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

Fifth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 26 - 28 September 2005 at the Montserrat Volcano Observatory, Montserrat

Part II: Technical Report

Issued: 21 October 2005

Contents

Introduction

1. This is the second part of the report resulting from the fifth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 26 - 28 September, 2005. Part I of that report, the Main Report[1], gives the principal findings of the meeting[2], and this, Part II, gives the technical data and analysis that led to those findings.

2. For this meeting MVO produced Open File Report 04/05[3], which synthesises the monitoring data and observations collected by MVO between April and September 2005 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 April 2005

3. The six-month period prior to April 2005 had been quiet. In fact the last significant prior surface activity was the explosion and dome remnant collapse of 3 March 2004. On 15 April 2005 a period of renewed surface activity began that led to the extrusion of a new lava dome about four months later. Vigorous gas and ash release occurred on 15 April from a vent in the northwest part of the crater and included smaller vents on the outer slopes above Tyer's Ghaut. These vents, outside the current crater, were probably localised by the old wall of English's Crater, still partly filled here by old dome rocks. Very shallow (< 1 km) volcano-tectonic earthquakes were recorded just prior to the activity, located on the east side of Gage's Mountain, near the vents. The main vent was difficult to observe, but may have been the one active in March 2004. Jet-like roaring sounds of escaping gas with pulsations in strength occurred. Ash and gas venting activity gradually diminished over the following two weeks

4. In May, mild steam venting from the 15 April 2005 vent continued, accompanied by some bursts of volcano-tectonic earthquakes. On 13 June a new series of vents with tuff rings trending NNE across the northern part of the crater were observed after a storm. This activity was again preceded by volcano-tectonic earthquakes, but also accompanied by long-period and hybrid events seemingly associated with the ash and gas venting (Fig.1). It also became apparent that between 4 and 6 June a major inflection of the GPS-measured deformation had occurred which, in the case of the nearby Hermitage station, reversed a change seen associated with the mid-April event.

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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 Panel members believe that they have acted honestly and in good faith, they accept no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can they accept any liability to any third party in any way whatsoever. See also Appendix 1.

[3] Bass, V., Jones, L., Loughlin, S., Luckett, R., Norton, G., O'Monghain, A., Ryan, G.A., Saranathan, R., Strutt, M., Syers, T. and Williams, P. Report to the Scientific Advisory Committee Montserrat, September 2005. MVO Open File Report 04/05, 2005.

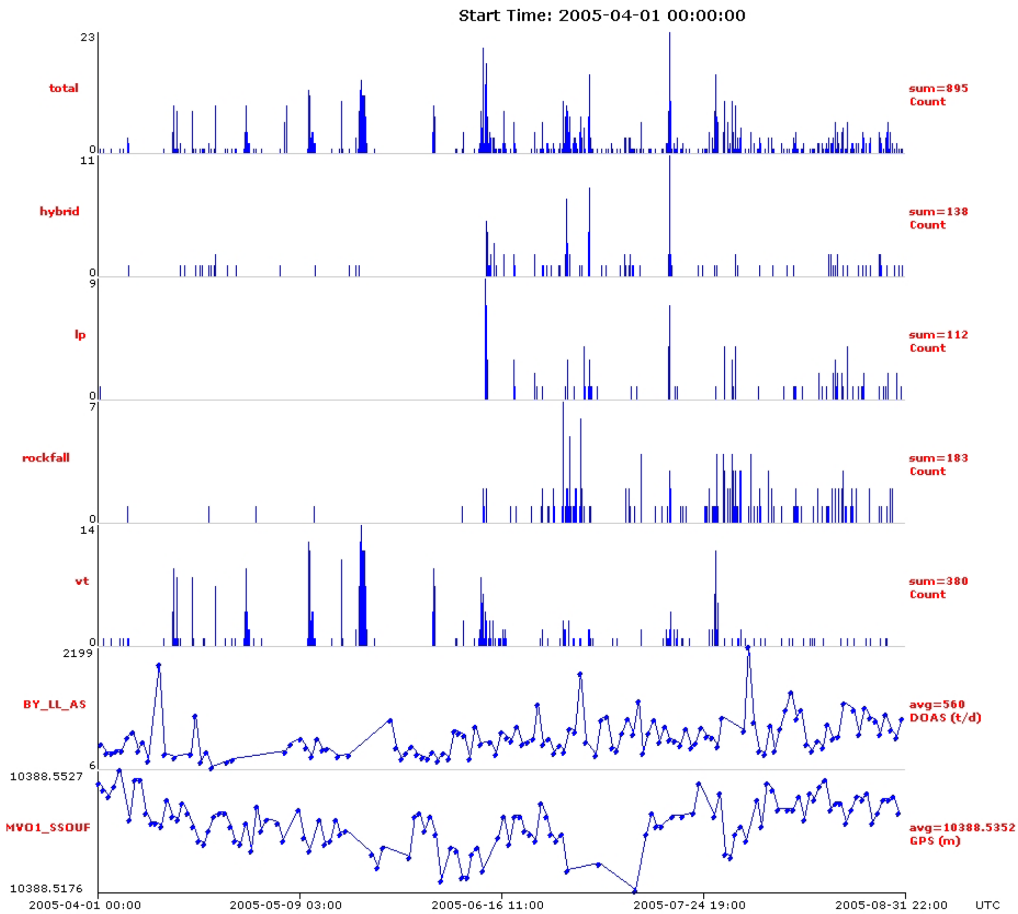

Fig.1 MVO plots of seismicity, gas and deformation data for April to September 2005. The plots are from the top: numbers of all seismic events, hybrid events, long-period events, rockfalls, volcano-tectonic events, daily sulphur dioxide emission rates and GPS line length changes between MVO1 and SOUF.

5. The 15 April and 13 June events involved fracturing of the rocks below the crater floor. The 15 April fracture was oriented NW-SE. The seismicity beneath Gage's suggests it may have propagated northwestwards, but it does not appear to intersect the surface north of the old crater wall. At this point it has been suggested that it may intersect an ENE-trending fault connecting Gage's Upper Soufrière in the west with Tar River Soufrière in the east. The NW-SE fracture sits on the same trend that controlled the phreatic phase of the 1995 activity and on which the main cylindrical conduit sits. The NNE-trending fracture of 13 June 2005 also appears to follow the fracture responsible for the fissure that formed on Castle Peak on 14 October 1995.

6. Elevated ash and gas venting continued with low amplitude tremor until 28 June when a moderate (0.1x reference) explosion occurred at 13:06 LT. A 7 km ash column collapsed to form pyroclastic flows that reached the sea on the Tar River delta and spilled over Farrell's

Wall for a few hundred metres. The source vent of the explosion is not known, but afterwards a new ENE-trending fracture with active vents was seen just south of the old transverse dome ridge and the old dome vent. This represents the third (or fourth) episode of fracturing that preceded the rise of magma to the surface. Over the following month, four more explosions of comparable size occurred on the 3rd (01:14 LT), 9th (20:02LT), 18th (03:01 LT) and 27th (01:14 LT) of July, interspersed with periods of vigorous ash and gas venting (Fig.1). The explosions had clear, high amplitude, monochromatic seismic signatures, but variable seismic histories before and after each event. Seismicity was generally located at a depth of ~ 1.5 km. The 18 July explosion column reached 10 km, the highest of the five events. Parts of the transverse dome remnant collapsed during the 27 July explosion. The source for this last explosion was probably the central vent from which the new dome was to appear.

7. Field measurements of the mass of ash per unit area from the five explosions allowed the total volume of the air fall deposits to be calculated which, together with estimates of the pyroclastic flow volumes, provided a basis for estimating the maximum total volume of the explosive events: ~1.6 million cubic metres dense rock equivalent (DRE). Assuming roughly equal sizes for each event gives ~ 0.3 million cubic metres per explosion. Each individual explosion would have evacuated about 1 km deep into the conduit, depending on the assumed geometry at depth.

8. The composition of the ash produced during this period has been studied by Dr. J. Devine. The early samples (e.g. 15 April 2005) consist of altered fragments of old andesite with abundant hydrothermal minerals (cristobalite, pyrite, mullite, gypsum). Extremely sparse examples of glass were found. By 13 June, the character had changed little and no fresh hornblende was found. In samples from the first explosion on 28 June, there were more glassy clasts though the ash was still dominated by low-temperature silica enrichment. The proportion of glassy clasts increased to the end of July and the evidence for hydrothermal minerals disappeared. The composition of the glassy clasts was variable, suggesting variable ascent rates. Ash samples from 19 August contained hornblendes without reaction rims from newly risen magma and older rocks. Several lines of petrographic evidence suggest that some components had risen rapidly from the magma reservoir whilst others had spent considerable time in the near sub-surface. Titanomagnetite in glassy clasts indicates that it has been exposed to temperatures well above the stability of hornblende, presumably because of heating by basalt in the reservoir. The relatively rapid rates of rise of the new magma and the relatively low rates of lava extrusion suggest perhaps either narrower conduit(s) or separation of components.

9. The new lava dome was first recognised from a helicopter on 8 August, following a period of cloudy weather. In order to have reached the size it was, we infer that it had begun to form during the first week of August 2005. At the same time it was observed that an area of the crater floor to the south of the ENE-trending fracture of 28 June had been uplifted by 20-30 metres. Displacement of this size suggests a small cryptodome-like intrusion. Intrusive deformation of the Castle Peak dome in September 1995 had also occurred to the south of this fracture, but further to the northwest. The early observations of the new dome show that it had a rubbly surface with a small talus apron, and has been fed from the main vent of the eruption. By 16 August a small spine on the western side developed, followed by a slab of lava that moved eastwards. The dome became increasingly asymmetric, with its long axis oriented northwest and dimensions of 195 x 150 metres and a height of 80 metres on 24 August. It abutted the transverse dome remnant on its northern side. During September the

dome continued to grow to the northwest with degassing mainly occurring near the 15 April vent. Endogenous (swelling) growth also apparently played a role at this time. Limited photogrammetric measurements made on 3, 16, 30 August and 20 September indicate extrusion rates of between 0.5 and 1 cubic metre per second, depending on which analytical geometrical shape is assumed to fit the dome. At night in September, the Perche's Mountain fixed camera captured images of very occasional incandescence on the southwestern side of the dome. Thermal camera images showed the dome surface to be cool, $<50^{o}$ C, except along the fracture vents.

Interpretation of the Re-start

10. It appears that magma began to rise up the central conduit in mid-April 2005. It probably got to within a kilometre or so of the surface, sufficiently close to open a NW-trending fracture system through the conduit from which gas and ash escaped as the conduit itself was probably still blocked. However, the evidence at the time was equivocal as to whether activity was caused by rising magma or by interaction between the volcano's groundwater and the hot rocks of the conduit zone. The next major change occurred in the first week of June when a change in the deformation indicated renewed movement of magma leading to the next fracturing episode a week later. Increased general levels of shallow seismicity followed, together with the first evidence of tremor indicating shallow fluid flow. The five explosions in late June-July reamed out the remaining conduit fill below the main vent and provided the first undoubted petrographic evidence of new magma in the ash, albeit still mixed with old material. The relatively slow phreatic precursory phase to this restart of dome growth, together with the re-activation of the same fracture system, shows greater similarities to the 1995 start of eruption than to the November 1999 restart. The big contrast with both previous events is the much lower overall level of seismicity associated with the restart, suggesting that the conduit and surrounding rocks are more "open" than they were previously (that is, hotter and more compliant) or that the magma flux rate is lower (or both).

11. The initial two months of dome growth were at fairly low extrusion rates (less than 1 cubic metre per second). However, evidence from the petrography of the ash suggests that some of the magma at least has risen rapidly. This could mean that the conduit overall is of narrower bore or width than in previous episodes, or that the ash is being separated from the rest of the rising magma at considerable depth and ejected up and out "sideways" through a fracture, whilst the bulk of the magma slows down considerably in the upper parts of the main, cylindrical conduit. The rate of extrusion during the coming months will be important for both hazard evaluation and the long-term development of the system. If the rate stays low then this could be indicative of a lowering of driving pressure within the reservoir or increased resistance to flow.

Deep Sulphur Dioxide Supply

12. One of the most remarkable aspects of the eruption has been the constancy of the emission of gases, specifically SO_2, from the volcano. In past reports we have used the observed emission rate of SO_2 in one of the three criteria for assessing conditions to be expected at the end of the eruption. We have argued that this has a direct link to the influx of

basalt at the base of the andesite reservoir that powers the eruption. Here we present the case for an extension of the way in which we evaluate SO_2 emission rates for this purpose.

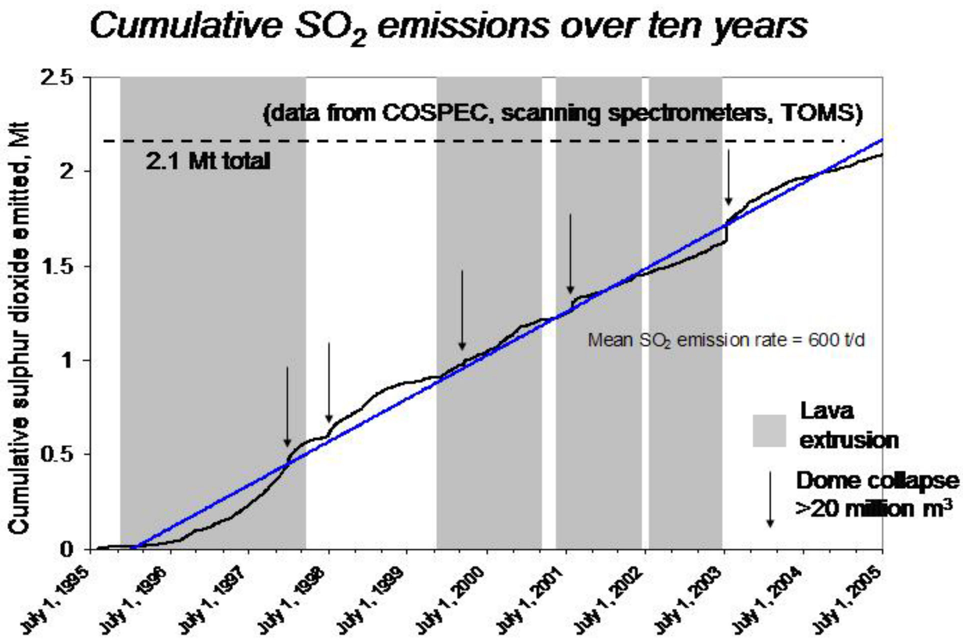

Fig. 2 Cumulative sulphur dioxide emissions to the atmosphere 1995-2005, blue line is best linear fit (from Edmonds, 2005)

13. Edmond's recent compilation[4] of emission rates since July 1995, that interpolates across the data gaps and accounts for the major collapse "instantaneous" releases, shows that the ten year record (Fig.2) is fairly linear, at least since late 1998. Over shorter time periods, the volcano also has a capacity to buffer the release of SO_2 by storage within the high level magma (e.g. dome lava), conduit margins and perhaps deeper, too. This leads to an apparent time-variable permeability. But it also shows that over a period of, say, a year, the determination of deep gas release could be masked by either the effects of pulses in the supply or by the effects of storage. We currently have no evidence for pulsatory supply and so assume that variable storage modulates emission rate over periods much less than ten years.

14. The SO_2 budget could be written as:

Atmospheric emission rate	=	basalt exsolution rate (constant)
		− influx to andesite reservoir storage
		− influx to conduit storage
		− influx to dome storage

Dome Storage

The only storage term for which we have any real observational data is dome storage. The TOMS satellite sensor measurements made after major collapses suggests that about

[4] Edmonds, M., 2005. Degassing at Soufrière Hills Volcano, Montserrat: an overview of research results. Ten Years On, Scientific Conference, Vue Pointe Hotel Montserrat, 24-29 July 2005.

100,000 tonnes of SO_2 were released on 12/13 July, presumably mainly from the disintegrating dome. Other major collapse releases suggest that the dome can release about 0.5 tonnes of SO_2 per 1000 cubic metres of collapsed dome (if we assume a linear fit to the data for 26/12/97, 3/7/98, 29/7/01,12-13/7/03). We can extend the argument to say that any un-collapsed dome accommodates at least 0.5 tonnes per 1000 cubic metres of SO_2 that has been transported from the basalt magma. A dome growing at the long-term average of about 2.3 cubic metres per second stores SO_2 at a rate of 0.00115 tonnes per second or about 100 tonnes per day. This is a factor of about 0.17 of the ten-year atmospheric emission rate (577 t/d). A corollary of this is that when a dome is not growing (and the gas by-passes any existing dome rocks) the atmospheric emission rate should be 100 t/d greater than when it is growing. We can model this by partitioning the atmospheric emission rates into three components: dome growth (494 tonnes per day), no dome growth (594 tonnes per day) and collapses.

Reservoir Storage
Unloading-induced pressurisation (by a few MPa's) of the reservoir after the 12 July 2003 collapse was measured by CALIPSO dilatometers[5] and was invoked in 2003 by S. Sparks (after Pinel and Jaupart[6]) to explain observed high gas flux rates.

Conduit Storage/Permeability
Conduit storage may vary during and after explosive evacuation, but we have no real information. In the latter part of both major periods of no effusion the SO_2 emission rates fell to values well below the average. We know from the ash sample analyses of Devine during the latter stages of the 2003-2005 pause that hydrothermally altered conduit fill contained high levels of low-temperature silica. The drilling results from Unzen[7] show that only ten years after the end of the eruption, temperatures in the conduit zone at 1.3 km depth had fallen to about 200C. This suggests that the permeability of the conduit at Soufrière Hills was reduced, probably progressively, by silica deposition during periods of no effusion. The deposits of Galway's and Tar River Soufrières were characterised by high levels of silica and its potential role in reducing conduit gas permeability was proposed by Boudon et al.[8]. Although we cannot be more quantitative here, the silicification process could be invoked to produce the curvilinear type of SO_2 emission rate curve seen during long periods of no effusion.

15. The variation of the cumulative SO_2 emission rate about the mean indicates that we can store up to about 0.1 million tonnes in the dome and perhaps about 0.1 million tonnes elsewhere. This is about twelve months worth of cumulative average SO_2 emission (annual total = 0.21 million tonnes). Thus, when depleted, these stores could receive SO_2 from basalt and not be detected at the time by MVO atmospheric monitoring. To take this argument to its, unlikely, extreme we could have zero SO_2 surface emission for months yet an active system releasing SO_2 below. More practically, we could make use in future end-of-eruption

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[5] Voight, B. et al. ,2005. Unprecedented pressure increase in deep magma resrvoir triggered by lava dome collapse. Geophys. Res. Lett.,(submitted)
[6] Pinel, V and Jaupart, C., 2003. Magma chamber behavior beneath a volcanic edifice. J. Geophys. Res., 108/B2, 2072 doi: 10.1029/2002JB001751.
[7] Nakada, S.,Uto, K., Sakuma,S., Eichelberger, J.C. and Shimizu, H., 2005. Scientific results of conduit drilling in the Unzen Scientific Drilling Project (USDP). Scientific Drilling, no.1, 18-22.
[8] Boudon, G., Villemant, B.,Komorowski, J-C., Ildefonse, P. and Semet, M.P. 1998. The hydrothermal system at Soufreiere Hills volcano, Montsterrat (West Indies): characterization and role in the on-going eruption. Geophys. Res. Lett.,25, 3693-3696.

assessments of the current position of the observed cumulative curve with respect to a model dome storage curve. For example, a zero, or very low emission rate for a year at the end of June 2005 (end of the record here) would be much more indicative of the end of basalt degassing (eruption) than the same observation in early 2004.

Likelihood of Large Explosions

16. Here we revisit the issue of the likelihood of extremely large magnitude (i.e. large volume), high intensity (i.e. violent) explosions from Soufrière Hills Volcano - i.e. 3x Ref and 10x Ref intensity events. In previous SAC assessments, a single linear power law relationship (red line in Fig.3) had been used to express the relative numbers of explosions in each reference class size from 0.3x Ref. Intensity to 10x Ref Intensity, inclusive. Relying on global data for the relative numbers of eruptions with given Volcanic Explosivity Index values, the slope of this relation was taken to be about –0.9. By anchoring to the elicited 50 percentile (median) probability of occurrence values for the 0.1x Ref Intensity event, the relationship fall-off of –0.9 was applied to obtain the 50 percentile probability values for each successively larger class of reference explosion, together with the associated 5 percentile and 95 percentile spreads for each (pink filled area in Fig.3). (In this illustration, we use explosion probabilities that are associated with a magma flux rate of 2 – 5 cubic metres per second).

17. There is evidence that for Soufrière Hills Volcano extrapolation of this simple linear power-law relation is over-conservative. There is no evidence of 3x Ref. or 10x Ref. Intensity event in the last 200,000 years (see para. 20). In addition, during the present eruption the relative frequency of occurrence of 1x Ref. Intensity explosions, compared to 0.1x Ref. Intensity events, implied a power-law slope much steeper than the –0.9 assumed earlier - that is, the frequency of occurrence of larger events is likely to drop off more strongly than with the prior assumption. On the basis of recent experience, an exponent closer to –1.2 was felt to be more appropriate.

18. The committee was elicited to revise the annual probability of occurrence for the 0.1x Ref. Intensity class event and then, separately, for their views on the annual probability of occurrence of a 10x Ref. Intensity class event (together with the associated 90 percentile spreads). For events in classes 0.3x to 3x Ref. Intensity, the equivalent probabilities of occurrence can be derived from the 0.1x Ref. Intensity value using the –1.2 exponent. The upshot of these changes are that while the current probability of occurrence for a 0.1x Ref. Intensity event is now considered slightly higher than in April 2005, the probability for higher intensity events declines more rapidly than before (bold black line with + markers in Fig. 3 *versus* continuous red line). Taking the results of the latest elicitation, the previous piece-wise extrapolation to the highest class (10x Ref. Intensity) is now truncated, as shown by the break in the black line. Furthermore, the upper uncertainty spread involved is appreciably reduced (compare grey filled area with pink, on plot), which will also have a significant influence on the results of the quantitative risk assessment.

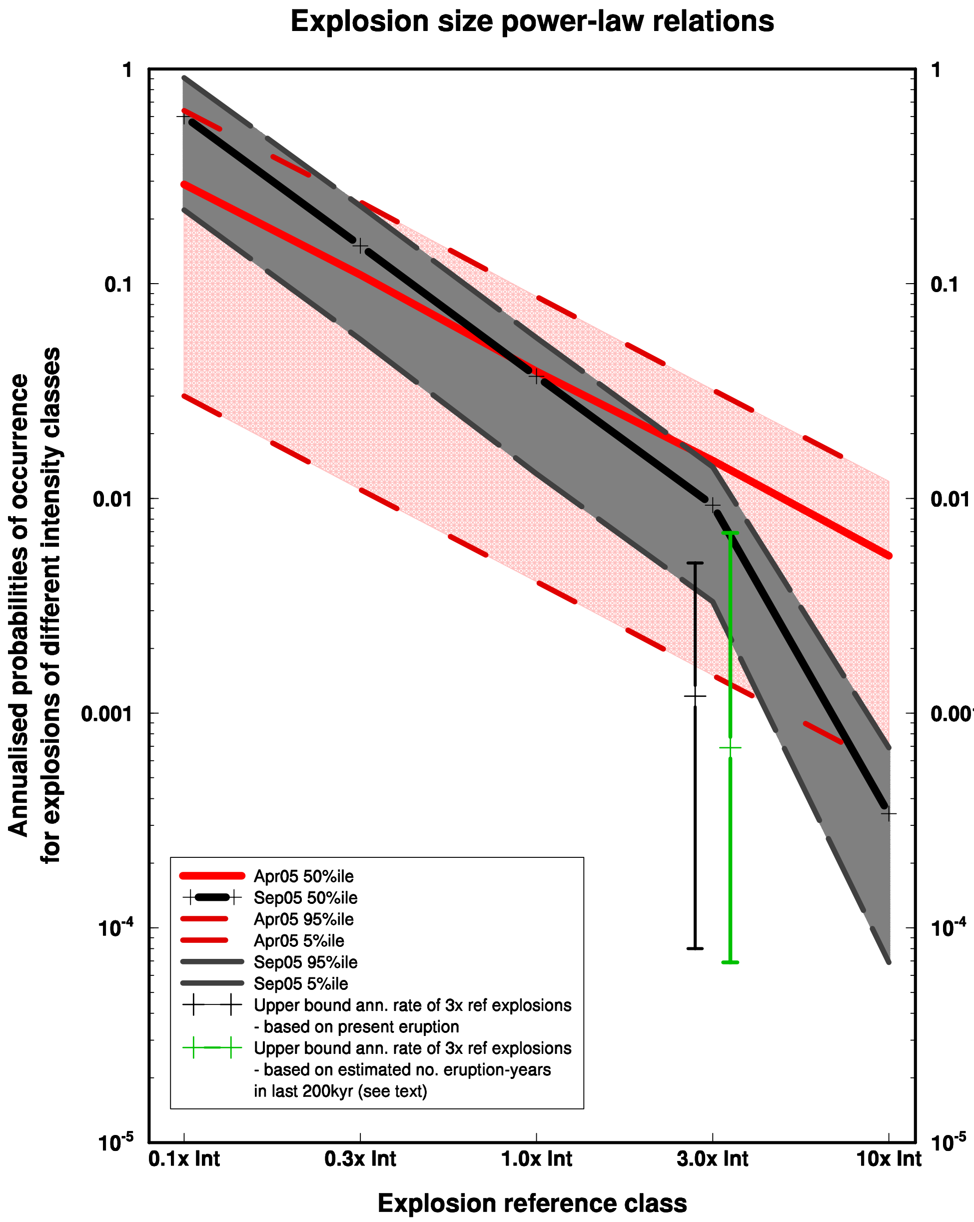

Fig. 3 Power-law relationships for explosion size, by intensity reference class (see text)

19. During the ten years of the present eruption, we have had no explosions greater than 1x Ref. Intensity, whereas we have had about eight 1x Ref. Intensity explosions. This suggests a physical impediment to tapping the magma reservoir directly during explosions. A 3x Ref. Intensity explosion, and certainly a 10x Ref. Intensity or bigger explosion, would have produced a recognisable airfall ash deposit "marker" horizon (>10-20 cm) that would be evident across much of Montserrat, particularly on the Centre Hills where the deposit would not be disturbed by later volcanic activity. Wind directions play a role as to where such deposits might accumulate, of course. However, no such horizons have been recognised. Recent coring and drilling offshore suggest no major andesitic airfall horizons from SHV (although the full analysis of cores is yet to be completed). Recent coring does suggest that

there were perhaps four major eruptive episodes with submarine deposition equivalent in volume to 1995-2005, during the last 200,000 years. The duration of these eruptive episodes is not known: they could, for instance, be measured typically in decades, like the present eruption, or might represent very intermittent eruptive activity taking place over several hundreds or thousands of years. On land, the domes of SHV suggest several major dome-building episodes have taken place that are not well represented by major submarine deposits.

20. For the purposes of estimating an upper bound on the frequency of occurrence of big explosive eruption events, one could conjecture that there may have been, say, 10 such eruptive episodes in the last 200,000 years, and that these lasted, on average, somewhere from 10 years to 1000 years in duration: this would suggest that Montserrat may have experienced between 100 and 10,000 'eruption-years' over this geological period during which times explosive activity took place. Assuming the biggest explosions occur as a Poisson process, if there has been no explosion of 3x Ref. Intensity or greater during 100 eruption-years (in the last 200,000 years), this suggests an upper bound on the underlying 'expected' activity rate for such events is no more than 0.007 events per eruption-year. If, as an alternative end member hypothesis, there had been as many as 10,000 eruption-years during the last 200,000 years, again with no explosion of 3x Ref. Intensity or greater, the expected rate upper bound would then be about 7×10^{-5} events per eruption-year. This range of possible upper bounds to the rate of 3x Ref. Intensity explosions is plotted as a (green) vertical bar in Fig. 3.

21. Another approach is to look at the experience within the present eruption: allowing that there have been, perhaps, as many as 120 significant explosions of one size or another in the last 10 years, none has tapped into the deep reservoir in such a way as to provoke a runaway massive explosion (as noted above, there could be physical reasons why this cannot happen). This limited sample of events, indicates a low hit rate, close to zero, for 3x Ref. Intensity explosions which could, however, still be compatible with an underlying Poisson process with a non-zero 'expected' mean rate for events of this class. A simple Gamma distribution analysis suggests the upper bound for the rate of occurrence of 3x Ref. Intensity events, given none has occurred in 120 cases, could correspond to an expected relative frequency of occurrence no greater than 0.006 per explosion. Thus, in the present eruption (given explosions have occurred in about 5 separate eruption-years in the last 10 years, but none has reached 3x Ref. Intensity size), the expected upper bound likelihood of such an event in any year with one or more explosions would be about 1×10^{-3} per year; the 90% confidence spread on this value is from 8×10^{-5} to 5×10^{-3} per year. This latter range is shown as a (fine black) vertical bar in Fig.3. Its range is surprisingly similar to that derived from the review of the long-term geological evidence.

22. The likelihoods, and hence risks, associated with the largest classes of explosive events (i.e. 1x, 3x and 10x Ref. Intensity) are now evaluated with much lower probabilities of occurrence than hitherto, and the extrapolation to an assumed rate for 10x Ref. Intensity explosions is truncated, relative to the smaller events. Even so, as a result of the changes brought about by the latest SAC elicitations and decisions, the estimated 50%ile occurrence rate for 3x Ref. Intensity explosions (derived for risk assessment purposes by extrapolating from the 0.1x Ref Intensity rate), is still higher than the upper extremes of either upper bound estimates based on the geological evidence and on our experience of explosion size scaling in this eruption. Thus, in terms of the largest classes of explosion, including the extreme 10x Ref. Intensity event, this new basis for estimating risks from explosions is considered to retain

a suitable level of conservatism and precaution. The impacts on the results of the related risk assessment are outlined in the discussion of societal risk (below).

Assessment of Volcanic Hazards

23. Given that the volcano has returned to a state in which lava extrusion has resumed, what are the hazards now posed by this volcano? If lava continues to be produced, the specific hazards likely to be present at some stage in the near future are:

explosions, with ash and rock fallout;
pyroclastic flows from explosive column collapse;
pyroclastic flows from dome collapse;
outward collapse of remnants of the former dome.

The nature and extent of these hazards will depend upon the rate at which magma arrives at the surface, and the way it accumulates once there.

24. In the light of this restart of lava extrusion, the main areas of specific concern for this meeting were, once again, the former DTEZ (which was re-opened for occupation in May 2004), and other areas within the present Exclusion Zone where economically important undertakings might be considered, such as tourist activities and industrial enterprises.

25. In assessing potential hazards, certain factors are judged to be important. Firstly, the likelihood that the lava extrusion rate could increase significantly within the period under concern (one year) is fundamental, and the degree of explosivity that might ensue, if this happens, is obviously important. The present topography of the volcano is also critical, in particular the geometry of features and slopes within the crater that will dictate how the new dome evolves, in terms of shape and size, and how it will collapse, if that happens. Pyroclastic flows are mainly guided by the topography and hence the vulnerabilities of different locations are determined by their neighbouring hills and valleys. (These factors were discussed in detail in the September 2004 Technical Report).

26. In addition to the on-land dangers, the volcano continues to pose a threat to sailors on boats and vessels in coastal waters (a Maritime Exclusion Zone has been in force for some time that was designed to minimise these risks). We have re-appraised the risks offshore, given the resumption of lava extrusion: while the zone offshore the Tar River Valley remains hazardous under any conditions of surface activity, other maritime zones are for the time being much less likely to be affected, but this will depend upon the exact way and intensity with which eruptive activity now progresses.

27. The activity of 15 to 19 April 2005 was of particular concern because it produced a vent on the outside of the crater. However, it seems highly likely that this vent lies on the boundary between the old crater (English's Crater) and the dome material that remained after the July 2003 collapse. Thus escaping gas probably followed an existing plane of weakness that dips to the south into the current crater. Sitting above this vent is part of the remnant Northwest Buttress that partially collapsed in March 2004. A concern is that the April gas-venting activity has excavated a new void within the near subsurface or weakened the stability of an old discontinuity adjacent to this rock mass and increased the likelihood of collapse.

Outward collapse in this area would send an avalanche into Tyer's Ghaut and possibly reach the Belham Valley near Cork Hill. To the southwest, another, pyramid-shaped remnant of the old dome overtops the crater rim above Gage's valley and has an estimated volume of about $2x10^6$ m^3. The collapse of March 2004, the current shape of the "pyramid" and the likely orientation of any failure plane all indicate that any collapse here will most probably be directed into the crater, to the east and the southeast. However, if an outward collapse were to occur, this volume of material could produce a debris avalanche or perhaps a pyroclastic flow (if it retains any pressurised gas). The study of Calder et al.[9] suggests that a volume of this size could have a run-out distance of three to four kilometres. This could send the avalanche into Gage's Valley to reach the upper part of Plymouth. We think that the likelihood of this hazardous outward collapse occurring in the next year is low.

28. In terms of other, secondary, hazards on land that can arise from the volcanic activity, mudflows are the most common. While many of these take place in valleys and ghauts within the Exclusion Zone, some develop and progress into the lower Belham River valley. Whilst many of the mudflows are triggered by heavy rainfall, not all heavy rainfalls trigger mudflows. The sediment being carried down the valley derives partly from the ash deposited during the eruption and partly from the erosion of older deposits. The generation of mudflows will only cease when the upper slopes of the valley are re-vegetated, a process that will take several years, even after the eruption stops. Given the resumption of lava extrusion and the continued elevated levels of gas production at the volcano, this state of affairs is now even further away than it was.

29. The effects of ash and gas on people in Montserrat are usually more of a nuisance than a threat to life and so are not usually considered in our reports. However, at this meeting we did consider the issue of plume gases and their potential impact of health. The four most abundant gases carried by the plume are water vapour, carbon dioxide, sulphur dioxide and hydrogen chloride, of which the latter two can be a problem at this volcano. The sector of the island from Old Road Bay to Kinsale is downwind from the gas vents most often. For example, Richmond Hill experiences about 84 days per year with the plume overhead, whilst the populated sector from Salem to St John's has on average only about 12 days per year with the plume overhead. The concentration of gases in the air experienced by someone on the ground also depends on the distance from the vent and whether the plume stays at height or falls to ground. MVO has been measuring the cumulative (every four weeks) ground concentrations of sulphur dioxide at five sites around the former DTEZ since 1997. These measurements (Fig.3) show two interesting patterns. Firstly, the average values of SO_2 measured during the last period of dome growth were substantially lower than during the periods of no dome growth. Secondly, measurement sites at higher altitude seem to have lower values (St. George's Hill) than neighbouring sites at lower altitude (Plymouth, Police HQ). At first sight these observations seem to be counter-intuitive. The low levels of ground-measured SO_2 from 2000 to mid-2003 when the dome was growing may have been due to higher, hotter and more buoyant plumes. As the plume reaches the ground it may act as a density current, flowing around hills and down valleys preferentially. Also as Longo et al.[10] found on Kilauea volcano,

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

[10] Longo, B.M., Grunder, A., Chuan, R. and Rossignol, A., 2005. SO_2 and fine aerosol dispersion from the Kilauea plume, Kau district, Hawaii, USA, Geology, 33, 217-220.

SO_2 may be lost by oxidation at higher altitudes caused by diurnal winds. More research into the micro-meteorology of the volcano would be required to understand these processes fully.

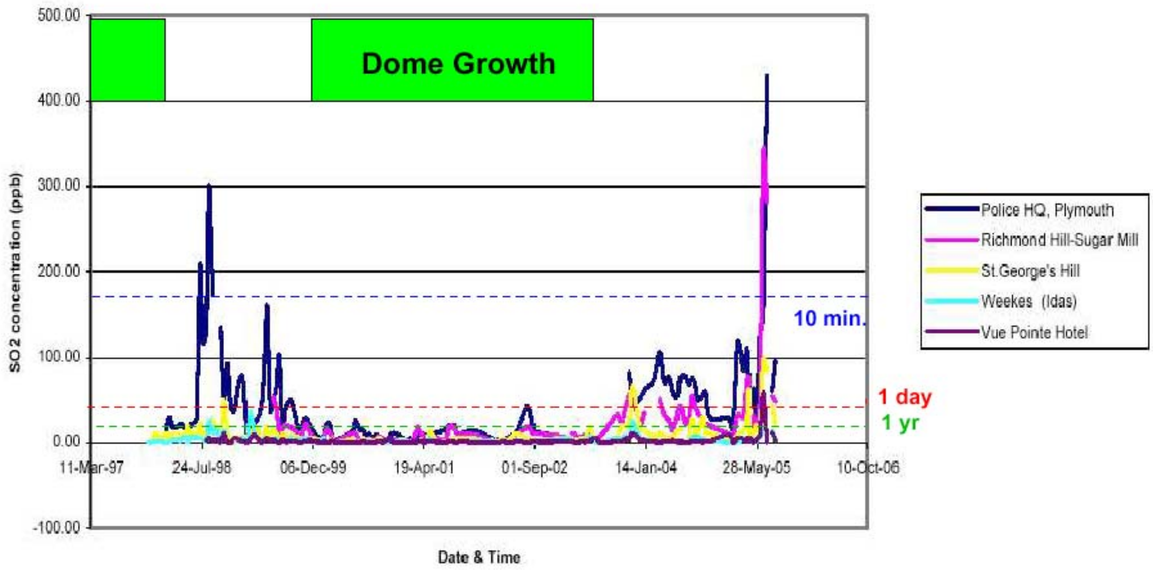

Fig. 4. Cumulative ground level sulphur dioxide concentrations measured by diffusion tubes in and around the former TDEZ from 1997 to 2005.

30. Allen et al.[11] pointed out that there are two groups in Montserrat exposed to volcanic gas: volcanologists, who sometimes work in the very high concentrations of gas close to the vent, and people living in vulnerable areas, specifically in the area of the former DTEZ. To this we can add a third group: tourists and others who occasionally visit the former DTEZ and Plymouth. There are guidelines for safe exposure over different periods (e.g. one year, one day, ten minutes) to sulphur dioxide concentrations issued by the World Health Organization[12] and the UK authorities (EPAQS), though they were not designed with volcanoes in mind. As can be seen from Fig.4, the one-day, and even the ten-minute, thresholds were exceeded in Plymouth and Richmond Hill during the build-up to dome extrusion in 2005. While limited exposure to levels exceeding such thresholds may not be dangerous for many people, people who are potentially at risk are those with asthma. As long as the plume is being emitted, the former DTEZ-Plymouth area will be an area of relatively high SO_2 (and HCl) concentrations. Simple warnings (signs, leaflets, verbal) to people suffering from asthma (perhaps one in five of the general population), particularly casual visitors such as tourists, on the need to have their inhalers available should help avoid many potential problems. In any case, the threat should be noted so that those who may be at risk can address the issue or seek medical advice. Gas levels are very much lower further north on the island.

[11] Allen, A.G., Baxter, P.J., and Ottley, C.J., 2000. Gas and particle emissions from Soufrière Hills Volcano, Montserrat, West Indies: characterization and health hazard assessment. Bull. Volcanol., 62, 8-19.
[12] Air Quality Guidelines for Europe, 2nd. Ed., Copenhagen, WHO Regional Office for Europe - WHO Regional Publications, European Series, No. 91, 2000.

Elicitation of Probabilities for Hazard Scenarios

31. 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. It should be noted, however, that the most recent estimate (October 2005) of magma flux rate is higher than that which existed at the time of the SAC meeting, but this is yet to be confirmed,. The following assessment of hazards and risks is based on that earlier average rate of extrusion (i.e. less than 1 cubic metre per second during the first two months of the new dome growth). If the recent extrusion rate increase is confirmed and continues, and it becomes apparent that the volcanic hazards have changed substantially from those presented here, then a re-analysis of the situation will be required within a period of weeks.

32. To update the risk assessment, fourteen items were discussed and re-elicited during the meeting on Montserrat. These are reported below as items *P2, P3a-d, P6a, P7a, P8a, P9a* where probabilities are involved, and *Q1*, *Q3b-d* and *Q4* when quantities are being 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.

33. 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.

34. *GIVEN current conditions, the probability that the present episode of dome growth will cease within 12 months (P2):*

Given that active processes at depth have not stopped and the volcano has started erupting magma again, this question measures views on the probability that the new episode of lava effusion will cease within one year.

Elicited Probability:

lower bound	*best estimate*	*upper bound*
1%	**21%**	**59%**

The chance of a cessation of dome growth within one year is thus judged to be about 4:1 against; whilst these odds are substantial, they are not strong and curtailment of magma extrusion would not be a great surprise.

35. *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*
1.3 months	**41 months**	**86 months**

36. *GIVEN what has happened to date, the probability that the lava flux rate will remain below 2 cubic metres per second (averaged over any month) for the duration of the present dome-building episode or for 12 months, whichever is the lesser (P3a):*
This and the following three questions seek to enumerate the probabilities of four different ranges of 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, and, on occasion, short term rates > 10 cubic metres per second may even have occurred briefly in 1996-97.

Elicited probability that magma flux rate will remain below 2 cubic metres per second:

Lower bound	*best estimate*	*upper bound*
19%	**58%**	**86%**

In the last assessment, this flux rate at restart was considered very likely (probability = 42%), although a rate in the next highest range, 2 - 5 cubic metres per second, was also given almost the same chance of occurring (41%).

37. *GIVEN what has happened to date, the probability that the lava flux rate will rise to peak at between 2 - 5 cubic metres per second (averaged over any month) during the duration of the present dome-building episode or for 12 months, whichever is the lesser (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 rise to peak at between 2 - 5 cubic metres per second:

Lower bound	*best estimate*	*upper bound*
10%	**32%**	**70%**

Thus, the SAC's opinion is that a peak flux rate in the intermediate range (*2-5 cubic metres per second*) is only half as likely as one in the lower flux rate range, – 0 - 2 cubic metres per second.

38. *GIVEN what has happened to date, the probability that the lava flux rate will rise to peak at between 5 - 10 cubic metres per second (averaged over any month) during the duration of the present dome-building episode or for 12 months, whichever is the lesser (P3c):*

Elicited probability that magma flux rate will rise to peak at between 5 - 10 cubic metres per second:

Lower bound	*best estimate*	*upper bound*
> 1%	**7%**	**30%**

As noted above, such high flux rates were last experienced during the second half of 1997. From this elicitation, the SAC therefore considers the chances of a recurrence of flux rates of this intensity are currently quite unlikely.

39. *GIVEN what has happened to date, the probability that the lava flux rate will rise to peak at above 10 cubic metres per second (averaged over any month) during the duration of the present dome-building episode or for 12 months, whichever is the lesser (P3d):*

This scenario involves exceptionally high (non-explosive) magma flux rates that may have occurred during brief peaks in activity in the early years of the eruption, but as such have never been maintained for more than a few hours at most. The present item considers an extreme situation in which very intense magma production, above 10 cubic metres per second, is sustained for a month or more.

Elicited probability:

lower bound	*best estimate*	*upper bound*
<0.01%	**2%**	**33%**

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. *If magma extrusion increases to peak at one of the elevated flux rates identified in items P3b-d, give the time in months from now when this rise might take place (Q3b-d):*

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

lower bound	*best estimate*	*upper bound*
0.2 month	**7.7 months**	**17 months**

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

lower bound	*best estimate*	*upper bound*
0.7 month	**8 months**	**20 months**

For peak flux rate above 10 cubic metres per second:

lower bound	*best estimate*	*upper bound*
1 month	**10 months**	**30 months**

41. *IF dome growth continues at a magma flux rate below 2 cubic metres per second, what is the probability of a subsequent 0.1x reference explosion (P6a):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
5%	**47%**	**78%**

42. *IF dome growth accelerates to peak at a magma flux rate between 2 - 5 cubic metres per second, what is the probability of a subsequent 0.1x reference explosion (P7a):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
22%	**61%**	**91%**

43. *IF dome growth accelerates to peak at a magma flux rate between 5 – 10 cubic metres per second, what is the probability of a subsequent 0.1x reference explosion (P8a):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
45%	**84%**	**98%**

44. *IF dome growth accelerates to peak at a magma flux rate above 10 cubic metres per second, what is the probability of a subsequent 0.1x reference explosion (P9a):*

Elicited Probability:

lower bound	*best estimate*	*upper bound*
57%	**93%**	**99.8%**

These four sets of probability distributions (P7a – P9a) 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.

Quantitative Risk Assessment

45. With the restart of dome growth in the first week of August 2005 signalling a new phase of activity at the volcano, we again make use of the same procedures for quantitative risk assessment that have been used since 1997. Once more, we revise our previous calculations of volcanic risk 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. (Again, we record the fact that this assessment was undertaken before the suspected increase in extrusion rate that took place in October 2005).

46. 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.

47. In response to requests from the authorities, the present assessment focuses principally on volcanic risk levels in the former Day-Time Entry Zone (DTEZ), and in certain areas that are 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 - i.e. Zones 1- 4 inclusive (see Fig. 1 of the March 2004 Report, Part II, and Fig.5).

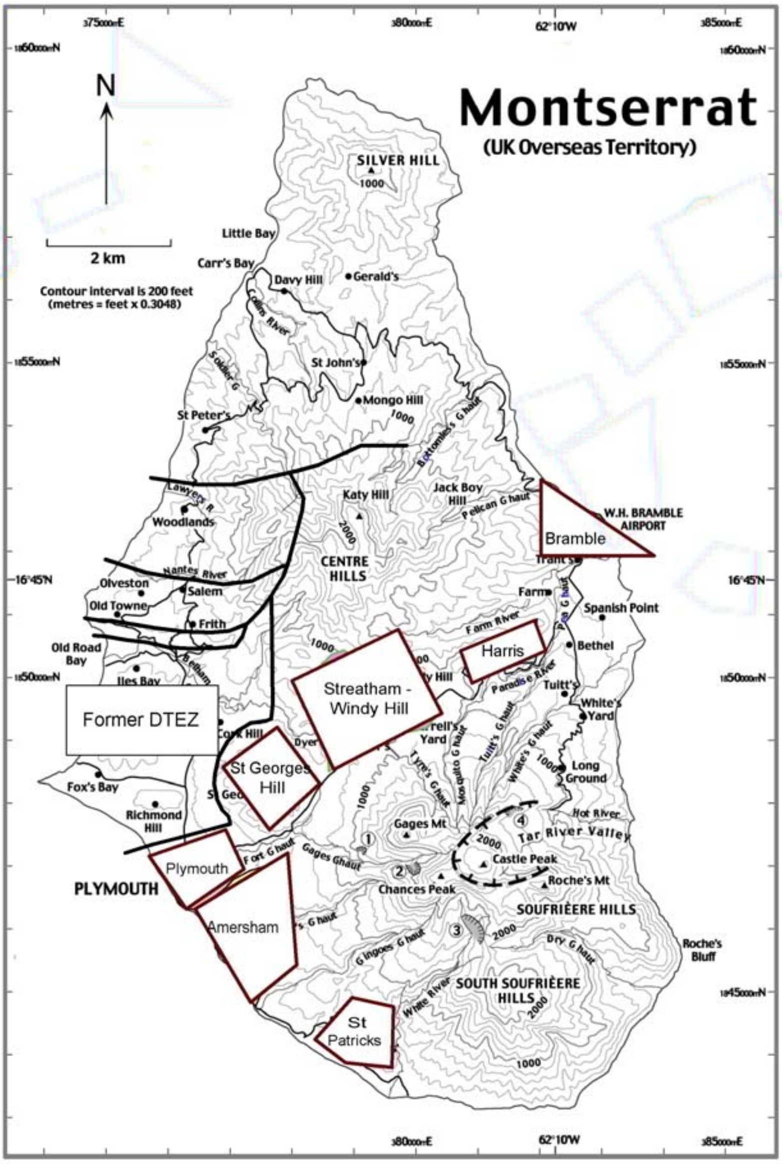

Fig.5. Map of Montserrat showing areas used for risk exposure calculations

Societal Risk Levels

48. *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 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: the elicited probability of this occurring is thought to be about 21%, that is, a 1 in 5 chance (or, 4 to 1 against, in odds).

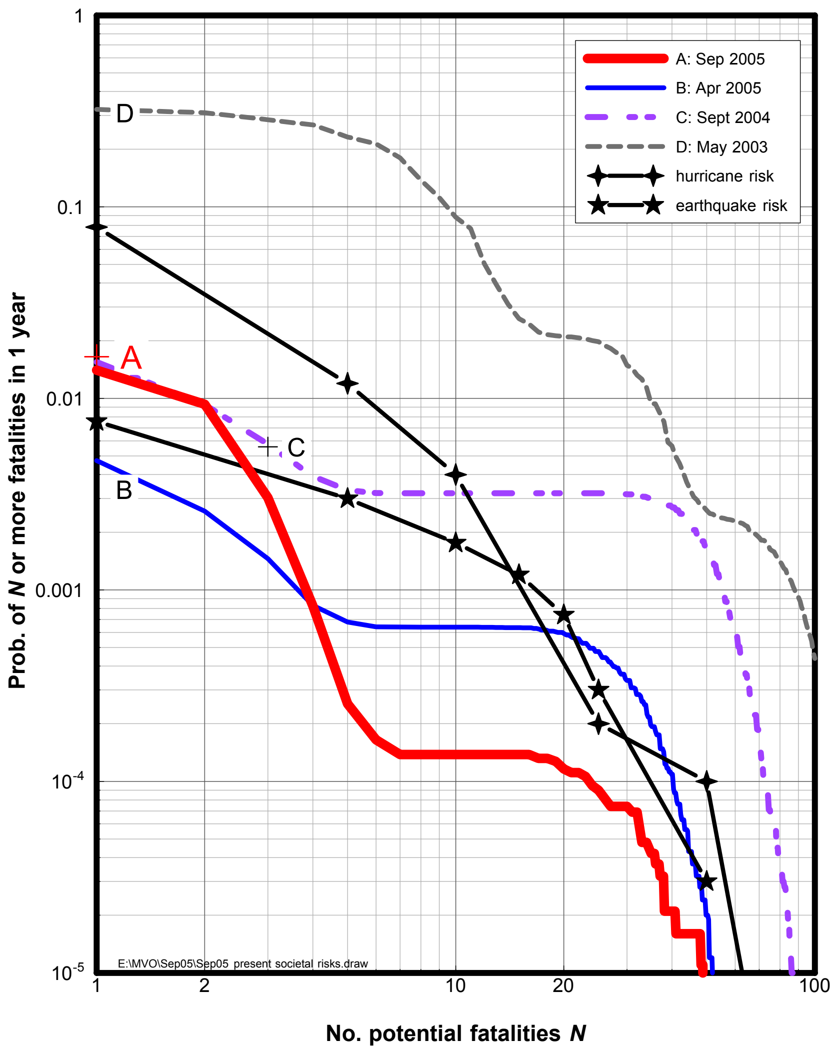

Fig. 6 Societal risk for present population of Montserrat, following restart of magma extrusion in August 2005

49. Fig. 6 shows the current annualised societal risk for Montserrat (curve A), together with those calculated in April 2005 (curve B) and September 2004 (curve C), and that which had been obtained earlier for May 2003 (curve D), when the last huge dome was still present. The first thing that needs to be said about this new risk curve is that there has been a change in its overall shape, reflecting a shift in balance between the relative likelihood of a few casualties (i.e. $N = 1 - 5$), and the likelihood of multiple casualties (e.g. $N > 20$). This change arises because the SAC committee has revisited the issue of high intensity explosions (i.e. the classes denoted as '3*x* reference explosion' or greater) and, on the basis of ten year's experience of the Montserrat volcano and a re-examination of the evidence accumulated in that time, has decided that previous evaluations of the probabilities of occurrence of such explosions can now be considered to have been conservatively expressed. It is these largest explosion scenarios that most strongly influence the risk of large casualty numbers. Thus, while there is a slight increase in risk levels for small numbers of casualties, given the restart in magma extrusion, the risk levels for large numbers of casualties are reduced compared to previous assessments. Overall, the threshold volcanic risk level at which one or more casualties may occur is slightly 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, over the next twelve months, magma flux rate could increase above its present rather low rate, and that increased flux rates could bring with them increased likelihood of explosive activity.

50. 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 now 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. 8 - 20 fatalities) the risks are lower than those from either of the other two natural hazards. Above about 20 casualties, and under present conditions, the threat posed by the volcano approaches those of hurricane or earthquake.

Individual Risk Exposure Estimates

51. 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).

52. *Risks in former DTEZ*
Given dome growth has only just restarted, and is proceeding at a low extrusion rate, the most immediate hazards to people residing or working in the former DTEZ 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 the DTEZ, and can be mapped from the simulation models. The hazards from column collapse pyroclastic flows would be concentrated in areas abutting flowpaths coming from Gage's Valley, and, marginally, in the Belham Valley near Cork Hill. With current conditions, the individual risk exposure for the former DTEZ is assessed LOW on the CMO's scale. However, the risk could move into the MODERATE or even HIGH categories if there is a switch to high rates of magma flux.

53. *Risk exposure for St. George's Hill*
Until a dome of significant size is rebuilt, the threat of hazards associated with dome collapse remain negligible in the St. George's Hill vicinity, so volcanic hazards are currently those from falling rock fragments from explosions, and/or pyroclastic flows from a column collapse eruption. Under the present conditions, our current hazards model indicates that the risk exposure for a person living full-time on St. George's Hill is LOW on the CMO's scale.

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

55. *Risks to tourists and short-term visitors in Plymouth*
For a tourist or person who makes a <u>single</u> short visit to an area with elevated risk (say, a trip into the middle of Plymouth of about two hours in duration), their limited time at exposure would correspond to an annualised individual risk of death or injury in the category NEGLIGIBLE on the CMO's Scale. For taxi drivers or others who make regular short-term visits week-on-week, although the chances of becoming a casualty would be higher, the individual risk can be expected to fall still in one of the categories MINIMAL, VERY LOW or LOW, depending on all the circumstances involved (i.e. number of trips made, and total time spent in Plymouth). However, it should also be recognised that whereas the risk levels involved are insignificant for any one individual tourist, the chances of suffering two or more casualties in a 12-month period from repeated multiple visits by different groups involving several persons may be non-negligible. For the scenario of a sudden onset explosive eruption and associated hazards (as discussed in relation to selected areas in the Exclusion Zone in see, para. 52 above), the probability of suffering a number of casualties amongst tourist visitors to Plymouth is estimated to be about 1.5×10^{-4} per year - i.e. there is a chance of about 1 in 6600 of this happening under present conditions, i.e. LOW RISK.

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

57. *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). 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.

Long Term Prognosis

58. At the last meeting we assessed the future likelihood of very large collapses and ash falls equivalent to the events of 12 and 13 July 2003. There is no need to revisit this analysis yet. In this report we have analysed the likelihood of future explosions very much greater than those of 13 July 2003. As a result of that we now think they are less likely to happen then we had previous thought.

59. The duration and vigour of this, the third major episode of lava extrusion during the eruption; the other two being 1995-1998 and 1999-2003, will depend on the state of the andesite magma reservoir and the continuing rate of supply of basaltic magma to it. The volcano could effectively repeat one of these two previous extrusive episodes or it may follow a different path. The first two episodes were very different from each other. The 1995-1998 extrusion rate started from very low values and accelerated into late 1997, whilst the 1999-2000 rate was much more even. The average extrusion rates of the two episodes over 2.5 and 3.5 years were about 3 and 2 cubic metres per second. This current episode has begun with a low extrusion rate (less than one cubic metres per second), more suggestive of 1995. The rate could rise to make the average more similar to either of the other two episodes. Alternatively, it could stay low. We think it more likely that the average extrusion rate will stay relatively low and that dome growth will continue beyond twelve months. Such a scenario would be expected from a system that was gradually losing the force driving magma to the surface. We do not yet have the evidence to test this idea.

60. There is a global database of dome-forming eruptions at andesitic volcanoes that we have used in other assessments to estimate given the likely 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 for 122 months in terms of its probability of lasting for five more years (0.77) and for another twenty more years (0.43). This is not very satisfactory because there are so few examples on which to base the calculation and the criteria that can be used to define when an eruption has ended cannot be rigorously applied across all volcanoes. For example, it could be

[13] See, e.g., 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.

argued that Soufrière Hills Volcano has had three eruptions in the last ten years, though from our position of knowledge this would be a misinterpretation.

61. The preceding assessment of hazards and risks and the long-term outlook are all based on views influenced by the average rate of extrusion that was measured during the first two months of the new dome growth. If the extrusion rate increases and it becomes apparent that the volcanic hazards and the long-term outlook have changed substantially from that presented here then we will recommend that the SAC re-analyse the situation formally again within a period of weeks.

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

A1.3 It is important to be mindful of the intrinsic unpredictability of volcanoes, the inherent uncertainties in the scientific knowledge of their behaviour, and the implications of this uncertainty for probabilistic forecasting and decision-making. There are a number of sources of uncertainty, including:

- Fundamental randomness in the processes that drive volcanoes into eruption, and in the nature and intensities of those eruptions.
- Uncertainties in our understanding of the behaviour of complex volcano systems and eruption processes (for example, the relationships between pyroclastic flow length, channel conditions and topography, and the physics of pyroclastic flows and surges).
- Data and observational uncertainties (e.g. incomplete knowledge of the actual channel and interfluve topography and conditions, material properties inside pyroclastic currents, the uncertain nature of future eruption intensities, dome collapse geometries and volumes etc).
- Simulation uncertainties, arising from limitations or simplifications involved in modelling techniques, and the choices of input parameters.

A1.4 These are all factors that are present when contemplating future hazards of any kind in the Earth sciences (e.g. earthquakes, hurricanes, floods etc.) and, in such circumstances, it is conventional to consider the chance of occurrence of such events in probabilistic terms. Volcanic activity is no different. There is, however, a further generic condition that must be understood by anyone using this report, which concerns the concept of validation, verification or confirmation of a hazard assessment model (or the converse, attempts to demonstrate agreement or failure between observations and predicted outcomes). The fact is that such validation, verification or confirmation is logically precluded on non-uniqueness grounds for numerical or probabilistic

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

models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[15].

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.

[15] 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.