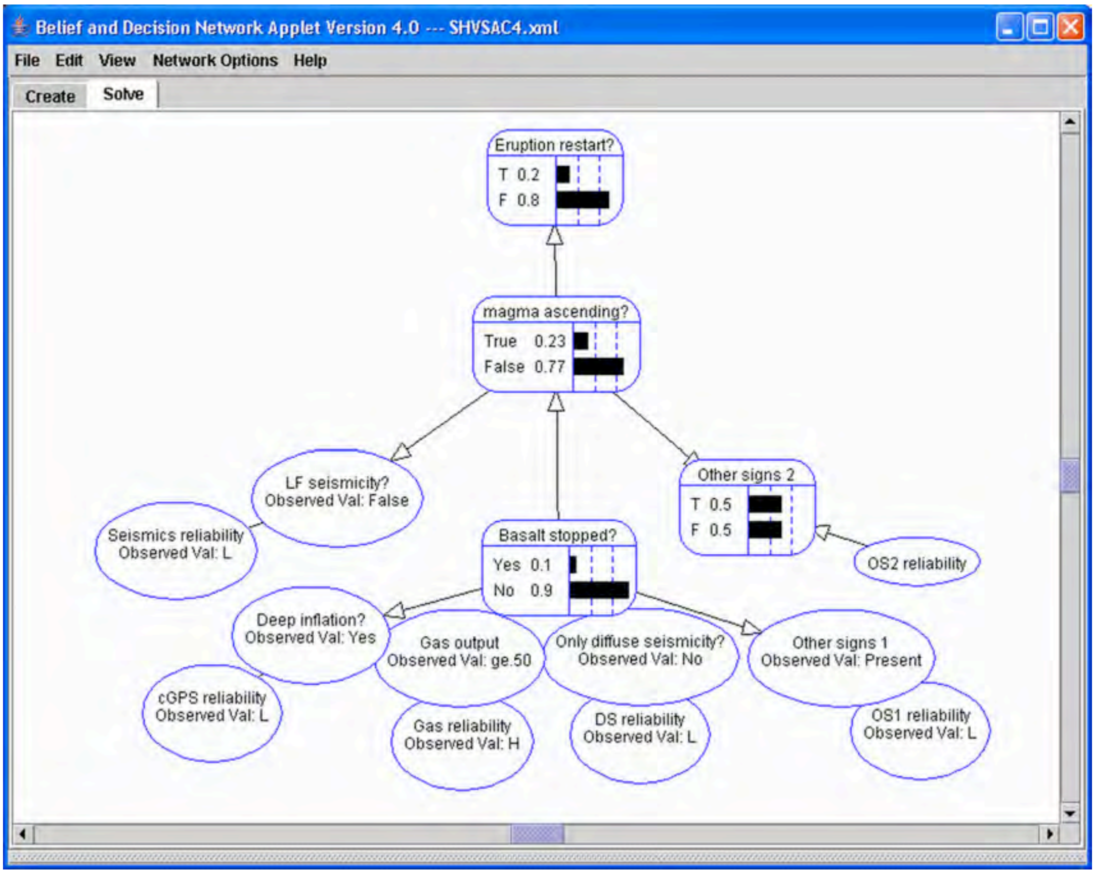

Fig. 3. Bayesian Belief Network solution for probabilities of the hidden nodes 'Basalt stopped?', 'Magma ascending?', and 'Eruption restart?' - given current observations and interpretations of evidential value and reliability

guarantee that this will result in eruption or effusion at the surface. 'Stillborn' volcanic crises are not unknown, with Guadeloupe 1976 being a type case. Thus, while the likelihood of eruption restart is conditioned on processes going on in the conduit, the state of the conduit is only indirectly inferable from LP seismic data or other evidences.

21. There is one further refinement that has been made to the BBN framework representation used here, in the form of evidence 'reliability' nodes. Following Bovens and Hartmann[7], the inclusion of these extra nodes derives from the recognition that although the underlying processes of concern may give rise to observable signs, the recording, analysis or interpretation of data relating to these signs may be unclear, misleading or flawed. In other words, the different forms of information collected through the monitoring endeavours may carry different levels of confidence, insofar as they are regarded as indicators of a hidden process. In deciding formally whether the evidence is important, it is necessary to consider how frequently the interpretation may be mistaken, as well as how often it is correct (an analogy here is with the true and false positive success rates, and diagnostic limitations of medical tests). The addition of these reliability nodes to the BBN on Fig.1 allows us to take some account of these additional sources of uncertainty when considering the likelihood of reaching a correct interpretation of the state of the volcano.

[7] Bovens, L. & Hartmann, S. (2003) *Bayesian Epistemology*. Oxford University Press, 159pp.

22. With this belief network, there is initially assumed to be no information from any of the four conditional nodes, and so the basalt influx state is unknown (i.e. the probabilities of magma influx 'stopped' or 'not stopped' are equal, at 0.5).

23. At the September 2004 meeting, the relative diagnostic values of the three principal forms of indicator ('Deep inflation', 'Gas output', 'LF [low frequency] seismicity') were elicited from the SAC members in terms of their views as to the sensitivity (true positive rate) and specificity (true negative rate) of each criterion. (It is necessary to know the specificity as well as the sensitivity, in order to properly establish the full diagnostic power of the criteria). From these values, the evidential strength of each criterion can be gauged from the associated 'likelihood ratios' (LR), which indicate the ratio of the probability of seeing the evidence given the proposition is true to the probability of seeing it given the proposition is false. Three other nodes are included in the network: one provides for the support that diffuse seismicity would give for determining the end of the eruption, if it were observed and all other indicators of eruptive potential were minimal, and two further nodes ('Other signs 1', and 'Other signs 2') allow for the possibility of the arrival of new evidence or indications (e.g. from a new monitoring technique).

24. With the individual diagnostic powers of the criteria decided, the next step is to set each node to its currently observed status and allow the BBN to calculate the probability that basalt influx has not stopped, that magma is ascending in the conduit, and that eruption at the surface will restart - <u>given</u> all the available observations. As noted above (paras 6&7), the criteria for deformation and gas output are not fulfilled over the last twelve months, and so these conditions can be applied to the relevant nodes connected to 'Basalt stopped?', as shown in Figure 3. However, interpretation of the recent deformation data is ambiguous as to whether a deep inflation signal is genuinely present or not, so while this node is set true its reliability is ascribed low confidence. The gas data are clear and unambiguous, and accorded high reliability as a consequence. Also, in connection with the state of basalt influx, it was agreed that there is, as yet, no evidence of diffuse relaxation seismicity in the volcano. It was also felt that the episodes of extremely strong gas output that had been observed during the last year could be considered as further partial evidence for unstable conditions in the magma storage region, so this factor was included by setting 'Other signs 1' to present, albeit with low reliability.

25. In connection with the 'Magma ascending?' node on Figure 2, it was considered that there had been an effective absence over the last year of LF seismicity of the sort associated with magma movement in the upper conduit, although in this case again the reliability of this evidence was deemed to be low, and reduced accordingly. At this stage, there was no other evidence available that might relate to magma movement, so "Other signs 2" is left in a state corresponding to 'unobserved'.

26. With these strands of evidence, our interpretation of their evidential value, and elicited prior probabilities for magma ascent and eruption in the next year, solving the relevant Bayesian inference equations produces the following outcomes: there is currently a probability of 0.9 that the basalt supply has **NOT** ceased, and a probability of 0.23 that magma might start moving in the upper conduit within the next year. Because there is a small possibility that even if magma does start moving it may not necessarily break surface, the probability of a magmatic eruption restart within a year, <u>given these current conditions</u>, is

therefore about 0.2. If, however, clear evidence of magma movement were seen in the near future (e.g. in the form of unequivocal LF seismicity), the state of the relevant nodes on the BBN would change, and the probability of a restart becomes more likely than not. This way of treating uncertain and indirect scientific evidence should not be taken as providing a definitive evaluation of the relevant likelihoods, but as serving as a basis for informing the SAC judgments and decisions in relation to the assessment of hazards and risks which follows.

27. We therefore conclude that an interpretation of the available evidence at the present time implies that the supply of basalt at depth has not stopped, and that there is less than a 1-in-10 chance (Pr = 1 – 0.9) that this interpretation is incorrect. Thus we cannot say the eruption is over, at least at this level of confidence.

Assessment of Volcanic Hazards

27. Given that the volcano is still in long-term eruption what then are the hazards now posed by this volcano? We can focus our attention on the hazards for two main cases: firstly, the situation as it is now, with no dome growing; and secondly, the situation if there is a restart of dome growth in the crater.

28. The specific volcanic hazards faced are:

> for the no dome case: sudden explosions with ash and rock fallout, pyroclastic flows from explosive column collapse, outward collapse of the remnant dome;
>
> for the dome growing case: explosions with ash and rock fallout, pyroclastic flows from explosive column collapse, pyroclastic flows from dome collapse, outward collapse of the remnant dome;

The main areas of specific concern for this meeting were the former DTEZ (re-opened for occupation), and other selected areas within the present Exclusion Zone, which might be considered for re-occupation or for access for industrial purposes.

29. In assessing the hazards, certain factors were judged to be of most importance. Firstly, the likelihood that lava effusion will restart within the period under concern (one year) is fundamental. The degree of explosivity of any renewed activity, particularly the potential for an explosion after a long period of no activity is obviously important. The topography of the volcano is important. Pyroclastic flows are partly guided by the topography and hence the vulnerabilities of different locations are determined by their neighbouring hills and valleys. Finally, perhaps the most important factor is the rate of magma flux to the surface, particularly in the initial stages of renewed effusion. These factors were discussed in detail in the last Technical Report.

30. Because we focus our attention on specific areas of the Exclusion Zone which earlier risk assessments had identified as being at particular risk from pyroclastic flows we have performed further computer simulation analyses of which areas would be most hazardous from these flows (see Figure 4). Details of the modelling methodology were given in

paragraph 25 of the September 2004 Technical Report. We have also revisited our evaluation of the hazardous effects of explosions, using the results of the simulation modelling of Bonadonna and Sparks described in MVO Special Report 9 [8] for the hazards due to fallout of ash and rocks from the eruption column. For both the pyroclastic flow hazards and the explosion hazards cases we quantify the hazards within specific areas covering some villages within the Exclusion Zone and other zones outside.

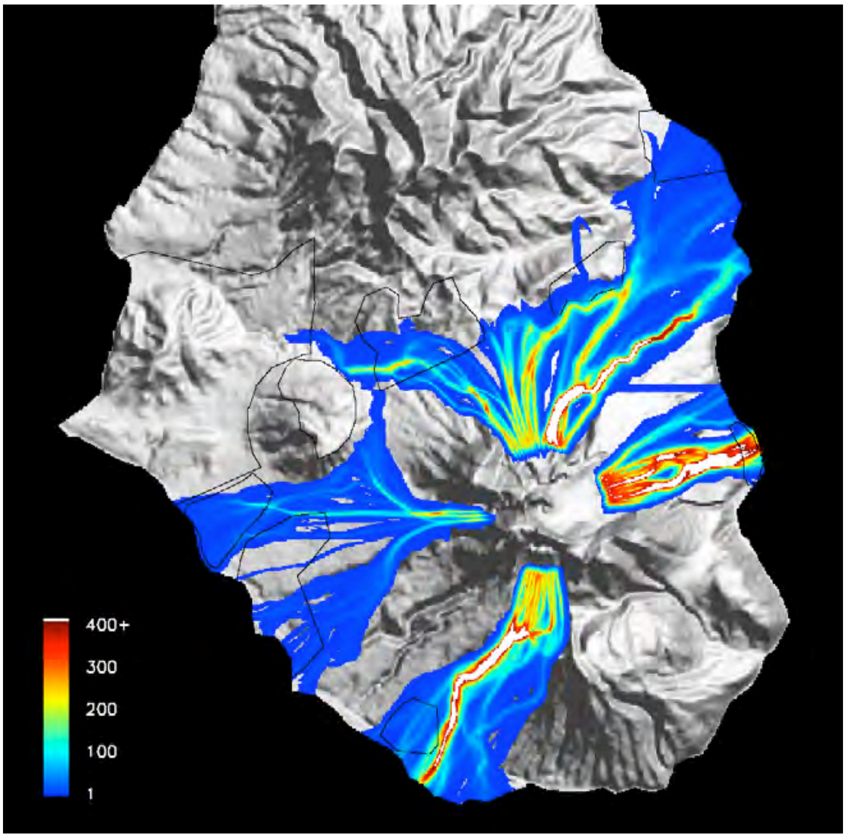

Fig. 4. Results of revised PYROFLOW modelling. This model uses a DEM in the region of Mosquito Ghaut that is modified from the one used for SAC3 calculations. The outlined areas are localities in the Exclusion Zone and former Daytime Entry Zone for which sudden onset eruption risks are assessed (see text).

31. In addition to the on-land dangers, the volcano might still pose a threat to sailors on boats and vessels in coastal waters, and a Maritime Exclusion Zone has been in force that was designed to minimise these risks. We have re-evaluated the risk offshore using the most recent analysis of pyroclastic flow hazards in the Exclusion Zone. The zone offshore the Tar River Valley is hazardous under any conditions of surface activity, but the other maritime zones are between ten and hundreds of times less likely to be affected, depending on the exact nature and intensity of the activity.

[8] Bonadonna, C. and Sparks, R.S.J. Assessment of tephra fallout hazard and risk for Montserrat. *MVO Special Report* 9, April 2002.

32. The activity of 15 to 19 April 2005 was of particular concern because it produced a vent on the outside of the crater. However, it seems highly likely that this vent lies on the boundary between the old crater (English's Crater) and the dome material that remained after the July 2003 collapse. Thus escaping gas probably followed an existing plane of weakness that dips to the south into the current crater. Sitting above this vent is part of the remnant Northwest Buttress that partially collapsed in March 2004. A concern is that the April gas-venting activity has excavated a new void within the near subsurface or weakened the stability of an old discontinuity adjacent to this rock mass and increased the likelihood of collapse. To the southwest, another, pyramid-shaped remnant of the old dome overtops the crater rim above Gage's valley and has an estimated volume of about $2x10^6$ m^3. The collapse of March 2004, the current shape of the "pyramid" and the likely orientation of any failure plane all indicate that any collapse here will most probably be directed into the crater, to the east and the southeast. However, if an outward collapse were to occur, this volume of material could produce a debris avalanche or perhaps a pyroclastic flow (if it retains any pressurised gas). The study of Calder et al.[9] suggests that a volume of this size could have a run-out distance of three to four kilometres. Depending on the location of the failure surface this could send the avalanche into either Tyer's Ghaut or Gage's Ghaut to reach the Belham Valley near Cork Hill or the upper part of Plymouth respectively. We think that the likelihood of this hazardous outward collapse occurring in the next year is low.

33. In terms of other, secondary, hazards on land that can arise from the volcanic activity, mudflows are the most common. While many of these take place in valleys and ghauts within the Exclusion Zone, some develop and progress into the lower Belham River valley. Whilst many of the mudflows are triggered by heavy rainfall, not all heavy rainfalls trigger mudflows. The sediment being carried down the valley derives partly from the ash deposited during the eruption and partly from the erosion of older deposits. The generation of mudflows will only cease when the upper slopes of the valley are re-vegetated, a process that will take several years, even after the eruption stops.

34. Even though eruptive activity levels may be low, another potential hazard related to the volcano is gas emissions, which can rise suddenly and without warning and, at high concentrations, could cause respiratory symptoms in some individuals close to and downwind of the volcano (e.g. Plymouth or St George's Hill). For instance, the ambient levels of SO_2 in Plymouth over a two-week period in February-March 2005 were about 117ppb, and peaks at up to 5 or 10 times this may have occurred over shorter periods. WHO guidelines[10] (2000 - at Chapter 7, page 5) state that lung function changes in exercising sensitive individuals can take place at 400ppb. We will report on this issue in more detail at the next SAC meeting.

[9] Calder, E.S., Cole, P.D., Dade, W.B. et al.(1999). Mobility of pyroclastic flows and surges at Soufriere Hills Volcano, Montserrat. Geophys. Res. Lett., 26, 537-540.

[10] Air Quality Guidelines for Europe, 2nd ed., Copenhagen, WHO Regional Office for Europe - WHO Regional Publications, European Series, No. 91, 2000.

Elicitation of Probabilities for Hazard Scenarios

35. 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.

36. To update the risk assessment, six separate issues were discussed and re-elicited during the meeting on Montserrat. These are reported below as items *P2 – P7* and where probabilities are involved, each is conditional on the presupposition that the eruption has not stopped (the relevant SAC deliberations on this issue are reported in paras 11–20, above). Previous values for three further probabilities that had been elicited at the last meeting, concerned with different flux rates upon restart, were accepted as remaining valid and not updated on this occasion.

37. An additional question was posed concerning the SAC's views on how long it is likely to be until the three criteria for cessation are met, if the present pause continues indefinitely.

38. Each class of event connected with any particular conditional probability represents one type of hazard with a given size or intensity. By assigning a distributional spread of sizes to a set of such events, it is possible to represent the uncertainties associated with each and combine them all into a model of the continuum of hazards that can arise at this volcano. The set of hazard events for the Soufrière Hills Volcano was initially defined in 1997, and has been progressively modified, as understanding has improved.

39. *Probability that the eruption has not stopped (P1)*

The decisive factors used for determining whether the eruption has stopped or not are given in the section on Magma Influx, above. The available evidence, when combined with the elicited views on the diagnostic strengths of the criteria, indicates that it is very unlikely that this is the case at the present time (i.e. *P1* = 0.9). The approach, outlined above, effectively measures our confidence in the test, but does not provide any definitive guidance as to whether or not dome growth will restart at the surface (it is conceivable that magma influx can continue at depth, without magma emerging at the surface). In these circumstances it is necessary to look to the experts' judgments as to whether the surface eruption will resume within a given time interval - this is considered for the period of one year, in *P2,* next.

40. *Probability that dome growth will not restart within one year (P2)*

Given that active processes at depth have not stopped and the volcano has the potential to start erupting magma again, this question measures views on the probability that there will **not** be a resumption of lava effusion within one year. We know that the magmatic system remained active without surface effusion for at least twenty months once before, and so presume it could do so again. However, during the 1998-1999 pause there was much more surface activity, on and off, over the months (Norton et al.[11]) than there has been during this most recent period of prolonged quiescence.

[11] Norton, G.E. and 15 authors, Pyroclastic flow and explosive activity at Soufrière Hills Volcano, Montserrat, during a period of virtually no magma extrusion (March 1998 to November 1999), In, Druitt, T.H. and B.P.

Elicited Probability :

lower bound	best estimate	upper bound
28%	**77%**	**94%**

The central probability of **no** restart of magma effusion within 12 months (*P2* = 77%) is much higher than that elicited in September 2004 (when *P2* = 40%) – that is, the chance of a restart within one year is now judged to be about 3:1 against. Whilst these odds are substantial, they are not strong.

41. *Probability of a restart to dome growth preceded by a 0.1x reference explosion (P3)*
The threshold for a significant hazardous explosion at the Soufrière Hills Volcano is judged to be about one-tenth the size of that of the reference explosion of 17 September 1996. That eruption is well modelled by the work of Bonadonna and Sparks and so the geographical extent and intensity of its hazardous effects are constrained. The 0.1*x* reference explosion is similar to many of the vulcanian explosions experienced during the latter part of 1997, most of which involved column collapse-generated pyroclastic flows. As mentioned earlier, the most recent explosions (in March) were assessed to be much less than 0.1*x* reference size.

Elicited Probability :

lower bound	best estimate	upper bound
1%	**10%**	**47%**

This result reflects a halving of the perceived likelihood of an explosive restart, when compared with the September 2004 assessment (P= 21%).

42. *Most likely duration of the current pause (P4)*
Given that we judge we are twenty-one months into the current lull, what is the most likely total duration of the present pause? The background to this question is discussed in more detail in paragraph 7 of the September 2004 Technical Report. The lower magma flux rate before this pause compared to that prior to the 1998-1999 pause may indicate that it could take longer to achieve some threshold reservoir overpressure value to trigger a restart.

Elicited Spread of Duration :

lower bound	best estimate	upper bound
21 months	**41 months**	**300 months**

This spread of values for the duration of the present pause suggests a view that relatively long periods without magma effusion can be expected at the Soufrière Hills Volcano, without the eruption necessarily ceasing altogether. At this stage, the expected value of the present duration is put at about 41 months, compared to 26 months in the last assessment exercise, six months ago. That is, another 20 months could be expected to elapse before the likelihood that the pause has peaked.

Kokelaar (eds). *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999.* Geological Society, London, Memoirs, 21;467-481, 2002.

43. *Probability of a magma flux rate upon restart of >5 m^3s^{-1} (P5)*
This and the following two questions seek to enumerate the probabilities of three different ranges of magma flux rates, spanning the full observed range of behaviour during this eruption, that would have different consequences in terms of the level of risk. High flux rates (*>5 m^3s^{-1}*) were experienced most notably during the second half of 1997.

Elicited Probability :

lower bound	*best estimate*	*upper bound*
2%	**16%**	**49%**

Compared with the last assessment, this result represents a reduction of about one-third in the perceived likelihood that a high flux rate may ensue if magma extrusion recommences.

44. *Probability of a magma flux rate upon restart of 2-5 m^3s^{-1} (P6)*
This is the range experienced for much of the eruption from 1996 to 2002.

Elicited Probability :

lower bound	*best estimate*	*upper bound*
13%	**41%**	**77%**

To within a percentage point here or there, the SAC's opinion is that an intermediate flux rate (*2-5 m^3s^{-1}*) upon restart is exactly the same likelihood as it was in September 2004. .

45. *Probability of a magma flux rate upon restart of <2 m^3s^{-1} (P7)*
This is the range experienced during most of the first year of the eruption and during part of 2003.

Elicited Probability :

lower bound	*best estimate*	*upper bound*
12%	**42%**	**80%**

For the case of low flux rate restart, an increase in likelihood of about one-third is obtained for this scenario, reversing the decrease provided by the September 2004 elicitation and balancing the reduction in the high flux rate restart in the present exercise (P5 above).

46. *Given dome growth recommences at a magma flux rate <2 m^3s^{-1}, the probability of a subsequent 0.1x reference explosion (P8)*

(n.b. this probability was not re-elicited at the April 2005 meeting, and the values obtained at the September 2004 meeting are thus retained.)

This scenario involves an explosion occurring almost immediately upon resumption of magma movement to the surface, but for the case where initial flux rate is low.

Retained Probability :

lower bound	*best estimate*	*upper bound*
<1%	**9%**	**47%**

47. *Given dome growth recommences at a magma flux rate of between 2-5 m^3s^{-1}, the probability of a subsequent 0.1x reference explosion (P9)*

(n.b. this probability was not re-elicited at the April 2005 meeting, and the values obtained at the September 2004 meeting are thus retained.)

This is the same as P8, but with an intermediate magma flux rate at restart.

Retained Probability :

lower bound	*best estimate*	*upper bound*
3%	**29%**	**64%**

48. *Given dome growth recommences at a magma flux rate exceeding 5 m^3s^{-1}, the probability of a subsequent 0.1x reference explosion (P10)*

(n.b. this probability was not re-elicited at the April 2005 meeting, and the values obtained at the September 2004 meeting are thus retained.)

This third and last version of the dome growth restart scenario considers the likelihood of a 0.1*x* reference explosion if the magma flux rate is high.

Retained Probability :

lower bound	*best estimate*	*upper bound*
8%	**56%**	**98%**

Quantitative Risk Assessment

49. Although the risks facing the people of Montserrat from the volcano were judged to have changed considerably following the giant dome collapse in July 2003, we continue to follow the same basic procedures for quantitative risk assessment that have been used since 1997, revising previous calculations of volcanic risk by making adjustments to probability and rate estimates, based on the committee's reappraisal of the likelihood of the various 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. Generally, these risk estimates do not include allowance for any reduction in exposure that could be gained from early warnings and civilian mitigation responses. Thus, while the quantitative risk assessment results are not full-blown worst-case scenarios, they do represent conservative estimates for policy-making purposes. The approach and methodology follow those described in the December 1997 MVO Hazards and Risk Assessment report, validated by the UK Government's Chief Scientific Adviser's consultative group.

50. The assumed total population on Montserrat is taken currently to be about 4,775 persons, a figure unchanged from previous assessments. 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.

51. In response to a request from the authorities, the present assessment focuses principally on volcanic risk levels in the former Day-time Entry Zone (DTEZ), and in certain areas that are still within the current Exclusion Zone (Figure 5). Nonetheless, we retain the main occupied zone delineations that have been used consistently throughout recent risk assessment updates for Montserrat as a reference frame - i.e. Zones 1- 4 inclusive (see Fig 1 of the March 2004 Report, Part II.) - and base our calculation of current overall societal risk levels on these established population divisions. That said, the Isles Bay area (former Zone 5) is now subsumed into the larger area of the former DTEZ (see Figure 5).

52. We address the government queries concerning the risks faced by an increased level of population within the DTEZ and other areas in the Exclusion Zone via a series of location specific scenarios. We emphasise, however, that the only way to undertake such analysis in terms of societal risk is by knowing how many people are within a given area and for what length of time. Because these figures are not fully specified, and dated census figures may not be applicable, we have assumed the relevant numbers of people that might be involved, and our quantitative assessments are therefore only valid for these assumed figures. That said, it is possible to estimate individual risk exposures in different localities even though such estimates are detached from the total numbers of persons involved.

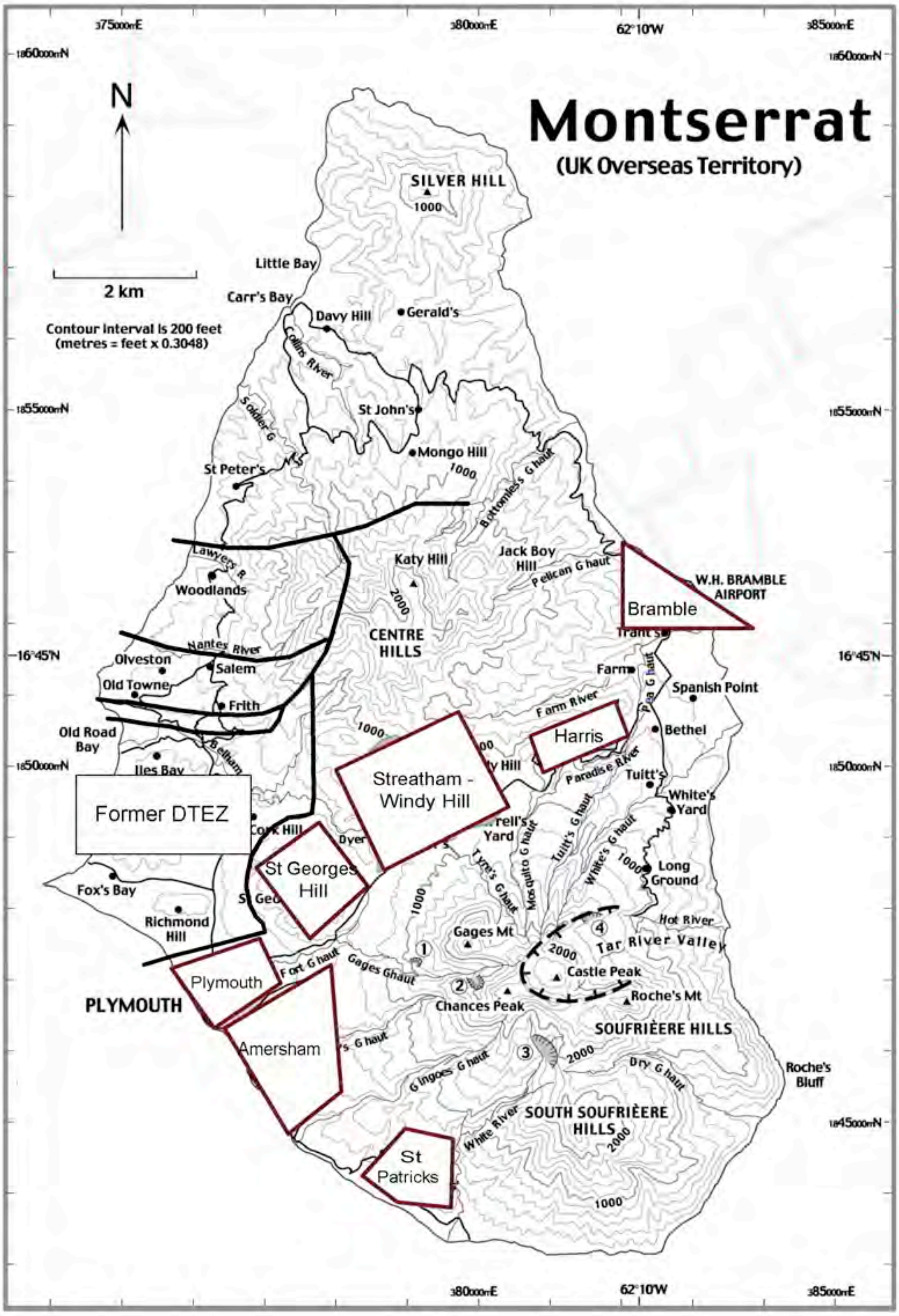

Fig. 5. Map of Montserrat, showing areas used to assess volcanic risk exposure.

Societal Risk Levels

53. *Risk levels with the present population distribution*
In order to assess societal risk levels, the impacts of different eruptive scenarios are modelled for the whole population. In addition to the population outside the former DTEZ, the model also has about 24 souls living full-time in that area (including those on Isles Bay). From the elicitation results reported above, it is considered less likely that magmatic eruption activity will restart during the next year than not ($P_{restart}$ ~ 0.23). If there is a restart, it is judged to be much more likely to be a new phase of dome-building (P_{dome} ~ 0.9 from elicitation), rather than an eruption initiated with explosive activity (i.e. $P_{explosion}$ ~ 0.1). In either case, a range of flux rates is allowed for in the modelling, weighted according to the elicitation results for their relative likelihoods.

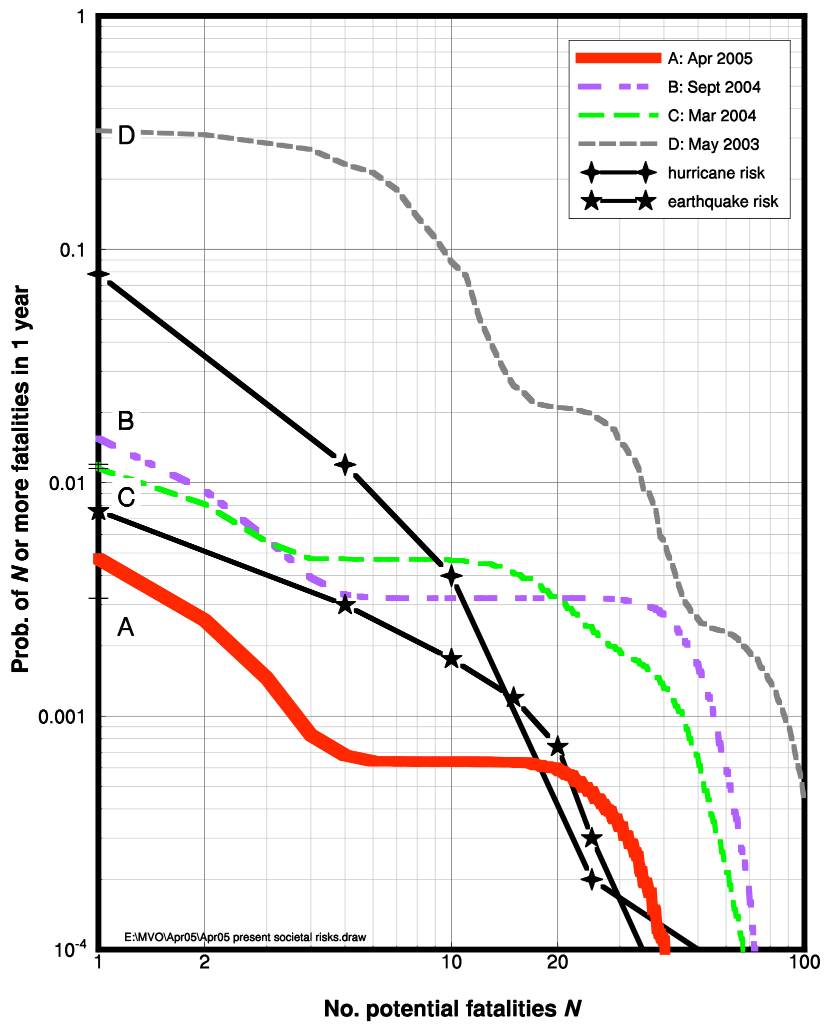

Fig. 6 Societal risk estimation for present population and a possible restart of magmatic eruptive activity in the next year.

54. In this analysis, it is also assumed for modelling purposes that no immediate mitigation measures are introduced as a consequence of a restart of magma eruption at the surface. For comparison, Figure 6 also shows the annualised societal risk that was calculated in September 2004 (curve B), March 2004 (curve C), and that which had been obtained earlier for the conditions of May 2003 (curve D), when a very large dome was present. The present volcanic risk is thus considered to be even lower than it was a few months ago, and substantially lower, by nearly two orders of magnitude, than it was in 2003, when the giant dome threatened occupied areas.

55. Comparative risk exposures for hurricane and earthquake are also shown: for smaller numbers of casualties, curve A indicates the volcanic risk is now assessed to be lower than the long-term hurricane and earthquake risk in the populated areas of Montserrat, while for large numbers of casualties (e.g. 20 or more fatalities) the risks similar to those from either of the other two natural hazards.

56. *Risk levels for an explosive restart*
With an active volcano like this, the possibility of a strongly explosive sudden restart to magma eruption at the surface in the near future cannot ever be precluded. Because such a change in behaviour is intrinsically unpredictable, it has to be allowed for with suitable probabilities of occurrence within any risk assessment. If there were a sudden explosive resurgence of magma eruption with a sustained high flux rate, the overall chances of suffering one or more casualties in an eruption of that sort are approximately double those that exist for alternative, more likely scenarios that are included in the preferred model. That said, the likelihood of such a strongly explosive restart is currently considered low, in the absence of any indications to the contrary.

Individual Risk Exposure Estimates

57. In terms of individual exposure, *individual risk per annum* estimates (IRPA) for people in different areas are calculated using the probabilities elicited from the committee, coupled with Monte Carlo population impact risk simulation modelling. The numerical risk estimates are also categorised according to the descriptive scale of risk exposure levels devised by the Chief Medical Officer (CMO) to the UK government (see Appendix 2).

58. *Risks in former DTEZ*
Given the current absence of dome growth, the most immediate hazards could come from: a) sudden explosions with fallout of rocks and ash, and b) sudden explosions with accompanying pyroclastic flows generated by column collapse. The hazards from fallout of rocks could occur anywhere across the DTEZ, and can be mapped from the simulation models. The hazards from column collapse pyroclastic flows would be concentrated in areas abutting flowpaths coming from Gage's Valley, and, marginally, in the Belham Valley near Cork Hill. These give a risk exposure in the VERY LOW category on the CMO's scale (*n.b. this*

assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity).

59. *Risks in former DTEZ with dome growth*
If dome growth resumes with people living in the DTEZ, then the initial hazards will be similar to those above, but dependent on the flux rate of magma. If this rate is high the likelihood of explosions is increased. Also as the dome increases in size the initial protection from all but the most vigorous column collapse pyroclastic flows afforded by the crater walls will diminish. Eventually dome collapse pyroclastic flows will recur, though these are likely to be mainly directed down the Tar River valley. We expect the growth rate of the dome to be low or moderate initially. While this too gives a risk exposure for a typical individual of LOW, the increase in risk because of a high rate magma flux could move into the MODERATE to HIGH categories. Specifically, a high explosive restart (1*x* reference explosion or greater) would approximately double the number of potential casualties compared to the non-explosive restart scenario.

60. *Mudflow risk in the Belham Valley*
The risks from mudflows in the Belham Valley were examined in detail for the September 2004 assessment. Nothing has changed since that time to alter the views expressed in the last SAC Report.

61. *Risk exposure for St. George's Hill*
The volcanic hazards in the St. George's Hill vicinity are currently those from falling rock fragments from a sudden-onset explosion, and/or pyroclastic flows from a column collapse eruption. If, however, significant dome rebuilding starts, then those hazards would become slightly less likely, but the threat of hazards associated with dome collapse would start to return. Under the present conditions, our current hazards model indicates that the risk exposure for a person returning to live full-time on St. George's Hill is VERY LOW on the CMO's scale. (*n.b. this assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity*).

62. *Risk exposure in Exclusion Zone for Amersham area*
The risk exposure for a person returning to live full-time in Amersham is assessed LOW to MODERATE on the CMO's scale. (*n.b. this assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity*).

63. *Risk exposure in Exclusion Zone for Streatham - Windy Hill*
The risk exposure for a person returning to live full-time in the Streatham – Windy Hill area would be MODERATE on the CMO's scale. (*n.b. this assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity*).

64. *Risk exposure in Exclusion Zone for Harris*
The risk exposure for a person returning to live full-time in Harris is MODERATE to LOW on the CMO's scale. (*n.b. this assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity*).

65. *Risk exposure in Exclusion Zone for St. Patricks*

The risk exposure for a person returning to live full-time in St. Patricks is MODERATE to HIGH on the CMO's scale. (*n.b. this assessment does not include risks that would be present if a person remains in this area after a restart of magmatic activity*).

66. *Risks to workers on Plymouth jetty*
The risk to workers at the Plymouth jetty in the present conditions with no dome growth, is assessed with a risk model based on 10 workers working on the jetty eight hours per day, five days a week. Potential hazards faced are sudden onset of explosive activity, collapse of the remnant Northwest Buttress and mudflows. The mudflow risk is considered to be at the same level as that in the Belham Valley. It is assumed for this analysis that there may be little or no effective early warning of an impending volcanic event which, although its probability of occurrence may be very low, could have a very rapid onset. It is also assumed that the stevedores may require as much as 30 to 45 minutes to make good their escape from Plymouth and reach the Belham Valley crossing (presuming further that they have adequate transportation and reliable vehicles, and behave responsibly at all times). Under these marginally pessimistic, but by no means worst-case, circumstances, the annualised individual risk of exposure of a worker on the jetty would be in the LOW category on the CMO's Risk Scale. The level of individual risk exposure implies there may be a non-negligible chance of losing two or more workers from volcanic activity, if such work is undertaken continuously for a full year under the present conditions assumed for the hazard model.

67. *Risks to people working at Thomson's Field*
The risks to individual workers involved in access to this area are approximately the same as those for working at the Plymouth jetty, although in this case the locality is further removed from likely pyroclastic flow paths, and opportunities for escape are marginally better. While this is true for individual shift workers, if 24-hour working were undertaken the collective risk of suffering casualties among the workforce might be quite significant (to quantify this, further operational details and a separate analysis are necessary).

68. *Risks to people working in the daytime at Trant's Quarry*
The risks to individual workers present in this area during normal working hours are judged to be equivalent to LOW to VERY LOW.

69. *Risks to fishing boats off the east coast*
The risk exposure to individual fishermen operating off the Trant's Bay to Spanish Point section of the east coast depends very much on the amount of time spent in the area, which information is not available. To give some comparative guidance, however, the individual risk exposure (IRPA) for someone in that area *full-time* would be assessed as LOW to MODERATE on the CMO's scale (with an IRPA of about 1 in 1700), whilst exposure in the area directly off the Tar River delta is in the upper part of the HIGH category (IRPA about 1 in 45). Thus, numerically, the risk levels are about forty times lower for the fishing grounds north of Spanish Point when compared with the sea area off Tar River.

70. *Risks to cruise ships off Plymouth*
Under present conditions, the chances of a major life-threatening volcanic hazard, such as a pyroclastic flow, affecting a big cruise ship making a short visit off Plymouth is regarded as almost negligible. There could be occasional high levels of gas that might be irritating or have medical implications for very susceptible persons on board, and acid rain from the volcanic plume could affect paintwork. There may also be an issue about the unknown and

presumably changing bathymetry off the jetty area, but this topic is outside our direct expertise. Slower, smaller vessels, especially sailing boats, might find it less easy to get out of the way of any sudden onset hazard, and would offer less protection to those on board.

71. *Risks to people using Bramble Airport as a diversion airfield*
If the Bramble Airport runway were to be operational no more than six times in a year, and for no more than 2 hours at any one time, the annualised risk for any individual who was in this area on such occasions would be NEGLIGIBLE for an 'out-of-the-blue' volcanic event.

72. *Risks to tourists and short-term visitors in Plymouth*
For a tourist or person who makes a <u>single</u> short visit to an area with elevated risk (say, a trip into the middle of Plymouth of about two hours in duration), their limited time at exposure would correspond to an annualised individual risk of death or injury in the category NEGLIGIBLE on the CMO's Scale. For taxi drivers or others who make regular short-term visits week-on-week, although the chances of becoming a casualty would be higher, the individual risk can be expected to fall still in one of the categories MINIMAL, VERY LOW or LOW, depending on all the circumstances involved (this does not apply to full-time workers in the Exclusion Zone, see para 65, above). However, it should also be recognised that whereas the risk levels involved are insignificant for any one individual, 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 the scenario of a sudden onset explosive eruption and associated hazards (as discussed in relation to selected areas in the Exclusion Zone in paras 60-64 above), the probability of suffering a number of casualties amongst tourist visitors to Plymouth is estimated to be about 1.5×10^{-4} per year - i.e. there is a chance of about 1 in 6600 of this happening under present conditions.

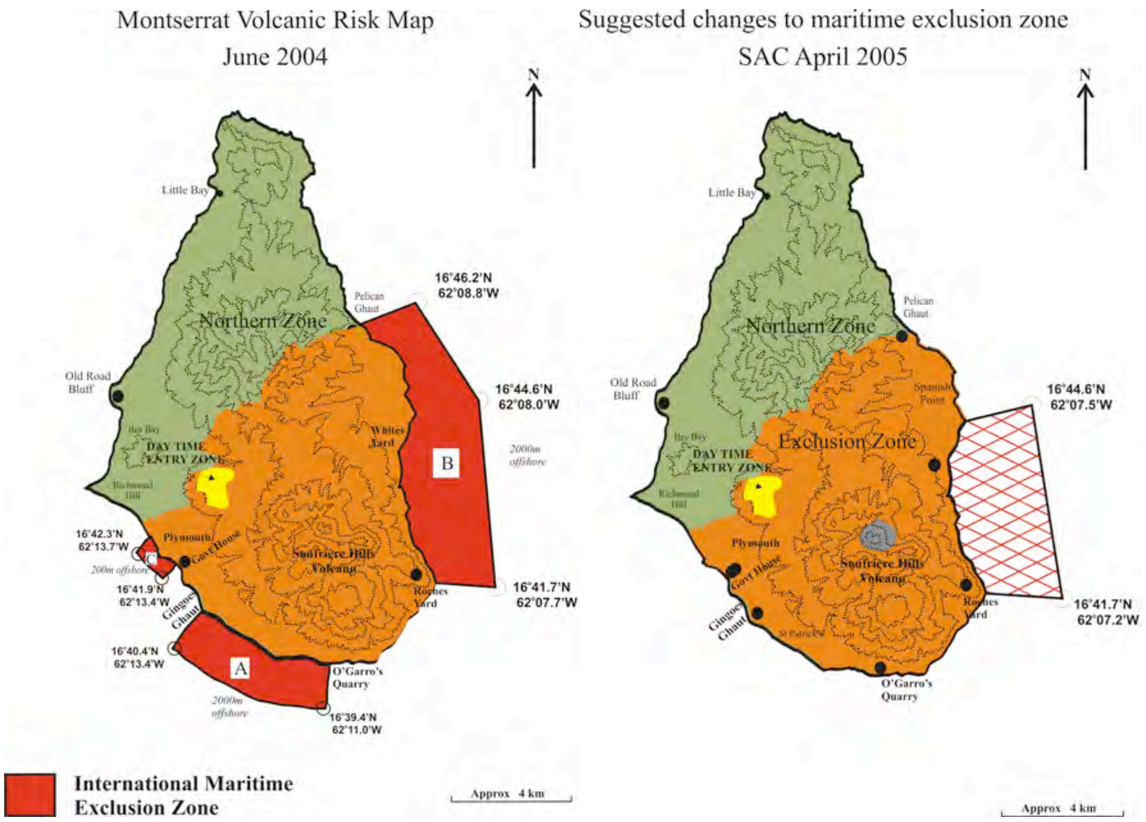

Fig. 7. Current Maritime Exclusion Zone (left) and possible new arrangement (right).

73. *Risks in Maritime Areas*
The levels of risk exposure in maritime areas and coastal waters around southern Montserrat can be reviewed in the light of the levels of assessed societal risk on land, reported in para. 53 above, and the risks to fisherman off the east coast, just discussed in para. 69. The low level of activity at the volcano and the reduction in our estimate of generic risks levels over the last year or more suggest that the area with potential for significant offshore volcanic hazards is currently restricted to coastal waters off the Tar River flank of the volcano. As a consequence, the Maritime Exclusion Zone map could be modified, and a suggested set of new boundaries is shown on Figure 7.

Long Term Prognosis

74. For long-term planning purposes, the authorities would like some indication of how frequently they might have to respond to major volcanic incidents, such as a massive dome collapse with ashfall deposits (similar to that of 12 July 2003), or a significant explosion event (such as that of 17 September 1996). The attendant likelihoods are most usefully considered in terms of probabilities of occurrence on two timescales:

(1) Probability of a massive dome collapse within 1 – 5 years
(2) Probability of a big explosion within 1 – 5 years
(3) Probability of a massive dome collapse within 5-20 years

(4) Probability of a big explosion within 5-20 years

The probabilities of a magmatic eruption restart, derived above (para. 41), can inform these queries, as follows.

Dome Collapses

75. In order to reach a condition in which a massive dome collapse was incipient (in scenario 1, above), there would need to be about two years of dome growth, sustained at the same flux rate and under similar vent conditions as those in 2001-2003. Thus, a 1-year time window would not be sufficient to achieve the necessary size of dome, unless the extrusion rate was more than doubled AND associated vigorous action in the dome did not disrupt growth (as happened in previous, more active times). Taking the global experience that 80% of dome-building eruptions have a restart within 20 years of their last recorded eruption, and using the SAC group's current elicitation for the likely duration of the present pause for the Soufrière Hills volcano (para. 42), a restart within one year has a probability of between 0.16 and 0.23. Using the additional arguments put forward at para. 65 in the September 2004 Technical Report, the likelihood of a massive dome collapse happening on a timescale of about one year is therefore now estimated to be about a 1-in-125 chance. Given multiple conditions must be precisely right to reproduce a dome of the required size, and do so very quickly, and then incite a collapse, the true probability is likely to be lower than that inferred here.

76. In the last report it was also argued that the influence of the abnormal wind direction during the 12 July 2003 collapse needs to be taken into account when assessing the effects of a future event of this scale. A reduction by a factor of 2 was proposed informally by the SAC to qualify the unusual wind effects, which in turn would lead to a revised estimated chance of a repeat event, like 12 July 2003, of no more than 1-in-250, over the timescale of one year.

77. For the longer time horizon of five years, the SAC group's current elicitation for the likely duration of the present pause (see para 42) indicates a restart of growth within that timeframe has a probability of about 0.5. In this case, it is assumed, conservatively, that a subsequent major collapse follows upon growth to full size (as opposed to the 1-year scenario above, which had an additional conditional probability limiting such association). Thus, in odds terms, there is perhaps about 1-in-45 chance of a recurrence of a giant collapse within 5 years. Again, the actual likelihood may be somewhat lower.

78. For a repeat dome collapse on a twenty-year timescale, the estimated overall upper likelihood probability for a repeat of an ashfall event like that of 12 July 2003 remains unchanged from that given in the September 2004 assessment - that is, about a 1-in-20 chance of a recurrence, over a period of 20 years.

79. Thus, given we are still in a situation in which there is no magma effusion taking place, an annualised recurrence rate for massive ashfalls of about 0.01 / year on average should be about the right order of the risk for clean-up planning or similar decision purposes, if the probabilities given above are realistic estimates. If, however, dome growth recommences, then the corresponding annual probability of a repeat event is likely to be of order 0.1 / year (which, crudely, is what the Montserrat experience over the last ten years indicates, as well). Further work could be undertaken to improve such estimates.

Explosions

80. For the explosion case, the same updated estimates for the probability of eruption restart can be used, and the arguments deployed in the September 2004 Technical Report (at paras 69-71) can be retained. Thus, on the basis of global pattern of eruptive activity resuming after a dome-building episode - and using the Montserrat 1997-2003 experience as a guide to explosive activity rates - there is, at the present time, an equivalent average annual probability of experiencing another explosion like that of 17 September 1997 of somewhere between 1-in-10 per year (given by the 1-year scenario), to 1-in-50 per year (from the 20-year scenario). If magma production at the surface resumes, these odds reduce, of course. In the absence of more detailed analysis, these provisional likelihoods may be considered appropriate for planning purposes

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[19], 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 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

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

models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[20].

A1.5 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.

A1.6 This appendix must be read as part of the whole Report.

[20] 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**:* 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**:* 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**:* 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**:* 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**:* 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**:* 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.