28th Report of the Scientific Advisory Committee on Montserrat Volcanic Activity[1]

Based on a meeting held between 27th and 30th November 2023,
at the Montserrat Volcano Observatory, Montserrat

Part II: Full Report

Issued on 30th January 2024

Photograph taken by Prof. Richie Robertson (UWI-SRC).

[1] The information provided in all 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.

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Summary

1. This is Part II of the report, resulting from the 28th meeting of the Scientific Advisory Committee (SAC) on Montserrat Volcanic Activity that took place at Olveston House and the Montserrat Volcano Observatory (MVO) from 27th to 30th November, 2023. Part I of this report, the Summary Report[2], gives the principal findings of the meeting in a non-technical form, and Part II gives the underlying technical data and analysis in more detail, including several appendices, that led to those findings.

2. The SAC meeting took place one year after we last met in November 2022, and involved seven SAC members, all MVO scientists and technicians. It was the fourth meeting under MVO director, Dr Graham Ryan. We also welcomed Dr Erouscilla (Pat) Joseph, Director and Prof Richie Robertson Ex-Director of Seismic Research Centre, University of the West Indies, as participants. A list of all participants and their affiliations is given in Appendix III. Prof Eliza Calder chaired the meeting.

3. The MVO produced two volcanic activity reports[3,4] to the SAC, which were distributed to all SAC members prior to the meeting. These reports covered the period between 1st October 2022 to 31st March 2023, and 1st April 2023 to 30th September 2023, respectively. MVO staff delivered several oral presentations on the monitoring data and observations covering the entire period as well as presentations on other aspects of MVO work including outreach activities on Montserrat. MVO staff also led an evening excursion on 27th November to view the murals created as part of the Curating Crisis project.

Fig. 1. Thiffanie Williams presented the work coordinated and led by MVO staff in the creation of the murals as part of the UKRI-funded Curating Crises project.

4. Acting on discussions held during the previous SAC meeting in 2022, as well as the MVO board meeting on 8th March 2023, in SAC 28 we decided to hold an opening

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[2] Assessment of the hazards and risks associated with the Soufrière Hills Volcano, Montserrat. Report of the 28th Scientific Advisory Committee on Montserrat Volcanic Activity, Part I, Summary Report, January 2024.

[3] Stinton et al., 2023, MVO Scientific Report for Volcanic Activity between 1 October 2022 and 31 March 2023, Open File Report OFR 23-01.

[4] Stinton et al., 2022, MVO Scientific Report for Volcanic Activity between 1 April 2023 and 30 September 2023, Open File Report OFR 23-02.

meeting with the Governor, HE Sarah Tucker, the Premier and the Attorney General online on Monday, 27th November, 2023. The purpose of this meeting was to frame and orientate SAC discussions on specific issues of current interest to the Government of Montserrat. This was helpful for our discussions and we would propose to continue this arrangement for next year's SAC meeting.

5. Scientific discussions that followed covered conceptual models that could explain the continuing deformation pattern and outgassing, as well as the observed evolution in seismicity and deformation rate. Discussions during SAC27 of the timeseries of deformation, seismicity and degassing gathered by **MVO monitoring had highlighted a general shift in behaviour of the SHV volcanic system that seems to have occurred between 2018 and 2022: the pattern of far-field deformation reflecting ongoing island-wide inflation continues**, while the seismicity rate and the rate of seismic moment release have all increased to higher values. After further scrutiny of the time series, we confirmed the changes in behaviour already noticed last year and noticed new step-like increases, especially in the seismic moment release, which occurred mid-2022. This appears to be due mostly to an increase in the proportion of larger magnitude earthquakes. Notably, in September there were several small LP events and one larger one that triggered the seismic system. **The rate of seismic activity appears now the highest over the last pause, but it is still below the level of activity during all but one of the previous pauses. These new values of the monitoring parameters do not appear to herald any impending restart of eruption, but do reinforce the understanding that the magmatic system of SHV is still active.**

6. On the basis of these discussions, we assessed the potential behaviour of the volcano in the longer term in the context of past eruptive cycles. Since the start of Pause 5, SHV is showing an evolution of its long-term behaviour from a deceleration of unrest to a new steady state, and perhaps subtle acceleration. It is not clear what is driving the unrest at SHV, but **in general in volcanology an increasing trend in unrest points to a higher probability of eruption in the future**.

7. MVO has undertaken a substantial new body of work in the form of the **SRC-MVO Hazard Map Series**, a GIS system compiling spatial information under four major categories: the distant past; recent volcanic deposits and impacts; present activity; and potential future activity. This information serves to support decision-makers by provision of clear spatial information relating to past and potential future volcanic activity which draws on over 50 already published academic papers as well as MVO data. MVO staff have held several meetings with stakeholders to raise awareness of the availability of this new information system, and communicate how it can be utilised to support decisions.

8. Acting on discussions held during SAC27, as well as recommendations from other reports, in SAC28 we initiated an **Open discussion on hazard and risk with stakeholders** from Montserrat during a session on the morning of Monday, 28th November. Four individuals representing the Disaster Management Coordination Agency (DMCA), the Chief Medical Officer, Principal Environmental Officer and Chief Physical Planner were invited and attended the meeting. Discussions focused on how support by MVO to those stakeholders can be maximised, as well as discussions

around the preliminary results presented by Prof Jurgen Neuberg from air quality monitoring by a UK-based research group.

9. Following discussions on both the internal volcanic system and also the hazard and risk aspects, we elicited the probabilities of a number of volcanic scenarios for the next 12 months. The elicitation results were, overall, similar to last year's and we decided to maintain the **same risk levels for the population of Montserrat in Zones A, B and C for the next year**.

10. **A Preliminary Statement** (Appendix IV) was issued and presented at the debriefing to the Governor, HE Sarah Tucker, the Premier, on Thursday, 30th November 2023 at a meeting at the MVO. The Financial Secretary, Hon. Lindorna Lambert-Sweeney and Director of the DMCA, Lt. Col. Alvin Ryan, were also present. An interview was recorded at the ZJB studios with five SAC members, including Dr Ryan MVO Director, attending the radio interview.

SHV Activity and Observations

11. The activity manifest at the SHV in the reporting period has been comprehensively detailed in MVO Open File Report OFR 23-01 and Open File Report OFR 23-02. In order to provide context for the rest of this report, we summarise key points from those MVO reports below:

12. **There has been no lava extrusion since the end of Phase 5 on 11th February 2010, which now constitutes a pause of 14 years. During this period, surface activity has been low but sustained ground deformation indicates that SHV is inflating, and along with still significant SO_2 fluxes, this indicates that the magmatic system at depth remains active and in a state of unrest**.

13. MVO monitoring data over the entire eruption are shown in Figure 2.

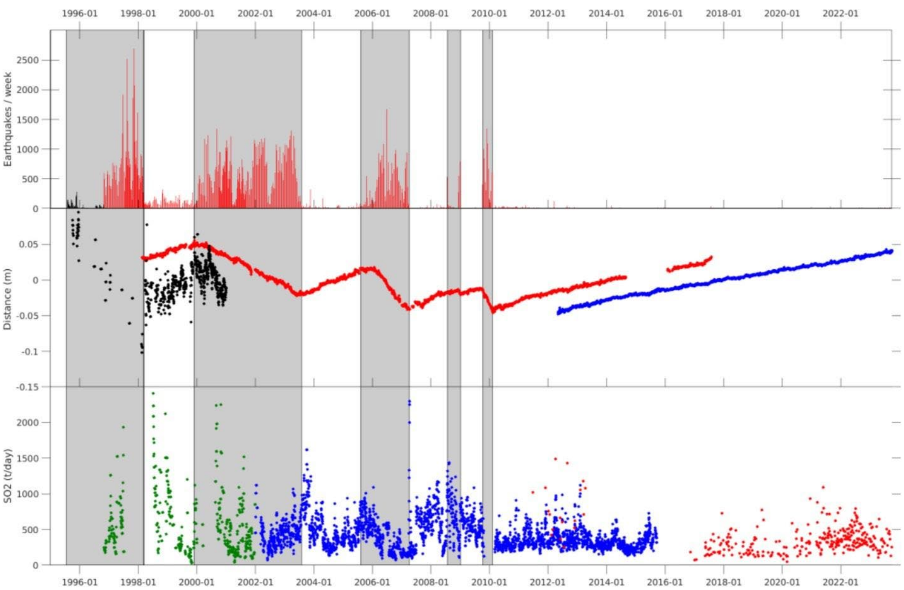

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Fig. 2. Summary of the Seismic, GPS and SO2 monitoring data for the entire eruption of the Soufriere Hills volcano between 1995 and November 2023. Extrusive phases are shown in grey. Top: Number of seismic events detected and identified by the seismic system. Middle: Radial displacement of cGPS stations MVO1 (red) and NWBL (blue) smoothed with 7-day running mean filter, Black: GPS Height of HARR. Bottom: Measured daily SO2 flux, filtered with 7-day running median filter. Green: COSPEC, Blue: old DOAS, Red: Traverse data. (Stinton et al., MVO OFR 23-02).

14. **Rockfall activity** during the reporting period has continued at very low levels, continuing the trend of dome stabilisation over the last few years. During this period there were only four recorded rockfall events on the lava dome although observations made from the helicopter confirm slow degradation of the outer surface of the lava dome has continued. The main areas of rockfall activity include the steep slopes/cliffs above the Tar River valley (east flank), inside the 2010 collapse scar (northern sector), in the summit crater and above Gage's Fan (west flank).

15. **Seismic activity** during this reporting period has remained low, although continuing the slight increase that started in mid-August 2021. Volcano-tectonic (VT) earthquake activity has been gradually increasing since early 2018, although it is still at a level consistent with a pause in extrusion. VT earthquakes make up the vast majority of the seismicity and 41 VT strings (brief swarms of VT's) occurred during this reporting period. There was no evidence for a relationship between string activity and any observable changes in SO_2 flux, fumarole activity, surface deformation or the occurrence of ash venting. There was an increase in the slope in the cumulative seismic moment in December 2020 and another increase around August 2022. The mean daily rate of VTs for the last six months is 1.72, higher than the average value of 0.79 across the whole of the current pause. Rockfall activity continues to be low, following an overall declining trend throughout Pause 5. There has also been a drop from the slightly-heightened rockfall rate that commenced in mid-August 2021. Low-frequency seismicity has been almost absent, with no hybrid earthquakes and one triggered long-

period earthquake on 8 September. This pattern, although showing signs of a very small acceleration, remains fairly typical of a pause in lava extrusion at SHV.

16. **Ground deformation** during this reporting period continues to show the long-term inflation trend, centred on the SHV that has been present since the beginning of Pause 5 (February 2010), although its rate has decreased slightly since the beginning of Pause 5. The long-term inflation of the edifice/island coincides with the continuation of the pause in surface activity and the most plausible explanation so far is pressurisation of the magmatic system (Neuberg et al., 2022[5], Hickey et al., 2022[6]).

17. **SO_2 fluxes** for the reporting period derived from measurements undertaken mainly via helicopter traverses under the plume have varied between a high 648 t/d on 26th April 2023 to a low of 111 t/d on 13th April 2023 with a daily mean of 303 t/d. The flux values obtained during the reporting period fit into the long term (18-24 month) cycle that has re-established itself in the SO_2 flux data since 2017.

Long-term Magmatic Processes at the Volcano

18. MVO seismologist Rod Stewart presented work on the **Evolving source location of VT earthquakes**. A small (overall 500 m) gradual shallowing in VT hypocentral depths has occurred. There is overall clustering of VTs source locations albeit with significant uncertainties on those locations. As highlighted by Stewart, changes in the seismic network can affect the retrieved hypocentres. For example, some key stations provide strong constraints so that, if there is a data gap, both random and systematic errors may be introduced. However, the results indicating a shallowing of the VTs do appear robust. **Individual earthquakes forming the same VT string do not share the same waveform, suggesting that a cluster of faults of different orientation (focal mechanism) are failing during the occurrence of each string**. This analysis further suggests that VT strings may be occurring due to stress interaction between the individual fractures of a cluster, each failing and triggering neighbouring fractures.

19. SAC member Prof Fidel Costa presented work compiling examples of **unrest at volcanoes with well-developed hydrothermal systems**. The examples discussed include Soufriere de Guadeloupe (Guadeloupe), Vulcano (Italy), and Hakone and Ontake (Japan). The cases included unrest episodes that have led to eruption, as well as those that did not. The general observations of the unrest included increased seismic activity, sometimes with swarms. The activity typically happens at a range of depths (0.5 to 5 km below the crater). The seismic unrest lasts for a few months, and this includes VTs and LPs. In some cases, there is no measurable or very short unrest before explosions, such as in Ontake in 2014. In addition, increased temperature of the fumaroles, and changes of the gas composition towards more magmatic values, can be

[5] J.W. Neuberg, B. Taisne, M. Burton, G.A. Ryan, E. Calder, N. Fournier, A.S.D. Collinson (2022) A review of tectonic, elastic and visco-elastic models exploring the deformation patterns throughout the eruption of Soufrière Hills volcano on Montserrat, West Indies, Journal of Volcanology and Geothermal Research, Volume 425. https://doi.org/10.1016/j.jvolgeores.2022.107518.

[6] Hickey, J., Pascal, K., Head, M, Gottsmann J., Fournier, N., Hreinsdottir, S. and R. Syers, 2022, Magma pressurization sustains ongoing eruptive episode at dome-building Soufrière Hills volcano, Montserrat: Geology, https://doi.org/10.1130/G50239.1

important indicators. Increased deformation (inflation) may or may not occur. Most of the interpretations propose an increased transfer of deep magmatic fluids to the shallower hydrothermal system. In some cases, such an increase is considered to be due to new magma intrusions. Such information could be used as background for the interpretation of volcanic unrest involving the hydrothermal system of SHV.

20. Time series of **ground deformation at Soufrière Hills Volcano (SHV)** suggest that deformation rates since 2018-2020 are approximately steady rather than decelerating. GNSS (GPS) processing work carried out by the MVO and their partners over the past few years dramatically increased the level of confidence in the interpretation of observed continued deformation signal being driven by pressurisation of the magmatic system at depth. Using our understanding of the system now published by Neuberg et al., 2022 and Hickey et al., 2022, we reiterate that **the simplest explanation for the island-wide deformation is either a continuing magma influx of about 0.10-0.57 m^3/s in a magma reservoir at about 6 km depth, or an equivalent pressurisation at the same depth of about 10 MPa/year. Such a magma input flux may also explain current SO_2 flux observations.**

21. **Based on the continued SO_2 emissions, and our understanding of degassing at SHV through, for example, the work by Christopher et al. (MVO)[7], we still work on the assumption that volatiles are being supplied from a gas reservoir deeper than 6 km depth, produced by the crystallisation and outgassing of mafic magma when mixed with resident cooler andesite**. The existence of an independent gas phase that could at least contribute to the pressurisation is plausible. It may also be the case that the buoyancy of a growing volatile reservoir may contribute to the observed inflation of the island. A Master's student working with Dr Thomas Christopher is currently working on the volatile contents of melt inclusions that could be used to constrain the relationship between SO_2 degassing rate and implied magma supply rate.

22. Design of conceptual model(s) for SHV: The SAC and MVO conducted an exercise aiming at pulling together key pieces of existing knowledge about the known structures and inner workings of SHV into a single conceptual model. **The intent of** such **conceptual models is to provide (1) a multidisciplinary, common understanding of the inner structure of the volcano, and the location of the key processes driving its activity and producing monitoring observables**, (2) a framework (i.e., **Common Operating Picture)** that can be used operationally by volcano observatories **to interpret monitoring data and forecast future volcanic activity**, and (3) **a basis for** further simplified versions that can be used for **engagement with key stakeholders and public outreach**. The outcome of the exercise during the SAC meeting was an initial draft that can be owned and used by the MVO as a framework upon which monitoring data can be interpreted (e.g., are the observed earthquakes close to the inferred location of magma or, instead, located near known faults?), and be further developed by the MVO, supported by the SAC and external academic partners as needed.

[7] Christopher, T., Taisne, B., Edmonds, M., Odbert, H., Costa, A., Hards, V., Wadge, G. (2014), Prolonged sulphur dioxide degassing at Soufriere Hills Volcano, Montserrat, and implications for deep magma permeability. (Geol. Soc. London Special Pub. "The role of volatiles in the genesis, evolution and eruption of arc magmas".

23. **Overall, MVO has observed a small increasing trend in seismic signals. This is consistent with an increased dynamism of the magmatic system which also creates the observed inflation and degassing at SHV**. We have several hypotheses which can explain these signals, but it is not currently possible to determine unequivocally which of these is correct. Currently, a model of magma supply is most favoured, as it explains why there might be an increase in volcanic unrest. **Continued close vigilance of the signals produced by SHV remains essential in order to swiftly detect any significant change in the system.**

Volcanic Hazard and Risk

Development of the SRC-MVO Volcanic Hazard Map Series

24. Over the last few years MVO members have led the development of a new hazard map. This has involved undertaking separate hazard assessments for lahars, ballistics and pyroclastic density currents, and combining the results of these assessments in a way that the map contains various hazard-level zones. The Hazard and Risk scientist that led the development of the hazard map, Dr Victoria Miller, left in June 2022. The new Hazard and Risk scientist, Dr Jose Marrero, arrived in September 2022, brought different but complementary scientific expertise, and has taken the hazard and risk work in a new direction.

25. During this reporting period, **the MVO, led by Dr Marrero, has undertaken a major new body of work related to hazard and risk work in Montserrat in the form of developing the SRC-MVO Hazard Map Series.** The new Hazard Map Series is developed and implemented through a GIS and was presented at the SAC meeting. For most of the SAC members this was the first time that they had seen this work. A detailed review of all the academic work involved in compiling the information and development of the SRC-MVO Hazard Map Series work is beyond the scope of this SAC report, but SAC members are happy to provide feedback if requested on the accompanying MVO Open File report when completed.

26. **The SRC-MVO Hazard Map Series in GIS compiles spatial information under four major categories, or layers: the distant past (based on the geological history of the Island); recent volcanic deposits and impacts (based on the 1995-2010 eruptive products); present activity; and *future activity* (map of potential hazards). The work is based on integrating extensive information on SHV and draws on over 50 published academic papers on the SHV as well as unpublished MVO data**. Most of the knowledge integrated into the map series is not, in itself, new knowledge. However, the development of the map series in this way, in a GIS, allows for and supports a structured and methodical system for using and comparing the available information in a way that maximises its usefulness and supports the use of this knowledge in a way that was simply not possible before. Developing the Map Series in GIS represents a tremendous amount of work and an impressive effort by Dr Marrero during his first year at the MVO. **The SRC-MVO Hazard Map Series is the most comprehensive hazard and volcanic map database for any volcano in the wider Caribbean and Central America region.** With its commitment to the

development of this work and alongside the efforts in stakeholder engagement related to how this tool can be utilised, the MVO is demonstrating its increased engagement in applied aspects of hazard and risk work on Montserrat.

27. During the development of this work, and in particular when compiling information for the recent volcanic impacts and deposits map, Dr Marrero highlighted the need to pay more attention to some infrequent but important hazard types, such as windblown co-pyroclastic flow ash plumes, shock waves, tsunamis and landward-directed blasts generated when pyroclastic flows enter the sea. Going forward, MVO will consider how to represent these hazards most appropriately in completion of the *future activity* map(s).

28. During the meeting, Dr Marrero showed how the **Hazard Map Series, essentially a decision-support tool, can be used** in a practical manner. He showed how the map layers can be used **to help answer questions about potential hazards and the associated risk control measures at a particular location. This can be done by systematically stepping through a set of conditions that need to be satisfied in order to identify areas around the volcano suitable for a given type of activity** (e.g., areas that are government-owned, but that have not been impacted by pyroclastic density currents or ballistics, and where the sirens can be heard). **The Map Series is extremely instructive and has high potential as a decision-support tool.** One suggestion is that MVO maintains a record of how and when it is used by stakeholders, providing accountability for any decisions made, and guiding ongoing development of the tool itself.

29. As part of the ongoing work and eventual completion of the SRC-MVO Hazard Map Series, it is important that its development is fully documented. All documentation regarding the sources of information, the way that information was integrated, or data sets interpolated, and the meaning of each GIS layer needs to be detailed in an accompanying report (we understand that this is already in progress). This is crucial for the Map Series to be used appropriately and is accountable, and its use defensible, by others at the MVO as well as for its future application and usage.

30. In addition to the tremendous amount of work that has already put into the MVO Hazard Map Series, **it is the SAC's opinion that the completion of what is referred to in this series as the *future hazards* layer(s) is very important for the following reasons**:
    (i) The future hazards layer(s), typically referred to in the wider volcanology community as a volcanic hazard map), is the only forward-looking component of the Hazard Map Series, i.e., it indicates potential hazard footprints, areas that might be impacted in the future. It is the visual representation of a comprehensive assessment of the different hazards, i.e., what the volcano is capable of doing based on available knowledge.
    (ii) The future hazards layer(s) currently comprise a near-complete body of work representing earlier efforts by different people as well as recent efforts by Dr. Marrero. The SAC believes that it should be prioritised for completion in the near future.
    (iii) The future hazards layer could be used as part of a workplace risk assessment system, such as is outlined in Section 38, to systematise assessments for access.

(iv) While details of a hazard map can always be improved, we believe that the work already undertaken on the future hazards layers(s) is sound and compares favourably to hazard maps from other volcanoes around the world[8,9].

Hazard related to lava dome stability

31. **The conditions and mechanisms for pyroclastic flow generation are now different to those during the eruptive period**. During periods of active dome extrusion, the first order control for pyroclastic flow generation is lava extrusion and associated dome instability. In the absence of dome growth, during pauses, or post-eruptions, other mechanisms come into play. Lava domes can collapse years, decades or millennia, after volcanic activity is over, due to intense rainfall, seismic activity, and/or weakening by hydrothermal activity and structural instabilities. **More relevant to the current situation, post-eruption collapses of lava domes, or parts of volcanic edifices are termed sector collapses and can generate mass flowse known as debris avalanches.** There is evidence across the Lesser Antilles volcanic arc[10], as well as elsewhere for both small-volume to extensive debris avalanches being sourced from collapses of lava dome complexes. **At any given individual volcano, these can be considered rare and rather extreme events, and as such for any given volcano, there are few data to constrain the anticipated time until one of these post-unrest events might occur. However, this is a type of hazard that is prudent to consider in hazard scenarios for Montserrat and as such is considered in question 9 of the elicitation (see section 53).**

32. **Prof Neuberg presented a report on an MSc project[11] at Leeds University that looked into how hydrothermal alteration can affect dome stability** on Soufrière Hills volcano using a technique often applied in the field of engineering geology. **The MSc student, Carlisle Vyphuis, originally from Montserrat, characterised the dome rock properties through geotechnical parameters in terms of the shear strength (cohesion and friction angle) and calculated the so-called 'factor of safety' (FoS) which gives an indication if parts of the dome are stable**. Numerical models have been developed for steep-faced eroded talus slopes and 2D slices through the dome topography. The DEM model was provided by the MVO under a data agreement. Based on the rather uncertain characteristics of the rock properties in the highly altered zones, the computational **results showed a sufficiently high FoS considering the slopes to be stable. However, if a potential earthquake hazard is taken into account by adding horizontal seismic acceleration of 0.2-0.25 *g* and a return period of 95 years which are representative for this part of the**

[8] Lindsay J.M., Charlton D., Clive M.A.T., Bertin D., Ogburn S., Wright H., Ewert J., Calder E.S., Steinke B. The diversity of volcanic hazard maps around the world: insights from map makers. (Submitted to Journal of Applied Volcanology)
[9] Ogburn, S.E., Charlton, D., Norgaard, D., Wright, H.M., Calder, E.S., Lindsay, J., Ewert, J., Takarada, S., Tajima, Y. (2023). The Volcanic Hazard Maps Database: an initiative of the IAVCEI Commission on Volcanic Hazards and Risk. Applied Volcanology.
[10] Boudon et al., 2007. Volcano flank instability in the Lesser Antilles Arc: Diversity of scale, processes, and temporal recurrence https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006JB004674 Sampler, et al., 2008. Radiometric dating of three large volume flank collapses in the Lesser Antilles Arc https://www.sciencedirect.com/science/article/pii/S0377027308002096.
[11] Vyphuis, C. 2023. The danger after the eruption stops: A study into how hydrothermal alteration can affect dome stability on Soufriere Hills Volcano. MSc thesis, University of Leeds.

Caribbean[12], the FoS dropped below the critical value, implying that a dome collapse could occur. Carlisle is now in contact with the MVO to explore potential co-operations, while Leeds University could provide the licensed software necessary for further studies.

Increasing volcanic risk awareness in the general public on Montserrat

33. **Related to work on increasing volcanic risk awareness on Montserrat is the *Curating Crisis Project*, the outcomes and ongoing work of which was presented by Karen Pascal and Thiffanie Williams**. The Curating Crisis Project is a UKRI-funded project led by Prof Jenni Barclay, a previous SAC member, which focuses on the histories of volcanic crises in Montserrat and St Vincent and in particular on the legacies left by the historical colonial attitudes to crisis response. The Montserrat murals and a short film are two of the outputs shown and discussed at SAC. **MVO staff led by Karen Pascal and Thiffanie Williams have been instrumental in raising local sponsorship which exceeded the initial external funding and secured partnership with a wide range of Government organisations, private businesses and individuals to develop the community project, and lead the project's development on Montserrat**. The work done evidences the increased engagement that the MVO has had with raising risk awareness in the general public in this reporting period, increased initiatives co-developing projects with and *for* the community, and also raised awareness of the MVO itself in the value-added and meaning of community-focused participatory work. **This work will be the focus of presentations given at the International Cities on Volcanoes conference in Guatemala in February 2024** (see Section 71).

Decision support for the Government of Montserrat

34. **Decision-making regarding access to Zone V is a Governor's Office/Government of Montserrat responsibility**. Scientific information about both the long term and short term state of the volcano, and the potential for future hazards around SHV is one of the strands of information that plays into the decision-making process. As such, the following statements are provided with the intention of being useful items for decision-makers to consider:

35. **The surface volcanic activity at SHV is very low, and the surface of the lava dome is substantially stable at present, based on the low number of rockfall events. However, our understanding of SHV indicates that volcanic activity is likely to reactivate at some point, but that there is no sign that this will happen soon (see Section 52). Thus, there is the possibility to consider the use of, and access to, some areas in Zone V where the hazard level is considered low. The likelihood of eruptive activity, for example, pyroclastic flows or significant explosions with no precursory warning (so-called 'out of the blue events', see Section 45), is considered very low indeed (see Section 55), and in the case that there was any precursory volcanic unrest, any activity within Zone V would be revised immediately.**

[12] Seismic Hazard Map – Eastern Caribbean – PGA (g) RP=95 years (no date) The UWI Seismic Research Centre. Available at: https://uwiseismic.com/downloads/seismic-hazard-map/

36. At a meeting with the Governor and the Premier on 27th November, it was clarified that the Government of Montserrat does not at this stage wish to make any changes to Zone V, either to change its boundaries, or to microzone (subdivide) it. The basis for this is that there is a need to maintain a clear delineation of zones of unrestricted and restricted access on the basis of potential impact by volcanic hazards. The restricted areas should be closely monitored and controlled with the ability to be quickly evacuated, if needed, based on changes in volcanic activity level. There is a recognised need to develop a structured, yet flexible, system to allow exceptions for certain activities with a controlled degree of access to Zone V and avoid, for example, requirements for access to Zone V being dealt with on an *ad hoc* basis.

37. The following items are offered for consideration for the Government of Montserrat with respect to the above stated need for the development of a system on which to make those assessments and, in particular, one that provides both evidence-based, and defensible, decisions that may cover those involved against legal risks.

38. **Volcanic risk assessments versus workplace risk assessments in volcanic environments**: Based on discussions during the SAC meeting, we consider it useful to clarify some aspects of how the term 'Risk Assessment' may be used in different contexts in relation to volcanic activity on Montserrat.

    Workplace/occupational safety and health risk assessments are commonly carried out for occupational safety and health (OSH) risk and management purposes in many work environments. These generally comprise explanatory text and a table where the diverse sources of hazard and risk in that working environment are identified, along with proposed associated mitigation strategies (see Appendix IV for an example). Typically, such risk assessments provide a framework for systematic considerations of the potential hazards and their impacts, to aid in developing a conceptual understanding of how, and to what extent the risk of these hazards can be controlled or mitigated in order to reduce the risk. Indeed, the specification of suitable and sufficient risk control measures is a key part of why they are undertaken. Such risk assessments are a critical component in the development and implementation of safe systems of work in support of 'work' activities. In the Montserrat context, companies/workers working in Zone V might undertake workplace risk assessments which take in considerations including non-volcanic hazards present in their work environment (such as the use of heavy machinery), but also related to the volcanic environment or landscape (including exposure to gas or particulates), as well as volcanic activity itself (volcanic unrest and eruptive activity).

    Scientific volcanic hazard and risk assessments are a very different kind of risk assessment which comprises a technical/academic quantitative assessment and determination of risk that can be developed and used in the context of understanding volcanic hazards and activity. Volcanic risk assessments, for example as previously undertaken by both MVO and SAC involve a quantitative assessment of risk to life safety undertaken for the purpose of understanding the degree of potential consequences of volcanic activity.

The two types of risk assessment are related, because they share the common broad goal of wanting to understand and eventually mitigate the impacts of the hazards on people and property. However, they are also fundamentally different in terms of how they are developed and their specific purposes. **One is the presentation of a *conceptual framework for workplace health and safety*, and the other is a *significant scientific endeavour, of a quantitative nature, to understand and quantify the likelihood of events, their impacts and resultant risk***, and which is often undertaken ***to support high-level decision-making***. Scientific volcanic hazard and risk assessments, where available, can and should be used to support workplace/OSH risk assessments, with the former providing the critically important scientific hazard identification and risk evaluation information to be used within, and as part of, the latter.

39. We offer for consideration the possibility that a system, as used in the OSH risk assessment in Appendix IV, could be adapted and tailored for use on Montserrat with respect to decisions to grant access to Zone V. The advantages that such a system offers is that it provides a means to systematise the evaluation procedure by the Government of Montserrat for any exceptions to work in Zone V, it gives structure to the thinking around the hazards and effective mitigation or control measures, and it could help the Government of Montserrat carry out due diligence in overseeing any access exceptions. All the relevant hazards related to working in a volcanic landscape and environment, and volcanic hazards and activity (river crossings, explosions, lava dome collapses and ballistics), could be explicitly assessed using such a matrix.

    A critical point is that the control measures vary depending on the specific hazard – from the use of dust masks, to the construction of a reinforced roof shelter or the clearing of an evacuation route – and it is the feasibility of implementing some of these mitigation measures that currently presents the limitation to reducing the *initial* risk (before the measures are in place) to the (lower) *residual* risk (after the mitigation measures have been implemented; see Appendix IV).

    One crucial component of a successful OSH system is clear targets for the level of residual risks (residual risk after mitigation measures are put in place). These would need to be clearly defined (e.g., low, medium, high; see Appendix IV), and communicated, to permit applicants by the Government of Montserrat. This would enable a consistent and transparent decision-making process for the issuing of permits.

    MVO's scientific expertise could contribute to information about, and the assessment of, those issues that specifically relate to SHV's activity, but it would not be appropriate for the MVO to hold responsibility for either completion of the forms on behalf of those seeking access, nor be responsible for final approvals of such OSH risk assessments.

    We note that our SAC does not have expertise in the legal aspects of implementation of OSH risk assessments and thus the feasibility of implementing such a system would need to be investigated by appropriate others. We also recognize that implementation, even if introduced in phases, and in particular the regulation of such a system, may have its complexities on Montserrat.

40. **We also offer for consideration an additional framework within which to begin to evaluate potential activities in Zone V. This is to relate the timescale of the investment or benefit to the timescale of the potential window of opportunity that the current pause provides such as illustrated in the matrix below (Fig. 3).** If there was considered to be a high probability that the current pause would be short lived (Scenario 1), even activities with short-term benefits would be impractical**.** In fact, SAC has, for a number of years, determined that probabilities for an eruption restart within 1 year are very low (see Section 52). Scenario 2, however, is a significantly more likely scenario, which provides some opportunity to consider activities that would provide benefits, either related to quality of life or economic benefits to the island over a short timescale. The same matrix illustrates that it would not be prudent to consider activities in Zone V that would only pay off in the medium to long term until we are much more convinced that an eruption restart would not occur in the 1 to 5 year time frame.

Exemplar matrix for considering restart scenarios and types of activities in Zone V

	Timescales of investments		
Timescales of Restarts	Activity 1: Short term (1-5 years) benefits	Activity 2: Medium term (5-20) benefits	Activity 3: Long term (20 year +) benefits
Scenario 1: Current pause continues but eruption restart within 1 year	X	X	X
Scenario 2: Current pause continues but eruption restarts after 5 years	Y	X	X
Scenario 3: Current pause continues but eruption restarts after 30 years	Y	Y	X
Scenario 4: Current pause continues but eruption restarts after 300 years	Y	Y	Y

Fig. 3. Exemplar matrix for considering restart scenarios and types of activities in Zone V

41. **The points covered in Sections 38-40 could all be components working along with other processes undertaken by the Government of Montserrat that would contribute to the provision of transparent, accountable and evidence-based decisions.** It is our experience of legal cases arising from volcanic hazard-related damage in the past that evidence-based decision making is the key defence in showing that sensible and reasonable risk assessment has been made.

Decision-making tools and multi-stakeholder involvement

42. On Tuesday 28th November, SAC for the first time held an **open discussion session with the following stakeholders**: Alvin Ryan – (Disaster Management Coordination Agency); Dr Sharra Greenaway-Duberry (Chief Medical Office); Garrett Stanley (Principal Environmental Officer) and Mr Clement Meade (Chief Physical Planner). The purpose of this meeting was to better gauge what questions related to volcanic

hazard the stakeholder groups are interested in, and to what extent MVO's work already does and can support their respective work.

43. During these discussions, access exceptions to Zone V for the following diverse purposes were mentioned: Tours to Plymouth for tourists, sand mining activities in the Belham Valley and proposed sand mining activities in the upper Belham and potentially Fort Ghaut. Other stated interests for access in the future were for tours to St George's Hill and access to farmlands, especially in the Molyneaux area. There is also interest related to purchasing/reconditioning houses in Foxes Bay and Richmond Hill in Zone C, which require access across the Belham valley. Longer term initiatives under consideration include national park/geoheritage site and Geothermal. These activities together represent a range of interests and priority levels, with potential contributions to island development for the GoM to decide on. The above information, however, does provide the context for the need to better understand the hazard and risk levels in Zone V in the current state of SHV.

44. There is recognition that some areas within Zone V are exposed to very low levels of hazard, that there is a need to have a shared understanding and definition of low risk, and that risk is also dependent on the risk mitigation measures in place. There was discussion and recognition that **MVO is a central component of the risk mitigation strategy**, as they provide support for and during access.

45. **So-called 'out of the blue' events are an important category discussed with this group. We can consider these as significant volcanic events (such as explosions, or lava dome collapses) that could occur without any precursors or warning and that could threaten the safety of people in Zone V. We consider these events as *highly* unlikely, but they remain plausible, and could have important consequences.** As such they should be considered amongst the volcanic hazard scenarios that are discussed and planned for on Montserrat. As a result of this discussion in SAC28, we introduced a new elicitation question to determine the likelihood of such events (see Section 55). **Any decision making about access hinges on response to and mitigation measures that relate to 'out of the blue' volcanic events.**

46. The question was asked, ***if there were a restart in the eruption, would the activity be of the same style that had been seen 1995-2010?*** It was clarified that there is no reason to believe that there would be a change in general eruption style of the SHV. Given the current level of unrest, it is clear that SHV is not returning to a dormant state, on the contrary, the probability of a restart is increasing, but still at a low level.

47. There was consensus amongst the stakeholders that the MVO Hazard Map Series will be a supportive tool. It is also clear that MVO will need to work with interested stakeholders in the application of the tool because of the sheer volume and complexity of all the information embedded within it. The siren sound coverage map was given as an example of useful information not previously available.

Air quality monitoring on Montserrat

48. Following the suggestion by former governor, HE Andy Pearce, a project was proposed by GoM to study the air quality (SO_2 and particulate matter PM) on Montserrat. This project was taken up by Leeds and Durham Universities after funding for a PhD project could be secured. Prof Neuberg presented preliminary results from a first field study in May and June 2023, carried out by a team comprising PhD student Rosie Lewis, and supervisors C Horwell (Durham), E Ilyinskaya, J McQuaid, and J Neuberg (Leeds). The team deployed, overall, 12 SO_2 and $PM_{2.5}$ sensors, first in a colocation set-up ('huddle test') then distributed throughout the island. SO_2 results had not been available at the time of the SAC meeting, but have since been presented to the MVO in the first 6-month report. **Most $PM_{2.5}$ results showed values not exceeding the WHO limit for small particles of a 15 μg/m^3, averaged over 24 hours**, except on one occasion (Nov 2023) where Sahara dust is the most likely candidate as the particle source. **At the Plymouth site, however, the WHO 24-hour limit was exceeded (16.5 µg/m^3 and 15.4 µg/m^3) on 17th and 18th May 2023. As the WHO 24-hour limit should not be exceeded for more than 3 days per year, it is highly likely that over a longer period Plymouth would exceed this, which has implications for any activity in that area, such as tourist visits and sand mining.** A longer time series will be available once instruments are re-deployed at the Plymouth site with the help of MVO technical support.

49. Exposure to PM and SO_2 is part of the wider question about life and work in the restricted areas, but currently the responsibility for air quality monitoring appears to fall in the gaps, being neither an MVO, Ministry of Health, or Department of Environmental Health Environment responsibility. Discussions with Sharra Greenaway CMO and Garrett Stanley Principal Environmental Officer, as well as Alvin Ryan DMCA, highlighted the problem of the co-location of the sand mining activities, seen to be an important source of airborne dust, and the tourist activities. Another point raised was that occupational safety and health risk assessments of any workers (e.g., taxi drivers, sand miners, MVO staff) in dust or SO_2-prone areas could ensure personal exposure sensors were employed as a means to monitor and control for exposure levels.

Future activity – hazard scenarios and elicitation results

50. We now summarise the results of the formal elicitation of the views of the SAC members and MVO scientific staff on the probabilities of occurrence over the next year of various hazardous events. 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 elicitation method that we have used in previous SAC assessments. The questions, explanations of their context and the ranges of uncertainties derived from the group's responses are presented in detail in Appendix VI. Here, on Table 1, we tabulate the central median probability values for each of the questions and compare them with the equivalent values obtained previously, at SAC27.

51. The first question asks what is the probability that the volcanic system (including its internal plumbing system) will remain active over the next 12 months. **The result of**

96% reflects the confidence that the group has that the volcanic system is still in a state of unrest.

52. The series of questions 2a-2d ask what the probability is that one of four scenarios will happen in the next 12 months: nothing significant occurs, resumption of lava extrusion, lava dome collapse, and explosive eruption. Between the elicitation of SAC27 (November 2022) and SAC28 (November 2023), the assessed median probability of (Scenario 2a) that **'nothing significant' occurs in the next 12 months has increased slightly from 85% to 87%**. The likelihood of a quiet resumption of lava extrusion taking place as the first significant event in the next twelve months (Scenario 2b) has decreased slightly from 8% to 7%. There is a slight decrease in the assessed likelihood of lava dome collapse (2c) from 3.5% to 3%, and slight increase in likelihood of vertical explosion (2d) from 2.8% to 4% as the first significant event in the next twelve months. **The scenario that 'nothing significant happens' is judged greater than ten times more likely than the next most likely scenario – 'resumption of lava extrusion'**.

53. We also elicited a conditional probability for magma extrusion or an explosive eruption to follow within one month of a major dome collapse (question 3) as 86%. **This result indicates that the SAC would not be surprised by the eventuality of new magma reaching the surface quite fast after an initial dome collapse**.

54. We discussed the stability of the lava dome in the context of intense bouts of rainfall and regional seismic activity and in line with previous years elicited for **'the probability over the next 12 months that there will be a significant, externally-triggered dome collapse' (question 9). The median probability value was 0.08%**.

55. At SAC 28, questions were raised by the DMCA about the likelihood of an '**out of the blue**' event, such as one which would affect the safety of workers in Zone V (by implication an event of considerable size). As a result, **we added a new question (10) to explore that query and elicit the probability that an eruption threatening people's safety in Zone V would occur without producing recognised precursors at least 24 hours prior to the eruption. The probability of such an event was determined to be 0.004% – i.e., a 1-in-25,000 chance event**. This question will probably be refined in the future and should be considered exploratory at this stage. But we feel that it provides a useful framework to assess residual volcanic risk in the context of workplace health and safety.

Table 1. Summary of SAC28-elicited central probability estimates for significant event scenarios over the next year.

	Elicitation Question **(summary description)**	**Probability SAC28** **(SAC27)**
1	The volcanic system will remain active over the next 12 months	98% (95%)
2a	Nothing significant happens	87% (85%)
2b	Resumption of lava extrusion	7% (8%)
2c	Collapse of the lava dome *Conditional on there being a collapse, the following are the elicited probabilities for collapses in different directions:* *NW* *N* *NE* *SE* *S* *SW*	3% (3.5%) *NW – 5%* *N – 29%* *NE – 46%* *SE – 3%* *S – 4%* *SW – 17%*
2d	Vertical explosion	4% (2.8%)
3	*Conditional probability of magma extrusion or explosion within one month if a major dome collapse is next event*	86% (85%)
10	Probability that an eruption threatening people's safety in Zone V would occur without producing recognised precursors at least 24 hours prior to the eruption?	0.004%

Long term evolution of risk results

56. It is useful to see how the elicitation results have evolved over time during this Phase 5 pause. The relative likelihood of the scenarios (nothing significant happens, resumption of lava extrusion, dome collapse, and explosive eruption) for the next year have now been asked during the elicitation for 13 consecutive years (see Fig 4). What we can see over this time, in general, is an increasing perceived likelihood that the pause will extend through the following year, with an accompanying slight decrease in the associated uncertainty. **In other words, as the pause in the eruption has extended, there has been increased confidence that it will remain in a paused state**. The other scenarios, the resumption of lava extrusion, dome collapse, and explosive eruption, have been perceived to be less likely through time, again with an overall decrease in uncertainty related to that. It is worth pointing out that **this data set is completely unique, worldwide, because the methods used by SAC are firstly quite specialised and secondly no other group worldwide has undertaken this type of assessments in such a consistent manner over such long timescales.**

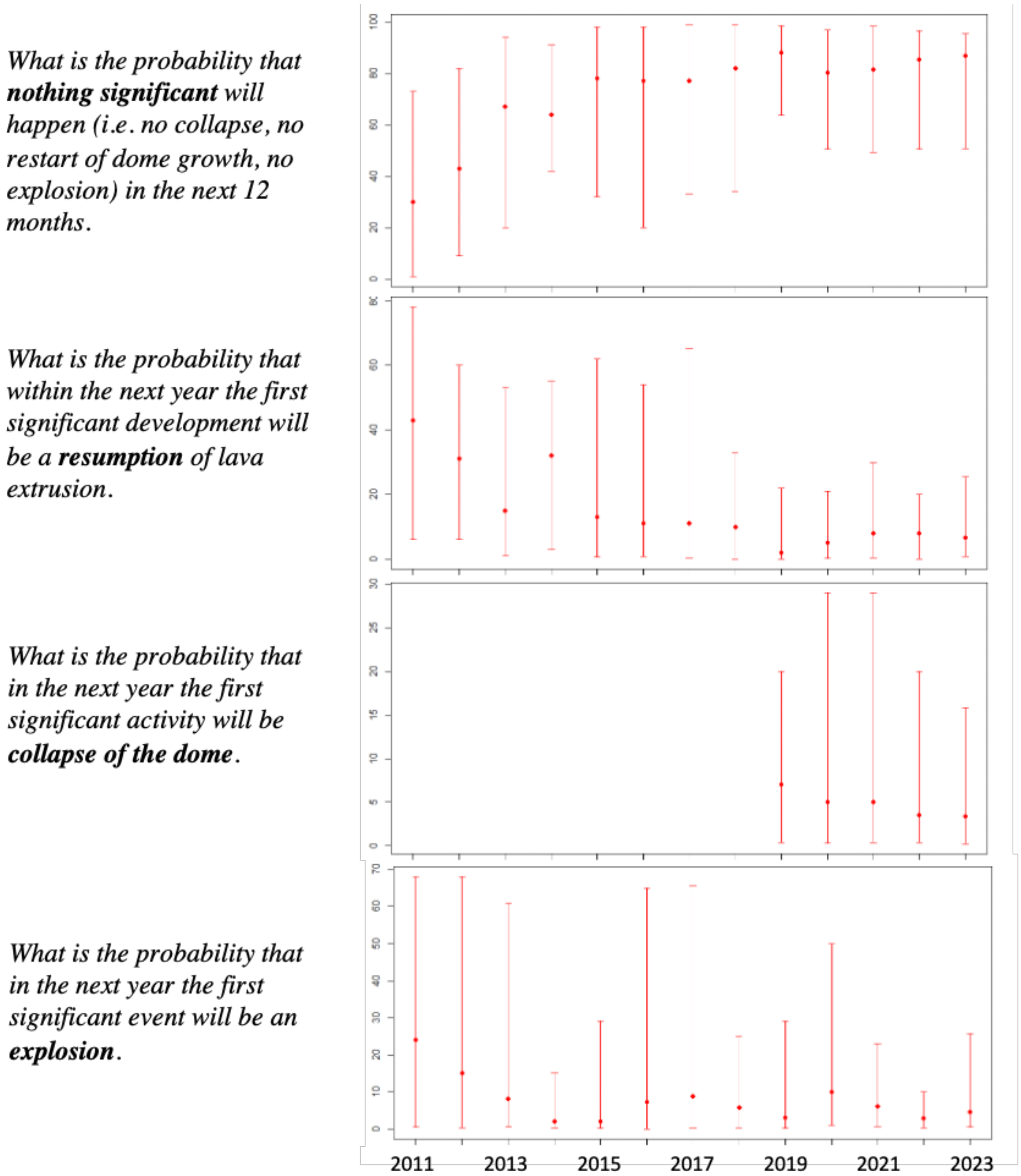


Fig 4. The relative likelihood of the different scenarios in the next year as determined by SAC elicitation results from 2011 to 2023. The red points represent the central median probability while the vertical bars represent the uncertainty.

57. **The lava dome configuration has been relatively stable over the last five years. If there is a collapse**, the elicitation results for the different likely directions are given by the plots in Fig. 5. Consistently, over the last five years, it is considered that **the most likely collapse direction would be towards the NE i.e. towards the Tar River valley, followed by the North, followed by the SW towards Plymouth.**

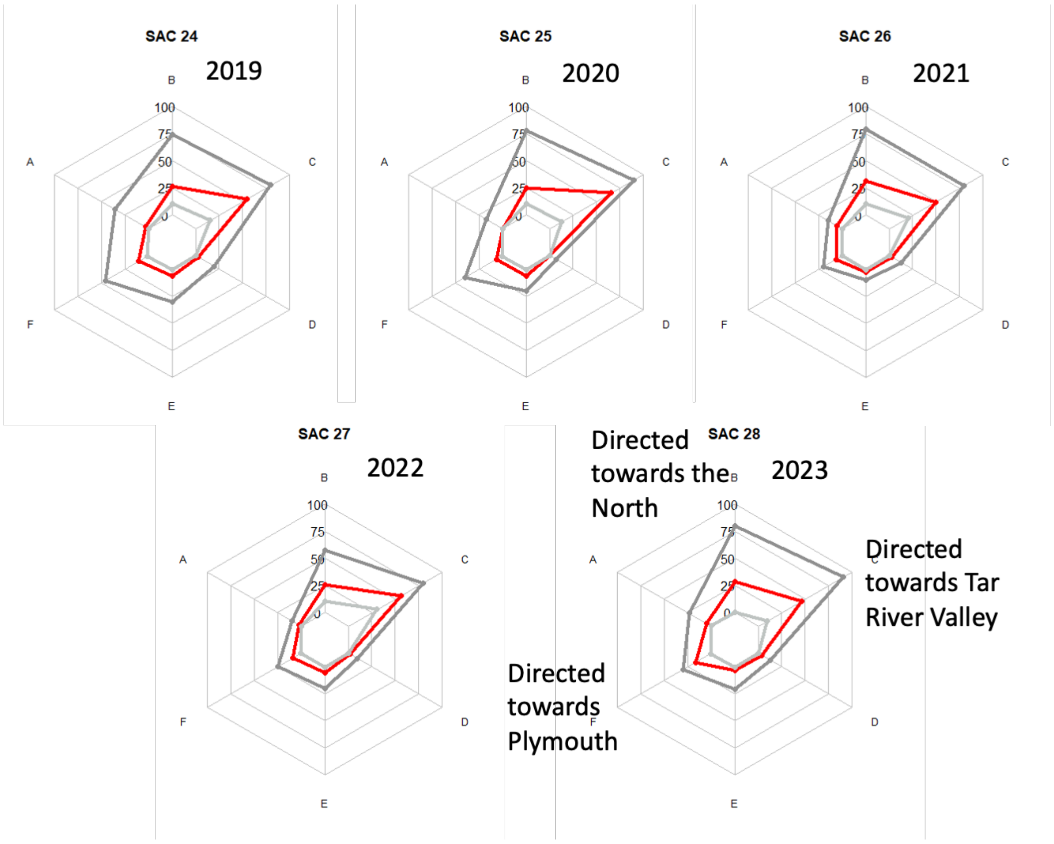


Fig. 5. Shows the elicitation results for the likely directions of dome collapse from 2019 (SAC 24) to 2023 (SAC 28). The numbers on the vertical axis are percentages. The directions of the 'spokes' relate to the different sectors around the dome as indicated on the elicitation questionnaire. A – centres on NW, B on N, C on NE, D on SE, E on S, F on SW.

Determination of risks in Zone V

58. Activities taking place in Zone V, such as sand exports from the Plymouth jetty, geothermal work, police operations, filming and tourist trips are managed by GoM in co-operation with the MVO. **Hazard levels within Zone V vary strongly from location to location and we consider it appropriate that MVO convey that information through its Hazard Map Series**. This approach will, in turn, facilitate a more detailed analysis of risk associated with specific activities in specific locations, and therefore facilitate a use of the current opportunity during this extended pause period for those activities in Zone V.

59. **Volcanic risk levels for certain activities will be determined by the MVO as required by the GoM, and based on the short-term hazard assessment (e.g., the probability of pyroclastic flows being generated in the next year).**

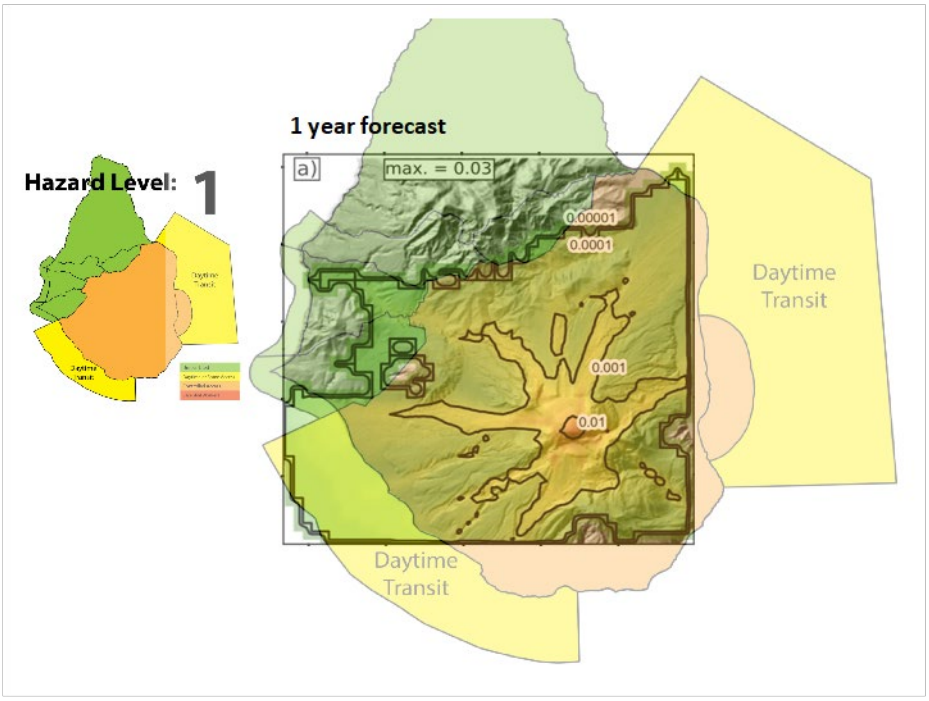


Figure 6. Probability of PDC inundation for 1 year from assessment time for a uniform distribution of flows around the dome superimposed on the current Hazard Level 1 map, with the full Hazard Level 1 provided as an inset on the right. Contours with inundation probabilities P = 1/100 (0.01) and P = 1/1000 (0.001) are plotted for visual reference. Of note is that areas that correspond to activities in Plymouth and the Belham valley lie in the P=1/1000 (0.001) to P=1/10,000 (0.0001) range.

60. **It is key to consider the different forecast time-scales and how these are most appropriately used for the types of decisions that might need to be made. Decisions around short-term access to sites – for example tourist access or sand mining, both of which have economic and livelihood implications – could be based on short-term, annual forecasts**. Such forecasts can be up-dated to reflect the extending time frame of relative quiescence, and should provide a defensible level of background hazard for visitors. **Alternatively, for decisions such as investment in infrastructure and longer-term planning and development, it is more appropriate to use 5, or even 20-year forecast maps**, all of which are available at the MVO.

The operation of MVO

61. **Seismic network**: Seismic monitoring is the backbone of real-time monitoring capabilities. During this reporting period, two new broadband seismic stations have been added to the network in the south of the island. The system is considered fit for purpose, however maintenance is a continuous challenge especially for the close-in Spider stations.

62. **Ground deformation**: Geodetic monitoring is mature and effective and provides essential insights into the long-term, deep volcanic processes (e.g., deep pressurisation of the system). The GPS network has been stable over the last year. There are some issues in network connections to the sites on the West of the Island, which generates

inconvenient delays in analysis. MVO staff have fruitful and longstanding collaborations with international partners related to work on processing and modelling the ground deformation data.

63. **Degassing:** The SO_2 monitoring system via scanners is still being completed (OpenSO_2 and NOVAC, 2 multigas instruments) and software is being developed to provide the real-time data. When operational, this will greatly support and add to the capacities of the MVO. Continued traverse-based SO_2 flux monitoring will still remain a priority, because this provides the highest quality measurement of SO_2 flux. Detection of changes in shallow degassing by measuring S/Cl ratios will be possible with a new OP-FTIR which is planned within the budget of the new MVO contract. This ratio reflects overall gas and heat flux in SHV, so can be a sensitive indicator of changes in the system.

64. **Dome morphology**: Monitoring of changes in dome morphology is well operationalized and provides valuable insights into extent of erosion and overall assessment of dome stability. The MVO currently has a network of 5 cameras that run continuously with nearly 360-degree coverage including several that work at night. These cameras will capture and archive images of surface activity. The thermal camera, which is critical for measurements of fumarole temperatures, has been in for repair since June, but the MVO has now also purchased a new one. The aim is to get both running which will be important for cross-calibration and will also allow for redundancy. Measurements and detection of changes in the fumarole activity on the lava dome is a key component of the monitoring system that might detect changes ahead of an eruption restart. The AVTIS instrument, a ground-based mm-wave imaging radar which can penetrate cloud, is located on Windy Hill, and is currently not operational and unlikely to be so without serious investment. It initially pertained to the University of St Andrews and now belongs to the MVO, but it has only been properly operational for a few months over the last 10 years. If lava extrusion restarts, the main tool for observing changes in the dome will be photogrammetry based on the camera network.

65. **Detection of precursors ahead on an eruption restart**: There is significant confidence, as determined by our elicitation results, in the MVOs ability to detect, and recognise precursory activity ahead of any restart in activity (Fig. 7). Two of our elicitation questions ask whether it is considered likely that there will be precursory activity in the 6 months before a restart (Fig 7, upper plot), as well as the likelihood that it will be recognised as such at the time (Fig 7, lower plot). The results from the SAC28 elicitation are that there is a **93% likelihood that there will be precursory signals** during this time, and an **88% likelihood that it will be recognised as such** at the time. The elicitation results for these questions over the last nine years indicate a gradual overall increase in confidence over this time for both questions, along with overall decreasing levels of uncertainty (as illustrated by the lengths of the vertical bars on each side of the data points representing the elicited mean) for both questions. This is an indicator that there is collective confidence in the MVO monitoring system being fit for purpose.

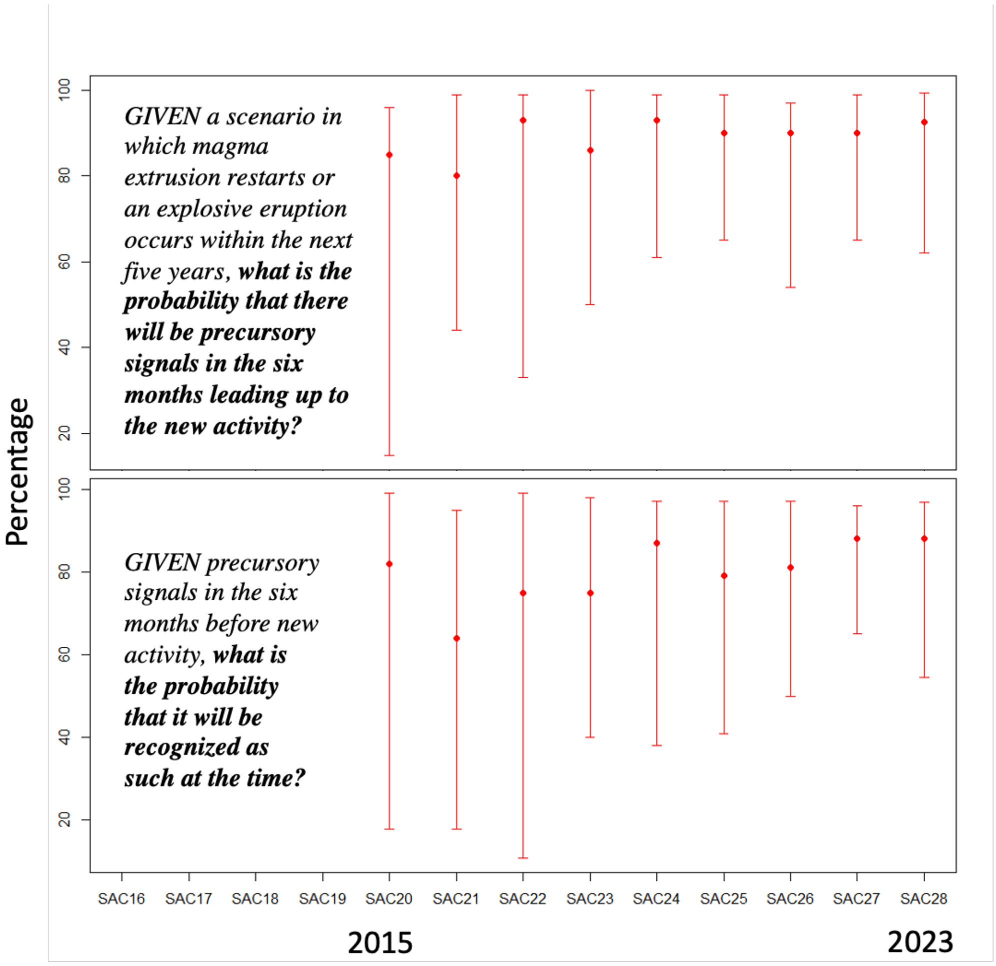


Fig. 7 shows evolution of the elicitation results between 2015 and 2023 for the two questions indicated on the right hand side of each plot. The red data points represent the elicitation result mean, and the vertical bars represent the uncertainty on each value.

66. **Education and Outreach:** MVO is undertaking excellent work in education and outreach and exceeding 'fit for purpose' expectations. During this reporting period there is an impressive list of activities accomplished, as well as leading and developing on the foundation of international research projects. We note that expectation on Montserrat of the extent to which the MVO should undertake outreach and in particular, support tourism, is very high. These expectations on Montserrat far exceed that which is undertaken by many volcano observatories worldwide.

67. **MVO overall performance:** Looking at the overall performance of the MVO, we state that due to the proficiency, competence and motivation of the scientific and technical staff, the monitoring capacity of MVO regarding the measurements of ground deformation, gas emissions, seismicity and dome stability can be considered as up to standard. We note that access to Zone V, as granted by the GoM, is entirely dependent on the MVO's capability to detect even the slightest changes in volcanic activity in a timely manner.

68. **Cautionary response to increased unrest**: On 8 September 2023, following the detection of a few LP earthquakes, the MVO suggested rapid precautionary closure of Zone V. This cautionary response was reverted once the seismic activity was studied and considered not to be of concern. Two key points were raised in the discussions about this: In the event of any unusual activity, the MVO procedure is to call an MVO meeting to discuss the situation, then advise DMCA and NDPRAC and provide a recommendation based on MVO's judgement of the situation. One suggestion that came out of the discussion was to ensure that the MVO decision making process during these episodes was documented. In addition to the accountability this provides the MVO, this documentation would support transparency in the overall decision making across organisations. MVO could also consider clarification of what stage in an unrest scenario, or in what circumstances, the Seismic Research Centre would be involved.

69. **Enabling and supporting access exceptions to Zone V**: MVO provides support for access to Zone V by provision of a professional operation in order to provide safeguarding, to the extent possible, to workers and visitors in Zone V. The vast majority of Zone V visits are for sand mining operations in the Upper Belham, as well as facilitating export of these volcanic materials via the jetty in Plymouth, and guided tours of Plymouth with tourists. Sand mining operations occur during normal MVO working hours during the week, on most Saturdays and on occasional Sundays. Outside of normal working hours Operations Room staff work overtime to provide cover. Guided tours of Plymouth are also frequent with much increased numbers during the high season. MVOs work enables these commercial activities through supporting access to Zone V.

70. **MVO response/collaboration in the Region**: **The collaboration and response activities of MVO staff in the region are important**. The MVO is a key source of local volcanology expertise in the region; the collaboration built with other professionals across the Caribbean, including from NEMO, St Vincent and from SRC in Trinidad, strengthens the broader regional volcanic crisis response 'system', which in turn reduces systemic and institutional risk both in Montserrat and elsewhere. During this reporting period invited visits have been made to the Martinique Volcano Observatory to present a talk and visit archives (Dr Karen Pascal), and to St Vincent (Dr Jose Marrero and Dr Thomas Christopher) to participate in a stakeholder workshop as well as install gas monitoring equipment and train staff.

71. **Engagement with the broader international volcanology community**: An important upcoming international volcanology conference Cities on Volcanoes 12 will be held in Antigua, Guatemala Feb 11-18, 2024. MVO will be represented at this conference by Dr Karen Pascal and Ms Thiffanie Williams who will give presentations on the Curating Crisis work, and Dr Jose Marrero who will give two presentations related to the work on the Hazard Map Series, one which was an invited talk. Montserrat will also be represented at this conference by Hermon Francis (cultural aspects of living in a volcanic context) and Annesta Fergus (volcanoes and geotourism). It is fantastic to see such strong and multidisciplinary representation from Montserrat at this conference, and to know that this broad involvement at the international academic level is something that is initiated and facilitated by MVO staff and their research collaborators.

72. **The MVO contract**: Lastly, important issues were discussed related to the recent MVO tender process and the new MVO contract which, when complete, will be for three years, extendable for two further years. We understand that at the UK-level, the political and structural systems currently in place *require* a tender process to occur on Montserrat in order to establish contracts for the MVO in open competition. Alongside that is the other reality, that the current tender process has real and tangible negative impacts on the operation of the MVO, an entity made up of an experienced team of highly specialised staff, and whose functionality is dependent on continuity. As part of our Terms of Reference to review the performance of the MVO, we would like to emphasise that these impacts be recognised and they are highlighted here:

(i) The major current concern relating to the contract is **timescale**. The uncertainty that renewal and short contracts have on the specialized staff is a major issue. The precarity of contracts is weary for existing staff, has contributed to staff turnover and dissuades those best qualified from applying, or accepting positions. MVO's key resource is its staff's situated knowledge and expertise, and the current situation limits and fundamentally undermines MVO performance and potential.

(ii) The current model of 3 years plus 2 is short with respect to the timescale of implementing the tender process and securing the contract on Montserrat. MVO's last full-term management contract concluded in September 2021. Since that time, the MVO has been managed under short-term interim contracts. Following the bidding process in November 2023, a new contract has still not been negotiated. For these last three years, it has not been possible for SRC to recruit permanent staff on long-term contracts. This particularly and currently affects the Seismologist and Hazard and Risk Officer positions, two key roles for the operation of the MVO.

(iii) The UK Goverment's approach to the management of MVO creates institutional vulnerability and as such increases systemic risk. If a crisis were to occur and MVOs performance or capacity to respond was undermined by deficiencies in staff or the monitoring system that were linked to the tender cycle, the managers of this process would ultimately hold liability.

(iv) A single-source justification and/or longer time-scale contract would help to remediate this problem. However, it is worth noting that volcano observatories around the world are *not* run on regular tenders for the overall observatory operation. Continuity in systems, staff and processes is recognised as fundamental for successful long-term monitoring.

(v) Continuity of the MVO as a functioning system (staff, monitoring system, data, etc.) is essential for the safety of the island. The evidence strongly suggests that Soufrière Hills volcano has been and will be in a state of unrest for a timescale that is much longer than 5 years. There is overwhelming consensus among the scientists that the volcano belongs in a category that requires indefinite monitoring by a local, dedicated observatory. The UK Government needs to consider the liability and risks associated with making the MVO staffing and processes precarious through regular tender procedures.

(vi) The overarching requirement for Montserrat is an effective MVO providing accurate and timely volcanic risk assessment. This means that the MVO requires long-term stability in funding, staffing, administration and renewal. Given the fundamental and long-term need to assess and minimise volcanic risks on Montserrat there should be a legal requirement that the UK properly supports a long-term, effective volcano observatory

We understand that the above represents a strong position statement, but we cannot stress enough how important we consider this to be. We offer to work with the FCDO to look at possible alternative models and to prepare an evidence-based case for changing the current management model going forward.

SAC Matters

73. SAC members charge fixed professional fees for the typically four official days of the meeting. This fixed maximum amount for all SAC members facilitates easier budgeting and forward planning. In this context, we would like to point out that SAC members provide significant input by preparing scientific documents, running numerical simulations and ploughing through the latest, relevant, scientific literature, an effort far beyond the official days of the meeting. During this reporting period the SAC Chair also attended two MVO board meetings and sat on the committee assessing the MVO tender applications. Without these in-kind contributions, the work of the SAC would not be possible.

74. If MVO does decide to continue to finalise the forward-looking hazard map layer as part of the SRC-MVO Volcanic Hazard Map Series, SAC member Prof Eliza Calder would be available to provide expertise. Therefore, and at MVO's request, if SAC input is required for completion of the hazard map, additional funding outside the SAC budget needs to be requested to support these efforts.

75. After a discussion amongst the SAC members, Prof Neuberg indicated that he will step down from SAC. We thank Prof Neuberg for his dedication and hard work on this committee for over twenty years, eight years of which he served as chair. We will liaise with the Montserrat desk officer at the FCDO about the process of advertising and selecting a replacement SAC member. There is agreement amongst the group that it will be important to seek expertise in volcano seismology for this position. Going forward, we will keep in mind the report by J.C Komorowski[13], and the recommendation that there should be rotation amongst SAC members and roles, and will continue to revise the situation annually.

76. We propose that the next meeting of the SAC will take place the week beginning 18th or 25th November 2024, to be confirmed after consultation with GoM, and unless a significant event on the volcano brings this forward. These dates are to allow for sufficient time after the established MVO six-month reporting period (April - September), for the reports to be compiled and reviewed internally by MVO before sending to SAC.

[13] Komoroski 2020 Review on Montserrat SAC to FCDO

Appendix I:

Terms of Reference of the Scientific Advisory Committee
(Amended in 2023)

Constitution of the Scientific Advisory Committee on Montserrat Volcanic Activity

This document outlines the main responsibilities of the Scientific Advisory Committee (SAC) on the Soufrière Hills Volcano, Montserrat. The document includes the terms of reference for the SAC and a membership template. The SAC is commissioned by the Overseas Territories Directorate (OTD) of the Foreign, Commonwealth and Development Office (FCDO). The SAC will work according to the Office of Science and Technology (OST) Code of Practice for Scientific Advisory Committees. The SAC will not incur expenditure without prior FCDO (OTD) authority.

Terms of Reference

The main responsibilities of the SAC are:

1. to carry out an annual hazard and risk assessment of the volcano in co-operation with the Montserrat Volcano Observatory (MVO) and to report its findings to HMG and the Government of Montserrat, and

2. to provide scientific advice at a strategic level to HMG and the Government of Montserrat outside these regular assessments in co-operation with the MVO.

NB: The "Government of Montserrat" will normally mean, in the first instance, the Governor as s/he has the constitutional responsibility for the safety of the Montserrat population. The Governor will be responsible for ensuring appropriate dissemination of SAC assessments or recommendations to the broader, elected, Government and people of Montserrat.

The SAC is also required to perform these additional functions:

3. to provide advice on the scientific and technical operations of the MVO to ensure that the work matches the level of risk;

4. to provide scientific advice and assistance to the MVO as required by the MVO Director; and

5. to offer advice on new developments that were not foreseen when the TORs were set up, and if appropriate make recommendations for changes to the TORs.

These general terms of reference are supplemented with the following specific points:

(a) The work of the SAC concerns annual scientific assessment of the volcanic activity and related hazards and risks, with a focus on the long-term risks posed by the volcano. This scientific work is underpinned by the monitoring data and interpretations arising from the work of the MVO.

(b) The MVO, with support from SAC as required by MVO, inputs to day-to-day decisions made by the HMG and the Government of Montserrat related to the safety of the people of Montserrat (such as evacuation and extent of Controlled Access Zones), to issues of planning and sustainable development of Montserrat and to the mitigation of external hazards (e.g. to civil aviation).

(c) The MVO Director (or scientific staff designated by the Director) participate in all SAC activities except for ToRs 3 and 4.

(d) The SAC has the function of giving advice and assistance to MVO relating to scientific matters as required by the MVO Director.

(e) With respect to ToR 3 the Chair of the SAC will be a member of the MVO Board of Directors and can provide scientific advice to the Board as required. The Chair will be expected to attend MVO Board meetings (currently twice a year).

(f) Given the special circumstances of Montserrat as a United Kingdom Overseas Territory, reports of the SAC would be provided for both Governments. Reports would also be given to the MVO Management Board.

(g) The SAC will be required to present its findings from SAC meetings in a manner suitable for release to the public and play a role, along with the MVO, in its dissemination. It will also be required to assist the Governments and the MVO in explaining the activity of the volcano and the scientific information pertinent to decision-making by the authorities.

(h) The SAC will liaise with other relevant scientific organisations or committees as required.

(i) The Chair of the SAC will make an annual report to the MVO Board of Directors.

MEMBERSHIP

Membership of the SAC will be at the invitation of the FCDO (OTD) and will cover the key areas of expertise required to assess the level of activity, hazards and risks of erupting volcanoes. Expertise will include such areas as volcanology, volcano geophysics, and hazard analysis. The SAC will continue the approach of the former Risk Assessment Panel that was endorsed by the UK Chief Government Scientist in December 1997. Thus, the Committee requires a facilitator as a member for applying expert elicitation methods to estimate volcanic risk. These considerations imply a minimum of four members, excluding the Director of the MVO. If a lack of expertise becomes apparent on a particular issue, additional experts will be sought as and when needed through open advertisement of the post and open competition with prior agreement from the FCDO (OTD). As required by the Code the SAC is expected to consider external opinion. The membership will be considered on an annual basis with a view to regular, 3-5 year changes, refreshment of membership and rotation of the chair.

MEMBERSHIP TEMPLATE

Members invited to serve on the SAC for the Montserrat Volcano are expected to attend all hazards and risk assessment meetings and to participate in the formalised elicitation procedure. Members have the responsibility to use their scientific judgement and expertise to meet the Terms of Reference. Opinions of the Members on scientific matters should be expressed through participation in the work of the SAC. Divergences of scientific opinion will normally be reported in terms of scientific uncertainty through the formal expert elicitation procedure. Differences that cannot be incorporated through the elicitation methodology should be included in the reports of the SAC as required by the OST Code. The Chair of the SAC, or his or her delegate from the Committee, will be responsible for presenting the findings of the SAC's work to the Governments of Montserrat and the United Kingdom and to the public in co-operation with the Director of the MVO. Any disagreement or divergence of opinion with the Director of the MVO that cannot be reconciled or incorporated through the elicitation method should be reported through the MVO Board of Directors.

SECRETARIAT

The FCDO (OTD) will provide a Secretariat for the SAC, as set out in the Code of Practice. FCDO (OTD) will reimburse premium economy travel costs, reasonable hotel accommodation, meals and professional fees (once agreed) in full. The SAC will not incur additional expenditure without prior FCDO (OTD) authority. The Secretariat's main point of contact is Martin Hogg, Montserrat Desk Officer – Caribbean and Bermuda Section, OTD. His contact details are as follows:

Email: Martin.Hogg@fcdo.gov.uk
Tel: +44 7784 039 818

Appendix II:

SAC Agenda

Monday, 27th Nov 2023 (MVO) – Volcanic System
09:00am-5:00pm Meeting (SAC & MVO staff)

- Welcome, and meeting agenda (Eliza – 10 mins)
- Summary of the two 6 months reports: Highlights from reports (Graham, plus MVO staff)
- Continuing discussion on scenarios that could explain the monitoring data (MVO led)
    - In-depth seismic analysis (Rod)

- General discussion of SHV unrest indicators, seismic, gas, deformation and conceptual models on volcanic activity:
    - New idea to explain degassing and deformation (Mike)
    - Updated interpretation of HCl flux data (Mike)

- 3pm – Online meeting with the Governor (30 mins)

- Continue discussion above

Mural tour after meeting sessions – followed by dinner somewhere in the north.

Tuesday, 28th Nov 2023 Volcanic Hazards and Risk

09:00-11:00am **(**SAC & MVO staff)

- Hazard and risk analysis and communications tools being developed at MVO (Jose)
    - Discussion of technical aspects (all)

11:00-1pm – SAC & MVO staff + DMCA & CMO

Confirmed:
Alvin Ryan – Disaster Management Coordination Agency
Dr. Sharra Greenaway-Duberry – Chief Medical Office
Garrett Stanley – Principal Environmental Officer
Mr Clement Meade – Chief Physical Planner

- Air quality monitoring on Montserrat (Locko)
- How scientific information on volcanic hazard can support stakeholders (Graham)
- Discussion of the practical application of decision-making tools and the need for multi-stakeholder involvement and information (Eliza/Graham)

2:00-5:00pm **(**SAC & MVO staff)

- Probabilistic hazard map for PDCs/ unrest scenarios (Eliza)
- Shock wave hazard – discussion about relevance to Montserrat
- Dome stability study by Leeds MSc project (Locko – intro the work not present)
- Curating Crisis project by MVO (Karen and Thiffanie/Richie)

Dinner with the Governor (SAC/w Graham + Pat and Richie) Watermelon Cottage at 6.30pm (until 8.45pm max)

Wed, 29th Nov 2023
09:00am-5:00pm meeting (SAC & MVO staff)

- Elicitation
    - Consideration of elicitation questions based on GoM needs.
    - Prep discussion of elicitation (Monitoring data & dome morphology recap (Adam).
    - Elicitation (30 mins-1h)
    - Discussion of elicitation results over past years (Eliza)

- Curating Crisis film (lunchtime showing).

- MVO matters
    - Monitoring networks (state, issues, plans)
    - Reactivation scenarios (in diverse volcanic activity scenarios – e.g., strong increase in degassing, lava effusion, explosion – what changes, if any, would be needed in monitoring strategy. Can any preparation be made so that these changes can be implemented smoothly)
    - MVO funding and management model and how to create a more stable system. Considering 1) the problem of delays in either contract extension or renewal that happens every five years or more and 2) the ongoing battle for the local budget to be disbursed (Richie/Graham).
    - SAC-MVO working practices, activities and working practices for research and collaboration.
    - MVO Support needed?
    - Ongoing/upcoming research, development and outreach including with other VO's
    - Website

Dinner with SAC-MVO

Thurs, 30th Nov 2023
09:00am-5:00pm meeting (SAC & MVO staff)

- Prepare preliminary statement (SAC)
- Discussion of relevant ongoing/published work **and ideas for future**
    - Deformation research (Karen)
    - Fidel/Eleanora – Thermal evolution of magma reservoir/Quantum gravimeters and signals expected from calculated magma fluxes
    - Hydrothermal systems, conceptual models & scenarios (Fidel and Nico)

- 2:30 pm Briefing meeting with the Governor and Premier

- SAC matters

    - SAC Membership
    - Expertise required
    - Next meeting

- Feed-back to MVO – SAC's comments & suggestions

- 'Volcano Vibes' with Kafu ZJB (time tbc)

Appendix III:

List of Participants

SAC Members	
Prof Eliza Calder	University of Edinburgh, UK (Chair)
Prof Mike Burton	University of Manchester, UK
Dr Nico Fournier	GNS, New Zealand
Prof Fidel Costa	IPGP, Paris
Prof Eleanora Rivalta	University of Bologna, Italy
Prof Jurgen W Neuberg	University of Leeds, UK
Dr Graham A Ryan	Director, MVO; University of the West Indies

MVO Participants

Mr Rod Stewart
Dr Thomas Christopher
Dr Adam Stinton
Dr Karen Pascal
Dr Jose Marrero
Ms Venus Bass
Mr Racquel 'Tappy' Syers
Mr Barry 'Pyiko' Williams

SRC Participants	
Dr Erouscilla Joseph (Director)	Seismic Research Centre, University of the West Indies
Prof Richard Robertson	Seismic Research Centre, University of the West Indies

Appendix IV: Exemplar *extract* from a workplace/OSH Risk Assessment

The table is completed for all the hazards that might be applicable under the categories listed in the left hand column of the table and the risk for each is assessed using the risk scoring system indicated below. The initial risk can be reduced to residual risk by the mitigating impacts of the control measures.

Volcanic landscape (including rough terrain), volcanic environment (including dust and gas) and volcanic hazards and activity would be listed under the Environment category (highlighted).

Hazard or dangerous activity, technique	Hazard	Risk Rating Initial Risk			Control measures	Risk Rating Residual Risk		
		Severity level 1-3	Likelihood level 1- 3	Risk (severity x likelihood)		Severity level 1-3	Likelihood level 1- 3	Risk (severity x likelihood)
Human related issues								
Musculoskeletal								
Safe movement of people								
Transport								
Work at height								
Equipment								
Mechanical								
Physical								
Electrical								
Fire and explosives								
Chemical								
Biological								
Environmental								
Environmental impact								

RISK SCORING SYSTEM

The precise scores are not of critical importance. The scoring system is provided as a tool to help structure thinking about assessments and to provide a framework for identifying which are the most serious risks requiring attention, and why.

Hazard – something with the potential to cause harm.

Risk – the likelihood of potential harm from that hazard being realised, in combination with the severity of injury, damage or loss that might foreseeably occur.

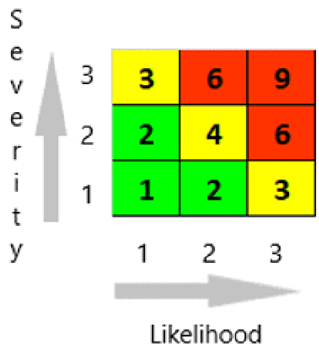
Severity score:

1. Hazard capable of resulting in minor injury requiring first aid, or inconsequential loss of equipment or environmental impact. (*e.g. food poisoning, bruises, irritation*)
2. Hazard capable of resulting in injury or illness requiring absence from work, or damage to equipment/environmental. (*e.g. bone fracture without displacement, minor burns or injuries*)

3. Hazard capable of resulting in death, severe injury or illness, or major loss/damage to equipment, buildings or the environment. (*incl. impaired alertness*)

Likelihood score:

1. Unlikely to occur – hazard exists infrequently and there is a low expectation of occurrence.
2. May occur in time – hazard exists intermittently or the operation occurs occasionally.
3. Likely to occur frequently or the hazard exists permanently.

Risk (IR – Initial Risk or RR – Residual Risk) = Severity × Likelihood	
1 or 2 – Low Risk (L) – Acceptable – no further action is required but should continue to be monitored. **3 or 4 – Moderate Risk (M)** – Lesser priority risk. Should be assessed to see if further control measures can be applied to reduce to low risk. **6 or 9 – High Risk (H)** – Priority risk. Must be reduced to a level that is acceptable through practical and effective control measures. Where the IR is 3 or above, appropriate measures must be put in place to reduce to an acceptable level of risk. Repeat the scoring with the control measures in place, review the Severity & Likelihood ratings and multiply these to give a Residual Risk (RR).	

Other Example – GNS Science internal risk assessment template (New Zealand)

It relies on the same principles as the first example. The whole system may not necessarily be relevant to Montserrat, but it offers another template that could be used and tailored, including volcanic (e.g., risk of gas) and non-volcanic (e.g., driving) risks).

JOB SAFETY AND ENVIRONMENTAL ANALYSIS – SAFE WORK METHOD STATEMENT

A. HAZARD IDENTIFICATION AND RISK ASSESSMENT PROCESS

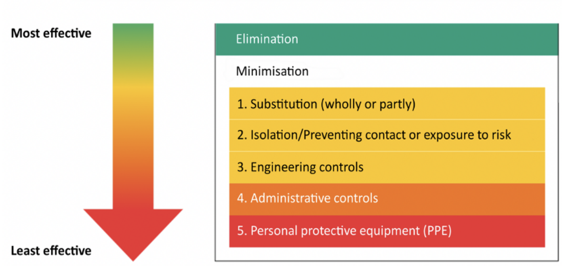
Stage 1	Break the activity into task steps. Each of the steps should be logical and describe the step - in simple terms.
Stage 2	Identify the hazards associated with each step. Consider uncontrolled sources such as Gravity, Electrical, Mechanical, Manual Handling, Pressure, etc.
Stage 3	Using the risk matrix rank the Consequence and Likelihood of the hazard becoming actual and note the overall Risk Rating.
Stage 4	Develop controls necessary to manage the hazards. Consider the Hierarchy of controls starting at Elimination and record the type of control.
Stage 5	Using the risk matrix Re-rank the Consequence and Likelihood to determine if the controls have reduced the risk to an acceptable level. Record the new Overall Risk Rating.
Stage 6	Nominate the person responsible for managing/working to the controls as nominated.

Risk Matrix

GNS Historic experience	Future Potential	LIKELIHOOD	RISK RATING				
Occurred repeatedly last year	Expected to occur regularly under normal circumstances	Almost certain (L5)	Medium (11)	Medium (16)	High (20)	Extreme (23)	Extreme (25)
Occurred once last year	More than an even chance of occurring at some time in the next year	Likely (L4)	Low (7)	Medium (12)	High (17)	High (21)	Extreme (24)
Has not occurred in the last two years	Above average chance the risk will occur at least once in the next 3 years &/or often reported elsewhere in the past	Possible (L3)	Low (4)	Medium (8)	Medium (13)	High (18)	High (22)
Has not occurred in the last five years	Not likely to occur in normal circumstances and/or is unlikely to occur within the next three years and/or often reported elsewhere every year or so	Unlikely (L2)	Low (2)	Low (5)	Medium (9)	Medium (14)	High (19)
Has not occurred at GNS for more than 5 years	Conceivable but would only occur in extreme circumstances &/or will probably not occur in the next 5 years and/or is known to have occurred elsewhere	Rare (L1)	Low (1)	Low (3)	Low (6)	Medium (10)	Medium (15)
			CONSEQUENCE				
			Negligible (C1)	Minor (C2)	Moderate (C3)	Major (C4)	Catastrophic (C5)
			• No injury or damage to health • Superficial injury	• First aid required, not affecting ability to work or causing long term damage	• Injury requiring medical attention and/or short-term injury, restricted or alternate duties may be required short term	• Notifiable injury or illness, significant duration lost time injury, several People injured, permanent or partial disability.	• Fatality or multiple fatalities

RISK RATING	RISK OWNER
Extreme	CE
High	An Executive Team Member
Medium	Line Manager
Low	Line Manager

Hierarchy of Controls



B. TASK RISK ASSESSMENT

STAGE ONE	STAGE TWO		STAGE THREE	STAGE FOUR – RISK REDUCTION STRATEGY / CONTROLS TO BE USED	STAGE FIVE	STAGE SIX
Job Step	Hazards	Risks	Risk Rating	1. **Eliminate risks to health and Safety (If you can) or** 2. **Minimise** risk to health and safety by doing one or more of the following; • **Substituting** a hazard to create a lesser risk, or; • **Isolate** the hazard from staff to prevent contact or, • Installing **engineering** controls. If the risk remains further minimise by: 3. Using **administrative** controls 4. Provide staff with required **PPE.**	Risk Rating	Responsible Person
			High	1. Elimination 2. Substitution, isolation or engineering 3. Administrative 4. PPE	Medium	
			Medium	1. Elimination 2. Substitution, isolation or engineering 3. Administrative 4. PPE	Low	
			Medium	1. Elimination 2. Substitution, isolation or engineering 3. Administrative 4. PPE	Medium	

Appendix V: Preliminary Statement SAC 28

30th November 2023

The Montserrat Volcano Observatory reports that activity at the Soufrière Hills Volcano has remained low but has shown measurable increase in the level of unrest in the last year. In particular, the volcano has produced higher rates of volcano-tectonic earthquakes since around 2019, and these have further increased in number over the last 12 months. Monitoring of ground deformation indicates a slow but continuous inflation over the island. This established long-term trend of inflation is consistent with that observed over the previous 13 years. Measured SO_2 fluxes have averaged ~300 tonnes per day over the last 6 months, a decrease from the previous year but still slightly above the long-term average. Thermal camera images of fumaroles on the dome were last acquired in March and indicate a maximum temperature of 522 °C which is consistent with the increased temperatures observed since 2018.

Overall, the unrest for the past 12 months is the highest observed during the current pause. However, based on previous restarts, we would expect a further increase in unrest prior to the resumption of any significant eruptive activity. The best explanation for this unrest is pressurisation of the magmatic reservoir at depth, possibly driven by a continued supply of magma and gas.

The volcano, with its large lava dome, is still a potential source of hazards within Zone V, including explosions, pyroclastic flows and lahars. Resumption of lava extrusion, or explosions, is still possible, however, the chance that explosions or pyroclastic flows will occur within the next year remains low. Continuous monitoring of the volcano is essential.

Appendix VI: SAC28 elicitation of probabilities for hazard scenarios

Target questions

1. GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that, *irrespective of whether there is eruptive activity at the surface, or not*, the volcanic system will remain active over the next 12 months.

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 16	51%	95%	99.9%
SAC 17	53%	97%	99.9%
SAC 18	56%	95%	99.9%
SAC 19	69%	98%	99.99%
SAC 20	47%	94%	100%
SAC 21	12%	86%	99.9%
SAC 22	39%	92%	99.9%
SAC 23	12%	93%	99.5%
	Slight change in question wording as indicated above		
SAC 24	50%	91%	99.9%
SAC 25	43%	91%	99.9%
SAC 26	70% (71%)	95% (95%)	99.8% (99.7%)
SAC 27	66%	95%	96%
SAC 28	**68%**	**98%**	**100%**

2a. GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that **nothing significant** will happen (*i.e., no collapse, no restart of dome growth, no explosion*) in the next 12 months.

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 16	1%	30%	73%

SAC 17	9%	43%	82%
SAC 18	20%	67%	94%
SAC 19	42%	64%	91%
SAC 20	32%	78%	98%
SAC 21	20%	77%	98%
SAC 22	33%	77%	99%
SAC 23	34%	82%	99%
	Slight simplification in question wording		
SAC 24	63.59%	88.11%	98.62%
SAC 25	50.36%	80.15%	96.84%
SAC 26	49.33 (49.34%)	81.57% (81.57%)	98.44% (98.44%)
SAC 27	50.38%	85.37%	96.52%
SAC 28	**51%**	**87%**	**95%**

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

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 16	6%	43%	78%
SAC 17	6%	31%	60%
SAC 18	1%	15%	53%
SAC 19	3%	32%	55%
SAC 20	0.5%	13%	62%
SAC 21	0.8%	11%	54%
SAC 22	0.2%	11%	65%
SAC 23	0.1%	10%	33%
SAC 24	0.1%	2%	22%
SAC 25	0.2%	5%	21%
SAC 26	0.35% (0.4%)	8% (8%)	30% (29%)

SAC 27	0.1%	8%	20%
SAC 28	**0.77%**	**7%**	**25%**

2c. GIVEN current conditions, what is the probability that in the next year the **first** significant activity will be collapse of the dome.

(This is a new question in SAC 24 – where we have asked for the combined probabilities for all the different possible flow directions that were previously split out into different drainages. We have moved to this approach because the probabilities were very low, and it was getting increasingly difficult to assess for such unlikely and specific events).

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 24	0.4%	7%	20%
SAC 25	0.3%	5%	29%
SAC 26	0.4% (0.5%)	5% (5%)	29% (29%)
SAC 27	0.4%	3.5%	20%
SAC 28	**0.25%**	**3%**	**16%**

2d. GIVEN current conditions, what is the probability that the **first** significant event will *be an explosion*.

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 16	0.5%	24%	68%
SAC 17	0.2%	15%	68%
SAC 18	0.5%	8%	61%
SAC 19	0.02%	2%	15%
SAC 20	0.04%	2%	29%
SAC 21	0.01%	7.3%	65%
SAC 22	0.05%	8.7%	65.5%
SAC 23	0.2%	5.7%	25%
	Slight simplification in question wording (i.e., not tied to reference event)		

SAC 24	0.1%	3%	29%
SAC 25	1%	10%	50%
SAC 26	0.6% (0.8%)	6% (6%)	23% (21%)
SAC 27	0.2%	2.8%	10%
SAC 28	**0.5%**	**4%**	**26%**

*In previous SAC assessments, this used to be question 2i.

*3. If, in the next year the **first** significant activity is a major dome collapse, what is the probability of magma extrusion or explosion within the following month:*

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 20	1%	67%	94%
SAC 21	1.2%	55%	85%
SAC 22	1.13%	28.7%	94.7%
SAC 23	3.3%	35%	98%
SAC 24	23%	68%	90%
SAC 25	27%	73%	95%
SAC 26	28% (29%)	75% (75%)	95% (95%)
SAC 27	52%	85%	99%
SAC 28	**50%**	**86%**	**95%**

*In previous SAC assessments, this used to be question 2c2.

4. GIVEN current conditions, what is the probability that within the next year the first significant event will be a dome collapse in the following sectors:

(New question for SAC 24)

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
4a) NW	0.0015	3.444	35.57

4b) N	10.06	26.48	74.40
4c) NE	15.19	54.98	79.95
4d) SE	0.0017	2.48	19.95
4e) S	0.5157	6.41	30.09
4f) SW	1.519	10.63	46.25

(SAC 25)

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
4a) NW	0.00001	0.097	16.99
4b) N	10.06	24.95	77.60
4c) NE	12.82	65.51	89.73
4d) SE	0.00001	0.051	6.95
4e) S	0.652	6.128	20
4f) SW	1.014	6.449	40.29

(SAC 26)

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
4a) NW	0.01656% (0.01833)	5.524% (5.523)	14.95%(14.93)
4b) N	10.23% (10.24)	31.69% (31.69)	79.51% (79.51)
4c) NE	20.32% (20.35)	49.45% (49.45)	79.59% (79.54)
4d) SE	0.1437% (0.1477)	2.926% (2.926)	13.15% (13.13)
4e) S	0.1351% (0.1544)	2.922% (2.921)	9.992% (9.983)
4f) SW	0.222% (0.2435)	6.462% (6.461)	19.89% (19.85)

(SAC 27)

	Credible interval lower bound	*Median value*	*Credible interval upper bound*

4a) NW	0.027%	2.387%	9.883%
4b) N	10.15%	25.73%	57.68%
4c) NE	30.83%	56.05%	79.78%
4d) SE	0.028%	1.659%	9.883%
4e) S	0.237%	5.21%	19.89%
4f) SW	0.422%	8.763%	24.84%

(SAC 28)

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
4a) NW	0.22%	**5%**	24%
4b) N	9%	**29%**	80%
4c) NE	9%	**46%**	91%
4d) SE	0.11%	**3%**	13%
4e) S	0.12%	**4%**	21%
4f) SW	0.62%	**17%**	30%

6. Supplementary Question: GIVEN what has happened up to the present and GIVEN current conditions, what is the probability that nothing significant will happen (i.e., no collapse, no restart of dome growth, no magmatic explosion) in the next 30 years?

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 18[§]	0.3%	16%	74%
SAC 19	8%	32%	85%
SAC 20	2%	39%	93%
SAC 21	1.9%	33%	90%
SAC 22	2.1%	38.9%	94.7%
SAC 23	7%	29%	98%
SAC 24	5%	16.8%	59.9%

SAC 25	5%	44%	70%
SAC 26	10% (10%)	35% (35%)	70% (70%)
SAC 27	5%	20%	50%
SAC 28	**4%**	**19%**	**54%**

§ This question had not been elicited in previous SAC meetings

.

7a. GIVEN a scenario in which magma extrusion restarts or an explosive eruption occurs within the next five years, what is the probability that there will be precursory signals in the six months leading up to the new activity?

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 20§	15%	85%	96 %
SAC 21	44%	80%	99%
SAC 22	33%	93%	99%
SAC 23	50%	86%	99.9%
SAC 24	61%	93%	99%
SAC 25	65%	90%	99%
SAC 26	54% (58%)	90% (90%)	97% (97%)
SAC 27	65%	90%	99%
SAC 28	**62%**	**93%**	**99%**

§ This question had not been elicited in previous SAC meetings

7b. GIVEN precursory signals in the six months before new activity, what is the probability that it will be recognized as such at the time?

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 20§	18%	82%	99 %
SAC 21	18%	64%	95%
SAC 22	11%	75%	99%

SAC 23	40%	75%	98%
SAC 24	38%	87%	97%
SAC 25	41%	79%	97%
SAC 26	50% (50%)	81% (81%)	97% (96%)
SAC 27	65%	88%	96%
SAC 28	**54%**	**88%**	**97%**

§ This question had not been elicited in previous SAC meetings

9. GIVEN current conditions, what is the probability that there will be a significant, externally-triggered, dome collapse ?

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 22§	0.0001%	0.012 %	7.51%
SAC 23	0.001%	0.07%	4%
SAC 24	0.0004%	0.1%	6%
SAC 25	0.000006%	0.0008%	2.7%
SAC 26	0.00009% (0.00009%)	0.00158% (0.00158%)	1.4% (1.4%)
SAC 27	0.000001%	0.00002%	0.24%
SAC 28	**0.0003%**	**0.08%**	**3%**

§ This question had not been elicited in previous SAC meetings

10. What is the probability that an eruption threatening people's safety in Zone V would occur without producing recognised precursors at least 24 hours prior to the eruption ?

	Credible interval lower bound	*Median value*	*Credible interval upper bound*
SAC 28§	**0.0001%**	**0.004%**	**11%**

§ This is a new question in SAC 28.

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Appendix VII: 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 (E): 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 (D): 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.

Appendix VIII: Glossary of Terms

Andesite: The name given to the type of magma erupted in Montserrat.
Basalt: The type of magma entering the magma reservoir below Montserrat.
cGPS: Continuously-measured Global Positioning System for repeated measurement of ground deformation.
Conduit: In a volcano magma flows to the earth's surface along a pathway known as a conduit. The conduit is usually thought to be a cylindrical tube or a long fracture.
Dyke: Vertical, tabular body of magma within a fracture below the volcano that can act as the conduit for flow to the surface.
EDM: Electronic Distance Measurements made by laser ranging to reflectors gives length changes of a few millimetres accuracy over several kilometres.
Fumarole: A vent in the surface of the dome where hot gases exit.
Hybrid/LP Seismicity: Varieties of earthquake signal often indicative of magma motion in the upper part of the conduit.
Lava: Once magma gets to earth's surface and extrudes it can be called lava. Below ground it is always called magma.
Lateral Blast: An energetic sideways-directed explosion from a lava dome that can generate highly fluid pyroclastic flows.
Low-frequency earthquake see LP (long period earthquake)
Magma: The material that erupts in a volcano is known as magma. It is not simply a liquid, but a mixture of liquid, crystals and volcanic gases. Magma must contain enough liquid to be able to flow.
Magnitude: The magnitude of an explosive eruption is the total mass of material erupted.
Mudflow: A flow of rock debris, ash and mud that occurs on many volcanoes particularly during eruptions and after very heavy rain (equivalent to "lahar").
Pyroclastic flow: These are flows of volcanic fragments similar to avalanches of rock in landslides and snow avalanches. They can be formed both by explosions and by parts of an unstable lava dome avalanching.
Pyroclastic surge: These are also flows, but they are dilute clouds rather than dense avalanches. A surge is a rapidly moving mixture of hot particles and hot gas and their behaviour can be compared to a very severe hurricane. Surges can be formed above pyroclastic flows or directly by very violent explosions.
Simulation: Use of a computer program to mimic (or model) the behaviour of a physical process.
Swarm: A large number of, in this case, earthquakes occurring in rapid succession with characteristics indicating they are generated from a similar region in the earth. Can merge into tremor.
Talus: A pile of cool lava blocks and ash that accumulate by rockfall around the core of the hot lava dome.
Volcanic ash: Ash particles are defined as less than 4 millimetres in diameter. Respirable ash consists of particles less than 10 microns (a micron is one thousandth of a millimetre) in diameter.
VT string: Bursts of seismic energy in form of several volcano-tectonic earthquakes, sometimes accompanied by ash venting.

Appendix IX: Limitations of Risk Assessment

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 four 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.

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.

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.

4. These are all factors that are present when contemplating future hazards of any kind in the Earth sciences (e.g. earthquakes, hurricanes, floods etc.) and, in such circumstances, it is conventional to consider the chance of occurrence of such events in probabilistic terms. Volcanic activity is no different. There is, however, a further generic condition that must be understood by anyone using this report, which concerns the concept of validation, verification or confirmation of a hazard assessment model (or the converse, attempts to demonstrate agreement or failure between observations and predicted outcomes). The fact is that such validation, verification or confirmation is logically precluded on non-uniqueness grounds for numerical or probabilistic models of natural systems, an exclusion that has been explicitly stated in the particular context of natural hazards models[15].

1. 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,

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

[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.

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.

2. 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.

3. This Appendix must be read as part of the whole Report.