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

Sixth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 27 – 29 March 2006 at the Montserrat Volcano Observatory, Montserrat

Part II: Technical Report

Issued on 26 April 2006

Contents

Introduction

1. This is the second part of the report resulting from the sixth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 27 to 29 March 2006. 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 02/06[3], which synthesises the monitoring data and observations collected by MVO between October 2005 and March 2006 and considers some of the new developments during the last six months. In addition we considered a number of short presentations and papers generated within the SAC membership on scientific and hazard analysis topics.

Activity since September 2005

3. The first two months of the current episode of dome extrusion that began in August 2005 was covered by the previous SAC(5) report[4]. Lava extrusion has continued since, giving the episode a current duration of over eight months, with no significant pauses. Dome growth prior to the end of October 2005 was constrained on the northeastern side by the transverse ridge remnant of old dome rock. At that time new lava began to overtop the ridge, completely burying it within one month. Up to mid-November the style of growth of the dome had been endogenous, with internal expansion, but this had changed at that time to an exogenous, shear lobe, style. A steep, east-dipping discontinuity within the

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[1] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Fifth report of the Scientific Advisory Committee on Montserrat Volcanic Activity, 26 – 28 September 2005: Part I, Main Report, issued 19 October 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 Committee members believe that they have acted honestly and in good faith, they accept no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can they accept any liability to any third party in any way whatsoever. See also Appendix 1.

[3] Bass, V., Christopher, T., Hards, V., Higgins, M., Loughlin, S., Luckett, R., Dunkley, P., Ryan, G.A., Strutt, M., Syers, T. Williams, D. and Williams, P. Report to the Scientific Advisory Committee Montserrat, March 2006. MVO Open File Report 02/06, 2006.

[4] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Fifth report of the Scientific Advisory Committee on Montserrat Volcanic Activity, 26 – 28 September 2005: Part I, Main Report, issued 19 October 2005.

growing dome was apparent during the following months as the style of growth alternated between endogenous and exogenous. This discontinuity may represent the expression of the buried transverse ridge.

4. In January 2006, particularly from the 11th, the style of extrusion changed to that of a flat-topped lava lobe flowing from west to east across the summit of the dome, accompanied by endogenous growth. On 7 February, following an episode of shallow volcano-tectonic earthquakes, rockfall seismicity and visual observations suggested that lava extrusion fell to very low levels. This was followed by a swarm of long-period earthquakes on 9 February involving a north-northeast oriented fissure from which steam and ash vented vigorously and noisily. This three-day period marked a distinct event that can be interpreted as fracture formation away from the conduit followed by groundwater heating by magma and eventually by increased lava flux. By 11 February lava had begun to effuse from the fissure, again from west to east at a high rate of growth that continued for nearly two weeks. The style of growth was that of the "pancake lobe" described by Watts et al.[5]. On its northern side this new lobe of lava banked up against the crater just below the rim and became visible for the first time during this episode from viewpoints to the north.

5. A spine began to grow on 26 February that appeared to have an unusually large diameter of about 50 m. This eventually leaned eastwards and collapsed. In past dome growth episodes the largest spine size has been estimated at about 30 m diameter[5]. If this 26 February measurement is reinforced with further similar observations, then this may mark a significant change in the volcano's behaviour. A wider spine implies a wider cylindrical conduit for the topmost few hundred metres and lower rates of rise of magma (by a factor of almost three) at equivalent flux. An implication of this is that gas exsolving from the magma has more time to escape and thence the likelihood of explosions is reduced. This may explain why there have been no explosions so far, despite high extrusion rates. Careful observations of future spines may help to test this supposition.

6. By 13 March the direction of extrusion had switched to the southeast and the danger of dome collapses into Gage's and Tyer's Ghauts was reduced. By the end of the period dome growth was continuing at a moderate rate with rockfalls and small pyroclastic flows into the Tar River Valley. However, it was noticeable that

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

these flows were weakly convective and had run-outs of no more than 2 km, less than the pyroclastic flows at equivalent times during the two earlier episodes of dome growth.

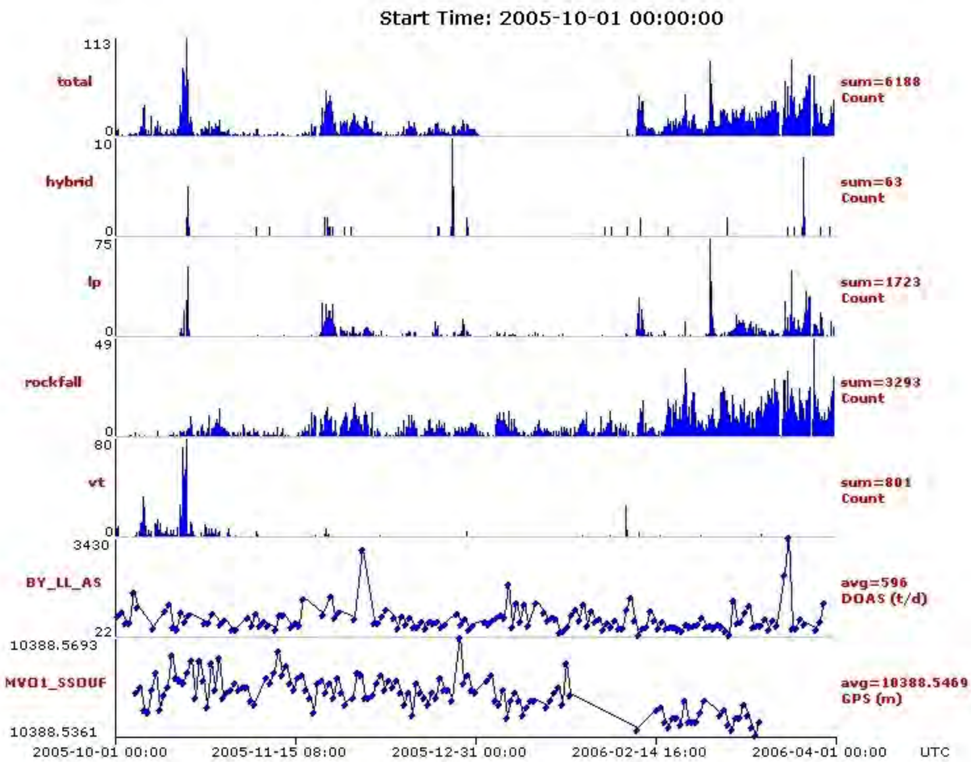

Fig.1 Integrated MVO monitoring data for October 2005 to March 2006. Variables plotted from top to bottom are: total daily counts of seismic events, hybrid seismic events, long period seismic events, rockfall seismic events, volcano-tectonic seismic events, daily sulphur dioxide emission rates, (tonnes/day), length of baseline between MVO1 and SOUF cGPS stations.

7. Seismicity over the last six months has been of low to moderate intensity (Fig.1). Compared to previous episodes of dome extrusion, volcano-tectonic earthquakes have been rare, similarly the number recorded as hybrids has been much less. The

two days of 18 and 19 October 2005 saw a period of increased seismic activity following a gradual reduction in peak energy release from 4-5 Hz to 2 Hz. Mid-October 2005 also saw a distinct increase in rockfall seismicity. For twenty-two hours prior to the vigorous venting of 10 February 2006, banded tremor occurred with intervals between bands of four hours. Seismicity increased on 18-19 October, 21-25 November, 25 December and 7 February, suggesting some periodic process. Whilst rockfall seismicity at Soufrière Hills can be good proxy for extrusion rate[6], the relationship is also highly dependent on the site of extrusion and the likelihood of lava blocks falling down steep slopes. Thus the very high extrusion rates immediately after 10 February to form the ”pancake lobe” produced relatively little rockfall seismicity, which only increased as the flow moved further east and began to disintegrate.

8. Six months ago no clear GPS deformation signal associated with the resumption of dome growth was evident. Now, however, the GPS data overall do indicate that since December 2005 the edifice has been deflating following a period of apparent inflation (e.g. line lengthening of MVO1-SOUF) after June 2005. This could be interpreted as a four-month lag in the elastic response of the magma reservoir in response to initial extrusion or as a shorter response to much faster magma rise rates that began in December. However, there is evidence that the Montserrat GPS network detects a semi-annual cycle of deformation, perhaps caused by the hydrological cycle. In the case of the last six months this effect may well be masking the crustal reservoir behaviour. The correlation of increased extrusion rates with the change in the sense of deformation in December suggests a more immediate forcing effect.

9. The EDM (electronic distance measurement) triangle of measurement stations established early in 2005 at Jack Boy Hill-Spanish Point-Hermitage, and the line from Windy Hill to Farrell’s Wall now yield good quality results. The Windy Hill-Farrell’s line shows essentially no change since the start of the current episode, giving reassurance as to the long-term structural stability of Farrell’s Wall. Similarly, Jack Boy Hill to Spanish Point shows no change. The Jack Boy Hill to Hermitage line, however, lengthened by about 30 mm during 2005, and in 2006 it has shortened by about 10 mm. The Spanish Point-Hermitage line also shows a lengthening of about 30 mm between March and October 2005, but changed little subsequently.

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[6] Calder, E.S., Cortes, J.A., Palma, J.L. and Luckett, R., 2005. Probabilistic analysis of rockfall frequencies during an andesite lava dome erutpion: the Soufriere Jills Volcano, Montserrat. Geophys. Res. Lett., 32, L16309.

10. Sulphur dioxide emission rates over the last six months have been close to the long-term average of 500 tonnes per day, but slightly higher than the previous six months with higher daily peaks. The most significant change in gas emission has been the rise in HCl emissions. The ratio of HCl: SO_2 began to rise from its “no extrusion” value of about 0.3 near the beginning of September, to values of almost 4 in mid-February. Although the measurement rate is fairly sparse there is no indication of any precursory signal nor any obvious lag effect. The absolute HCl values seem to correspond well with the extrusion rates.

11. As we indicated in our last report the expected drop has taken place in sulphur dioxide (and other volcanic gas) levels measured at ground level by the diffusion tubes in and around Plymouth as the dome has grown. However, the levels have not yet fallen as low or as fast as they did at the beginning of the last episode of dome growth.

Rate of Growth of the Lava Dome

12. This last six months have been characterised by a major increase in the rate of growth of the lava dome. The techniques used to survey the dome and measure its growth have also evolved during this period. Early on, analytical shapes for the dome were parameterised by point measurements taken from theodolite or automated camera photos. A more accurate photogrammetric method was then developed, using high resolution digital photographs from Perche’s and Galway’s Mountain sites, though this has been limited by the need for helicopter access. The AVTIS radar imaged the dome on 25 October and 4 November 2005 from Perche’s[7].

13. The early estimates of dome growth rate for the first two months were below one cubic metre per second. After the increase in seismicity in mid-October 2005 the extrusion rate increased and the average rate measured by AVTIS over ten days from 25 October to 4 November was 1.1 ± 0.1 cubic metres per second (Fig.2). The dome had an altitude of about 740 m above sea level (asl) at this time, about 60 m above its base. Although poorly constrained, the extrusion rate increased to about 4 cubic metres per second between the latter half of December 2005 and the end of January 2006, during which time the dome increased its altitude from about 800 m asl to 850 m asl. The very vigorous effusion after 10 February is bracketed by two dome volume estimates on 27 January and 28 February. If the measured

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[7] Wadge, G., Macfarlane, D.G., James, M.R., Odbert, H.M., Applegarth, J.L., Pinkerton, H., Robertson, D.A., Loughlin, S.C., Strutt, M.C., Ryan, G., Dunkley, P.N., 2006. Imaging a growing lava dome with a portable radar. EOS AGU (in press).

volume difference was entirely extruded after 10 February, it yields an extrusion rate of about 16 cubic metres per second for a two-and-half week period, if it is averaged over the whole month it averages 9 cubic metres per second. The higher rate is as high as anything estimated during the first dome growth episode in 1997. The altitude of the dome grew to about 960 m asl, 280 m above its base. During March the extrusion rate dropped significantly, probably to values of around two cubic metres per second. The proportion of the extruded material finding its way into the talus apron around the dome only began to increase significantly in November 2005. However, addition to the talus can be reduced when exogenous "pancake lobe" extrusion is occurring, and also when the dome is expanding endogenously.

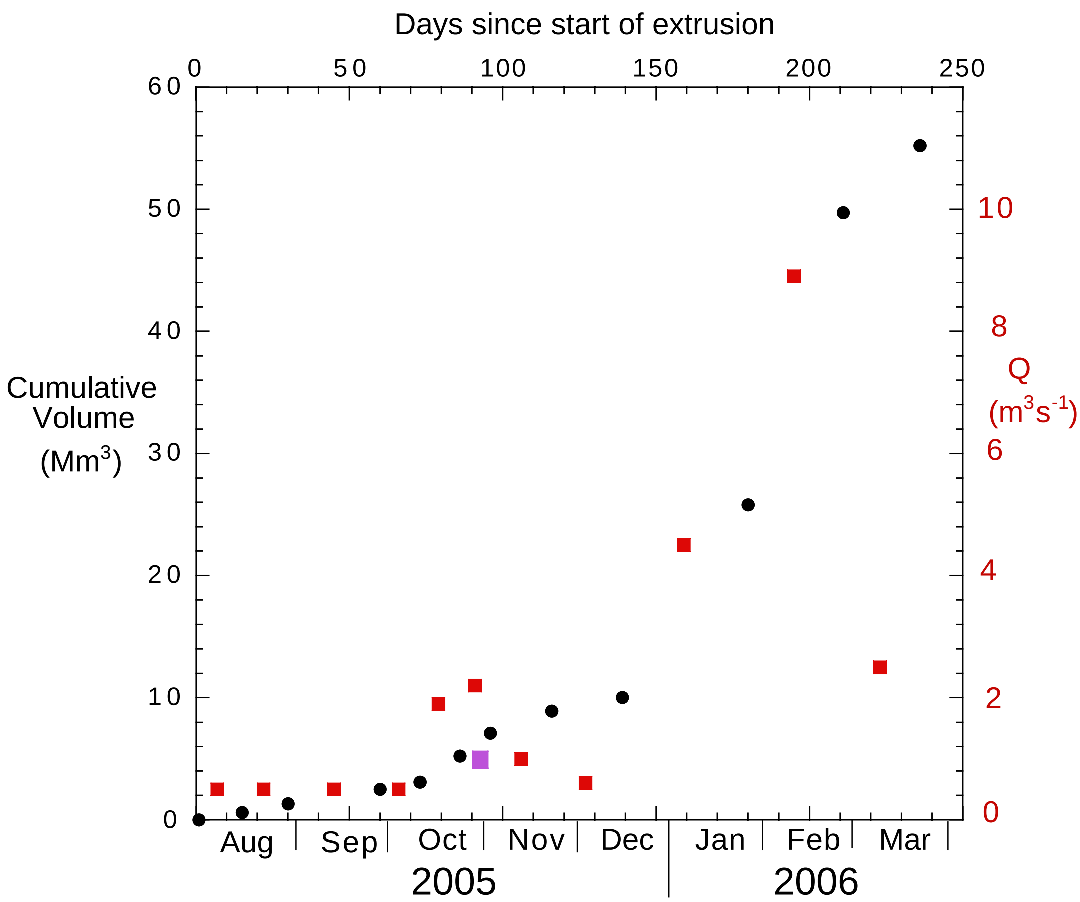

Fig. 2 Plots of the volume of the dome (and talus) since August 2005 (black circles) and the extrusion rate (Q, red squares) plotted at the mid-points between the volumes from which they are derived. The extrusion rate values for October 2005 and March 2006 are thought to be over-estimated. The purple square is the AVTIS-measured extrusion rate between 25 October and 5 November 2005.

14. In the last report we speculated that the relatively slow re-start of extrusion during the first two months might mean that this third episode would have a lower overall extrusion rate than the first two episodes and that this would involve lower "peaks" of short-term extrusion rate. The average rates of extrusion of the three episodes over their first eight months have been: 1.3, 1.6 and 2.3 cubic metres per second respectively. Thus the third episode has started more vigorously than the previous two, though this trend may not necessarily continue. The last six months have also shown that the extrusion rate "peaks" are not lower either. The accelerating rise in extrusion rate over the first seven months of this episode (Fig.2) contrasts with the re-start of the second episode in 1999-2000, which reached levels of about 2 cubic metres per second quite quickly (Fig.3). A peak extrusion rate (for the second episode) of about 8 cubic metres per second was measured over four days prior to the collapse on 20 March 2000. This was much less than that measured in February 2006. However, the measurement intervals for these flux values are varied and often long, with the attendant danger of aliasing the true signal. The conclusion we can draw unequivocally from the flux data is that the volcano is still capable of high rates of sustained extrusion even after over ten years of activity.

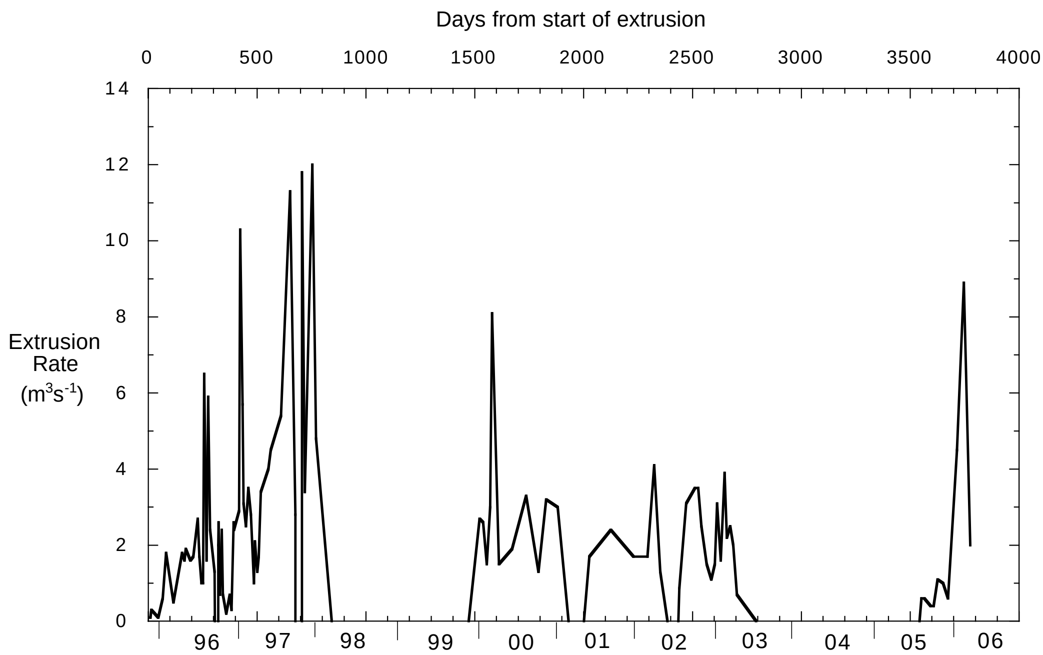

Fig.3 Plot of the variation in lava extrusion rate throughout the whole eruption

Composition of the Lava

15. Three sets of rock samples from the new lava dome have been acquired by MVO, together with some new ash samples. These are from the first pyroclastic flow deposit on 15 November 2005, deposits from the spine collapse at the end of February 2006 and also from a pyroclastic flow deposit of 25 March 2006. A petrological report was produced by Dr. J. Devine[8] based on the 15 November 2005 samples.

16. During collection of the field samples it was noted that the lava seemed to be less dense than before and also that there seemed to be a higher than usual proportion (~ 1%) of mafic inclusions in the andesite. These qualitative observations need to be substantiated if they are to be considered significant.

17. The 16 November 2005 sample is an andesite of similar character to that erupted in previous episodes. This is expected. The amphibole phenocrysts in these rocks have been generally oxidised in near-surface conditions. Nevertheless, it is clear that some of the amphiboles underwent thermal breakdown prior to this. Similarly, plagioclase, orthopyroxene and titanomagnetite phenocrysts all show evidence from zonal variations of composition that they have been recently re-heated or mixed with magma of different composition. These features cannot yet be interpreted in terms any different from previously inferred basalt/andesite interactions.

18. The evidence that basaltic magma mixes and exchanges heat with an andesitic magma comes from the mafic inclusions, common to most lava from Soufrière Hills. Petrological evidence of mineral disequlibria and zonation within phenocrysts have been interpreted in terms of heat exchange and magma mixing within the magma reservoir[9]. By understanding these mineral histories, the events in the magma reservoir could be open to better interpretation. Devine also suggested that there may be geochemical evidence for a more thorough mixing event between andesitic and basaltic magmas prior to the Castle Peak dome eruption about four hundred years ago. The implication is that this could happen again, perhaps if the net heating at depth continued and reached a critical level.

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[8] J. Devine, 2006. Final report of petrologic monitoring of Soufriere Hills Volcano, Montserrat (21 March 2006).

[9] Devine, J.D., Rutherford, M.J., Norton, G.E. and Young, S.R. (2003). Magma storage region processes inferred from geochemistry of Fe-Ti oxides in andesitic magma, Soufriere Hills Volcano, Montserrat, W.I., J. Petrology, 44, 1375-1400.

19. Recent work on lavas from Mount St. Helens, which produced a series of lava domes in the 1980s and again since 2004, suggests another explanation for the type of disequilibrium features seen in the Soufrière Hills lavas. There is evidence that as groundmass crystallises, with pressure reduction in the top two kilometres of ascent then latent heat is released, capable of raising temperatures by 30-40 ˚C. This range is similar to that recorded in the iron-titanium oxides. Although not yet proven for Soufrière Hills, if it were to be shown that latent heating was responsible for many disequilibrium features in phenocrysts then it would reduce the usefulness of phenocryst disequilibria as a way of interpreting events in the crustal magma reservoir. Latent heat-driven variability of phenocrysts will largely record the integrated dynamic history of magma rise in the upper part of the conduit, whilst heating and mixing-driven variability will record the interaction of basaltic and andesitic magmas, perhaps at very local scale. More frequent sampling and analysis of the dome lavas would help hugely to determine trends and relate them to other dynamic observations. Also the mafic inclusions should yield more information about their role from more detailed study.

Assessment of Volcanic Hazards

20. The growth of the new lava dome during this third episode of extrusion has been generally similar to that experienced in the previous two. The composition of the lava is essentially the same, the feeding conduit for the magma is in the same location, and the early evolution of the dome's morphology has been similar to previous episodes. However, there have been differences that may have a bearing on future hazardous behaviour. The base level of this dome (~ 680 m asl) was lower than the first (~ 790 m asl) or second (~ 800 m asl) episode domes. During the current episode the crater contained a, now-buried, transverse ridge of dome rock that had survived the July 2003 collapse. This may act as a stable barrier to future deep-seated potential collapse failure surfaces. It is notable that there have been no major collapse events on the dome during this past eight months, whilst the first major collapses were after ten months in the first episode and after four months in the second. The re-start of this episode began slowly and accelerated to a high peak of extrusion rate more rapidly than in 1995-98. There have been no significant explosions and pyroclastic flow deposits have had smaller run-out distances than at equivalent times in previous episodes. This could be possibly explained by lower gas pressures in the high level magma. One, so far unsubstantiated, observation that might explain this is the increased spine diameter of 50 m, which could mean the upper conduit has a wider bore than hitherto. A wider conduit (perhaps caused by reaming during the July 2003 explosions) would reduce the average rate of magma rise (even though extrusion rates are elevated) allowing more time for gas to escape.

21. The main types of hazard posed by the volcano continue to be:

Pyroclastic flows from dome collapse;
Rock avalanches from collapse of crater walls;
Explosions with ash and rock fallout;
Pyroclastic flows from explosive column collapse.

The likelihood of future occurrence is strongly controlled by the rate of extrusion, with high rates more likely to initiate collapses and explosions. The paths and hence the hazardous consequences of flows and collapses depend on their sources and the down-slope topography.

22. Our attention had been focused by the high extrusion rate flows of February 2006 on the potential for both pyroclastic flows and rock avalanches down the Gage's Valley into Plymouth and down Tyer's Ghaut and into the Belham Valley and neighbouring area. We also considered the former Day Time Entry Zone (fDTEZ) and the Maritime Exclusion Zone.

23. In the last report we discussed the possibility of gravitational failure of the remnant part of the Northwest Buttress that sits atop the Gage's Wall. The situation has changed in two ways since. Firstly, the February 2006 dome lava now abuts the base of the Buttress only just below the level of the gaps to north and south which feed into the Gage's Valley. Secondly, on 8 March 2006 fumaroles were noticed for the first time at the base of the remnant and on the southwest outer Gage's Wall. When new lava rises behind the buttress it may apply a lateral outward pressure that causes it to fail. The resulting rock avalanche with a volume of perhaps up to 2 million cubic metres could reach up to 3 - 4 km, the upper part of Plymouth. The new fumarole may mark a fracture through the Gage's Wall which could be another source of structural weakness. However, we note that the Gage's Wall showed no signs of structural failure during either of the two previous episodes of dome growth and loading. Unfortunately, it is effectively impossible to monitor the wall for structural failure by EDM because of the westerly path of the gas plume, in addition to which, the original wall face itself is no longer exposed for inspection, having been covered by talus from previous domes. The Farrell's Wall above Tyre's Ghaut is also close to being overtopped by the dome. Unlike Gage's, there is no separate mass standing above the main sweep of the crater wall. There is a steaming fracture here though that trends roughly northerly, orthogonal to the wall. The EDM line from Windy Hill to the Farrell's Wall somewhat to the east has shown no deformation since the re-start of extrusion. The one part of the crater wall that has failed in the past is Galway's Wall, on 26 December 1997. This was distinct from these other two cases in

having a precursory history of deformation and by being extensively underlain by weakened hydrothermally altered rocks. The lava dome currently has not begun to load the Galway's Wall.

24. The next time that the locus of lava dome growth shifts to the north and west then there will be the potential to overtop the remaining crater rims above Gage's and/or Farrell's Walls. Then any over-steepening by new lava lobe growth or other source of instability may result in a volume of dome lava detaching itself and collapsing under gravity to form a pyroclastic flow. During 1997, a few dome collapse flows (as well as column collapse flows) travelled down both Gage's Valley and Tyer's Ghaut for at least three kilometres. There were no known dome collapse pyroclastic flows down Gage's Valley during the 1999-2003 episode. The potential volume available for collapse depends on the central height of the dome and the shape of the failure surface. At the moment, with the top of the dome at about 930m asl, only perhaps 2 or 3 million cubic metres are available to collapse to the north or west. Also the direction of failure must fall within the sector 260 - 290˚ for flows to enter Gage's Valley and 330 – 355˚ for Tyer's Ghaut. Failures directed from 355 - 20˚ will flow to the northeast and all other azimuths will send flows down the Tar River Valley.

25. As in the past, the likelihood of dome collapse pyroclastic flows down Tar River Valley is very much greater than elsewhere. Also, as we have seen before, any large collapse (volume > 10 million cubic metres) will immediately reduce the hazard from subsequent pyroclastic flows in other directions as the new extrusions tends to refill the collapse scar formed.

26. If the dome does collapse down Gage's Valley or Tyer's Ghaut at some stage in the next year, what are the likely consequences? The case for Gage's is relatively straightforward: almost any collapse volume of 2 million cubic metres or more will be capable of reaching Plymouth, perhaps within less than two minutes as happened in the latter part of 1997. In addition, there would be the potential for momentum-driven uphill surge onto the southeastern flank of St. George's Hill. The path down Tyer's Ghaut and the Belham Valley is longer and more winding. Both these factors mean that for pyroclastic flows and surges to reach the lower parts of the Belham Valley requires a much larger collapse mass. Using computer models of such flows (e.g. PYROFLOW[10] and LAHARZ) suggests that flows of about 5 million cubic metres could reach Cork Hill but that it would take a flow with a volume of greater than 10 million cubic metres to reach the sea at Old Road

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[10] Wadge, G., Jackson, P.A., Woods, A.W., Bower, S.M. and Calder, E.,(1998). Computer simulations of pyroclastic flows from dome collapse. Geophys. Res. Lett. 25, 3677-3680.

Bay. The largest flows that have entered Tyer's Ghaut so far in the whole eruption have probably been about 2-5 million cubic metres, reaching as far as Weekes. Simulating the surge component of pyroclastic flows in three dimensions is still very difficult to do. Future analysis of the risks in the Lower Belham could be improved with more advanced simulation capability. We will endeavour to achieve by the next SAC meeting.

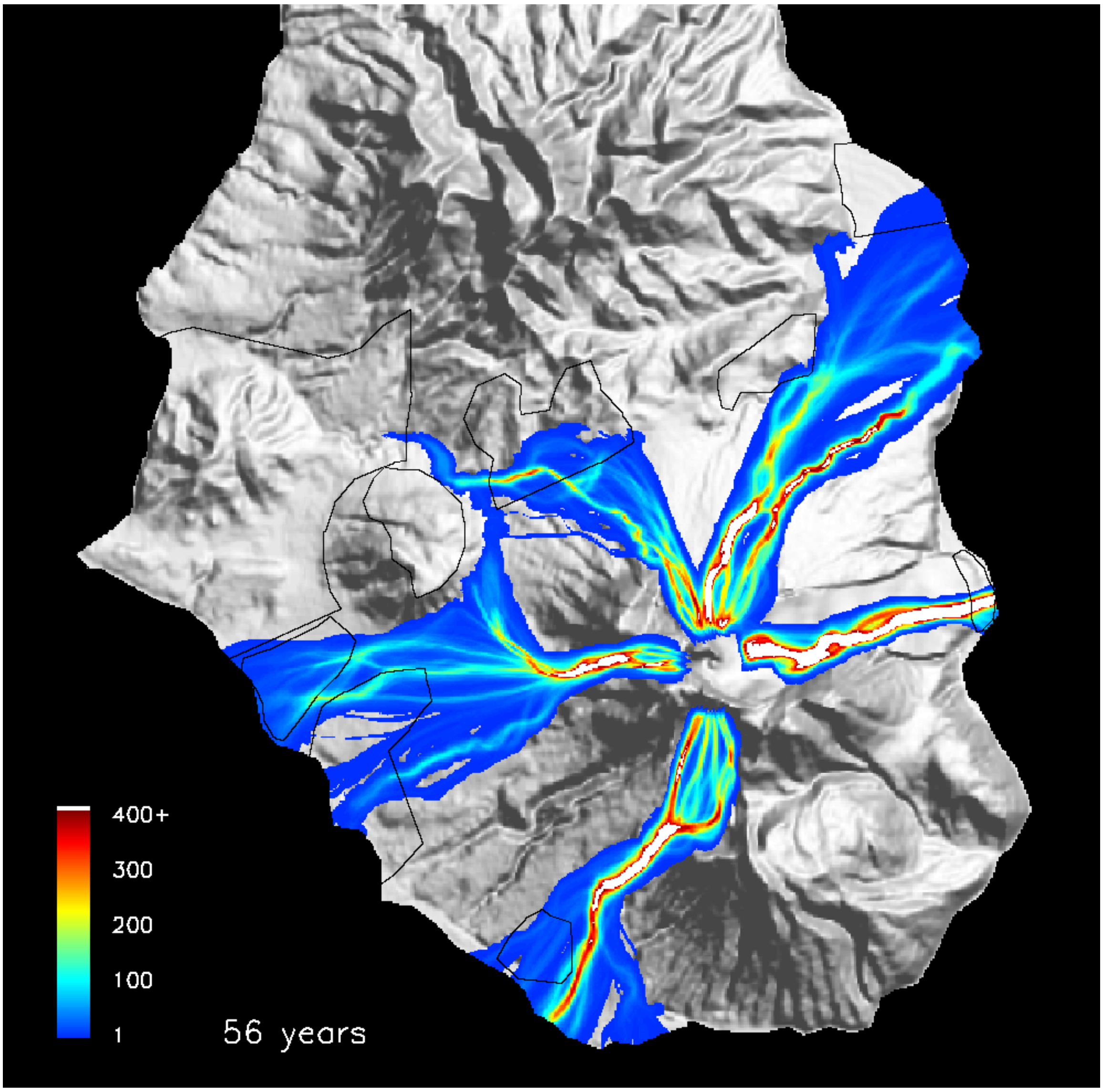

Fig. 4 PYROFLOW ensemble Monte Carlo simulation of pyroclastic flow and surge hazard from Soufriere Hills Volcano. The ensemble represents an equivalent of 56 years of typical 1996-98 activity and the colour scale shows how many times a given spot is overrun by flows and surges in that period. Four sources of flows are simulated: Gage's, Farrell's, Tar River Valley and Galway's.

27. The above tells us about the minimum volumes required, but not about their probability of occurrence. To do this we use PYROFLOW in a Monte Carlo ensemble modelling approach as we reported in the SAC3 Technical Report[11]. Here we have modified that analysis by using an improved digital elevation model of the crater and surrounding area[12] and by increasing the azimuthal weighting assigned to Gage's Valley (from 260 - 270˚ to 260 - 290˚). The results (Fig.4) show an increased likelihood of flow hazard in Plymouth and Amersham compared to the last analyses (SAC3 and 4). What are not captured by this method are the probabilities of flows down the length of the Belham Valley because we have not had flows of that length on-land on Montserrat during the current eruption.

Long Term Prognosis

28. We see no clear signs yet that the current extrusive episode is significantly different from the previous two in terms of the way in which it is being fed by magma from depth. Hence the likelihood is that this episode will continue for many months yet - our best estimate is twenty-eight months - before another major pause in extrusion, or it stops altogether.

29. We have again used the global database of dome-forming eruptions at andesitic volcanoes to estimate the full duration of the Soufrière Hills eruption. If we treat these examples as though they represented a Generalised Pareto distribution[13] we can calculate the survivor function for the Montserrat case of now having lasted 128 months in terms of the probability of it lasting five or more years (P = 0.80) and for another twenty more years (P = 0.47). This is not very satisfactory because there are so few other examples on which to base the analysis and the criteria that can be used to define when an eruption has ended cannot be applied rigorously across all volcanoes. However, until evidence emerges that confirms the volcano has entered a waning phase, this global experience is all that can be used by way of guidance for the long-term outlook.

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[11] Assessment of the hazards and risks associated with the Soufriere Hills Volcano, Montserrat. Third Report of the Scientific Advisory Committee on Montserrat Volcanic Activity. 28-30 Sept. 2004. Part II, Technical Report

[12] Wadge, G., Odbert, H.M., Macfarlane, D.G. and James, M.R. 2006, The November 2005 DEM of the Soufriere Hills crater. MVO Open File Report 03/06.

[13] See Sparks, R.S.J. and Aspinall, W.P. (2004) Volcanic activity: frontiers and challenges in forecasting, prediction and risk assessment. In, "State of the planet: frontiers and challenges" (eds. R.S.J.Sparks, and C.J.Hawkesworth) IUGG/AGU: Geophysical Monograph 150, IUGG Vol. 19, 359-373.

Elicitation of Probabilities for Hazard Scenarios

30. Next, 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. During the meeting, the opportunity was taken to renew the individual expert's performance-based calibrations with an extended set of 'seed' item questions[14]. The outcome of this exercise was a rationalization of the scores used for pooling and combining the contributions of the experts and, for many of the participants, represented the first revision of their scores in over eight years of applying the methodology to the Montserrat volcanic crisis.

31. In order to update the present quantitative risk assessment, nineteen separate items were discussed and re-elicited during the meeting on Montserrat. These are reported below as items *P1, P2, P3a-c, P4a-c, P5a-d, P6a-b, P7a-b, P8a-b* - where probabilities are involved - and as *Q1* where a specific quantity (duration of dome growth) was sought. Where appropriate, a number of other values, mainly for conditional probabilities that had been elicited in previous meetings, were accepted as remaining valid and not updated.

32. 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.

33. *GIVEN current conditions, the probability that the present episode of lava extrusion will cease within 12 months (P1):*
Given that active processes at depth have not stopped and the volcano has been erupting magma for the last eight months, this question elicits views on the probability that the latest episode of lava effusion will cease within one year (from March 2006).

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[14] See Aspinall, W.P. (2006) Structured elicitation of expert judgment for probabilistic hazard and risk assessment in volcanic eruptions. To appear as Chapter 2 in IAVCEI Volume "*Statistics in Volcanology*", 31pp.

Elicited Probability:

lower bound	*best estimate*	*upper bound*
1%	**14%**	**44%**

The chance of a cessation of dome growth within one year is thus judged to be about 6:1 against. Whilst these odds are slightly longer than those assessed at the last SAC meeting (then, 4:1 against cessation) they remain 'substantial', rather than 'strong'. Thus, curtailment of lava extrusion within one year is thought to be unlikely, but if it happened it would not be a great surprise.

34. *GIVEN current conditions, the probability that within 12 months the next significant activity will be a harmless major dome collapse that takes away the bulk of the dome (e.g. to Tar River Valley) (P2):*
This question elicits views on the probability that within a year a major collapse of the dome could occur such as would remove potential hazards to the Belham and Gages Valleys.

Elicited Probability:

lower bound	*best estimate*	*upper bound*
5%	**28%**	**63%**

That is, the assessed chance of such a collapse within one year is judged to be about 1 in 3, and is about twice as likely to happen as dome growth is to cease (*P1*, above).

However, the product of the complements of these two probabilities ({1 – *P*1}*{1 - *P*2}) indicates there is a joint probability of about 62% (= 0.86 * 0.72) that lava dome growth will be on-going <u>and</u> uninterrupted by major collapse throughout the next twelve months. In other words, it is almost twice as likely that the threats from a growing dome will still exist rather than they are removed.

32. GIVEN present conditions, what is the likely further duration of the current dome growth episode, in months from time of meeting (Q1):

Elicited duration:

lower bound	*best estimate*	*upper bound*
6 months	**28 months**	**67 months**

The values obtained for this question in the current SAC6 meeting are notable for the more limited range of credible durations that the experts now appear to consider plausible. The lower bound value for the credible interval seemingly excludes the possibility of a cessation within six months and, given the episode has already lasted 8 months, thus implies a minimum total duration of not less than 14 months. The upper bound credible interval value pulls the envisaged maximal total duration down from just over seven years (SAC5 Report) to just over six years, whilst the best estimate duration is now considered to be closer to three years rather than four, as elicited in SAC5.

36. *GIVEN the average flux rate over the last 8 months has been ~ 3 m^3/sec, AND assuming dome growth continues for the next twelve months, what is the probability that the overall average flux rate will turn out to be less than 2 m^3/sec for the 12 months (P3a):*

This and the following two questions seek to enumerate the probabilities of three different ranges of overall average magma flux rates, spanning the full range of observed behaviour during the Montserrat eruption. Each, potentially, could engender different consequences in terms of the level of risk. High flux rates (i.e. >>*5 cubic metres per second*) were experienced, most notably during the second half of 1997. On occasion, short-term rates greater than 10 cubic metres per second may have occurred briefly in 1996-97, and again during February- March 2006.

Elicited probability that magma flux rate will turn out to be below 2 cubic metres per second over the whole 12 months:

Lower bound	*best estimate*	*upper bound*
7%	**29%**	**59%**

Compared to the last assessment, the probability of experiencing this low overall flux rate is exactly halved (SAC5 prob. = 58%).

37. *GIVEN the average flux rate over the last 8 months has been ~ 3 m^3/sec, AND assuming dome growth continues for the next twelve months, what is the probability that the overall average flux rate will turn out to be between 2 – 5 m^3/sec for the 12 months (P3b):*

This range encompasses the average flux rate experienced for much of the eruption from 1996 to 2002.

Elicited probability that magma flux rate will average out at between 2 - 5 cubic metres per second over the whole 12 months:

Lower bound	*best estimate*	*upper bound*
24%	**58%**	**88%**

Thus, the SAC's opinion now is that an average flux rate in the intermediate range (*2-5 cubic metres per second*) is about twice as likely as was assessed in SAC5 (prob = 32%).

38. *GIVEN the average flux rate over the last 8 months has been ~ 3 m^3/sec, AND assuming dome growth continues for the next twelve months, what is the probability that the overall average flux rate will turn out to be 5 m^3/sec <u>or greater</u> over the 12 months (P3c):*

Elicited probability that average magma flux rate will exceed 5 cubic metres per second over the next 12 months:

Lower bound	*best estimate*	*upper bound*
3%	**14%**	**42%**

As noted above, such high flux rates were experienced during the second half of 1997, and again in February – March 2006. From this elicitation, the SAC considers the chances of sustained flux rates of this intensity are twice as probable as indicated by the SAC5 elicitation (prob = 7%), but still remain quite unlikely.

39. *GIVEN what has happened to date, the probability that the lava flux rate will peak at less than 5 cubic metres per second (averaged over any 30-day period) during the next 12 months (P4a):*

This scenario implies that the high magma flux rates seen during the last few months do not recur in the next twelve months, even for one month.

Elicited probability:

lower bound	*best estimate*	*upper bound*
2%	**22%**	**65%**

In responding to an associated question by elicitation, the group provided the view that a probable upper limit for sustained magma flux rate is about 20 cubic metres per second.

40. *GIVEN what has happened to date, the probability that the lava flux rate will peak at between 5 - 10 cubic metres per second (averaged over any 30-day period) during the next 12 months (P4b):*

This scenario involves quite high magma flux rates that may have occurred during brief peaks in activity, but have never been maintained for more than several days. At such rates, the volcano may be expected to be bordering on a change to explosive activity. The present item thus considers an acute situation in which intense magma production is sustained for a month or more at between 5 to 10 cubic metres per second.

Elicited probability:

lower bound	*best estimate*	*upper bound*
23%	**59%**	**89%**

This represents a major change in the likelihood of such a flux rate being experienced: in SAC5, the corresponding probability was elicited at only 7%.

41. *GIVEN what has happened to date, the probability that the lava flux rate will peak at 10 cubic metres per second <u>or greater</u> (averaged over any 30-day period) during the next 12 months (P4c):*

This scenario involves very high magma flux rates that may have occurred during brief peaks in activity, but have never been maintained for more than several days. At such rates, the volcano may be expected to be close to changing to strongly explosive activity. The present item thus considers an extreme situation in which intense magma production is sustained for a month or more at rates exceeding 10 cubic metres per second.

Elicited probability:

lower bound	*best estimate*	*upper bound*
2%	**20%**	**49%**

Thus, on the basis of recent behaviour, there is thought to be a 1 in 5 chance of experiencing this extreme situation within the next twelve months; that said, intermediate or lower levels of peak flux (*P4a,b)* are much more likely.

42. *If magma extrusion increases to peak at one of the following (30-day period) flux rates, what is the conditional probability of a 0.1x ref or greater explosion occurring (P5a-d):*

P5a: for peak flux rate no more than 2 cubic metres per second:

lower bound	*best estimate*	*upper bound*
1%	**9%**	**25%**

P5b: for peak flux rate between 2 - 5 cubic metres per second:

lower bound	*best estimate*	*upper bound*
6%	**30%**	**64%**

P5c: for peak flux rate between 5 - 10 cubic metres per second:

lower bound	*best estimate*	*upper bound*
8%	**48%**	**82%**

P5d: for peak flux rate above 10 cubic metres per second:

lower bound	*best estimate*	*upper bound*
16%	**63%**	**91%**

These four sets of probability distributions (P5a-d) allow the likelihoods of explosions of different sizes to be included in the quantitative risk assessment as a function of attained peak magma flux rate.

43. *What is the probability in the next 12 months of a failure of Gage's Wall or the dome remnant sitting on it giving rise to a flow (hot, cold or mixed) towards Plymouth (P6a):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
1%	**11%**	**47%**

44. *What is the probability in the next 12 months of a failure of Farrell's Wall part of the crater rim giving rise to a significant flow on the northern flanks of the volcano (P6b):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
0.001%	**0.15%**	**4%**

45. *What is the probability that dome material will accumulate <u>on or above</u> Tyer's Ghaut notch such that 5 x 10^6 m^3 or more is in a position to collapse into Tyer's Ghaut within the next 12 months (P7a):*

The figure of 5 million cubic metres of material is judged on the basis of numerical modelling to be the minimum amount required to generate a flow with a run-out potential at least as far as the middle reaches of the Belham Valley (i.e. capable of approaching the vicinity of the former Belham Bridge).

Elicited Probability:

lower bound	*best estimate*	*upper bound*
32%	**70%**	**94%**

46. *GIVEN that 5 x 10^6 m^3 or more of dome material does accumulate* on or above *Tyer's Ghaut notch, what is the conditional probability that at least 5 x 10^6 m^3 of that material will collapse into Tyer's Ghaut within the next 12 months (P7b):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
1%	**14%**	**50%**

47. *What is the probability that dome material will accumulate* on or above *Gage's Wall such that 2 x 10^6 m^3 or more is in a position to collapse into Plymouth within the next 12 months (P8a):*

The figure of 2 million cubic metres of material is judged on the basis of numerical modelling to be the minimum amount required to generate a flow with a run-out potential at least as far as the outskirts of Plymouth.

Elicited Probability:

lower bound	*best estimate*	*upper bound*
43%	**78%**	**98%**

48. *GIVEN that 2 x 10^6 m^3 or more of dome material does accumulate* on or above *Gage's Wall, what is the conditional probability that a flow of at least that volume material or greater will collapse into Plymouth within the next 12 months (P8b):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
2%	**23%**	**69%**

Quantitative Risk Assessment

49. We make use of the same procedures for quantitative risk assessment that have been used since 1997. Once more, our previous calculations of volcanic risk are revised by making adjustments to probability and rate estimates in the light of the new developments in the volcano, and on the basis of the committee's reappraisal of the likelihood of the various associated threats. The risk levels are mainly expressed as potential loss-of-life estimates and as annualised individual risk exposures - that is, the risk of suffering a given number of casualties in the society as a whole, or the risk of an hypothetical individual losing his or her life during one year. 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 to remain at about 4,775 persons, a figure unchanged from previous recent 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 requests from the authorities, the present assessment focuses principally on volcanic risk levels in the former Day-Time Entry Zone (fDTEZ), and in certain areas that are connected with tourist or industrial activities. For overall societal risk estimates, we retain the main occupied zone delineations that have been used consistently throughout recent risk assessment updates for Montserrat - (see Fig. 1 of the March 2004 Report, Part II, and Fig.5).

Societal Risk Levels

52. *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 assumes there are about 20 people living full-time within that area (including those on Isles Bay). Using the elicitation results reported above, the risk assessment analysis uses Monte Carlo re-sampling to explore possible outcomes from a range of scenarios relating to dome-building, at different flux rates, and from associated

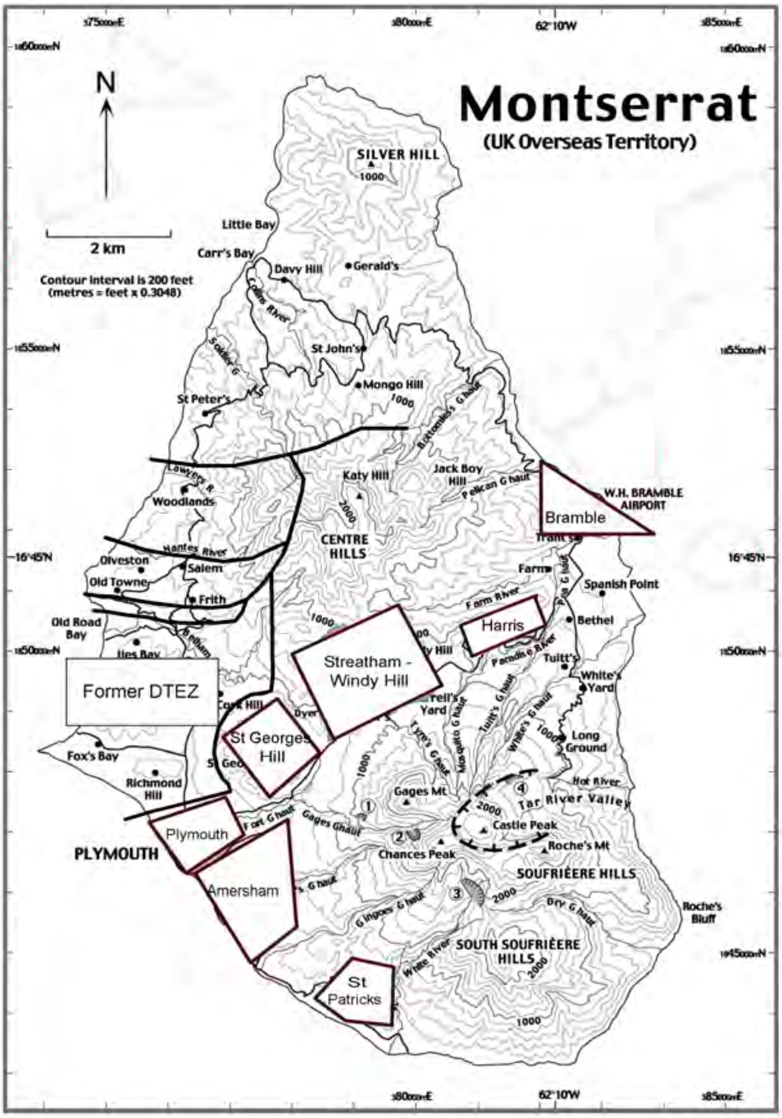

Fig.5. Map showing areas used for risk exposure calculations

explosive activity that might develop within the next twelve months. Each scenario is weighted according to its elicited relative likelihood of occurrence.

These scenarios also include the possibility that magma extrusion may cease within 12 months or that a major collapse will remove the threats of a growing dome; as noted above, the joint probability of one of these two eventualities occurring is thought to be about 38% (that is, 13-to-8 against, in odds).

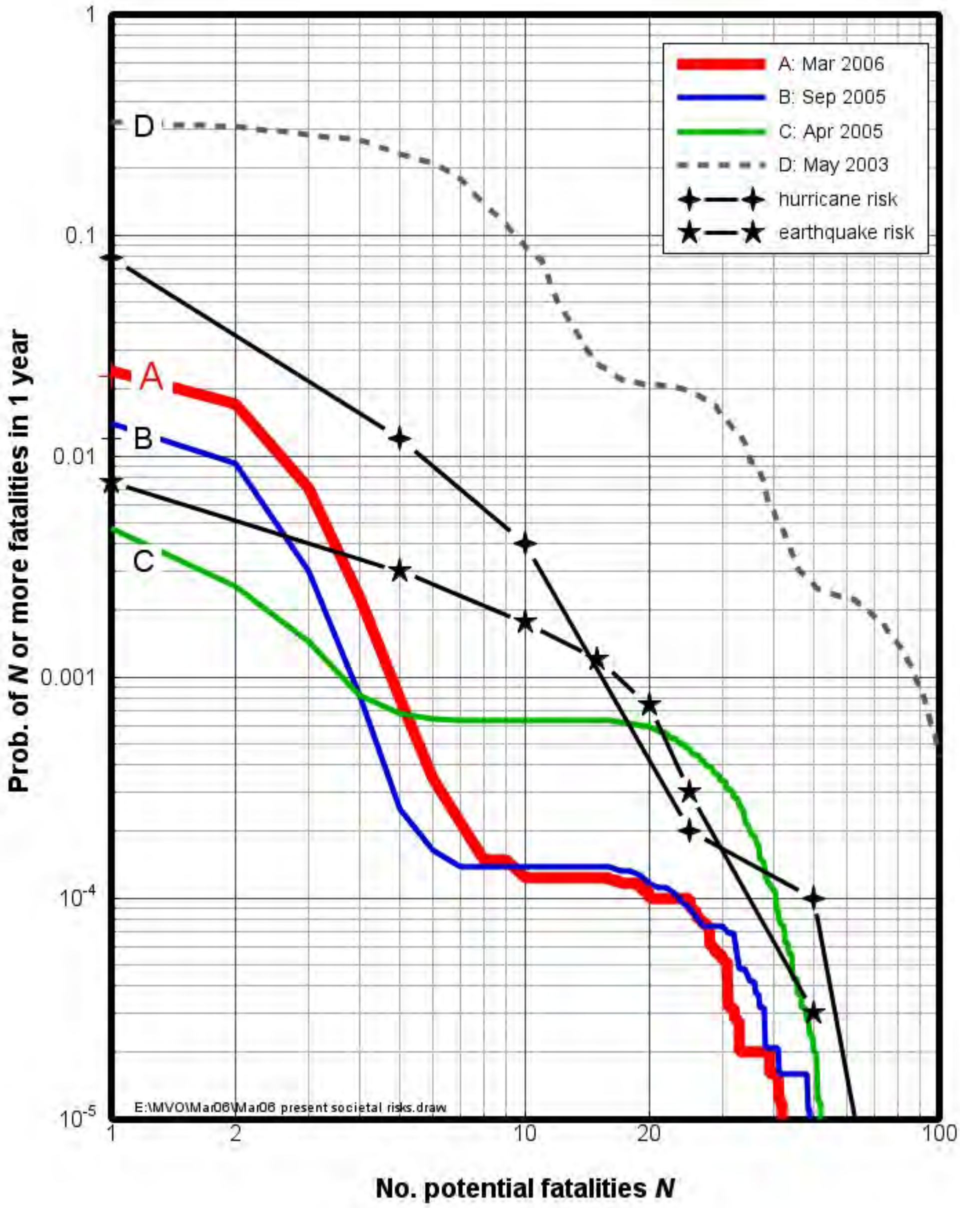

Fig. 6 Societal risk for present population of Montserrat, following restart of magma extrusion in August 2005

53. Fig. 6 shows the estimated current annualised societal risk for Montserrat (curve A), together with those calculated in September 2005 (curve B) and April 2005 (curve C), and that which had been obtained previously for May 2003 (curve D), when the last huge dome was still present. The latest risk curve is very similar in its overall shape to that obtained in September 2005. (It may be recalled that in SAC5 the committee revisited the issue of high intensity explosions and, on the basis of ten year's experience of the Montserrat volcano and a re-examination of the evidence accumulated in that time, decided that previous evaluations of the probabilities of occurrence of such explosions had been too conservatively expressed). Thus, there is a slight increase in the estimated risk levels for small numbers of casualties, although perhaps not as marked as might have been anticipated given the current conditions at the volcano. Further examination of pyroclastic flow hazard modelling (reported in Paras. 26-27) indicates that the likely frequency of pyroclastic flow inundation of areas in the fDTEZ and Lower Belham could be a factor of two lower than previously estimated, and restating this element in the risk assessment model has had a further moderating influence on the societal risk exposure. Overall, the threshold volcanic risk level at which one or more casualties may occur is fractionally higher than it was a few months ago, but it remains substantially lower, by nearly two orders of magnitude, than it was in 2003, when the giant dome threatened occupied areas. This threshold risk level incorporates the possibility that, within the next twelve months, magma flux rate could again increase, and that increased flux rates could bring with them increased likelihood of explosive activity.

54. Comparative risk exposures for hurricane and earthquake are also shown on Fig.6; for small numbers of casualties, curve A indicates the present volcanic risk in the populated areas of Montserrat is still assessed to fall approximately between that of long-term hurricane risk exposure and that from the regional tectonic earthquake threat, while for larger numbers of casualties (e.g. 5 - 30 fatalities) the risks are lower than those from either of the other two natural hazards.

Individual Risk Exposure Estimates

55. 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).

56. *Risks in the Lower Belham Valley and former DTEZ areas*

Given dome growth has not yet reached the point when over-topping the crater is taking place (and currently is proceeding at a reduced extrusion rate in the eastern part of the crater), the most immediate hazards to people residing or working in the Lower Belham Valley and former DTEZ (including Isles Bay, and Friths/Happy Hill/Old Towne south) could come from: a) small to moderate explosions with fallout of rocks and ash, and b) larger explosions with accompanying pyroclastic flows generated by column collapse. The hazards from fallout of rocks could occur anywhere across these areas, and can be mapped from simulation models. The hazards from column collapse pyroclastic flows and surges would be concentrated in areas abutting flowpaths coming from Gage's Valley, and, marginally, in the Belham Valley near Cork Hill. With current conditions, the individual risk exposure for people residing in these areas is assessed LOW on the CMO's scale. However, the risk could rapidly move into the MODERATE category if there is a switch to higher rates of magma flux and/or if dome growth becomes re-focused towards the northwest.

57. *Other occupied areas*

In the adjoining occupied area to the north of the Lower Belham Valley (i.e. Old Towne north/Olveston/Salem – see Fig. 5), currently the risk exposure is MINIMAL, and the same category of risk applies to the Flemmings area where the MVO is sited. Significant changes in conditions at the volcano would be required to raise these risk levels.

58. *Risks to workers on Plymouth jetty*

There is potential interest from three commercial operators for loading barges at Plymouth Jetty, and the following conditions for such operations are proposed by the authorities:

(a) no more than one operator to load a barge at any one time,

(b) loading is restricted to Monday to Friday and

(c) the barge has to be loaded within a working day i.e. 8 hours

Three possible scenarios are envisaged for such activities:

(1) One barge per week, with 20 employees in the area for 8 hours

(2) Three barges per week (Monday, Wednesday and Friday), with 20 employees in the area for 8 hours

(3) One barge per day (Monday to Friday), with 20 employees in the area for 8 hours.

It is assumed here that half the workers are truck drivers travelling to and from the Jetty, and that they spend about 60% of their time in the Exclusion Zone.

The potential hazards faced are: sudden onset of explosive activity and associated column collapse pyroclastic flows; dome collapse pyroclastic flows; collapse of the remnant Northwest Buttress, and mudflows. 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 low, could have a very rapid onset, possibly affecting the Plymouth area within two minutes, or even less. 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 pessimistic, but by no means worst-case, circumstances, the annualised individual risk of exposure of a worker involved in jetty operations under scenarios (1) and (2) above is assessed in the LOW category on the CMO's Risk Scale, and under scenario (3) whilst the individual risk exposure is numerically equivalent to LOW it is very close to the MODERATE category.

In all three of the Plymouth Jetty operational scenarios, the individual risk exposure estimate from volcanic activity is currently assessed potentially higher than even the most hazardous UK industrial accident activity, which is coal-mining and quarrying of energy-producing materials. These levels of individual risk exposure also imply there is a non-negligible chance of losing several workers from dangerous volcanic activity: if such work were undertaken by 20 people every working day for a full year, under the conditions currently assumed for the volcanic hazard model.

59. *Risks to workers in Belham Valley*

The SAC was also requested to assess the risk exposure of construction workers building foundations for the new Belham Bridge, should this project proceed. The suggested conditions are: 20 workers present in daylight hours, 6 days per week, for a 6-month construction period, working at a location about 300 metres upstream of the former bridge site. Under these circumstances, the estimated IRPA for an individual worker on this project falls into the VERY LOW category on the CMO's scale. Depending upon the exact location concerned, a similar level of volcanic risk exposure would exist for sand quarrying activities in the lower Belham Valley.

60. *Risk exposure for St. George's Hill*

The annualised probability of pyroclastic flow inundation affecting the St George's Hill area has been reappraised somewhat higher than previously modelled (see Paras. 26-27). That said, however, the threat of hazards associated with dome collapse will remain small in the St. George's Hill vicinity unless dome building to the northwest becomes re-established. Thus, volcanic hazards in this particular area are currently those from falling rock fragments from explosions, and/or pyroclastic flows from a column collapse eruption. Under the present conditions, our current estimates indicate that the risk exposure for a person living full-time on St. George's Hill falls in the LOW category on the CMO's scale, but not far removed from the threshold for MODERATE. The individual risk for individuals (e.g. tourists) making short visits to St. George's Hill is much less, but should now be regarded as falling in the MINIMAL category. For taxi drivers who return to the area frequently, the risk exposure is more likely to fall in the LOW category (depending on the number of trips made, and time at risk). However, it must also be recognized that whilst the risk levels are insignificant for any one individual tourist, the chances of suffering two or more casualties in the period of a year, with repeated multiple visits by different groups comprising several persons, is potentially non-trivial; the actual risk exposure involved depends upon a number of contributory factors.

61. *Risks in the Maritime Exclusion Zone*

The levels of risk exposure in maritime areas and coastal waters around southern Montserrat can be viewed against the background of levels of assessed risk on land. However, the risk exposure to individual fishermen operating anywhere in the Maritime Exclusion Zone depends very much on what area they are in, and the amount of time they spend in that area (such information is not available to us for undertaking a detailed risk analysis). As before the most hazardous part of the sea around Montserrat is offshore Tar River Valley. To provide some comparative guidance, the individual risk exposure (IRPA) for someone *full-time* in the area directly off the Tar River delta would be classed HIGH on the CMO's scale (IRPA less than 1 in 100), while off St. Patrick's the equivalent risk category would be MODERATE. For offshore Plymouth, the *full-time* risk exposure would be assessed as LOW-to-MODERATE, while for the Trant's Bay to Spanish Point section of the east coast, the risk would fall mid-range in the category LOW. Put into numerical terms, when compared with the sea area off Tar River, the risk levels are about five times lower for fishing grounds off the south coast, sixteen times lower off Plymouth, and about thirty times lower for the seas north of Spanish Point.

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[1], 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.

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

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 models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[2].

A1.5 This report may contain certain "forward-looking statements" with respect to the contributors' expectations relating to the future behaviour of the volcano. Statements containing the words "believe", "expect" and "anticipate", and words of similar meaning, are forward-looking and, by their nature, all forward-looking statements involve uncertainty because they relate to future events and circumstances most of which are beyond anyone's control. Such future events may result in changes to assumptions used for assessing hazards and risks and, as a consequence, actual future outcomes may differ materially from the expectations set forth in forward-looking statements in this report. The contributors undertake no obligation to update the forward-looking statements contained in this report.

A1.6 Given all these factors, the Committee members believe that they have acted honestly and in good faith, and that the information provided in the report is offered, without prejudice, for the purpose of informing the party commissioning the study of the risks that might arise in the near future from volcanic activity in Montserrat. However, the state of the art is such that no technical assessment of this kind can eliminate uncertainties such as, but not limited to, those discussed above. Thus, for the avoidance of doubt, nothing contained in this report shall be construed as representing an express or implied warranty or guarantee on the part of the contributors to the report as to its fitness for purpose

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

or suitability for use, and the commissioning party must assume full responsibility for decisions in this regard. The Committee accepts no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG, GoM, or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor do they accept any responsibility or liability to any third party in any way whatsoever. The responsibility of the contributors is restricted solely to the rectification of factual errors.

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

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.