SCIENTIFIC AND HAZARDS ASSESSMENT OF THE SOUFRIERE HILLS VOLCANO MONTSERRAT

First Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Meeting held 5th – 7th May 2003 at the Montserrat Volcano Observatory, Montserrat

Part II: Technical Report

20 June 2003

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First Report of the Scientific Advisory Committee on Montserrat Volcanic Activity - Part II: Technical Report

Introduction

1. The Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity operates under the Office of Science and Technology (OST) Code of Practice for Scientific Advisory Committees, published by the UK Government Department of Trade and Industry. The Code recommends, among other things, that such committees document the scientific basis for their advice. Since the Code was published in December 2001 the Risk Assessment Panel that preceded the new committee has adopted this recommendation and has published pertinent technical information. The Montserrat SAC met for the first time at the Montserrat Volcano Observatory (MVO) between 5 – 7 May 2003, and a record of the meeting is provided in a two-part report: the principal findings[1] of the committee are given in a separate document: Part I – Main Report[2], while Part II, this document, focuses on the technical issues and analyses that were discussed and tabled at the meeting, or dealt with in subsequent work for the committee.

2. Those who attended the meeting were: Prof. R.S.J. Sparks (SAC - Chairman), Dr. W.P. Aspinall (SAC), Dr. P.N. Dunkley (MVO/SAC), Dr. M. Edmonds (MVO), Dr. J.-C. Komorowski (IPGP), Dr. J. Neuberg (SAC), L. Rodriguez (MVO), Dr. K.C. Rowley (SAC – present for part of the meeting), Dr. G. Thompson (MVO), Dr. R.I. Tilling (USGS), and Prof. G. Wadge (SAC – present for part of the

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[1] 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.

[2] Scientific and Hazards Assessment of the Soufrière Hills Volcano Montserrat. First Report of the Scientific Advisory Committee on Montserrat Volcanic Activity, 5 – 7 May 2003: Part I: Main Report, issued 20th June 2003.

meeting). Drs Tilling and Komorowski were present as independent observers. (See also Part I for information on affiliations, etc).

3. The technical information about the Soufrière Hills volcano and its eruption exists in a number of forms. Detailed scientific interpretations have been published in the peer-reviewed journals (e.g. Volume 25 of Geophysical Research Letters, 1998[3,4], and Memoir 21 of the Geological Society of London, 2002[5]). Much technical information appears in a series of Open File reports of the Montserrat Volcano Observatory (MVO). For the present assessment, MVO Open File Report 1/03 provides a detailed summary of the eruptive activity and monitoring results with special focus on the activity since November 1999. In such instances, the SAC Report itself does not enter into detail, but summarises key points and gives references to the available sources. Other kinds of technical information and analyses, that are not yet in the public domain, include new data, computer modelling results related to hazards assessment, discussions at the meeting and the assessment of probabilities as input to the quantitative risk assessment. In these cases, the documentation in this part of the Report is more detailed and provides transparency about the scientific approach and analysis methods.

4. In order to inform the SAC meeting as fully as possible, the MVO prepared an Open File Report 1/03 which synthesises factual information on the eruption. The Open File Report places emphasis on monitoring data and observations from the third phase of the eruption, that is, from November 1999 onwards. All members of the Committee received a copy prior to the meeting and this document formed the basis for much of the current assessment of the eruption.

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[3] Aspinall, W.P., L.L. Lynch, R.E.A. Robertson, K.C. Rowley, R.S.J. Sparks, B. Voight and S.R. Young. The Soufrière Hills Eruption, Montserrat, British West Indies: Introduction to Special Section, Part 1. Geophys. Res. Lett., Vol. 25, No. 18, pp. 3387; 1998.

[4] Young, S.R., B. Voight, K. Rowley, R.S.J. Sparks, R.E.A. Robertson, L.L. Lynch and W.P. Aspinall. The Soufrière Hills Eruption, Montserrat, British West Indies: Introduction to Special Section, Part 2. Geophys. Res. Lett., Vol. 25, No. 19, p. 3651; 1998

[5] Druitt, T.H. and B.P. Kokelaar (eds). *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**; 645pp; 2002.

Method of hazards and risk assessment

5. The assessment of volcanic risk on Montserrat involves three stages. In the first stage, the hazards posed by the volcano, the areas that hazardous processes might affect and the nature of the effects are identified. In the second stage, there is an assessment of the probabilities of hazardous phenomena affecting different places around the volcano. Finally, these probabilities and their associated uncertainties provide the information needed to carry out a quantitative risk assessment.

6. Volcanoes are complex natural systems and there are many different hazards and different processes that control hazardous processes. As far as is possible, assessments of the hazards, their probabilities and uncertainties are made using empirical information from the monitoring work and quantitative models of the physical processes. There is wide variation in the understanding of different volcanic processes, the extent to which they can be either modelled or observed, and the confidence that can be given to the interpretation of observations or results of models. In some cases, processes are well understood and there is large amount of empirical observations to validate the models and to assign uncertainties to modelling results. In other cases, there are large amounts of empirical data and observations to constrain assessments of hazards and estimation of probabilities even though the underlying processes are not yet well-understood and rigorous models do not yet exist. In yet other cases, the data are so sparse or so limited that understanding of either a theoretical or empirical nature is poor. In such cases, judgements still have to be made. Some generic limitations to this approach are outlined in Appendix 1.

7. The Committee uses as one of its tools for hazards assessment and estimation of probabilities the concept of Expert Opinion Elicitation (EOE), based on the

EXCALIBR method described by Cooke[6]. This method has found wide application in many safety critical situations (including the safety of engineered structures, nuclear facilities and aviation), where there are large uncertainties, and in many other situations involving ‘low-probability/high-consequence’ events. EOE provides a systematic approach to estimating probabilities of hazardous processes and for structuring scientific discussions. It helps avoid some of the biases that enter into scientific judgements from the influence of highly opinionated or charismatic individuals. EOE does not replace the primary methods of rigorous scientific analysis and application of well-validated models, but is adopted for the assessment work on Montserrat as a utility, and only used when appropriate. The support of EOE tends to be needed less as scientific knowledge and understanding of a particular problem advance, and this has been the case with respect to the Montserrat eruption in the time since the first risk assessment was undertaken in December 1997. However, even in cases where good quantitative models exist for hazards assessment, EOE can provide a valuable structured approach to assessing the uncertainties in parameters that feed into such models, and this is true for the risk simulations undertaken for Montserrat. One of the members of the SAC, an Earth Scientist with experience in modern risk assessment methods and in the application of the EXCALIBR method, acted as ‘facilitator’ to the meeting in applying the elicitation procedures.

Pyroclastic flow modelling

8. At the May 2003 meeting, a critical issue concerned the hazards due to pyroclastic flows from dome collapses entering into the lower part of the Belham Valley between Belham bridge and the sea at Old Road Bay. This area was occupied until the evacuation on 9th October 2002. For the September 2002 risk assessment, computer modelling of dome collapse pyroclastic flows was carried out by

[6] Cooke, R. M. *Experts in Uncertainty - opinion and subjective probability in science*. New York, Oxford University Press, 321pp, 1991.

Professor Barry Voight (Penn State University), details of which are contained in Appendix 6 of the September 2002 MVO Hazards and Risks report[7]. These models were based on an approach that has been well established in the scientific literature (Wadge et al.[8]).

9. The basic approach of the modelling is to take a digital elevation model of the volcano and to allow flows of known volume to move under gravity down the valleys. The movement of the flow is assumed to follow some friction law. Friction coefficients are calibrated by finding models which agree with the kinetic behaviour and known distribution of pyroclastic flow deposits; for example, the model in Wadge et al. was tested against the deposits of the 12 May 1996 pyroclastic flow and the model of Voight was calibrated against the 25 June 1997 flows. Assumptions also have to be made about the starting conditions of the flow. The models are based on an underlying physical theory for pyroclastic flows, but they are strongly empirical in that the modelling parameters are adjusted until the results fit closely to observed flow distributions and run-outs. From a hazards perspective such models are better than general models since they implicitly incorporate specific features of the Montserrat system through the calibration.

10. A number of caveats need to be considered with respect to the models. First, to reproduce the distribution of flows the frictional parameters have to be varied; that is, each flow that is used to calibrate the model gives somewhat different best-fit values. These differences reflect not only variation in the frictional parameters themselves, but also variations in the interactions with topography, variability and

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[7] Professor Voight provided the following statement about his model results: "The information I have provided is advisory for the use of the panel. It has been prepared honestly and in good faith, but has been done quickly, is based on numerous approximations, and the results may be flawed. Nothing in this document (the collection of the emails and attachments) shall be construed as representing an express or implied warranty or guarantee as to its fitness for purpose or suitability for use. I assume no responsibility or liability for any conclusions drawn by the risk panel, or for any decisions made by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided, nor do I accept liability to any third party in anyway whatsoever".

uncertainty in the volumes involved, and uncertainties in the evolution in time of collapses, which often involve multiple events. Second, there has not yet been a large enough flow down the Belham Valley in the current eruption, sufficiently energetic to reach beyond the bridge, so there is no case history that can be used to calibrate the run-out characteristics down the topography of that particular valley. Third, the models do not predict the distribution and dispersion of the associated surge clouds that are of considerable importance to the hazards assessment. The modelling simplifications suggest uncertainties of the order 30% in run-out length for a given volume, consistent with the uncertainty derived by inspecting correlation of flow volume against run-out length from empirical data (Calder et al.[9]).

11. There are detailed differences between the models of Wadge and Voight: they use different mathematical representations of the friction parameters and different initial conditions. Further, Voight's models are run on a topography modified by the current eruption whereas Wadge's models are on the pre-existing topography.

12. Professor Wadge presented to the meeting some further calculations that he had carried out since the publication of Wadge et al. These later calculations involved using all the observations on pyroclastic flow distributions from the eruption during 1996-98 to estimate best-fit frictional parameters by a Monte Carlo technique. He presented results of a 5 million cubic metre collapse directed down the Belham Valley and showed that this collapse had a high likelihood of reaching the sea. These results were similar to calculations presented in the September 2002 assessment by Professor Voight for a 3 million cubic metres collapse. Given the inherent uncertainties, the agreement between the two independent models was considered very encouraging and was thought to provide good evidence that

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[8] Wadge, G., Jackson, P., Bower, S.M., Woods, A.W., Calder, E. Computer simulations of pyroclastic flows from dome collapse. Geohys. Res. Lett., **25**, 3677-3680, 1998

[9] Calder, E.S., Cole, P.D., Dade, W.B., Druitt, T.H., Hoblitt, R.P., Huppert, H.E., Ritchie, L., Sparks, R.S.J. and Young, S.R. Mobility of pyroclastic flows and surges at the Soufriere Hills Volcano, Montserrat. Geophysical Research Letters **26**, 537-540, 1999.

collapses of 3 million cubic metres or above would reach the lower Belham Valley, beyond Belham bridge.

13. There are, as yet, no reliable quantitative models for how surge clouds are generated and dispersed from dome collapse pyroclastic flows. Thus estimating the extent of spread of surge clouds around the edge of pyroclastic flows has to be based on observations from previous events. For collapses in the 3 to 10 million cubic metres volume range, the flows themselves have lost all kinetic energy by the time they reach their final run-out distance, but in the last kilometre or so speeds in the range 5-20 m/s are still possible. In these conditions, the associated surge clouds spread out a few hundred metres in unconfined settings, and singe to heights of a few tens of metres in confined areas. Such observations are the basis for placing a hazard line at 100 metres above the floor of the lower Belham Valley for these particular hazards (see also Part I of this Report).

14. There have been some significant topographic changes on the dome and upper slopes of the volcano during the eruption that affect the conditions for collapse into the Belham Valley catchment area and increase the hazard in that valley. Mosquito Ghaut, which used to divert pyroclastic flows to the northeast as in the example on 25 June 1997, has been completely filled with pyroclastic flow deposits so that it no longer cuts and partitions the Farrells Plain. A contemporary collapse to the north, similar to that on 25 June 1997, would be expected to spread across the plain and a significant proportion of such a flow would now be diverted into the Belham catchment area. Rainfall and erosion by some recent small pyroclastic flows have widened and deepened Tyre's Ghaut, increasing its capacity to entrain future pyroclastic flows. Since the last assessment in September 2002, growth of the dome to the north has advanced over and buried minor topographic features, which have tended to divert small northward direct collapses to the northeast in the past. The net effect of these changes is that a sector of the dome of about 30^{o} sits directly above the slopes of the volcano that lead into Belham valley.

Longevity of eruption and nature of magma system

15. In Part I of this Report (paras 30-32), the longevity of the eruption is considered. Here, a brief synopsis of the recent observational evidence from Montserrat which informs that discussion is provided. The basis for characterising the fundamental statistical properties of dome-building eruption durations was originally presented in Appendix 7 of the March 2002 MVO Hazards and Risks Assessment Report, and that analysis is updated for Montserrat at the present time in Part I.

16. There is a good correlation between extrusion rate and ground deformation (see MVO Open File Report 1/03). When the dome extrusion rate is close to its long-term average of about 2-3 m^3/s the Harris-South Soufrière deformation line contracts and there is subsidence. Contraction of about 1.4 mm/month was measured early in the second phase of the eruption, and more rapid contraction of around 1.9 mm/month during 2001, most of 2002 and early 2003. During periods when dome growth stops or stagnates the Harris – South Soufrière deformation line expands at around 1.7 mm/month and the ground uplifts.

17. These deformation data are consistent with the hypothesis that a magma chamber is continually being pressurised by a source of new magma. Two possibilities for the pressurisation process have been postulated. One is the exsolution and expansion of volcanic gas in the chamber due to crystallization, and the other is influx of new magma from greater depths in the Earth. The latter hypothesis is favoured on the basis of volcanic gas data and petrological observations. The fluxes of SO_2 throughout the eruption are much higher than the expected fluxes of this gas due to an origin from the andesite magma (Edmonds et al.[10]). Thus the currently favoured interpretation is that basaltic magma is being supplied from greater depths into a

shallow chamber at depths of 5 to 6 km. This hypothesis is also consistent with petrological observations that the magma has been recently reheated (Murphy et al., 2000[11]; Couch et al.[12]) and observations of magmatic basaltic inclusions in the andesite (Murphy et al., 1998[13]).

18. There are well-established models for magma chamber behaviour which predict that a chamber being emptied without recharge will have a continuous decrease in internal pressure and extrusion rate with time. A chamber being recharged will not decline in extrusion rate with time, and will inflate (pressurise) in periods of non-extrusion; this is the behaviour observed on Montserrat. The measurements of ground deformation are most easily reconciled with a recharge rate that is approximately half of the time-averaged extrusion rate. Given that the recharge appears to have been approximately constant over most of the eruption (see Fig. 1 in Part I), it seems unlikely that the recharge will suddenly stop and the eruption of magma at the surface cease.

19. Thus the eruption is much more likely on the basis of this analysis to continue in a near steady state or show only a very slow decline over many years or possibly decades. For known dome-building events in the global database, this mode of increasingly-prolonged eruptive behaviour is exhibited in cases which persist episodically or continuously for 5 years or more, to which class the current Montserrat eruption now belongs.

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[10] Edmonds, M., D. Pyle and C. Oppenheimer. A model for degassing at the Soufriere Hills Volcano, Montserrat, West Indies, based on geochemical data. Earth and Planetary Science Letters **186**(2): 159-173; 2001.

[11] Murphy, M.D., Sparks, R.S.J., Barclay, J., Carroll, M.R. and Brewer, T.S. Remobilisation origin for andesite magma by intrusion of mafic magma at the Soufriere Hills Volcano, Montserrat, W.I., a trigger for renewed eruption. Journal of Petrology, **41**, 21-42, 2000.

[12] Couch, S., Sparks, R. S. J. and Carroll, M.R. Mineral disequilibrium in lavas explained by convective self-mixing in open magma chambers. Nature **411**: 1037-1039, 2001.

[13] Murphy, M.D., Sparks, R.S.J., Barclay, J., Carroll, M.R., Lejeune, A.M., Brewer, T.S., MacDonald, R. and Black, S. The role of magma mixing in triggering the current eruption of the Soufriere Hills Volcano, Montserrat. Geophysical Research Letters **25**, 3433-3436, 1998

Assessment of volcanic hazards - generic scientific issues

20. Discussions of the Scientific Advisory Committee took place at MVO on 7 May 2003 to assess information and exchange views on the probabilities of various volcanic phenomena relevant to risks from pyroclastic flows. Those present for this part of the discussion were R.S.J. Sparks, W.P. Aspinall, P.N. Dunkley, M. Edmonds, J.-C. Komorowski, J. Neuberg, L. Rodriguez, G. Thompson and R.I. Tilling. Drs Tilling and Komorowski were present as independent observers, and participated in the scientific discussions and in the subsequent scientific elicitation. Prof. G. Wadge and Dr. K.C. Rowley, who were absent from the meeting on this day, were sent a transcript of the scientific information and discussions, and provided their values for elicited variables independently. (Had their values differed significantly from the other panel members then it was agreed that a further round-robin discussion would have to take place by email - however, this proved not to be necessary). The notes on individual hazard scenarios, that are presented later, are preceded by a discussion of the generic factors that contribute to, or control dome collapse; these include details on the background observational evidence that is needed for evaluating volumes and directions of collapse for hazard and risk assessment purposes.

21. On Montserrat, two principal modes of dome collapse have been recognised. The first mode occurs predominantly in the direction of lava dome growth, with the dome typically forming well-defined shear lobes (Watts et al.[14]). Occasionally, collapses initiate off the side of a shear lobe, but most commonly they are frontal failures, in the direction of axial growth. Such collapses develop on the upper parts of the dome and progressively affect deeper parts of the dome in large collapses as they work their way downwards. The directions of shear lobe extrusion can be on

[14] Watts, R.B, R.A. Herd, R.S.J. Sparks and S.R. Young. Growth patterns and emplacement of the andesitic lava dome at the Soufrière Hills volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 115-152, 2002.

any bearing, but do not appear to be completely random: a new lobe will commonly form in some direction away from that of a previous, stagnated lobe, the latter forming a barrier. Also, there have been relatively few collapses to the W, suggesting that Chance's Peak and Gage's Mountain thus far have acted as ramparts that inhibit growth in these directions (see Fig. 1). The second collapse mechanism involves the effects of intense rainfall on the dome (Matthews et al.[15]). Observations of the slow build-up of such rain-induced collapses and interpretations of concurrent seismological evidence support an argument for a process of erosion of the talus slopes near the base of the dome, which can retrogressively undermine material and work backwards and upwards into the dome. The major collapses related to rain have involved exceptionally intense rainfall; both the collapses of 20th March 2000 and 29th July 2001 involved rainfall with peak intensities probably exceeding 60 mm/hr.

22. In addition to these two modes of collapse, another important factor in considering the potential size of dome collapses is the volume of available material: clearly, collapses in any given scenario cannot be larger than the volume available. In the MVO Hazards and Risks Assessment 2nd Addendum report of January 2003, some approximate estimates of available volumes were given, based on the configuration of the dome on 18 December 2002. Since then, there has been substantial growth, so the volume estimates have had to be updated.

23. With respect to collapses to the N and NW, the volume of active dome above 930 m elevation has been re-calculated as 14 million m^3, compared with an estimate of 8 – 9 million m^3 on 18 December 2002. This volume of material is freely available for collapse and sits up to 160m above the Central and NW Buttresses (both at ~930 m asl), which, structurally, might provide some restraining influence on development of deeper collapses (but see below). The volume of material that is available were a collapse to develop at 800 m asl (taken to be the height of

[15] Matthews, A. J., Barclay, J. et al. Rainfall-induced volcanic activity on Montserrat. Geophys. Res. Lett., **29**(13): 1644, 2002

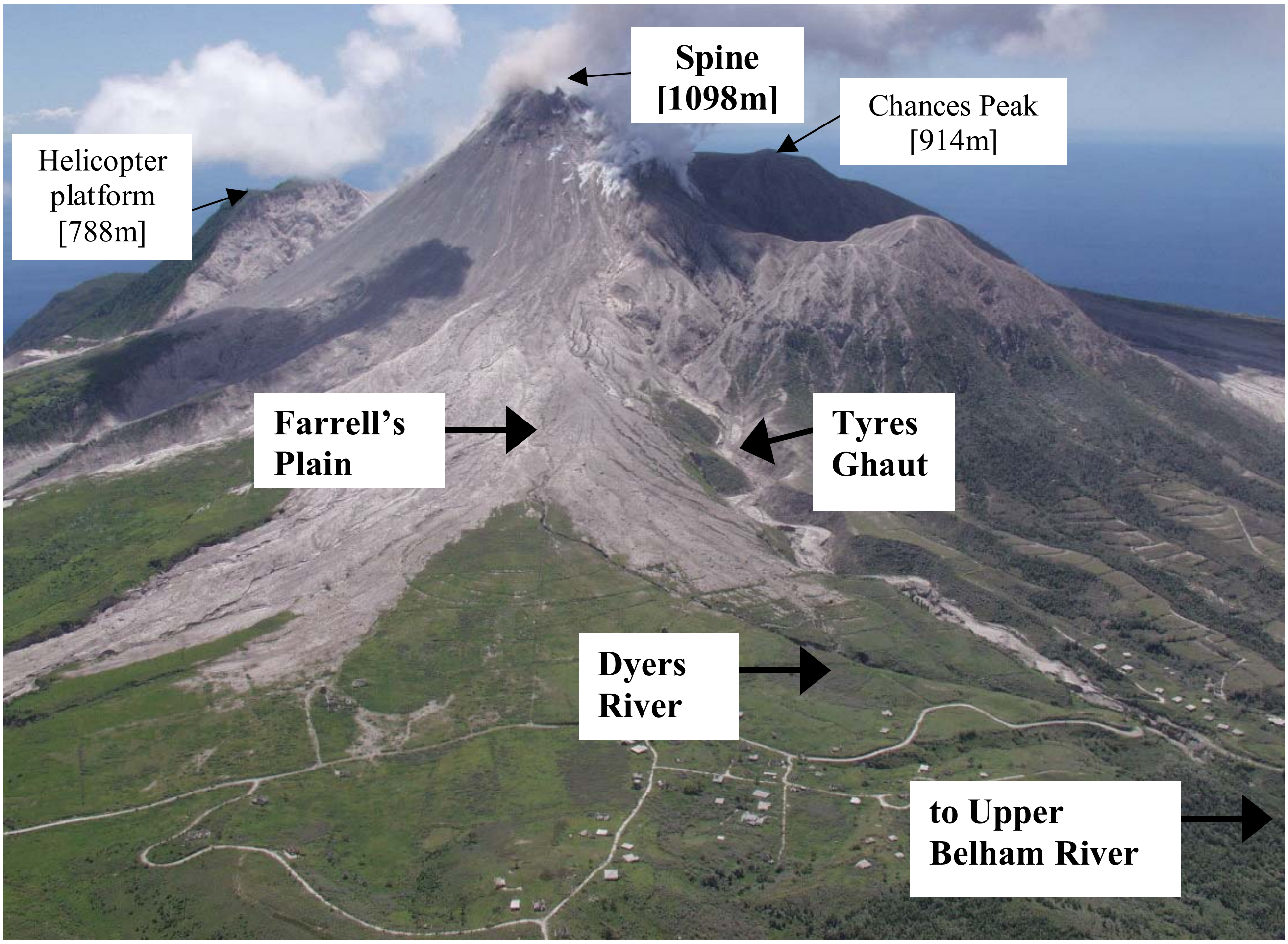

Figure 1 View of north flanks of Soufrière Hills volcano - May 2003, showing features mentioned in text, and heights asl (photo courtesy MVO)

English's Crater rim on the northern flanks directly below the Central Buttress) is now estimated at 35– 45 million m^3, compared with 25 – 35 million m^3 in December. In this later calculation the maximum estimated available volume is assumed to be between one half and two-thirds of the total dome volume above the 800 m elevation based on the proportions of the dome that collapsed in previous large events.

24. A critical issue in considering large volume collapses to the N (i.e., 30 million m^3) is the stability of the now-buried Central Buttress. Although this element has been present since October 1997, and apparently stable, it has been and continues to be the locus of vigorous fumarolic activity (see Fig. 1, just below and to left of label

for 'spine'). This buttress was also emplaced on the gently-sloping crater floor formed by the series of vulcanian explosions in October 1997. Therefore, the committee is increasingly concerned about the possibility of hydrothermal weakening of this 1997 dome remnant and its consequent failure, but recognises the difficulties involved in making a quantitative evaluation of probabilities associated with this particular question.

25. One other factor to be considered in respect of dome collapse pyroclastic flows is the increase in their initial potential energy due to the increase in the height of the dome. For example, since 25 June 1997 the dome has increased in height by 140 m, and the top now stands well above 1000m above sea level, see Fig. 1. A collapse involving the first mechanism, outlined above, sourced high up on the active dome may have significantly more energy and have a greater run-out than a flow of equivalent volume in 1997. While this effect would be amenable to quantitative modelling, such results and guidance were not available to the meeting.

Elicitation of probabilities for specific hazard scenarios

26. This part of the Report summarises the results of a formalised elicitation of the meeting's views on the probabilities of occurrence in the following six months of certain volcanic hazard 'class' events that are key inputs to the risk simulation modelling. Each class event depicts one type of hazard at a given magnitude or intensity, and a set of such scenarios, with distributional spreads to represent their associated uncertainties, is used to represent the continuum of hazards that can arise at the volcano. The range of different hazards that can be considered plausible or possible in the eruption of the Soufrière Hills volcano was originally defined at the December 1997 risk assessment meeting in Antigua[16]. Some scenarios were

[16] The report of the December 1997 Montserrat Volcano hazards and risks assessment was presented in two parts: the risk aspects were dealt with in the MVO Report 'Preliminary Assessment of Volcanic Risk on Montserrat', issued as a final draft version, 23 December 1997; the hazards were addressed in the MVO document 'Assessment of the Status of the Soufrière Hills Volcano, Montserrat and its Hazards', dated 18 December 1997.

subsequently revised or removed for the March 2002 MVO Hazards and Risk Assessment; details of those changes are given in Appendix 6 of that report. (In the paragraphs which follow, each scenario is given a numbered identifying label - e.g. DC = dome collapse; EX = explosion - and a probability or conditional probability label - such as an initiating event probability Pinit, or other conditional probability CP*n*, where the indexing *n* denotes directivity, trajectory, run-out distance, etc., given an event occurs).

27. Probability of a dome collapse 0.3x Ref volume (i.e. 3 million m^3) or greater, in the next 6 months [DC2 Pinit]. On the first day of their meeting, the participants had noted that the hurricane season was soon to start, prompting discussion of the role of intense rainfall in influencing large dome collapses. Intense rainfall had been associated with at least half the moderate and large collapses thus far in the third phase of the eruption, and certainly with three of the largest examples (20th March 2000; 29th July 2001; 2nd October 2002). As a rough approximation, it was suggested that days of intense rainfall were at least five times more frequent in the 'rainy' season than in the 'dry' season, based on rainfall data from Montserrat, Antigua and Guadeloupe. Given moderate-to-large collapses (0.3x Ref collapse ≡ 3 million m^3) were occurring at a rate of about once every six months, on average, the application of Bayes' Rule would suggest that the probability of rainfall-induced large collapse during the 'rainy' season is about double that in the 'dry' season (this accounts, in approximate terms, for the fact that, while there are many more intense rainfall days to trigger collapse, there are also more occasions when there is intense rain but NO collapse).

28. Carrying the discussion forward during the second day of the meeting, a simple recurrence-rate was calculated for 3 million m^3 collapse events, based on six dome collapses of that size or greater that had occurred in the three-and-a-half years since November 1999. Adjusting for the periods when the dome was too small for large collapses and was rebuilding from a previous collapse, and on the assumption that the timings of subsequent collapses would tend asymptotically to a Poisson arrival

process (in some suitable compound exponential manner), it is possible to calculate on this basis the probability of collapse in the next six-month period: an estimate of Pr = 37% was obtained informally, given the significant rebuilding period since the last major resetting collapse of 29 July 2001.

29. It was also reported that the next hurricane season is forecast to have 20% more tropical storms than the recent long-term average. Whilst the impact of this on intense rainfall probabilities, and hence rain-induced collapse probability, could be more formally estimated if need be, for immediate purposes it was suggested that the probability derived above should be multiplied by a factor of 1.2 as a improvised modification. This adjustment would yield a probability of 44% for a 0.3x Ref collapse in the next six months.

30. This preliminary value was thought by the meeting to be too low, bearing in mind recent events like 2 and 22 October 2002, and 8 December 2002, all of which involved approximately this volume or more, and may indicate an increasing rate of such collapses (the first two were associated with heavy rainfall). As the Pr = 44% estimate did not incorporate the temporary increase in probability of rainfall-induced collapse from a large dome that would be associated with the rainy season, which had been discussed earlier, this latter factor should also be considered when the probability was being elicited. The view of the committee was that an event of this magnitude, or greater, seems "quite likely" to happen in the forthcoming rainy season.

Outcome of elicitation:	*lower bound*	*best estimate*	*upper bound*
Prob:	**40%**	**70%**	**98%**

31. <u>Given a 3 million m^3 collapse or greater, the probability it will be directed NW (or N and drain into the Belham catchment from Farrell's Plain) [DC2 CP1]</u> There is now enough accumulated talus that it is plausible that a rainfall-induced collapse

could also occur on the NW or N slopes, if it is accepted that erosion of talus by intense rainfall is a mechanism capable of inducing dome collapse under favourable conditions, as proposed by MVO, and by Matthews et al. (2002). Such an event indeed occurred on 22 October 2002, but was directed NE into White's Ghaut by topographic controls that no longer exist. Given the relative sizes of the talus aprons that are now present, this is less likely to occur on the N-NW flanks than it is to the east, into Tar River, or to the northeast, but otherwise is judged more likely on this side of the volcano than elsewhere. For a non-rainfall-induced collapse, some account should be taken of the probability of a growth switch to the N or NW occurring in the next 6 months. There have been 6 switches in direction of dome growth in the past 12 months: i.e. one every 2 months on average. Of these, two have been a switch to the N or NW.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**2%**	**17%**	**34%**

32. Given a collapse of 3 million m^3 or more that enters the Belham catchment, the probability that this will reach the pre-October 2002 exclusion zone boundary [DC2 CP2] Given the modelling evidence from independent studies by Wadge and by Voight on run-out distances for collapse volumes of 3 million m^3, the group considered that this probability is quite high, especially in the light of the volume added to the dome in recent months. The added fall height gained by this extra dome material, which now sits as much as 160m above the 930m level, provides increased potential energy for a collapse, and the prospective run-out range is enhanced by topographic smoothing of the catchment area by material in-filling in the ravines and ghauts. It was suggested that it would be appropriate to increase the central probability value and raise the lower uncertainty boundary (the central value elicited in Sept 2002 was 60%).

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**45%**	**80%**	**96%**

33. <u>The probability of a 1x Ref collapse, i.e. 10 million m^3, or greater [DC3 Pinit]</u>
Based on the recent average return rate of events of this size during the third phase of the eruption, assuming a similar asymptotic Poisson process would describe arrivals, and multiplying by the 1.2*x* factor to account for the hurricane season forecast, as above, a preliminary probability of 37% in the next six months was estimated as a start-point for the discussion. If a stochastic relationship between event size and frequency holds (i.e. a natural power-law distribution describes the relative frequencies of large and small events), then this value appears rather high relative to the 0.3x Ref scenario, above, for the case of a power law exponent close to unity. For typical relationships in natural systems, an increase in 'size' by a factor of 3 times would normally be accompanied by a halving, or more, in the relative frequencies of occurrence.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	7**%**	**35%**	**76%**

34. The two collapses of this size or greater during the third phase of the eruption have all been much larger than 10 million (20 and 35 million respectively). The meeting felt there might be a tendency for the mix of dome collapses on Montserrat to be a combination of (a few) very large events and (many) small collapses, but not many events of this particular intermediate size. Although mechanisms that might produce such an effect can be conjectured, there is no scientific evidence available (empirical or otherwise) to support this idea in the present case, apart from the observation that, since March 2000, there have been no dome collapse events involving dome volumes of between 8 and 45 million m^3. This could simply reflect

the situation that the data available come from a time interval that has been too short to obtain a representative sample of collapse sizes for statistical purposes. (There were at least 4 events of this size or greater in the first phase of the eruption, 1996 – 97).

35. Given the 10 million m^3 collapse scenario, the probability it is directed NW into the Belham catchment [DC3b CP1] This probability is considered to be more likely than it was in previous risk assessments, as calculations show that an available volume of new material of around 14 million m^3 (above the central buttress height on the NW sector of the dome) could now be involved in such a collapse, which could plausibly be directed entirely into the Belham catchment. The current dome volume compares to an available volume of 8 - 9 million m^3 existing at the time of the risk assessment in September 2002. If the collapse direction is considered random over a total arc of 270º, which reflects the angular segment in which the dome has been active over the last 3.5 years, then the chances of a collapse in any 30º sector would be 1 in 9 (Pr = 11%), other things being equal. While such a collapse had no precedent in the N and NW directions, they have happened on other parts of the dome. The meeting considered the likelihood is probably higher than a simple geometric estimate would suggest because rainfall-induced events are now quite plausible and, if these are favoured on larger talus slopes then, while the E flank is still the most likely locus, the N flanks are now more likely than any other, alternative direction.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**2%**	**17%**	**35%**

36. Given a 10 million m^3 collapse, the joint probability that the collapse is directed N or NE, with 3 million m^3 or more of the material entering the Belham catchment [DC3c CP1] This scenario involves a double conditional probability and it was

thought helpful to assess the first and second probabilities separately, and then multiply them together to get the required value. The first value to elicit is the probability that, given a collapse of this size, it occurs to the N or NE. The second is the probability that a portion of the dome material, incorporated into pyroclastic flows and associated surges, will overflow into the Belham catchment with a material volume equivalent to 3 million m^3. This scenario is also deemed slightly more likely now than in September 2002, given that a sufficient volume exists on the north side of the dome, above the height of the central buttress. A 10 million m^3 collapse directed to the N will divide approximately equally on Farrell's Plain, in the absence of the topographic control previously exercised by Mosquito Ghaut. The photograph in Fig. 1, looking south at the northern flank, clearly illustrates this, with recent deposits indicating the position and influence of the drainage divide down Farrells Plain.

Outcome of elicitation:	*lower bound*	*best estimate*	*upper bound*
Prob:	**1%**	**16%**	**54%**

37. <u>Probability of a 1x ref blast (equivalent in energy flux to the 17 September 1996 explosion) to the NW, given a 10 million m^3 collapse [DC3d CP1]</u> This scenario was not considered for elicitation, as it was felt that this event was not associated with any significant probability. Previously it was given a central value of 1% probability of occurrence. It was noted that, in the past, collapses of this volume have been associated with increases in extrusion rate. During the second phase of dome building, this particular condition has been notably absent at times of collapses of this size. Even in the first phase of dome growth collapses of this size have not generated true volcanic blasts although they were associated with vigorous surge clouds (e.g. 25 June 1997).

38. The probability of a 3x ref collapse, i.e. 30 million m^3, or greater [DC4 Pinit] Based on average return times and the fact that the next 6 months includes much of the hurricane season (for which a factor of 1.2x is added as discussed above), a preliminary probability value of 31% was suggested as a basis for the elicitation. Again, this probability, when considered with DC2 Pinit and DC3 Pinit, does not reflect a typical stochastic relationship between collapse volume, regrowth time and repeat interval, but there is little empirical evidence to corroborate or disprove the implied recurrence behaviour. The three largest magnitude collapses have all been associated with exceptionally intense rain, and this has to be taken into consideration when assessing the probability of another collapse of this size in the next six months.

Outcome of elicitation:

	lower bound	*best estimate*	*upper bound*
Prob:	**6%**	**32%**	**69%**

39. Probability that given a 30 million m^3 dome collapse, it will be directed N [DC4b CP1] In principle, a 30 million m^3 collapse could occur in any direction; enough material is currently available on the dome (including older parts). However, to date only two sectors (Tar River, White River) have precedents of collapses on this scale. In respect of that sector of the dome which overlooks the NW, the dome's current configuration of the dome and its surrounding topography are such (Fig. 1) that it would be difficult to focus all the material in such a big avalanche from the active dome so that the entire volume can be captured by Tyre's Ghaut outlet - unless the collapse also involves older dome material. In this context, the meeting had concerns about the central buttress, which is now buried below the new dome and its talus. At present, the area of burial is one of strong fumarolic activity (see Fig. 1 just below label marked 'spine'); earlier, visual inspections of the central buttress had indicated that fumaroles were active on and around it, long before it was buried. The enhanced possibility of a failure of this buttress due to fumarolic

alteration is of concern: with about 40 million m^3 in place behind and above it, a 3x Ref collapse appeared possible, if the failure were sudden.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**0.2%**	**5%**	**25%**

40. <u>Given a 30 million m^3 dome collapse or more, the joint probability it is directed to N/NE and 3 million m^3 will be directed NW, into the Belham catchment [DC4c CP1]</u> This scenario also involves a double conditional probability. The first is the probability that the collapse will occur to the N or NE. This represents roughly a 90º sector of the dome. Other than the special case of the Boxing Day 1997 event, collapses of this size have a precedent only in Tar River, on the eastern side. The second is the probability that a tenth of the material will spill into Tyre's Ghaut. If the collapse is directed to the N, it was considered likely that a part of it will drain into the Belham catchment (the drainage divide on Farrell's plain will direct anything going directly N into Tyre's Ghaut or Dyer's River: see Fig. 1). If the collapse is directed NE, it is less likely that so much material will be directed into Tyre's Ghaut, as Tuitt's and White's Ghauts remain characterised by incised channels and are therefore expected to channel most of the material to the NE. These are the factors that the group considered when eliciting the conditional probability to attach to this scenario event.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**2%**	**21%**	**45%**

41. <u>Given a 30 million m^3 dome collapse, the joint probability it will be directed to N/NE AND 10 million m^3 will flow into the Belham catchment [DC4d CP1]</u> This scenario may be thought of as similar to the above, except as much as one-third (rather than one-tenth) of the collapse volume enters Tyre's Ghaut and hence into the Belham catchment. The same arguments as above apply to the first part of this double conditional probability elicitation. For the second part, the scenario of a larger proportion of the dome collapse volume directed into Tyre's Ghaut should be considered. It is considered probable that a collapse directed due north could divide in these proportions, given the position of the drainage divide, but slightly less likely than the scenario described in the above section.

Outcome of elicitation:	*lower bound*	*best estimate*	*upper bound*
Prob:	**0.4%**	**16%**	**37%**

42. <u>Given a 30 million m^3 dome collapse, the joint probability it will occur through Gages outlet AND 3 million m^3 will flow round into the Belham catchment [DC4e CP1]</u> This scenario involves a major failure of Gage's Wall, which is now being overtopped by talus. The path of a major collapse of this kind would be directed by the Gage's Valley walls directly towards St George's Hill (as has happened in the past), and whilst this would disrupt the momentum of the flow, a major proportion would be channelled round St Georges Hill on its north side, into the upper Belham Valley between Lee's and Molyneux.

Outome of elicitation:	*lower bound*	*best estimate*	*upper bound*
Prob:	**0.2%**	**7%**	**30%**

43. Probability of a 30 million m^3 dome collapse with a directed blast (of the order of 26 Dec 1997) to the NW [DC4f CP1] This scenario was given a central value of 0.6% during the September 2002 risk assessment. Such an event has occurred before, associated with a dome collapse of approx. 45 million m^3 during the Boxing Day sector collapse. The second phase of dome growth appears to be associated with less pressurisation at shallow levels in the interior of the dome. Evidence for this includes the lack of major explosive activity following large dome collapses and the absence of a directed blast in the large collapses of 20 March 2000 and 29 July 2001. Such an event appears to be less likely now than in the first phase of dome growth, when extrusion rates were generally higher and more variable. While it was noted that there was no volcanic blast component associated with the pyroclastic flows in the 29 July 2001 dome collapse episode (athough some surge clouds spilled out of the Tar River Valley into Long Ground, about 1 km away), there were two vulcanian explosions, each of which coincided with the two peaks in energy of the collapse activity, respectively. The possibility of the extrusion rate increasing markedly in the next six months, resulting in an elevation of shallow level pressurisation and a return to the conditions of 1997, should be assessed when considering this scenario.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**<0.01%**	**0.7%**	**14%**

44. Probability of a 10x ref dome collapse (100 million m^3) or greater [DC5 Pinit] This event is certainly possible and for the first time it is suggested that a not insignificant probability be attached to this scenario, as the total dome volume now exceeds 200 million m^3. The Boxing Day event in 1997 involved at least one-third of the total dome volume, and other big collapses have removed as much as 60% of the dome. Such a scenario would involve half of the present total dome volume, a good proportion of which is talus and older dome remnants. A dome collapse of

this magnitude would be unprecedented in historic times at Soufrière Hills volcano, and possibly during dome eruptions anywhere in the world in recent years. The central value of the probability elicited during the September 2002 risk assessment was 0.02%, and the meeting felt this now seems "a little too low", given substantial dome growth since then. It should be re-elicited. This event may fall outside of the region of a linear stochastic relationship between return times and dome collapse volume: the probability of occurrence inferred from return rates of occurrence would appear to be as high as one-third of the probability of a 30 million m^3 dome collapse, and this seems a little too high in relative terms at least. The meeting noted that a collapse volume cannot exceed that of the dome itself (if no older material were implicated) and that any power-law relationship between collapse volume and recurrence rate must fall away from a straight-line relationship for volumes approaching this maximum. It was suggested that the probability of this event occurring in the next 6 months may be within the bounds of 0.1-10%. In six months time, at the current rate of dome growth, the dome volume could reach 240 million m^3, so the plausibility of such an event would increase[17].

Outcome of elicitation:	*lower bound*	*best estimate*	*upper bound*
Prob:	**0.01%**	**1%**	**12%**

45. <u>Given a 100 million m^3 dome collapse, 3 million m^3 will be directed to the NW, into the Belham catchment [DC5c CP1]</u> It was considered likely that this event can only be focussed on the east, as on the north it would have to involve a major failure of Farrell's Wall. This is also corroborated by recent large collapses (although not as large as this) that occurred on the eastern side of the dome. The central question appeared to be "how likely is it that such a giant collapse will be focussed in one direction?" The possibility of explosive activity during this event

[17] *The issue of tsunami hazards associated with such a major collapse is noted in Part I – Main Report, where it is identified as a topic requiring further discussion.*

was thought more likely than in smaller collapses, thus increasing the consequent possibility of a portion of the collapse being directed to the NW, from column collapse flows and the disruption and collapse of peripheral talus during explosive activity. The probability of material spilling into the Belham catchment should therefore be slightly higher than the values elicited for DC4c CP1. Previous, smaller events have involved coincident pyroclastic flows in more than one direction, e.g. November 1998, but this involved a much smaller volume and occurred during a time of zero lava extrusion. All of the largest dome collapses appear to have occurred in one direction only. On 29 July 2001, a very small pyroclastic flow deposit was observed in Gage's after the event, but all other flows appear to have occurred in the Tar River Valley.

Outcome of elicitation:			
	lower bound	*best estimate*	*upper bound*
Prob:	**0.01%**	**4%**	**19%**

46. Given a 100 million m^3 dome collapse, the joint probability it is focussed towards the N with (i) 3 million m^3 and (ii) 10 million m^3 being directed into the Belham catchment [DC5d CP1] These scenarios were considered to have a negligible probability of occurrence, owing to the fact that a 100 million m^3 collapse cannot be sourced from the northern portion of the active dome, without eating back to the southern side and/or failing the Farrell's Wall. This has no precedent, and would require the unlikely formation of a deep, U-shaped listric (scoop-like) failure plane that would remove both the existing talus and dome material, the gently-angled older lobe material in the Central Buttress, and a substantial part of Farrell's Wall and the outer slopes to the N. The latter actually provide stability to the Farrell's Wall locality, contrary to the earlier situation with Galway's Wall, which was a near-vertical free-standing wall with a large dome pushing it outwards from above and behind. This type of failure mechanism appears to occur preferentially on the eastern side. Indeed, this is the side of the volcano where the most pronounced

asymmetry in the E-W topographic profile of the mountain exists, and where there is a lack of any large, buttressing structure such as the Chance's Peak and Gages domes. It is also down the axis of the Tar River valley that previous large-scale edifice collapses have occurred in the last few thousands years, and as recently as about 4000 years ago (Young et al.[18], 2002, Le Friant et al., submitted). Also, this direction is aligned with the general structural trend of the Soufrière Hills massif (tilted Roche's Bluff, alignment of hydrothermal areas, tilted blocks of George's Hill and Garibaldi Hill).

Quantitative risk assessment results

47. This part of the assessment revises earlier calculations of volcanic risk by making adjustments to quantitative risk estimates, based on the committee's reappraisal of the probabilities of the various threats. The risk levels are mainly expressed as potential loss-of-life estimates and as annualised individual risk exposures, and generally do not include allowance for any reduction in risk 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 suitably conservative estimates for policy-making purposes. The approach and methodology follows that described in the December 1997 MVO Hazards and Risk Assessment report, validated by the UK Government's Chief Scientific Adviser's consultative group.

48. Estimates of the potential numbers of persons that might be injured by volcanic action are not included. For emergency planning purposes, medical and volcano emergency specialists can infer casualty numbers from the probable loss-of-life estimates. As in previous assessments, updating of the forecast of future volcanic

[18] Young, S.R., Voight, B., et al. Hazard implications of small-scale edifice instability and sector collapse: a case history from Soufrière Hills volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 349-362, 2002.

activity levels has been restricted to the next six months only. (The long-term outlook has been considered in Part I of this Report, and at paras. 15 – 19, above).

49. The population zones that have been used consistently throughout recent risk assessment updates for Montserrat are shown on Fig. 2. The Day Time Entry Zone (DTEZ), although officially unoccupied, is retained in the assessment (as Zone 6) in order to estimate individual risk exposures for authorized entrants. Zone 5 and parts of Zones 4 and 3a are also now unoccupied, following the evacuation of 9th October 2002. When specific issues of risk exposure arise in the present assessment in respect of these areas, suitable adjustments to the population numbers in the latter two zones are made in the model.

50. The assumed total population on Montserrat is taken currently to be about 4,775 persons. This number is unchanged from the last assessment, but, when necessary, the numbers of people in Zones 4 and 3a, and the geographical distribution of population numbers from south to north in the remaining occupied areas have been modified slightly to reflect the extended Exclusion Zone.

51. As mentioned in paragraphs 15 - 19 above, analysis of historical dome-building eruptions elsewhere provides a basis for quantifying the statistical likelihood of the duration of the present eruption. Taking the findings reported in Appendix 7 of the March 2002 assessment as indicative, the possibility of a final cessation of the magmatic eruption within the next six months has a probability of 3%; in other words, there is considered to be a *1 in 33* chance that magmatic activity will cease within the next six months. The committee accepted this estimate for the purposes of calculating risk estimates.

52. The committee, having reviewed all the hazard scenarios that comprise the model for simulating volcanic threats to the population (see Appendix 6 of the March 2002 MVO Hazards and Risks Assessment Report), re-assessed the relevant probabilities of occurrence of the key initiating events, as recorded above (paras 26

- 46). In particular, the probabilities relating to the occurrence of and extent to which pyroclastic flows and surges in the Belham Valley could impact nearby populations were re-evaluated in detail (see paras 31; 32; 35-37; 40-43; 45; 46), and the risk model adjusted accordingly.

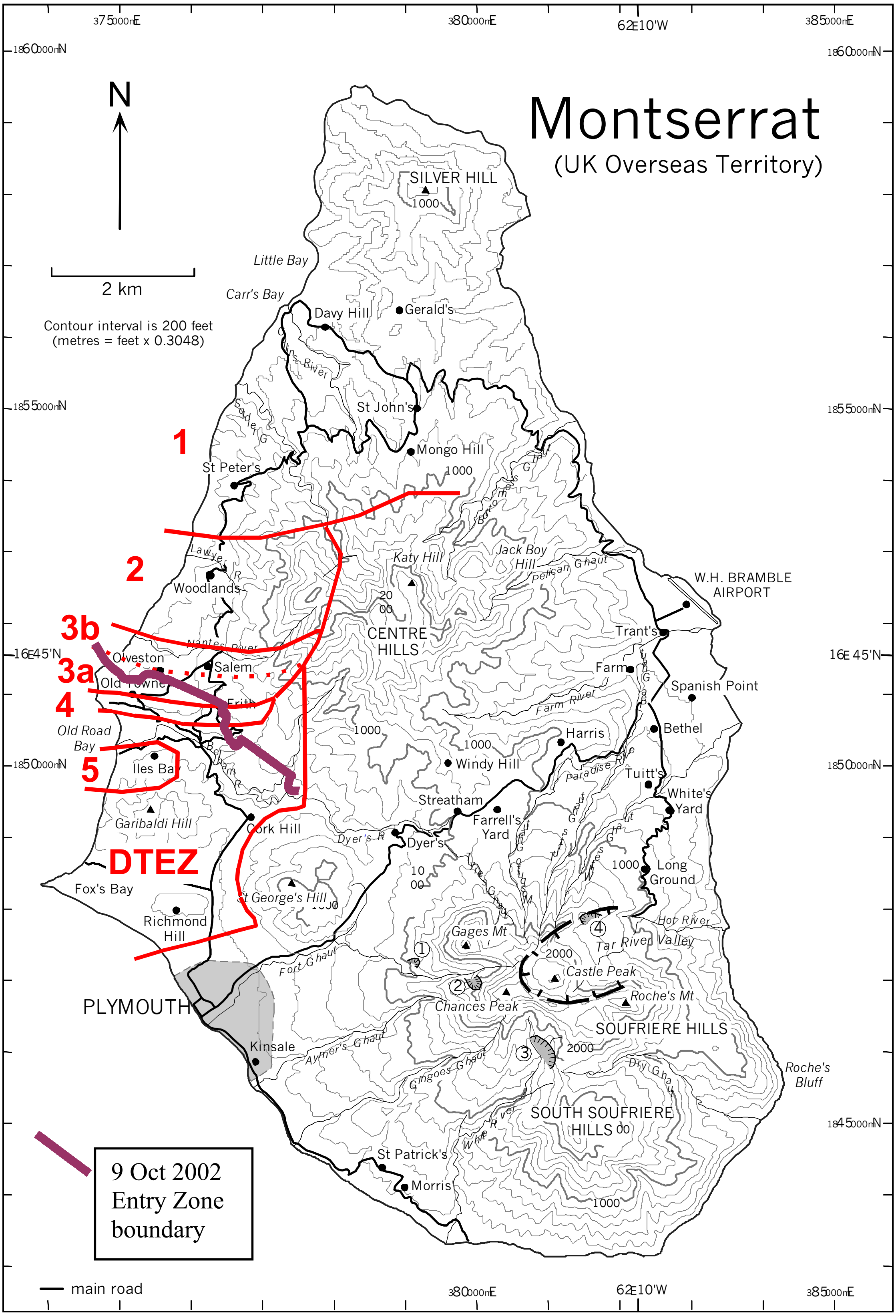

Fig. 2 Montserrat: population zones used for risk assessments, showing approximate position of the 9 October 2002 administrative Entry Zone boundary in relation to Zones 4 and 3a (see text)

Societal risk levels

53. The resulting risk model generates estimates of potential loss-of-life estimates for the population living in areas outside the Exclusion Zone (and for restricted, temporary visits to the current 0900-1400hrs Entry Zone), and these are summarized on Table 1, together with corresponding results from two preceding assessments. The third row results in bold type on Table 1, for May 2003, are thus the latest updated *societal risk* estimates for the whole population of the island, while the bottom row shows the contribution of the occupied area between the present Exclusion Zone and Nantes River to that overall risk.

Assessment	**N ≥ 1**	**N ≥ 5**	**N ≥ 10**	**N ≥ 50**
September 2002	0.12	0.07	0.037	9×10^{-4}
January 2003	0.23	0.083	4.9×10^{-3}	1.1×10^{-4}
May 2003 (+1σ level)	**0.18 (0.26)**	**0.12 (0.18)**	**0.04 (0.07)**	$\mathbf{1.2 \times 10^{-3}}$ $\mathbf{(2.1 \times 10^{-3})}$
May 2003 Zones 3a(part) & 3b only	0.17	0.09	0.03	1.0×10^{-3}

Table 1: ***Societal risk: probability of N or more fatalities in the next six months, compared with previous assessments.***

54. The overall societal risk is also shown graphically in Fig. 3 as a probability-exceedance curve, together with the spread on this curve which corresponds to the +1σ level of scientific uncertainty in scenario probability estimates. Also shown are the risk curves that would be obtained if the Exclusion Zone were extended to north of Salem, and to north of Nantes River. For comparative purposes, population risk curves for two other, long-term natural hazards in Montserrat, hurricanes and earthquakes, are included on the plot (based on provisional analyses by Dr. Aspinall).

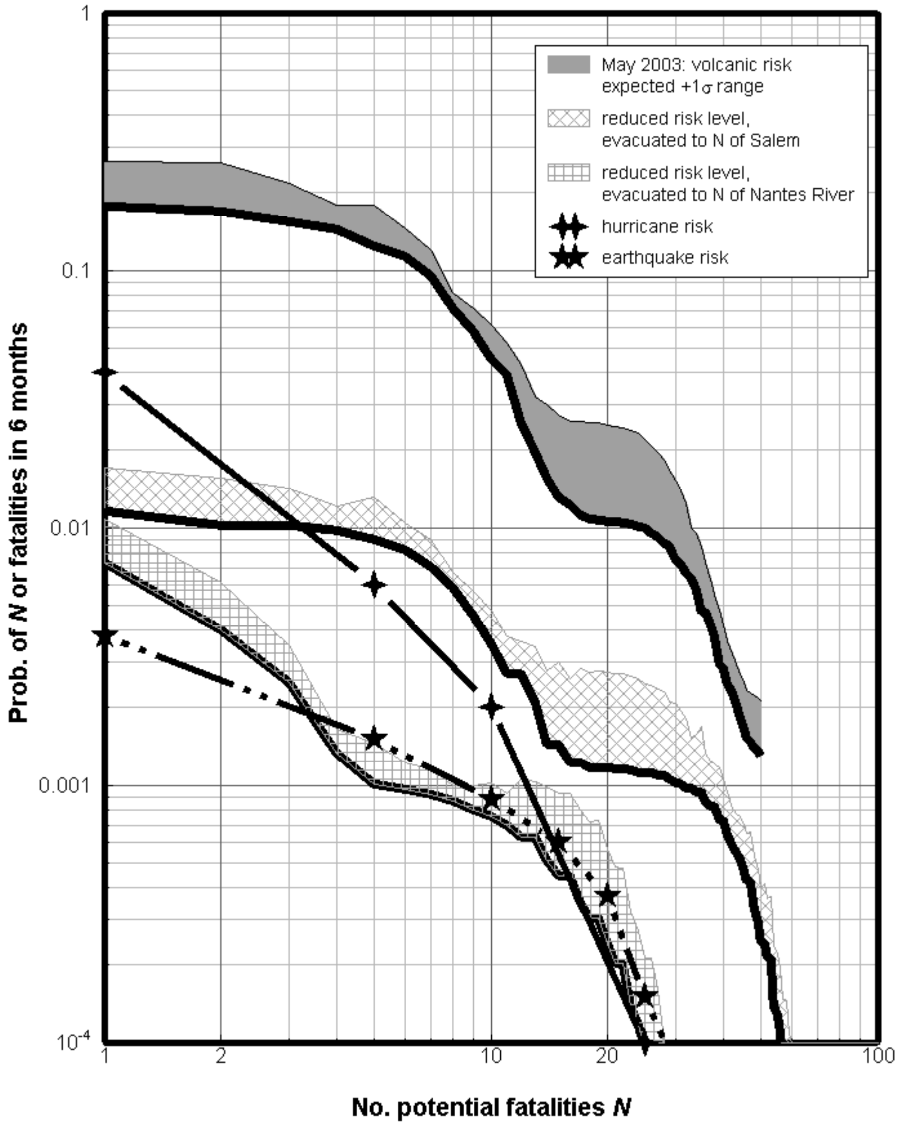

Fig. 3 Expected and +1σ range societal risk curves for: a] present situation; b] evacuation to N of Salem; c] evacuation to N of Nantes River. (Long-term hurricane and earthquake risk estimates for Montserrat given for comparison).

55. This analysis indicates that under present conditions there is a chance of about 18% (about 1 in 6) for one or more fatalities from volcanic activity on Montserrat in the next six months, with a corresponding likelihood of 82% that there will be no fatalities. The chances of suffering five or more fatalities (*i.e.* so-called "mass"

casualties, as defined by medical considerations) in the same period are now assessed to be about 9% in the next six months.

56. The risk of a massive number of casualties (e.g. 50 or more) is now assessed somewhat higher than previously, however. The main reason for this change in balance in societal risk levels is that the present hazard elicitation has taken into account the most recent behaviour patterns of the volcano, slightly reducing the expected frequency of occurrence of some of the classes of 'small' hazards and, hence, the corresponding chances of these just affecting the populated areas. But this assessment has also recognised that, with an ever-larger dome, a long elapsed time since the last major collapse, and an on-coming rainy season, the chances are now marginally elevated of experiencing one of the events which might generate much bigger pyroclastic flows or even lateral blasts. Flows and blasts of such size have the capacity to affect wider areas, further away from the volcano, and hence impact larger numbers of people.

57. While the calculated societal risk levels results are not greatly changed from those estimated in January 2003 (and small differences fall within the uncertainties associated with such simulations), the risk of suffering some casualties is raised a little, overall, and a clearly sustained increase over the assessment made in September 2002.

58. The simulation models used are designed to produce conservative estimates for potential casualty figures, and these can be taken as upper bounds for the true risk exposure. As noted in earlier assessment reports, the overall societal risk from volcanic activity is strongly dependent upon which areas are populated at the time of any activity. Moving north from the Belham Valley, there is a decline of risk to residents. If, at any time, it were required to reduce total overall societal exposure, this could be achieved by sequential evacuation of areas bordering the Exclusion Zone. Early warning and other mitigation steps would also reduce exposure.

Individual risk exposure estimates

59. 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. A summary of some key results is given in Table 2, where 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 for details of the CMO's scale).

60. For an individual living north of Lawyer's Mountain (Area 1 on Fig. 2) the risk of death by eruptive activity is classified as *NEGLIGIBLE* under the CMO's scale. For the Woodlands area (Area 2: *i.e.* north of Nantes River) the risk estimate is calculated at between about a 1 in 240,000 chance and a 1 in 100,000 chance of being killed for a full-time resident, which places the level in the *MINIMAL,* bordering on the *VERY LOW* category on the CMO's scale (n.b. in the September 2002 Hazards and Risks Assessment Report, the individual risk for this area was labelled *NEGLIGIBLE* in text and on Table 2, when it should have been classified *MINIMAL* on the basis of the numerical risk estimate).

61. The exposure of people living full-time in the North Salem-Hope-Glebe areas (Area 3b on Fig. 2) is *VERY LOW* risk. For the Old Towne North/Upper Friths/Olveston/Lime Kiln Bay area (Area 3a), the risk is assessed *LOW*, bordering on *MODERATE* in the more southerly parts of this area. In the neighbouring areas to the south, along the northern slopes and ridge of the Belham Valley (*i.e.* Area 4: Lower Friths-Happy Hill-Old Towne South) people carry a *MODERATE* risk.

62. <u>Assessment of risk for the Belham Valley Exclusion Zone compared to the Jan/Sept assessments if the population were to return.</u> In quantitative terms the individual risk exposure in this area has increased to a 1 in 45 chance (best estimate) of being killed for a full-time resident, from a risk of 1 in 75 estimated in January 2003, i.e. increased by a factor of 1.6. The level of risk at the 84%ile level in the spread of

scientific uncertainty is evaluated at about 1 in 25, which makes this a very serious risk exposure if the Precautionary Principle is invoked to the corresponding degree. The level of hazard has risen due to the increasing size of the dome and potential for large collapses, and the individual risk exposure is HIGH in terms of the CMO's scale. If, however, the dome growth direction switches and is directed consistently to the north or northwest in the near future, this risk could become even greater.

63. Risk to those entering the E.Z. 0900-1400 hrs The individual risk for this situation (in which entry is allowed between the hours of 0900 and 1400 when conditions permit) is obtained straightforwardly by adjusting the risk obtained in the last paragraph *pro rata* for the number of hours spent in the area. Thus, someone spending 30 hours per week in the EZ will have an annualised equivalent risk exposure of between 1 in 440 (best estimate) and 1 in175 (at the 84%ile level in the spread of scientific uncertainty), or MODERATE on the CMO's scale. Again there is a significant numerical increase associated with the risk estimate when compared to the last assessment. (n.b. for the present assessment, the effects of existing mitigation measure were discounted for two reasons: first, a large collapse of the dome could happen with little warning and could take less than 3 minutes for a large flow to reach the sea at Old Road Bay - in these circumstances any mitigation measures are unlikely to be effective; and second, the incorporation of administrative mitigation measures into a risk assessment requires assumptions about how effective, timely and dependable such measures might be. The Committee did not feel it had enough information to make reliable assumptions for modelling the effectiveness of such measures).

64. Risk to E.Z. 0900-1400hrs with access extended to daylight hours. Again, the individual risk for this situation is obtained straightforwardly by adjusting the risk obtained before *pro rata* for the number of hours spent in the area. Thus, for someone spending most of the daylight hours (i.e. about 12 hours per day), six days per week, say, in this area, the numerical individual risk would work out at between about 1 in 185 (best estimate) and 1 in 74 (at 84%ile level) - i.e. the risk is close the boundary between MODERATE category and HIGH category.

65. Risk in Isles Bay. The risk in this area is evaluated as the same as the Belham Valley area evacuated on 9th October 2002, that is, HIGH for permanent occupation, and MODERATE for very limited short-term entries.

66. Risk in the old Day Time Entry Zone. For anyone who spends 4 hours per week or less in this zone, the individual risk exposure is numerically estimated by the simulation model at about 1 in 1750 or LOW (best estimate), to about 1 in 700 or MODERATE (at 84%ile level). The risk would be HIGH for anyone spending daylight hours (e.g. 10 hours per day), or more, in the DTEZ.

67. Risk (societal and individual) in the area from the EZ boundary to Nantes River. These areas sit adjacent to the Belham Valley and could become vulnerable to a very large collapse of the dome. The Committee considered whether the current hazard line needed adjustment at this stage and concluded that this was not necessary. However, if the dome increases in size over the coming months, at some point more modelling work will be needed to give reassurance that this area is not vulnerable to such collapses. More discussion of this issue appears in Part I – Main Report. At the moment, the individual risk exposure in this area is currently evaluated to fall in the MODERATE category, taking the area as a whole (individual risk would be less in the more northerly parts, and higher closer to the volcano, of course). Although it has not been general practice to estimate societal risk for sub-groups of the population in Montserrat, the current quantitative risk assessment indicates that this particular area contributes a very high proportion of the risk exposure for small numbers of casualties, and a significant amount (generally more than two-thirds) to the overall societal risk for the island in its entirety.

68. For all cases, there is a concomitant risk of injury (as opposed to fatality) that would involve significantly greater risk exposures in probability terms.

69. In considering this assessment, the authorities are reminded that scientific recognition of a change in the volcano to a much more dangerous condition may emerge only a matter of hours, or less, before the occurrence of a hazardous event.

Thus, although the arrangements for mitigation and evacuation of the populated areas around the Belham Valley area are not the responsibility of the scientific team, the advisory group emphasizes that the risk to people in these areas could change to *HIGH* at very short notice.

	NUMERICAL ANNUALISED INDIVIDUAL RISK EXPOSURES BY AREA (WITH EQUIVALENT CMO's RISK SCALE RANGE)				
Scenario	**Belham Valley Exclusion Area** Re-occupied	**Belham Valley Exclusion Area** Entry from 0900 – 1400 hrs	**Belham Valley Exclusion Area** Entry in daylight hrs	**Area 5** Iles Bay re-occupied	**Former Daytime Entry Zone** Entries more than 10 hrs/day [Entries less than 4 hrs /week*]
Current conditions	***HIGH*** ***1 in 45***	***MODERATE*** ***1 in 440***	***MODERATE*** ***1 in 180***	***HIGH*** ***1 in 45***	***HIGH*** *1 in 100* *[LOW to MOD.]** *1 in 1750*

Table 2 ***Estimated annualised individual risk (IRPA) of death by volcanic action in each identified area, with equivalent categories of risk on the CMO's Risk Scale.***

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 rapid 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[¶], 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

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

the converse, attempts to demonstrate agreement or failure between observations and predicted outcomes). The fact is that such validiation, 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[¶].

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.

[¶] 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.