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

Twelfth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity

Based on a meeting held between 9 and 11 March, 2009 at the Montserrat Volcano Observatory, Montserrat

Part II: Technical Report

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Introduction

1. This is the second part of the report resulting from the twelfth meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at the Montserrat Volcano Observatory from 9 to 11 March 2009. 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 a report[3], which synthesizes the monitoring data and observations collected by MVO between October 2008 and March 2009 and considers some of the new developments at MVO during the last six months. There were a number of short presentations from the SAC membership and MVO staff on scientific and hazard topics, including preliminary findings of an analysis of the performance of the SAC/RAP assessments over the past twelve years.

Activity and Observations since October 2008

3. Following the explosive and minor extrusive activity of May-August 2008, relatively little happened until 2 December 2008 when a series of four explosions began a period of extrusive activity that lasted until 3 January 2009, culminating in another major explosive episode. Since then surface activity has been much reduced.

4. The erosion of the upper talus on the eastern side of the dome by Hurricane Omar in mid-October 2008 exposed a 150 m-high, near-vertical cliff on the southeastern side of the dome that has been the source of small collapses that generated pyroclastic flows into the Tar River valley on 20 October, 27 October, 29 November, 13 and 16 December in 2008 and on 24 February and 6 March in 2009. Larger scale collapses from this cliff could induce a more sustained, major collapse of the dome.

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

[2] The information provided in both parts of this Report is advisory. It is offered, without prejudice, for the purpose of informing the party commissioning the study of the risks that might arise in the near future from volcanic activity in Montserrat, and has been prepared subject to constraints imposed on the performance of the work. While Committee members believe that they have acted honestly and in good faith, they accept no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG or GoM or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor can they accept any liability to any third party in any way whatsoever. See also Appendix 1.

[3] Stewart, R., Bass, V., Christopher, T.,Dondin, F.., Finizola, N., Fournier, N., Joseph, E., Komorowski, J., Legendre, Y., Robertson, R., Syers, R. and Williams, P. MVO Report for the SAC12 9-11 March 2009 meeting.

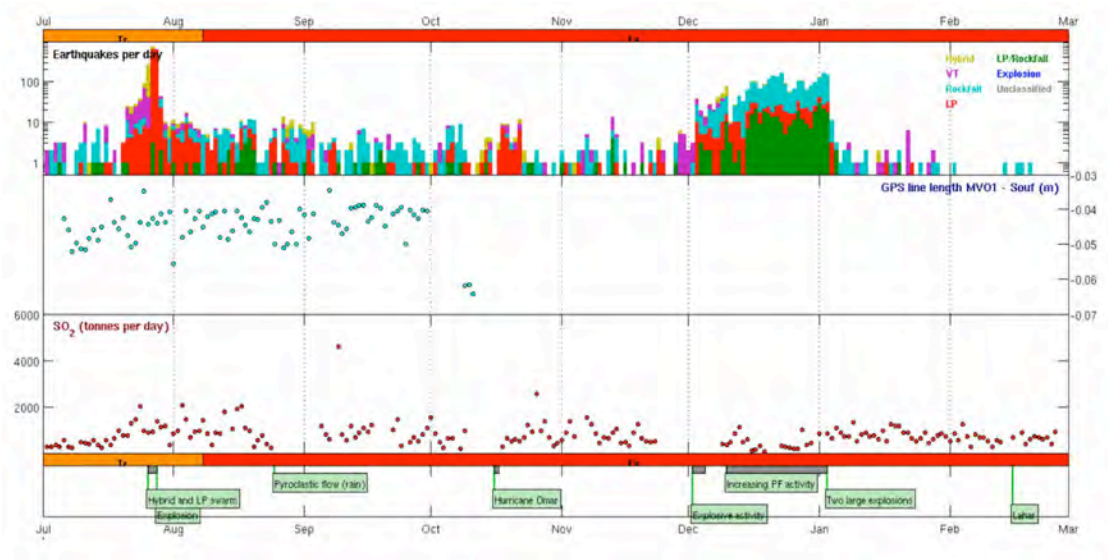

Fig.1 MVO's seismic, GPS (MVO-SSOUF line) and SO_2 flux data for July 2008 to March 2009.

5. In mid-November there were a few possible episodes of mild, banded tremor. But the explosion of 9:35 pm local time on 2 December had no recognizable precursory seismicity. It began with a small dome collapse that generated a pyroclastic flow into the Gage's Valley. Ninety seconds later there was an explosion and an ash cloud to 15 km in height with accompanying lightning. The explosion sent incandescent blocks up to 2 km away, particularly over Gages Mountain, and ash was blown to the west. The OMI satellite measured the sulphur dioxide content of the advected ash cloud the following day as about 3000 tonnes (S. Carn, pers. comm.), similar to that of the 28 July 2008 explosion. However, the lack of pumice in the tephra shows that the source material for the explosion in this case was pressurized lava within the dome and shallow conduit, not magma deep within the conduit.

6. The pyroclastic flow travelled to the west reaching the sea within about two minutes and starting fires at buildings in Plymouth. A lobe of the flow blanketed part of the 28 July pumice flow near Lees Yard, but did not extend as far. The main pyroclastic flow collided with the steep southeastern side of St George's Hill producing a surge that reached the top (120 m higher), but did not travel across the summit plateau. Surges also extended to the south across Aymer's Ghaut and to Richmond in the west.

7. Three smaller, explosions occurred at 8:43 pm on 3 December, at 4:22 pm on 4 December and at 5:41 am on 5 December. More ballistics were transported in the first and third of these events. Only in the third event was there another pyroclastic flow, almost reaching the sea at Plymouth. Three other shorter (less than 3 km) pyroclastic flows were produced during this period, all within the Gage's Valley, as well as copious amounts of ash-laden vapour. None of these three explosions had sufficient sulphur dioxide loading of the atmosphere to be detected by the OMI sensor. Seismicity during this four-day period included volcanic-tectonic, hybrid, long-period and rockfall events and two periods of low

level tremor. The vent for all this activity was apparently above the Gage's Wall vent that had formed during the 28 July explosion.

8. Between 5 and 10 December surface activity was not observed, but seven pyroclastic flows entered the Gage's Valley between 10 am and 5:30 pm on 10 December. Hybrid seismicity declined after this time and rockfall activity increased markedly, indicating that lava extrusion had begun. The main point of extrusion was above the Gage's Wall vent and a lobe of lava was built out onto the easternmost part of Chance's Peak, with rockfall into the Gage's Valley and several small pyroclastic flows. The largest of these, on 17 December, did not reach into Plymouth. Incandescence and ash emission on the western side of the dome during this period suggests that the same fractures in the dome created during the July event were being used as conduits by magma and gas in December. By 19 December the new lobe had grown sufficiently high that it began to send pyroclastic flows to the south into the upper part of the White River and then, on 20 December, to the north into Tyer's Ghaut.

9. From about 21 December onwards the seismicity showed an increasingly cyclic pattern with a period of about 4 hours between peaks that correlated with visual levels of activity, similar to the 1997 and late 1999-2000 activity. The rate of extrusive activity increased and generated larger pyroclastic flows into White River, Gage's Valley and Tyer's Ghaut. On 24 December a flow down Gage's Valley reached Plymouth and possibly the sea. Pyroclastic flows entered Tyer's Ghaut on its eastern side with some surge deposits onto Farrell's plain. Although poorly constrained, a preliminary estimate of the extrusion rate during the period from 10 December to 3 January is ≤ 5 cubic metres per second.

10. On 2 January a 3 km pyroclastic flow to the north reached as far as Lee's via Tyer's Ghaut. A period of increasing seismicity followed, culminating in two explosions on 3 January at 4:47 am and 7:07 am with a 500 m-high jet phase that lofted ash to about 11 km, with minor ash deposition over northern Montserrat. The OMI satellite does not appear to have detected a significant sulphur dioxide signal associated with this explosion. Unlike the 2 December 2008 explosion, tephra from this explosion was pumiceous, like that of 28 July 2008.

11. With the evacuation of the conduit by the explosions on 3 January 2009, magma supply stopped at the surface, and seismicity dropped to very low levels. It is apparent from the morphology of the December-January addition to the western side of the dome that the extrusion of lava had been focused in the west-central part of the dome, forming a lobe that reached a height of about 1050 m asl, similar in elevation to the neighbouring lobes from the 2007 activity. Incandescence and gas observations show that the more central part of the dome is now more active, suggesting that the Gage's Wall vent is now blocked , that the western episode of extrusion may be over for the time being and that the locus of any future extrusion will be more central.

12. The rainfall associated with Hurricane Omar (15-17 October 2008) seems to have triggered a small family of long-period earthquakes, though these did not result in any major dome instability. In hindsight the initial seismic activity related to the December-January episode was a modest increase in volcano-seismic events that

began on 28 November. However, the increase was too small to enable the events to be seen as precursory to the 2 December explosion. From about 5 December to 3 January seismicity increased gradually, dominated by hybrid and increasingly, long-period and rockfall events. As noted earlier, 1-minute RSAM data from 21 December to 3 January showed increasingly strong periodic behaviour. In addition, from October 2008 to March 2009 there were five large volcano-seismic earthquakes that were not apparently associated with surface activity (5 October, 6 November, 6 December 2008, 4 and 5 February 2009). Apart from the event in November, they all had very similar waveforms, suggesting the same source. However, apparent timing offsets in some of the recordings need to be resolved before any firm seismological interpretation can be made. A very long-period event was recorded at the St George's Hill seismic station on 30 November 2008 and may have been caused by a nearby landslide.

13. The switch over of the GPS processing method, from the Harris-as-reference frame to a global reference frame, has been completed by MVO. However, data from the South Soufriere station have not been available, as a result of which the MVO1-SSOUF reference line used previously has not been measured. Nevertheless, it is clear from the new processing of both the MVO GPS stations and the CALIPSO stations that for most of the period the same inflationary trend detected previously has continued. The exception to this is December 2008. Stations to the north and east (at Trants (TRNT), Geralds (GRED) and MVO1) show a sharp deflationary (south and down) motion during the month of explosions and lava extrusion. Stations to the west (at Air Studios (AIRS) and Olveston (OLVN)) show a much weaker signal. No EDM measurements were made during the last six months.

14. Since July 2007 (three months after the start of the last pause) the measured average flux of sulphur dioxide (~700 tonnes/day) has been above the eruption-average (~ 500 tonnes/day). In 2008-2009 this pattern was interrupted by a period of below-average flux between May and August 2008 when explosions, ash and minor lava production indicated magma rise within the conduit. Similarly, but less markedly, low fluxes were measured during the December 2008 period of lava extrusion. This suggests that permeability to sulphur dioxide rise was inhibited by the presence of high-level andesite in the conduit during both these episodes. Since January the sulphur dioxide levels have again largely been above the eruption-average level. No FTIR measurements of the HCL/SO_2 ratio during the December 2008 extrusion were made.

Interpretation of the December 2008 – January 2009 episode

15. The episode of increased activity that began on 2 December 2008 and ended on 3 January 2009 was unusual in that it involved a short period (about 25 days, 10 December – 3 January) of moderate to high lava flux (perhaps 5 cubic metres per second) and two sets of explosions, one at the beginning and one at the end of the episode. Such a distinct, relatively short and vigorous episode has not been recognised as an independent entity before during the eruption.

16. The volcano-tectonic seismicity that was precursory to this episode was very much weaker than that which preceded the 28 July 2008 explosion. This suggests that any rising magma was able to use the pre-existing pathway that fed the July event.

17. The intervals between the five explosions from 2 and 5 December were 23, 20,13 and 9 hours long. This is suggestive of an accelerating process or a moving boundary condition such as a rising magma column. The non-pumiceous character of the tephra from these explosions, the block-and-ash character of the pyroclastic flows, their confinement to the Gage's Valley, and the high pressures required to send ballistic blocks up to 2 km distance are all consistent with relatively shallow explosions of new, rising magma that involved existing lava from the same vent created during the July-August activity. The atmospheric SO_2 loading and the extent of the pyroclastic flow deposits were similar to those of 28 July, but the aggregate thickness of the block-and-ash component was greater for the 2-5 December events, with a total non-dense rock volume of perhaps up to 1 Mm^3 (compared to 0.2-0.3 Mm^3 for 28 July 2008)

18. It is possible that between 5 December and 10 December, when the resumption of pyroclastic flows suggests that lava reached the surface, the voids created by the explosions were being filled by lava. TerraSAR-X radar images show that the vent for the explosions was directly above the 28 July vent and further to the east. The gradual increase in the seismic amplitude over the following days reflects the increased levels of rockfall as the lava created a new lobe in the west. As the elevation of the point of extrusion increased from perhaps 900 to 1050 m asl, more rockfalls and pyroclastic flows were directed to both the south and north. The increasingly evident, ~4-hourly period to the seismicity from 21 December onwards is indicative of a repeating process, probably similar to the stick-slip type mechanism invoked for the May-September 1997 period, and also November 1999-January 2000[4], when the characteristic period was about 9 hours.

19. The cause of the 3 January explosions is notknown. That they involved deep (~1-2 km?) evacuation of the conduit is evident from the pumiceous nature of the tephra. The pumice from the 28 July 2008 explosion has water contents in its matrix glass indicative of fragmentation depths of at least 2 km[5]. The variability of hornblende rims further suggests that the magma ascent rate was not constant. The explosions could have been initiated by high internal pressure or a prior large collapse event. However, the explosions apparently did not disrupt the western lava lobe built up by the previous 25 days of extrusion, instead the vent must have been to the east of this lobe and close to a position above the original central feeder conduit for most of the eruption. Another explanation for these explosions is that they mark the re-establishment of this pathway to the surface for the first time since April 2007. Certainly the subsequent observations of central incandescence favour this explanation. This may mean that the western system of vents above Gage's is currently blocked and will not play a role in the next activity.

[4] Young, S.R., Voight, B., Duffell, H.J., 2003, Magma extrusion dynamics revealed by high frequency gas monitoring at Soufriere Hills Volcano, Montserrat. Geol Soc (London) Spec. Pub. 213, 219-230.
[5] Humphreys, C.S. (2009) Petrology of samples from 28th July 2008. Report to MVO.

20. A full analysis of the deformation associated with this event is needed, but some preliminary analysis suggests the following. The deflationary signal detected by GPS that corresponds to this eruptive episode was effective immediately at the start and end, with no lag (to within a few days). This rapid response, and the apparent non-axisymmetric nature of the deformation field can be explained by a source of the deformation that was elastic around a dyke oriented NW-SE.

Significance of the July-August and December-January eruptive episodes

21. The eruption has been characterised by 2-3 year cycles (Fig.3) of lava extrusion and slightly shorter periods of non-extrusion (pause). The last pause began in April 2007. In the last (SAC11) report we debated whether the July-August episode of activity represented the end of this, third, pause or was a transitional step to the renewal of continuous extrusion. We are again faced with a similar issue after a second brief resumption of (much more vigorous) extrusion and explosions has failed to lead to the establishment of sustained rise and extrusion of magma. Now the pertinent questions is - Will the activity continue as a more frequent series of short extrusive episodes like those two just experienced, or will the former longer-period regime be re-established?

22. Underlying the above question is the issue of the physical mechanism that has allowed these two episodes to occur. One distinctive feature of the current state of the volcano is that this is the largest (volume ~210 Mm^3) and highest (~1050 m asl) lava dome through which magma has tried to reach the surface following a pause, during the whole eruption. An extra 10 MPa of magmatic pressure is required to raise magma to the top of the current dome compared to say the case during the re-start of extrusion in August 2007. It is possible that the system cannot currently sustain the required overpressures for longer than about one month. This concept is shown schematically in Fig.2 as a pressure valve acting at thebase of the dome. Alternatively, the periodicity may be controlled at a deeper level, say within the magma reservoir, whereby smaller discrete batches enter the conduit (Fig.2). We favour the dome-control mechanism because this is a factor that is unequivocally present, in unique to this period and the underlying magmatic processes appear unchanged.

23. A periodically-pressurised dyke conduit for the magma could help to explain the GPS observations associated with the December-January extrusive episode. The sudden response and the assymmetry of the deformation field may be indicative of a NW-oriented dyke. Costa et al.[6] and Hautmann et al. [7] proposed such a conduit to explain the 5-7 week periodicity first detected by the Chances Peak tiltmeters in 1997. The wider movement field detected by GPS in December 2008 would require a deeper dyke.

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[6] Costa, A.,Melnik, O.,Sparks, R.S.J., Vight, B. (2007) Control of magma flow in dykes on cyclic lava dome extrusion. Geophys. Res. Lett., 34, L02303, doi:10.1029/2006GL027466.

[7] Hautmann, S., Gottsmann, J., Sparks, R.S.J., Costa A., Melnik, O. and Voight, B. (2009) Modelling groud deformation caused by oscillating overpressure in a dyke conduit at Soufriere Hills Volcano, Montserrat. Tectonophys., doi:10.10116/j.tect.2008.10.021

24. Provided there is not a major dome collapse, the large-dome-as-pressure-valve mechanism may continue to produce a series of shorter extrusive episodes. Alternatively, there may an evolution to a steady state regime such that long-term extrusion is re-instated from the next episode. We think that over the next year the former is about twice as likely as the latter.

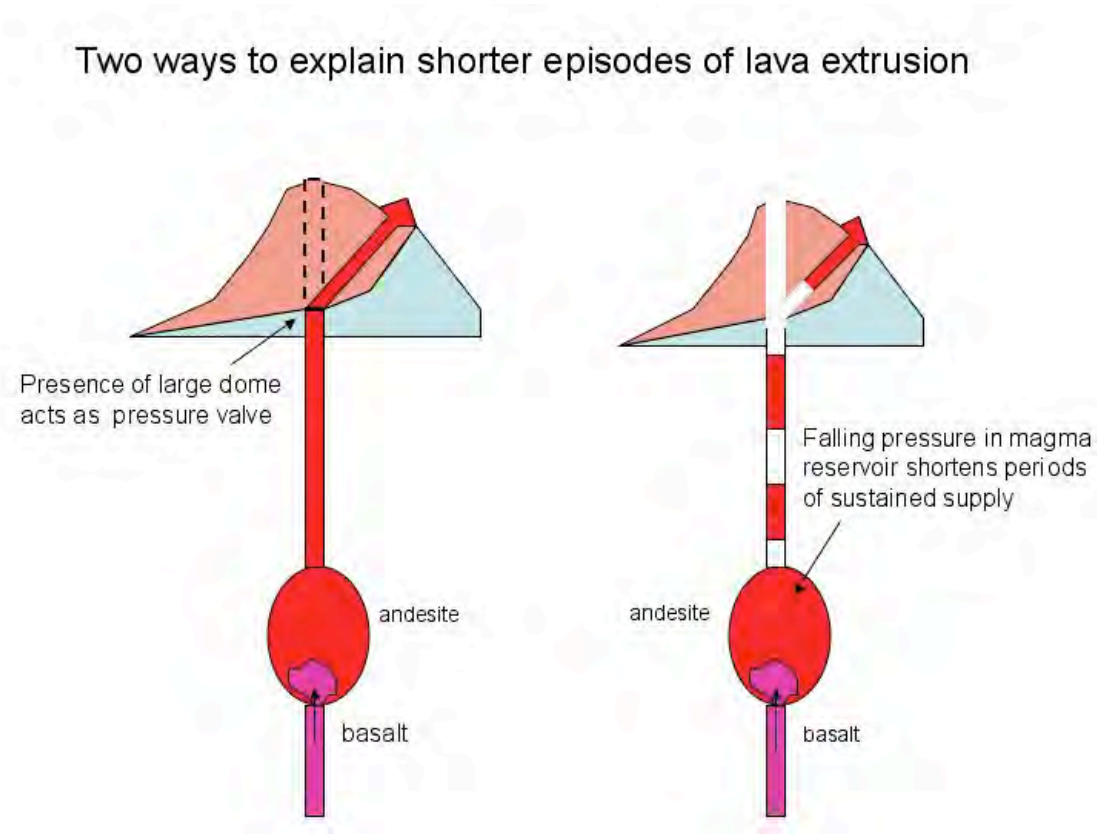

Fig.2 Two schematic mechanisms for generating shorter episodes of magma supply. Left: the mass of the dome acts as a pressure valve. Right: the magma arrives through the conduit in pulses. The non-vertical conduit represents the feeder to the Gage's Wall vent.

End of the eruption?

25. As for the previous SAC meeting, we assume the volcano is in a paused state and test the established criteria for detecting whether this paused state may in fact be the end of the eruption:

Criterion 1. The SO_2 daily emission rate averages less than 50 tonnes per day.

Criterion 2. An absence of low frequency seismic swarms and tremors associated with the magmatic system.

Criterion 3. No significant surface deformation from a demonstrably deep source.

26. All three criteria need to be tested retrospectively against the measurements of the previous period. When all three criteria have been met for one year the eruption can be declared over. Our confidence in the outcome of such a test depends on the quality of the measurements and the correctness of our interpretation of them, and we assess the uncertainty in these using a Bayesian Belief Network (BBN: see a previous report[8] for a description of this methodology).

27. We find again that over the past year none of the criteria have been met, and therefore infer that basalt is continuing to enter the system at depth. Our confidence in this interpretation is based on the evidence-weighting concept of likelihood ratios, quantified in probabilistic terms using the BBN analysis technique. We did not repeat the analysis again this time but consider that it remains very high (numerically, the inference that basalt related intrusion is on-going has a probability of being correct greater than 0.99 – in other words, there is a less than 1% chance this interpretation is fallacious).

Long Term Prognosis

28. This fourteen-year eruption is one of the longest-lived dome building eruptions on record. One definition of this type of volcano, with 97 examples worldwide, makes Soufriere Hills now the fifth longest-lived. Using the Generalised Pareto distribution derived for the global database, as in the last report, we calculate the survivor function for the present Montserrat eruption. Because the eruption is now very long-lasting, this duration function is changing more slowly than before, and statistical estimates of the potential duration of the eruption are much the same as they were six months ago. Given this eruption has now lasted 164 months, we obtain an estimate that the statistical probability of it lasting another five or more years is 0.83. For an eruption that has already lasted 164 months, the expected duration (0.50 probability) is about 36 years, corresponding to a further twenty-two years in the present case.

29. On the basis of the global data, the probability of this eruption stopping within one year is no more than about 0.04 (i.e. a 1-in-25 chance). Reflecting upon the present state of the volcano and its most recent behaviour, an elicitation of the SAC12 experts puts their current assessment of this probability slightly higher: at about 0.07. This, however, is still a low likelihood: a 1-in-14 chance.

30. A study underway (by T. Christopher and A. Donovan) of whole-rock geochemistry samples since 2000 shows some interesting secular trends in major element contents. For example, the content of Fe_2O_3 decreases across both the second and third eruptive episodes. Any interpretation of the significance of such trends in isolation is necessarily speculative. Extension of the study to earlier phases and fuller analysis are awaited but should enable a more robust assessment of long-term changes within the system at depth.

[8] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Tenth report of the Scientific Advisory Committee on Montserrat Volcanic Activity. Part II, Tech. Report.

31. We may be entering a period of shorter episode of extrusion and pause (Fig.3). If the mechanism responsible for the putative change to shorter periods of extrusion lies in the magma chamber (Fig.2, right), or deep supply, this may signal a change in the system as a whole. As discussed in the last SAC report, a long-term loss of pressure in the magma storage system could be responsible for an inability to maintain continuity of supply to the surface over a period of a few years, leading to a point where the system has insufficient driving pressure for magma to reach the surface at all and the eruption would stop.

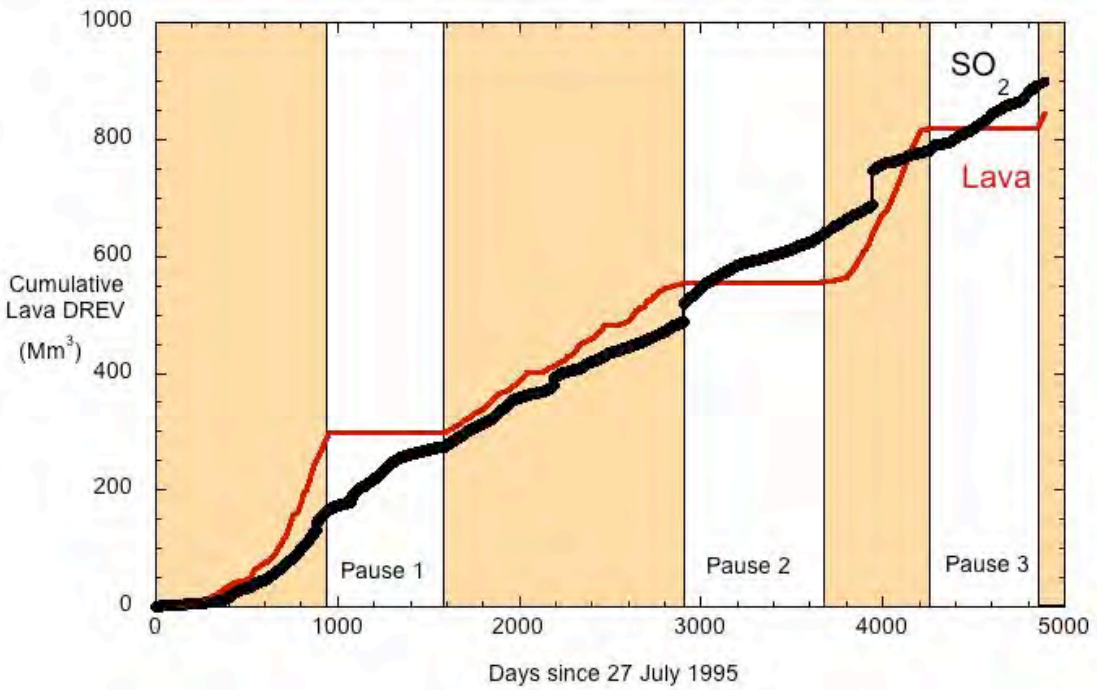

Fig. 3 Cumulative volume of lava and mass of sulphur dioxide produced by Soufriere Hills from July 1995 to January 2009. The sulphur dioxide curve is arbitrarily scaled for visual comparison with the lava curve.

Assessment of Volcanic Hazards

32. The dome is now larger than six months ago, mainly as a result of the December 2008-January 2009 extrusion of lava. This lava was added to the western side of the existing dome mainly above the Gage's Valley. Thus the hazards from lava dome collapse and explosions that were present six months ago are still relevant. Despite the extra loading produced by the new lobe there have been no visible signs of any structural deterioration in the stability of the Gage's Wall Pyroclastic flows during the December 2008 – January 2009 episode reached the sea at Plymouth and at the White River delta, with runouts of over 4 km. One flow reached Lees in the upper part of the Belham Valley. However, despite the concentration of dome growth above the Gage's Valley and the preponderance of rockfall and collapse events to the west there were no flows that were diverted

northwards through the Lees's gap between St George's Hill and Gage's Mountain and into the Belham Valley.

33. One reason for this is that the locus of extrusion in late December 2008 moved eastward from the site of the Gage's vent as the new lobe of lava grew. Thus the extrusive vent was increasingly able to send rockfall and pyroclastic flows to both north and south as it grew in height and moved eastward. Currently, the new lobe shows no sign of heat or fumaroles, whilst the old northwestern lobe of 2007 on which it was built shows both. This may mean that the pathway to the Gage's vent is now blocked and the next lava will find egress in a more central, higher location. Lava at a moderate to high flux from such a vent could send sizeable pyroclastic flows into Tyer's Ghaut.

34. The explosions of 2-5 December 2008 sent large bombs up to 2 km to the northwest and a surge derived from moderate dome collapse almost overtopped St George's Hill. These phenomena and the suddenness of the onset of the first 2 December explosion could have proved fatal to any people visiting Lees's Yard or St George's Hill. Zone C generally remains at risk from the effects of such explosions.

35. Does the prospect of more frequent extrusive episodes bring any new hazards? Probably not, but it may change the level of hazard and the way the risk is managed. Every occasion that magma has to force its way to the surface through a choked or new conduit, as it will have to do at the start of each new episode, brings the increased risk of destabilising the dome and a major collapse or lateral blast. The length and magnitude of the 26-28 July 2008 seismic crisis and the surface fracturing shows that there was probably significant deformation of the western part of the dome. The seismicity prior to the 2 December 2008 event was much weaker, suggesting that the previous pathway through the dome was re-used. Both of these events were on the western side of the dome. It may be that new magma rising in another direction will be more likely to destabilize the dome. Around the last extrusive episode the hazard level was increased on 10 December 2008 and reversed on 26 February 2009. Public response to frequent changes in hazard level with each new extrusive episode could be negative because of their unsettling consequences. Alternatively, people may co-operate more fully because they are used to it.

36. With the present conditions, the principal sources of volcanic hazard currently posed by Soufriere Hills Volcano are:

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

    Lesser hazards include tsunamis from large flows entering the sea, mainly at Tar River Valley and mudflows in the Belham Valley.

Elicitation of Probabilities for Hazard Scenarios

37. We now 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.

38. We follow the general framework of questions used since the start of 2007, but with the addition of three new items relating to the possibility that the volcano may be changing to a shorter, more episodic lava extrusion regime (see discussion in paragraphs 21-24). As before, questions 1-2 and 10-16 capture the exclusive set of scenarios for hazardous volcanic activity thought possible over the next year based on the first significant event to happen during that period with the focus being on events capable of threatening people living around the Lower Belham Valley. As discussed in earlier reports, we envisage a pyroclastic flow would require a volume of 10 million cubic metres or more going down the Belham Valley in order to reach the sea. Questions 17 and 18 test the conditional probabilities that flows in the Gages Valley and on the north-eastern flanks of the volcano could also generate hazardous flows within the Belham Valley. The other, repeated, questions (3-9) explore the likely location of the next point of extrusion (central vent, Gage's Wall vent, Farrells Wall or elsewhere) and the likely rate of extrusion in those locations (<1, 1-5, >5 cubic metres per second).

39. Three new questions (2a – 2c) have been added in which the first two assess the scenario likelihoods that the next resumption of lava extrusion, if it happens (question 2), will find the volcano reverting to the previous "20-month" pause-extrusion regime, or that it will next go into a more intermittent mode with shorter periods of intense magma extrusion, such as was experienced in the December 2008 – January 2009 episode. A third supplementary question (2c) asks how many such occurrences might be expected in the next twelve months, if a shorter episodic pattern does develop.

40. The following boxes summarise the results of the SAC elicitation for the identified scenarios, with counterpart values from SAC11, where available, given in the lower panels (n.b. the list is not ordered strictly according to the question identification numbers). Where noted in the description of each item, the particular scenario relates solely to the **first** occurrence of any significant event that happens in the next year. If such an eruptive event occurs, all scenario-associated probabilities will need to be updated in the light of the new conditions.

1. GIVEN what has happened over the last 6 months and current conditions, what is the probability that **nothing** significant will happen (i.e. no collapse, no restart of dome growth, no magmatic explosion > 0.1x ref) <u>in the next 12 months.</u>

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**1.0%**	**11%**	**32%**
SAC11	0.005 %	9.9 %	51.9 %

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

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**12 %**	**47 %**	**84 %**
SAC11	6.3 %	34.1 %	66.1 %

2a. GIVEN the **first** significant development is a **resumption** of lava extrusion, what is the probability it will be a reversion to the "20-month" extrusion/pause pattern?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**9 %**	**35 %**	**70 %**

2b. GIVEN the **first** significant development is a **resumption** of lava extrusion, what is the probability it will follow a shorter episodic on-off pattern, similar to Dec 2008 – Jan 2009?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**17 %**	**65 %**	**95 %**

2c. If the short on-off pattern occurs, how many episodes will occur in the next 12 months?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**1**	**2**	**5**

10. GIVEN current conditions, the probability that in the next year the **first** significant activity will be collapse of the dome (e.g. to Tar River or the south, but not to W, NW or NE) which takes away the bulk of the dome harmlessly (if HLS restrictions are observed):

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**5.5 %**	**21 %**	**69 %**
SAC11	6.7 %	25.2 %	59.2 %

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

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.04 %**	**3 %**	**13%**
SAC11	0.5 %	4.3 %	45.2 %

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

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.02 %**	**2 %**	**12 %**
SAC11	0.1 %	2.1 %	29.7 %

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

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.9 %**	**5.9 %**	**37 %**
SAC11	0.5 %	4.3 %	35.4 %

14. GIVEN current conditions, the probability that within next year the **first** significant event will be a major dome disruption event - with an associated blast - involving enough material avalanching **to the NW** (Tyre's/Belham) to generate a flow/surge runout to reach the sea:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.001 %**	**0.05 %**	**3 %**
SAC11	0.001 %	0.02 %	8.5 %

15. GIVEN current conditions, the probability that within next year the **first** significant activity will be a major dome disruption event involving enough material avalanching **to the W** (Gage's), with lateral blast, such that the flow/surge would reach the sea at Plymouth:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.01 %**	**0.2 %**	**6 %**
SAC11	0.005 %	0.07 %	10.5 %

16. GIVEN current conditions, what is the probability that the **first** significant event will be a vertical explosion of 0.1x reference size or greater (with limited associated dome disruption):

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.7 %**	**8 %**	**35 %**
SAC11	1.6 %	20.1%	62.6 %

17. IF there is a big collapse **to the NE** that would reach the sea at Trants, what is the **conditional probability** this will also involve enough material (i.e. at least 10 M m^3)

spreading to N / NW to generate a flow/surge with runout to reach the sea **down the Belham**:

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**1 %**	**12 %**	**34 %**
SAC11	0.5 %	6.9 %	35.5 %

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

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**0.1 %**	**9 %**	**37 %**
SAC11	0.1 %	3 %	10 %

3. GIVEN magma extrusion resumes within the next year, what is the probability that extrusion will be focussed mainly in the western part of the dome (i.e. near Gage's Vent location)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**3 %**	**20 %**	**54 %**
SAC11	18.2 %	58.5 %	88.8 %

3b. GIVEN magma extrusion resumes within the next year, what is the probability that extrusion will be focussed mainly in the N & NW (Farrells) part of the dome (i.e. above Tyre's Ghaut)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**3 %**	**26 %**	**79 %**
SAC11	2.1 %	9.0 %	38.0 %

4. GIVEN magma extrusion resumes within the next year, what is the probability that extrusion will be focussed mainly in the central part of the dome, as it was in earlier phases?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**14 %**	**46 %**	**82 %**
SAC11	6.1 %	32.3 %	73.7 %

5. GIVEN magma extrusion resumes within the next year, what is the probability that extrusion will be focussed mainly in a new location elsewhere (other than Farrells, central or Gages?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**1 %**	**8 %**	**48 %**
SAC11	0.005 %	0.25 %	38.5 %

6a(i). GIVEN magma extrusion resumes within the next year in the western part, what is the probability that peak extrusion will be very low (i.e. not exceed 1 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**2 %**	**12 %**	**49 %**
SAC11	7.9 %	52.0 %	93.6 %

6a(ii). GIVEN magma extrusion resumes within the next year in the western part, what is the probability that peak extrusion will be moderate (i.e. 1 - 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**18 %**	**64 %**	**94 %**
SAC11	10.6 %	35.2 %	71.2 %

6a(iii). GIVEN magma extrusion resumes within the next year in the western part, what is the probability that peak extrusion will be high (i.e. > 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**4 %**	**24 %**	**64 %**
SAC11	2.1 %	6.7 %	48.1 %

7a(i). GIVEN magma extrusion resumes within the next year in Farrells, what is the probability that peak extrusion will be very low (i.e. not exceed 1 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**3 %**	**18 %**	**49 %**
SAC11	10.1 %	58.8 %	93.6 %

7a(ii). GIVEN magma extrusion resumes within the next year in Farrells, what is the probability that peak extrusion will be moderate (i.e. 1 - 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**21 %**	**69 %**	**95 %**
SAC11	12.3 %	32.7 %	70.7 %

7a(iii). GIVEN magma extrusion resumes within the next year in Farrells, what is the probability that peak extrusion will be high (i.e. > 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**2 %**	**13 %**	**60 %**
SAC11	2.1 %	6.7 %	47.8 %

8a(i). GIVEN magma extrusion resumes within the next year in the central part, what is the probability that peak extrusion will be very low (i.e. not exceed 1 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**2 %**	**10 %**	**49 %**
SAC11	4.7 %	19.0 %	48.1 %

8a(ii). GIVEN magma extrusion resumes within the next year in the central part, what is the probability that peak extrusion will be moderate (i.e. 1 - 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**19 %**	**62 %**	**89 %**
SAC11	18.9 %	57.8 %	84.5 %

8a(iii). GIVEN magma extrusion resumes within the next year in the central part, what is the probability that peak extrusion will be high (i.e. > 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**4 %**	**28 %**	**79 %**
SAC11	5.2 %	21.6 %	52.9 %

9a(i). GIVEN magma extrusion resumes within the next year elsewhere in the crater, what is the probability that peak extrusion will be very low (i.e. not exceed 1 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**2 %**	**12 %**	**55 %**
SAC11	3.2 %	20.2 %	56.6 %

9a(ii). GIVEN magma extrusion resumes within the next year elsewhere in the crater, what is the probability that peak extrusion will be moderate (i.e. 1 - 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**18 %**	**64 %**	**94 %**
SAC11	18.2 %	50.1 %	77.7 %

9a(iii). GIVEN magma extrusion resumes within the next year elsewhere in the crater, what is the probability that peak extrusion will be high (i.e. > 5 m^3 / sec)?

	Credible interval lower bound	*Best estimate*	*Credible interval upper bound*
SAC12	**3 %**	**24 %**	**64%**
SAC11	4.4 %	29.9 %	68.6 %

41. Most of the probabilities that we assigned to the more likely scenarios over the next year do not vary appreciably from those in the SAC11 assessment (the non-

bold figures just below the boxes, above), but there are some differences to note. We consider that a restart of magma extrusion is more likely to be the most probable significant development (up from 34 % to 47%), with a major Tar River Valley collapse still another good possibility (although slightly down from 25%, to 21%). Our judgment is that a significant explosion currently is somewhat less likely than before (down from 20% to 8%), whilst nothing new happening is still an outside possibility (an 11% chance, essentially unchanged from SAC11).

42. Some conditional probabilities, such as those relating to pyroclastic flows to the Belham from major dome collapses for instance, are slightly elevated compared to the last assessment, reflecting the fact that the dome is not reduced in size, and topographic controls on flow directions may be less favourable in this regard, than before. Similarly, in the light of the dome's size, its recent vigorous extrusive activity and obvious incandescence in northern and northwestern parts of the dome, the conditional probabilities for a lateral blast that may be directed towards the NW, are also considered slightly greater than before; this is an important factor in the assessment of societal and individual risk exposures for the bordering inhabited areas.

43. With respect to the most likely scenario, resumption of lava extrusion, the elicitation has drawn out some additional potential changes. A restart of extrusion in the western part of the crater, where it was focused recently until December 2008, is now thought much less likely than six months ago (probability drops from 59% to 20%). Instead, we see either a return to a central locus (up from 32% to 46%), or a change to a position above Farrells/Tyre's Ghaut (up from 9% to 26%), as more likely than the western location. In addition, the elicitation indicates the next extrusion episode will probably take place with higher extrusion rate than most previous restarts - the rates 1 - 5 cubic metres per second and >5 cubic metres per second having higher likelihoods than a rate of <1 cubic metre per second.

44. A third element in the present outlook concerning the renewed lava extrusion scenario is the possibility that the volcano may be changing its pattern of behaviour, and moving to a state in which shorter, more intense episodes of magma production take place at the surface, as in December 2008 – January 2009. The SAC elicitation puts the likelihood of experiencing this more punctuated extrusion mode as almost twice as likely in the next twelve months as a reversion to the former 20-month pattern (65% probability versus 35%). It is anticipated that two such episodes could be expected in the next twelve months, with perhaps as many as 5 being plausible under more extreme conditions. Such repeated episodes seem sure to add increased stressing and forcing on the dome, and multiply the chances of its failure.

45. These several factors relating to renewed extrusion action – prospective multiple episodes, less favourable locus and higher extrusion rate - carry the plain implication of engendering potentially hazardous threats to the populated areas to the north-west of the volcano. These threats would be represented most worryingly by incursion into neighbouring areas by pyroclastic flows or, even more ominously, by blasts. Given the present conditions, the mean values for probabilities of such incursions are assessed higher overall than those of the

previous SAC11 elicitation, for all areas. As a consequence, for Zone B the elicited probability of a pyroclastic flow reaching this far over the next year is about 1-in-70. For a lateral blast-derived surge the probability is 1-in-2000. For Zone A, the elicited probability for a pyroclastic flow incursion stands at about 1-in-210 over the next year. For the case of a lateral blast-derived surge reaching the area, there is a lower 1-in-2200 mean chance within the year.

46. Although the area between Nantes and Lawyers Rivers (Woodlands) is not a Hazard Zone under the HLS, for consistency with previous SAC analyses we have calculated the likelihoods of pyroclastic flow or blast surge reaching this area in the next year. These are very small: about 1-in-10,000 and 1-in-30,000 respectively.

Quantitative Risk Assessment

47. 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 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.

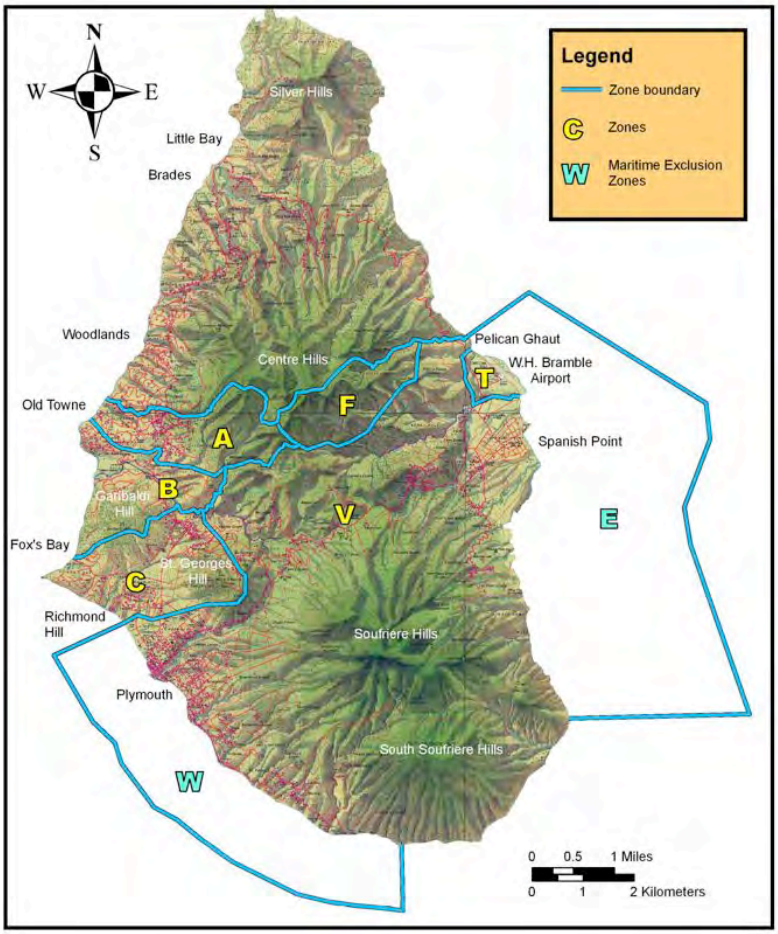

Fig. 3 The MVO Hazard Level System map of zones used in the current risk analysis

48. The issue of population numbers is critical to the estimation of societal risk levels, but not individual risks. Based on figures received by MVO from GoM for the last SAC11 meeting, we use the numbers of 336 people living in Zone A, and 95 people in Zone B (Fig.4). For Woodlands, a total of 315 persons is assumed, as before.

Societal Risk Levels

49. In order to assess societal risk levels, the impacts of different eruptive scenarios are modelled for the present population of Montserrat, and aggregated according to likelihood of occurrence. Using the elicitation results reported above, the risk assessment analysis uses Monte Carlo re-sampling to explore possible outcomes from a range of scenarios relating to dome collapse, lateral blast, and from associated explosive activity that might develop within the next twelve months. The potential impacts of each scenario are weighted according to the elicited relative likelihoods of their occurrence. Our estimates of risk are based on one year ahead.

50. As noted above, the area north of Nantes River lies outside of the MVO Hazard Level System defined Zones. However, we continue to assess the contribution of this area to the overall societal risk estimation.

51. Fig. 5 shows the calculated current annualised societal risk curve for Montserrat using the estimated population numbers stated above (red line). Also shown are the societal risk curves produced five months ago in October 2008 (SAC11, dark blue line), and back in March 2007 (SAC8) when the dome was still active and still growing vigorously (purple dashed line). All three of these curves are well above the corresponding line for SAC10 (April 2008), when activity was much lower and a long-term pause was thought to be in prospect. Lines are added also for long-term risk exposure on Montserrat from hurricanes and earthquakes (black lines with symbols).

52. The main conclusions to be drawn from these curves are: (a) the overall societal risk level for a few fatalities is increased slightly from five months ago; (b) the likelihood of larger numbers of casualties (i.e. fifty or more) is even more elevated than before, due to an increase in the likelihood, albeit small, of a blast event; (c) the societal risk is still lower than that assessed in March 2007 but has moved closer to that level, and (d) with the present population distribution the societal risks due to the volcano exceed those due to hurricanes or earthquakes.

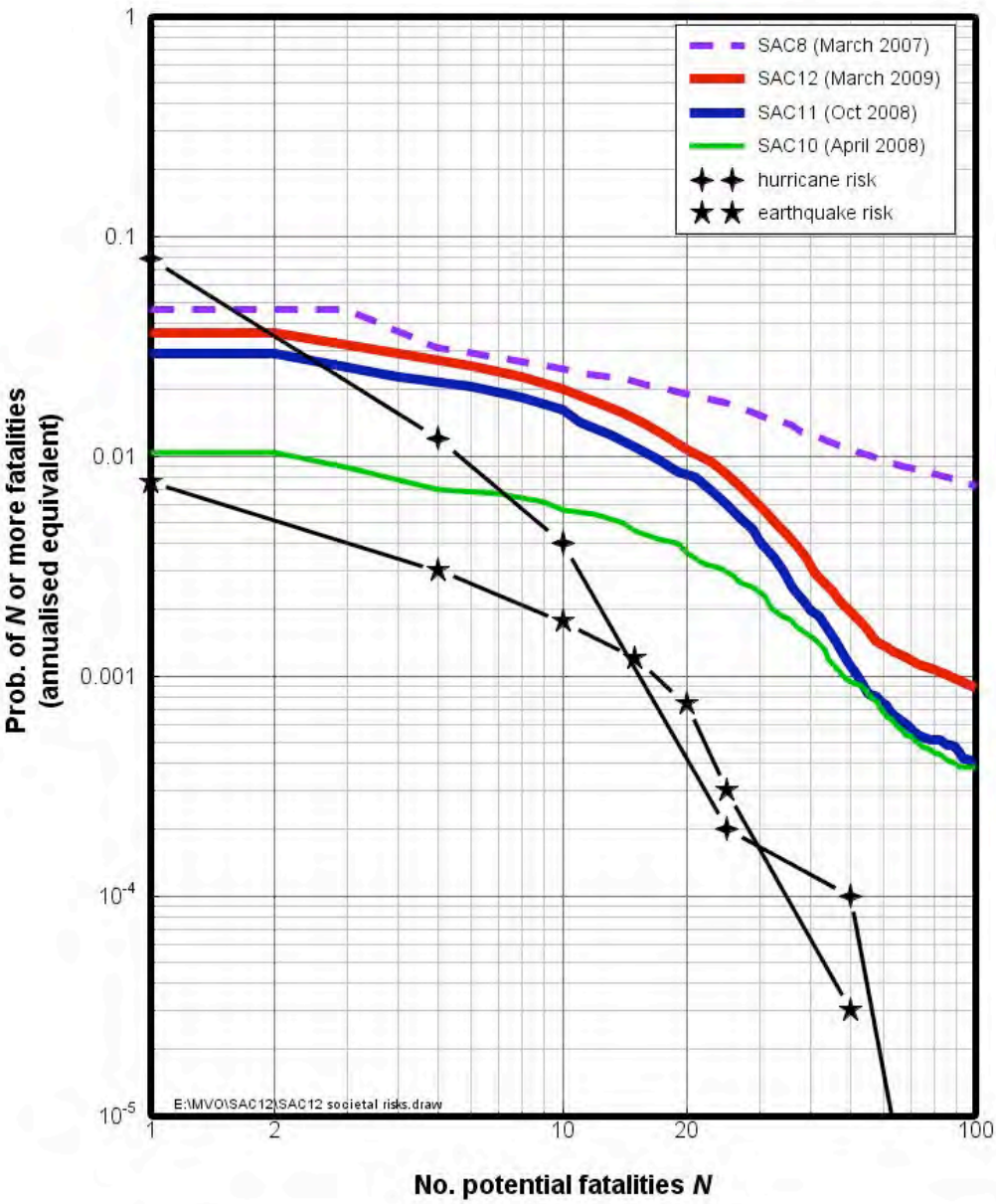

Fig. 5 Societal risk curve (red) for the population at the time of the SAC 12 and comparisons with other risk assessments.

Individual Risk Exposure Estimates

53. In terms of individual exposure, *individual risk per annum* estimates (IRPA) for people in different Zones are calculated using the probabilities elicited from the SAC committee, coupled with Monte Carlo population impact risk simulation modelling. We have categorised the levels of risk exposure using the six-point risk divisions of the scale of the Chief Medical Officer of the UK government in which we have replaced the labelling of these factor-of-ten divisions with an alphabetical ordering, which we term the Modified Chief Medical Officer's scale (CMO*) (see Appendix 2).

54. We also indicate, in numerical terms, the extent to which the active volcano increases an individual's risk over and above the 'background' risk of accidental death for a person living in Montserrat, currently assumed to be 28-in-100,000 (the value in the US Virgin Islands). Table 1 shows how the current evaluation compares according to these two measures. In Table 2 we use the same scheme to show the relative risk levels faced by workers in various scenarios. The two types of risk are also displayed jointly in a graphical manner in Figs. 6 and 7, which show the range of risks faced on a vertical logarithmic scale.

55. On the basis of our quantitative risk modelling, we now consider the level of annualised risk of death (IRPA) due to volcanic hazards for an individual in each of the populated Zones (A and B) of Fig. 4:

    Zone A (full-time resident): 1-in-9,100, C on the CMO* scale, 1.4*x* background risk level of accidental death

    Zone B (full-time resident): 1-in-720, B on the CMO* scale, 6*x* background risk level of accidental death.

    For Zone A the individual risk exposure level has increased when compared to that determined at the last, SAC11 assessment, from 1-in-11,000; for Zone B the individual risk exposure level has also increased, from 1-in-900. The IRPA for the Woodlands area remains extremely low, about 1-in-4 million (for SAC11 the corresponding risk was 1-in-5 million).

56. Because no occupation of the areas is allowed at present, the issue of individual risk for residents in the St Georges Hill – Richmond Hill areas is not considered here.

Table1. SAC12 Individual Risk Per Annum (IRPA) estimates for volcanic risks to occupants in the populated Areas

Residential Area	**CMO* Risk Scale#**	**Annualised Probability of Death**	**Risk Increase Factor**	**Other Natural Hazards**
	A			
		1 in 100	36x	
Zone B (full-time occupation)	B	**1 in 720**	**6x**	
		1 in 1000	4.6x	
Zone A (full-time occupation)	C	**1 in 9,100**	**1.4x**	
		1 in 10000	1.35x	
Whole island	D	1 in 35,000	1.1x	Hurricane hit on Montserrat
		1 in 100000	1.03x	
Whole island	E	1 in 200,000	1.02x	Earthquake striking Montserrat
		1 in 1000000	1.003x	
Woodlands (full-time occupation) N. Montserrat	F	**1 in 4 million** **less**	**1.001x**	

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

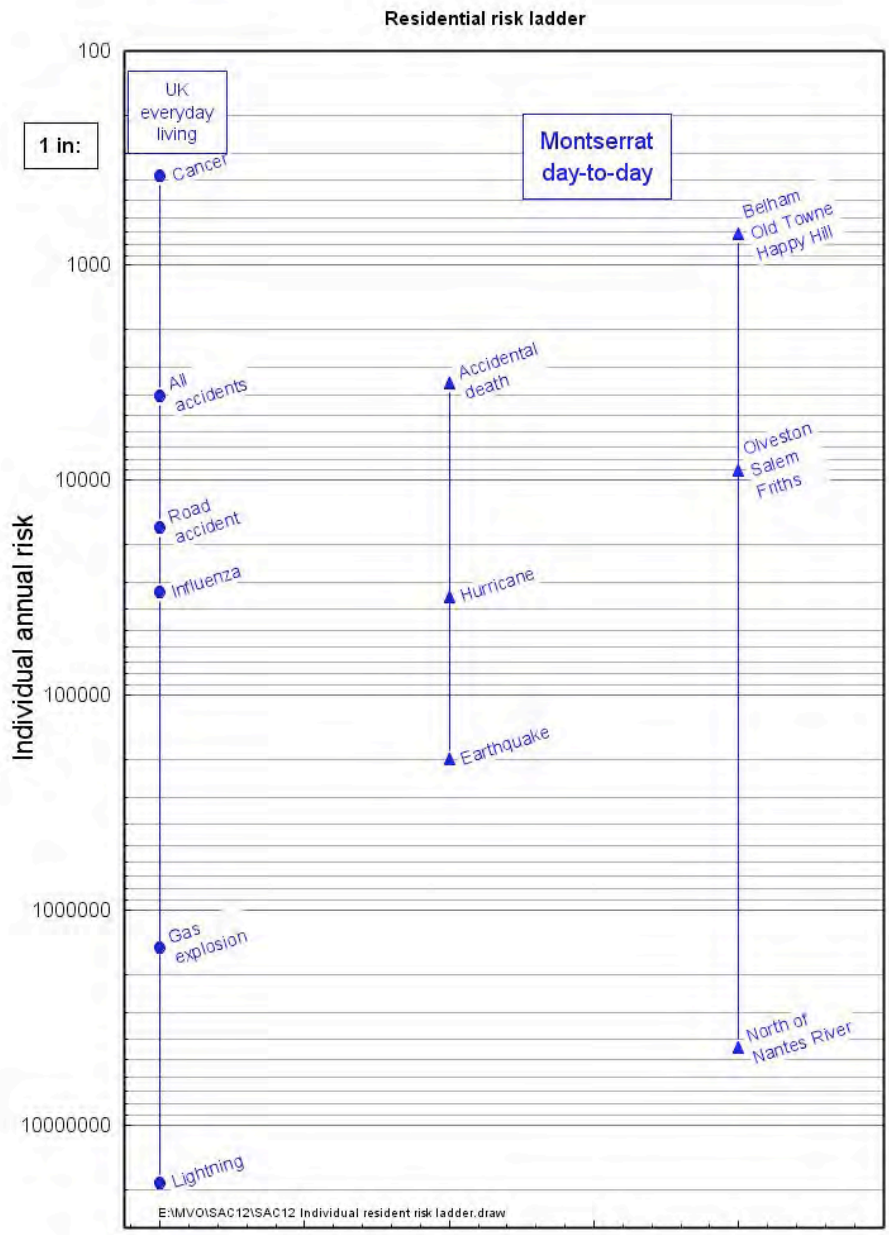

Fig. 6 Residential individual annual risk estimates expressed graphically

57. *Risks to workers in Zone F (Corbett Spring-Locust Valley)*
This area is one designated for agricultural production with controlled access of limited daytime workers. The individual risk exposure to a person working normal hours in this area is about 1-in-8500 (in the CMO* C band).

58. *Risks to workers in Zone T (Trants)*
Workers extracting sand and gravel from Trant's beach and neighbouring flow deposits are at risk from pyroclastic flows. The probability of a major collapse to the NE, such as would generate big flows towards Trants, is now assessed marginally lower than it was in previous SAC meetings (3% probability in next 12 months: see elicitation question 11, above). Assuming relevant mitigation

measures are used (as discussed in SAC11 report, for example) the Trants workers' situation produces an IRPA of about 1-in-8300, or about 3.1x higher than the occupational risk level for the (UK) extractive & utility supply industry. If these protection measures fail, or are not implemented, then the IRPA would be considerably elevated, and closer to 1-in-3300 (as shown for conservatism on Figure 6), or about 6*x* the UK exposure rate.

59. *Risks to workers at Fox's Bay and at Isles Bay*
The construction of a ramp somewhere on the south-western coast of Montserrat would enable barges to be loaded with aggregate trucked from mining sources. One proposal has been to build the loading stage at Fox's Bay. There, the present risk exposure for a worker would be about 1-in-1100 per annum equivalent, or about 19*x* the corresponding UK occupational risk (see Table 2). If the loading stage is located on the coast in the accessible southern part of Isles Bay, behind Garibaldi Hill, the worker risk is estimated to be about 1-in-1730, which is about 12*x* the equivalent UK occupational risk (and currently roughly the same as the SAC11 risk estimate was for Fox's Bay, back in October 2008). Thus, there is a modest margin of additional safety associated with the Isle's Bay site relative to the Fox's Bay option. This said, worker exposures relating to the transportation of aggregate would need to be considered also, but more detail of any proposed operations would be required to address this aspect of the risk discussion.

60. *Risks to workers in Plymouth*
The MVO risk assessment for the salvage of barges beached at White River in October 2008 considered in detail the risk of operations at the Plymouth Jetty under conditions at the volcano at the time (see Komorowski et al., Appendix 3 of MVO Open File Report 09/01). To give a measure of context to that assessment, the annualised individual risk for a worker at the Plymouth Jetty, working normal hours for a whole year under those particular circumstances, would equate to an IRPA of less than 1-in-10, given the risk exposure at Plymouth Jetty estimated by MVO in October 2008. Such a level of risk is unconscionably extreme, by any standard, exceeding the exposure of a soldier in a major war (see Table 2). Although the situation at the volcano has changed somewhat since the events of December 2008 to January 2009 (the ensuing further destruction of Plymouth having been admirably anticipated by the MVO risk assessment), similar conditions could return to the volcano very rapidly. Thus even with the quieter, less active conditions at present, it would be imprudent to think in terms of returning to an IRPA of about 1-in-500 per year, which was the value determined for SAC11, prior to the escalation of activity in the western part of the crater. From the elicitation, the chances of a collapse down Gage's towards Plymouth are assessed about 1.6*x* greater than they were last October, so an IRPA of about 1-in-300 might strike the right balance now; any resumption of activity in the west would immediately precipitate the risk exposure in and around Plymouth. As with the Plymouth Jetty situation in late 2008, in all the estimates of worker risk just discussed exposure levels could rise significantly and rapidly if renewed activity develops in an unfavourable location on the volcano. Thus the individual risk estimates should be taken simply as comparative, and each case needs to be assessed on its own particulars and with an eye to how fast conditions could deteriorate.

Table 2. SAC 12 Individual Risk Per Annum (IRPA) estimates for volcanic risks to workers in specific locations

Activity	**CMO* Risk Scale**	**Annualised probability of death at work**[1]	**Volcanic risk relative to Extractive industries risk**	**Occupations**
	A			Soldier at war
		1 in 100		
Plymouth jetty	B	**~ 1 in 300**	**70*x***	Deep sea fishing
		1 in 1000		
Fox's Bay ramp **Ile's Bay ramp** **Trants sand** **Corbett Spring**	C	**1 in 1100** **1 in 1730** **1 in 8300**[2] **1 in 8500**	**19x** **12*x*** **3.1*x*** **3.0*x***	Mining & quarrying
		1 in 10000		
	D			Construction Forestry Extractive & utility supply industries
		1 in 100000		
	E			Services
		1 in 1000000		
	F			

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

[2] estimate subject to certain safety precautions being in place and acted upon; otherwise risk closer to 1-in-3300 (see text).

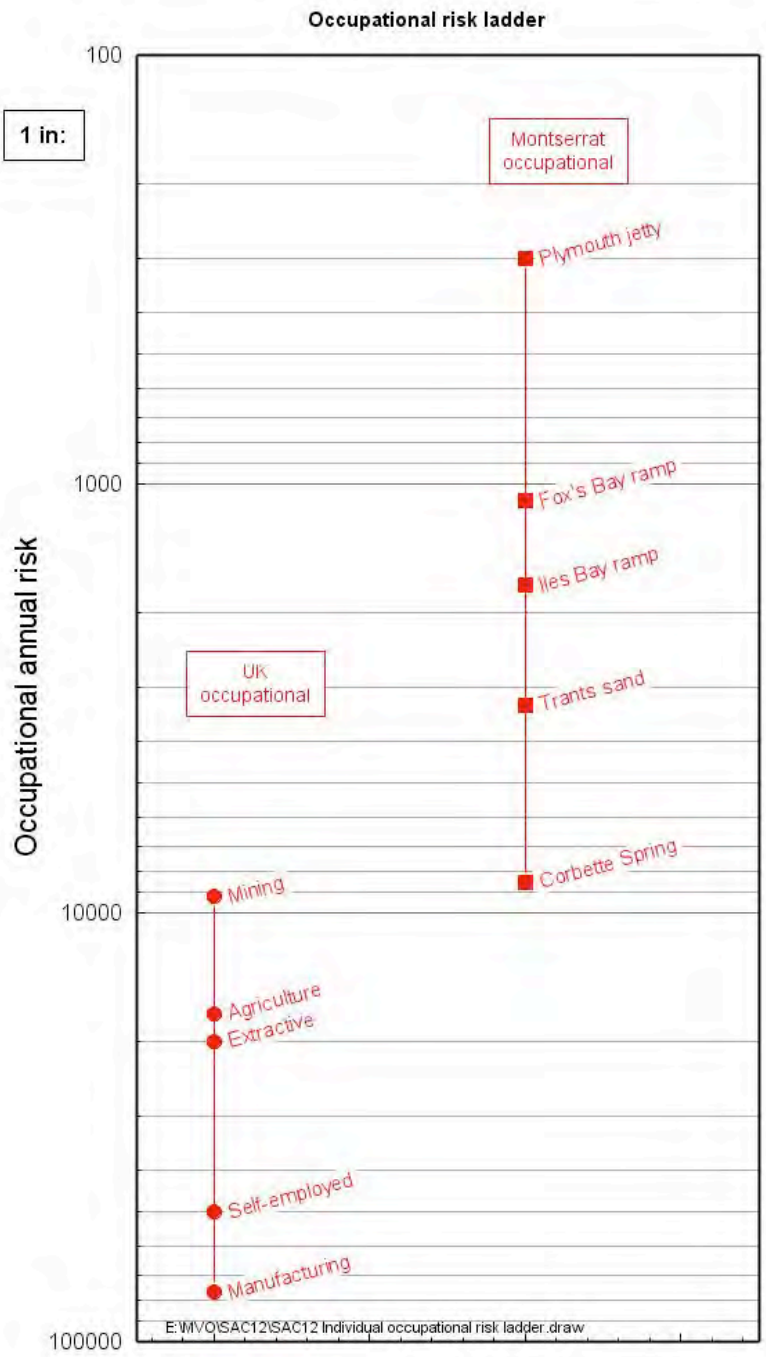

Fig. 7 Work-related individual annual risk estimates expressed graphically

61. *Risks in the Maritime Exclusion Zone*

The pyroclastic flows and surges of 29 July 2008 almost reached the sea at Plymouth and some of those of the December 2008 – January 2009 episode did reach the sea there and at the White River delta, showing the value of the western component of the Maritime Exclusion Zone. Whilst the probability of flows

entering the sea via the Belham Valley at Old Road Bay is much smaller than at Plymouth it is not negligible. Presently, if the hazard rises to Level 4 and Zone B is evacuated, then the area offshore Zone B would not be in the Exclusion Zone. It would be better if this offshore area were to become part of the Maritime Exclusion Zone automatically as the Hazard Level increased. Thus we re-iterate our recommendation from SAC11 that the Hazard Zone boundaries of Zones A, B and C be extended offshore for 2 km as in Fig.4 and the sea areas be subject to the same restrictions as the rest of Maritime Zone W (i.e. daytime transit, at Levels 2 and 3 and essential workers only at level 4 and above) when the adjacent land Hazard Level changes (Fig.8).

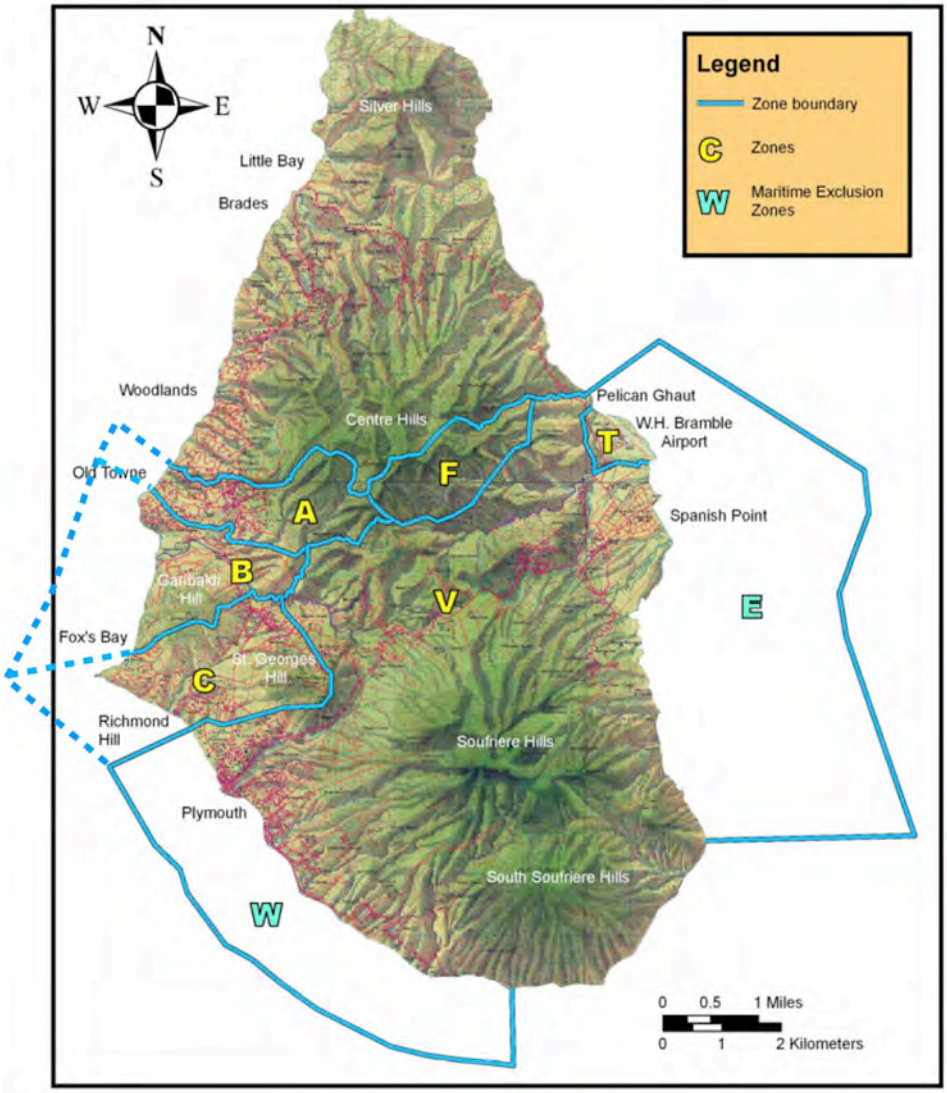

Fig.8 Recommended extension of the Hazard Zone boundaries offshore western Montserrat to better represent the Maritime Exclusion Zone.

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[9], 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

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

agreement or failure between observations and predicted outcomes). The fact is that such validation, verification or confirmation is logically precluded on non-uniqueness grounds for numerical or probabilistic models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[10].

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

A1.6 Given all these factors, the Committee members believe that they have acted honestly and in good faith, and that the information provided in the report is offered, without prejudice, for the purpose of informing the party commissioning the study of the risks that might arise in the near future from volcanic activity in Montserrat. However, the state of the art is such that no technical assessment of this kind can eliminate uncertainties such as, but not limited to, those discussed above. Thus, for the avoidance of doubt, nothing contained in this report shall be construed as representing an express or implied warranty or guarantee on the part of the contributors to the report as to its fitness for purpose or suitability for use, and the commissioning party must assume full responsibility for decisions in this regard. The Committee accepts no responsibility or liability, jointly or severally, for any decisions or actions taken by HMG, GoM, or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor do they accept any responsibility or liability to any third party in any way whatsoever. The responsibility of the contributors is restricted solely to the rectification of factual errors.

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

[10] 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: Modified Chief Medical Officer's Risk Scale (CMO*)

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

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

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

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

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

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

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