An overview of the eruption of La Soufrière Volcano, St Vincent 2020–21

Richard E. A. Robertson[1]*, Jenni Barclay[2], E. P. Joseph[1] and R. S. J. Sparks[3]

[1]University of the West Indies Seismic Research Centre, St Augustine, Trinidad & Tobago, WI

[2]School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

[3]School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK

REAR, 0000-0001-5245-2787; JB, 0000-0002-6122-197X;
EPJ, 0000-0002-4836-8715
*Correspondence: Richard.Robertson@sta.uwi.edu

Abstract: This paper provides an overview of the eruption of La Soufrière Volcano on the island of St Vincent which occurred between 27 December 2020 and 22 April 2022. It sets the stage for the 17 papers included in this Special Publication that showcase the initial scientific findings arising from analysis of the crisis. Here we present a chronology of the eruption and discuss the key findings from these papers while underscoring the areas for which further research is needed.

The detailed account of the eruption offers several lessons for volcanic crisis management and provides insights into the most effective communication process through this type of crisis. It highlights the need for and benefits of planning and preparedness activities prior to an eruption as well as of long-term engagement with disaster management officials and at-risk communities. The value of partnerships both within the island and with external collaborators was shown to be critical as was the use of a multiparametric dataset to assess the course of the eruption. We contend that the papers contained in this publication provide key insights into the mechanisms by which volcanic eruptions can impact populations at risk. The suite of analyses and data have generated a canonical dataset that can provide the framework for new advances in understanding the causes and consequences of varying eruptions worldwide.

The impact of the 2020–21 eruption on the environment and society

La Soufrière, St Vincent, is the most active subaerial volcano in the Eastern Caribbean, with historical eruptions that have resulted in mass fatalities via explosive flows and fallout. Although there was no loss of life, the 2020–21 eruption latterly forced the evacuation of ~16 000 people from the northern third of the island and caused significant damage to the environment from multiple hazards, including volcanic gases, ballistic projectiles, pyroclastic density currents (PDCs), ashfall and mudflows. During the initial effusive phase of the eruption (27 December 2020 to 8 April 2021) damage was confined to the upper flanks of the volcano with extensive vegetation damage caused by persistent emissions of volcanic gases. The explosive phase of the eruption (9–22 April 2021) produced volcanic ash, which blanketed most of the island and generated PDCs that caused the destruction of flora and fauna on the upper flanks and in valleys draining the volcano. The ashfall caused significant disruption to infrastructure and agriculture. The end of the eruption is officially noted as 22 April 2021, but evacuated populations only began returning to their homes from 15 September when the Alert Level was lowered to Yellow. Subsequent rainfall produced lahars that extended the spatial and temporal extent of flow-related damage and destruction to communities surrounding the volcano and caused disruption beyond the evacuation period.

New insights generated from the eruption

This eruption was observed at close quarters by the local monitoring team and remote observation was greatly enhanced by the utilization of satellite-based technologies. This created an opportunity for close tracking of the development and evolution of a lava coulée; the impact of volcanic gas emitted during lava emplacement on the surrounding environment; the phenomena associated with the rapid switch from effusive to explosive activity; impacts of PDCs on the environment; the impact of tephra on St Vincent and surrounding islands; and the occurrence and impact of syn- and post-eruptive lahars. The eruption also occurred during the global Covid-19 pandemic, creating multiple additional challenges for risk management and communication.

From: Robertson, R. E. A., Joseph, E. P., Barclay, J. and Sparks, R. S. J. (eds) 2024. *The 2020–21 Eruption of La Soufrière Volcano, St Vincent*. Geological Society, London, Special Publications, **539**,
https://doi.org/10.1144/SP539-2023-95

It provided an opportunity to study the use and application of a wide range of science communications tools and especially social media in the management of a volcanic crisis.

What this Special Publication represents

This Special Publication presents 17 papers that showcase the initial scientific findings arising from analysis of the 2020–21 eruptive episode at La Soufrière. To reflect the innovation and effort generated in multiple fields, it is split into two parts: the first presents geological and volcanological advances, while the second has papers focused on the impacts of the eruption and the challenges presented for the management of the volcanic crisis. This Special Publication follows similar publications that presented initial findings on closely monitored volcanic eruptions such as La Soufrière 1902 (Anderson and Flett 1903), Pinatubo 1991 (Newhall and Punongbayan 1996), Mt St Helens 1980 (Lipman and Mullineaux 1981) and the Soufrière Hills Volcano 1995 (Druitt and Kokelaar 2002) and ongoing eruption (Wadge *et al.* 2014). These past monographs have demonstrated their value in creating a space for rapid analysis and review combined with a record of the unique new insights created by close observation of an eruption in real-time.

The volume will benefit the volcanological community and those interested in volcanic emergency management (including crisis communications and public awareness), especially within the Caribbean and other volcanic island regions.

This introductory paper synthesizes the scientific and management context of the recent volcanic crisis and provides a factual record of the chronology and phenomena of the eruption. This serves as a framework for the analysis presented in the rest of the volume, as well as creating a descriptive record. Finally, we use this to highlight the key findings of the papers in this Special Publication and to signpost areas rich for further work and investigation.

Setting of the volcanic crisis

Geological setting

The Eastern Caribbean Island Arc results from the subduction of the Atlantic oceanic crust beneath the Caribbean plate. Arc volcanism has been active since 40 Ma (Martin-Kaye 1969; Bouysse and Guennoc 1983; Bouysse *et al.* 1990) resulting in the production of several volcanic islands.

North of Dominica, the arc bifurcates into two groups of islands. The older outer part, where carbonate platforms cover the volcanic basement, is called the Limestone Caribbees. The younger inner arc consists of volcanic rocks younger than 20 Ma and includes all the active volcanoes (Bouysse *et al.* 1990). The arc becomes a single arc south of Dominica as the older and younger parts are superimposed.

Physiography

Located in the southernmost segment of the Eastern Caribbean Island arc, St Vincent is wholly volcanic, with the most recent and largest volcanic centre, La Soufrière, comprising the northern part of the island (Fig. 1). The island is located at latitude 13° 15′ and longitude 61° 10′ and is 29 km long and 17.5 km wide and consists of a series of north–south-trending volcanic centres that show a northward migration in age from ~3 Ma, near the south of the island, to the recently active La Soufrière volcano in the north. Pre-Soufrière volcanism can be grouped into several volcanic centres, including the Southeast Volcanics and the Grand Bonhomme and Morne Garu volcanic centres (Robertson 2005). The Southeast Volcanics contains the oldest dated rocks on the island (2.74 ± 0.11 Ma; Briden *et al.* 1979) and is a dissected volcanic terrain dominated by monogenetic basaltic volcanism. The Grand Bonhomme Volcanic Centre is a large stratovolcano that rises to 1021 m and contains lava flows with ages of 1.16 ± 0.08 Ma and 1.33 ± 0.09 Ma (Briden *et al.* 1979). The Morne Garu Volcanic Centre consists of Richmond Peak to the west and Mt Brisbane to the east. These peaks are considered remnants of a large Morne Garu crater that may have been up to 3 km in diameter (Sigurdsson 1981). Ar–Ar ages of 180 ± 20 ka and 11 ± 14 ka obtained from this centre suggest that the waning stages of activity at this centre may have overlapped with the early evolution of La Soufrière.

La Soufrière is a stratovolcano with a base diameter of ~9.5 km and height of 1178 m above sea level (a.s.l.). Its summit area features four craters: the 2.2 km-wide semi-open Somma caldera enclosing the 1812 crater, the 1.6 × 1.4 km-wide pre-2021 crater and the currently active crater formed during the 2021 explosive phase of the 2020–21 eruption (Fig. 2).

Prior to the 2020–21 eruption geothermal activity manifested in a diffuse set of fumaroles (70–98°C) located on the 1979 dome in the crater and a cluster of thermal springs (37–38°C) located 2.7 km SW of the crater on the floor of the Wallibou River (~280 m a.s.l.).

Brief history of St Vincent and the Grenadines (SVG) leading to the eruption

In the historical record (post-1700s) La Soufrière, St Vincent, has erupted multiple times, including explosive eruptions in 1979, 1902–03, 1812 and

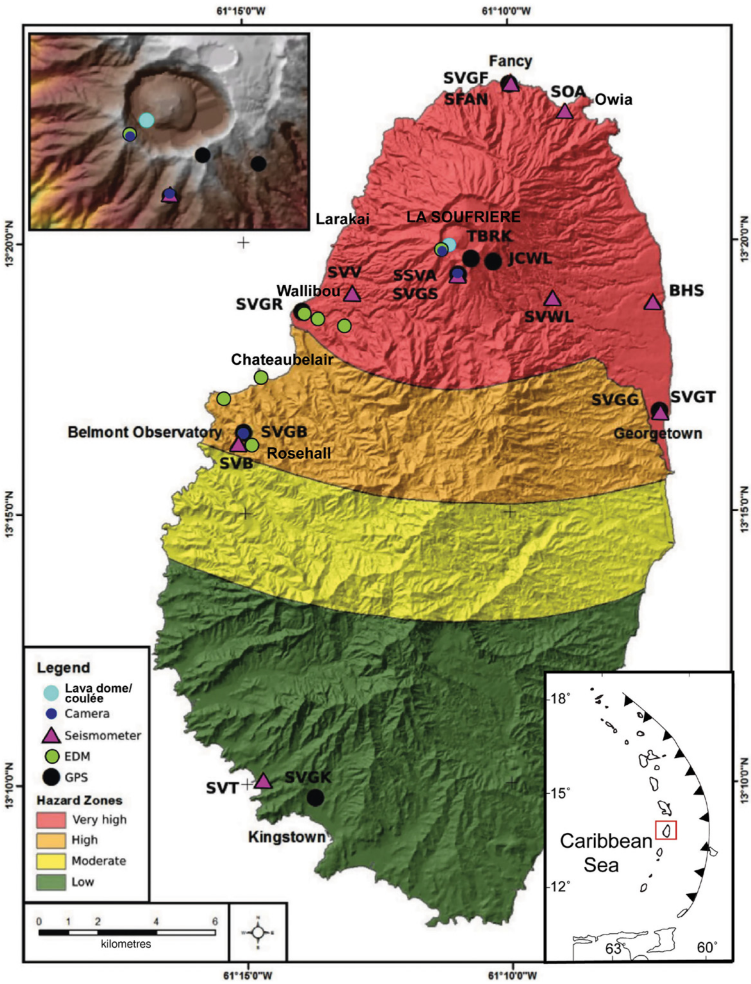

Fig. 1. Volcano monitoring network for La Soufrière Volcano superimposed on the integrated volcanic hazard map for St Vincent. Location of the island within the Eastern Caribbean is shown on the inset map. The seismic (purple triangles) and GPS (black circles) monitoring stations are labelled with their station codes (e.g. SVT, SVWL, etc.). Source: adjusted from Joseph *et al.* (2022*b*, fig. 1).

1718 (Fig. 3). Predominantly effusive eruptions occurred in 1784 and in 1971–72. In addition to 2020–21 the eruptions of 1979 featured rapid transitions between effusion and explosion (and the 1902–03 eruptions could well have begun with some effusive activity obscured by the deep crater lake in the vent region). The presence or absence of a crater lake has exerted a significant control on eruptive behaviour and impacts. The size and duration of eruptions has varied from a Volcanic Explosivity Index (VEI) of 1 to 4 and lasted days to years. This rich historical record of past events (Anderson and Flett 1903; Aspinall *et al.* 1973; Robertson 2005; Pyle *et al.* 2018; Cole *et al.* 2019) provides a useful framework against which to compare the events of the most recent eruption.

To compound its exposure and vulnerability to volcanic hazards, St Vincent is also at risk from hydro-meteorological and other geophysical hazards, although located towards the southern end of the Atlantic hurricane belt. Its high and steep topography makes it vulnerable to the impact of hydro-meteorological hazards. Periods of heavy rain occur more frequently than hurricanes or tropical storms and so have significant impact on the lives and livelihoods of local communities and can amplify the effects of volcanic eruptions (Wilkinson *et al.* 2016).

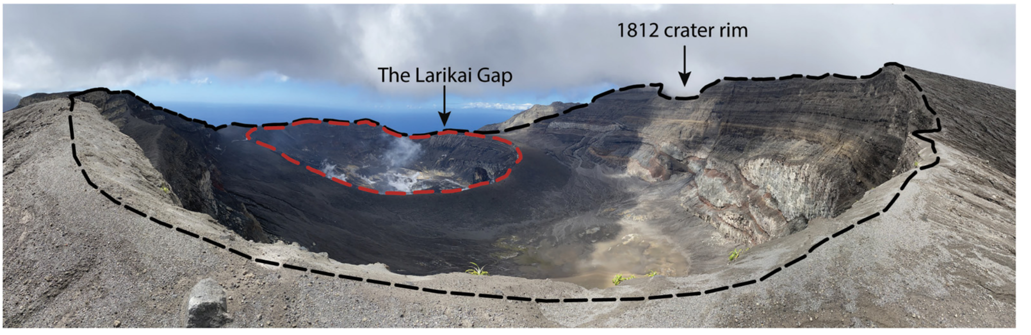

Fig. 2. Panoramic view of La Soufrière crater taken from the SE crater rim showing the pre-existing summit crater (dashed black line) and inner 2021 explosion crater (dashed red line), 1812 crater rim and the gap that leads into the Larikai River Valley (the Larikai Gap).

It is likely that the indigenous population witnessed and endured some near-historical volcanic events in 1400 and 1550 CE, as identified by Cole *et al.* (2019). St Vincent and the Grenadines were a colony of France at the time of the first historical eruption in 1718, but by the 1784 eruption were largely a British colony continuing for the 1812, 1902–03 and 1971–72 events. St Vincent and the Grenadines gained independence during the closing stages of the 1979 eruptive event in October 1979. At the onset of the 2020–21 eruption the National Emergency Management Organisation (NEMO) (along with its Soufrière Monitoring Unit (SMU)) was responsible for coordinating response to the eruption on the island, supplemented by the monitoring work of The University of the West Indies Seismic Research Centre (UWI-SRC) based in Trinidad. Some 5062 of the population live in the Red Zone of the island, where the threat of eruption renders evacuation necessary which, in the near past, has been for periods of weeks and months (Barclay *et al.* 2022). Most of the population within this zone are among some of the most marginalized on the island, both geographically and in terms of access to resources and services, and the relative proportion of vulnerable individuals (Ferdinand *et al.* 2012). Nonetheless there can be a strong sense of community identity and cohesion amongst these communities (Ferdinand *et al.* 2012).

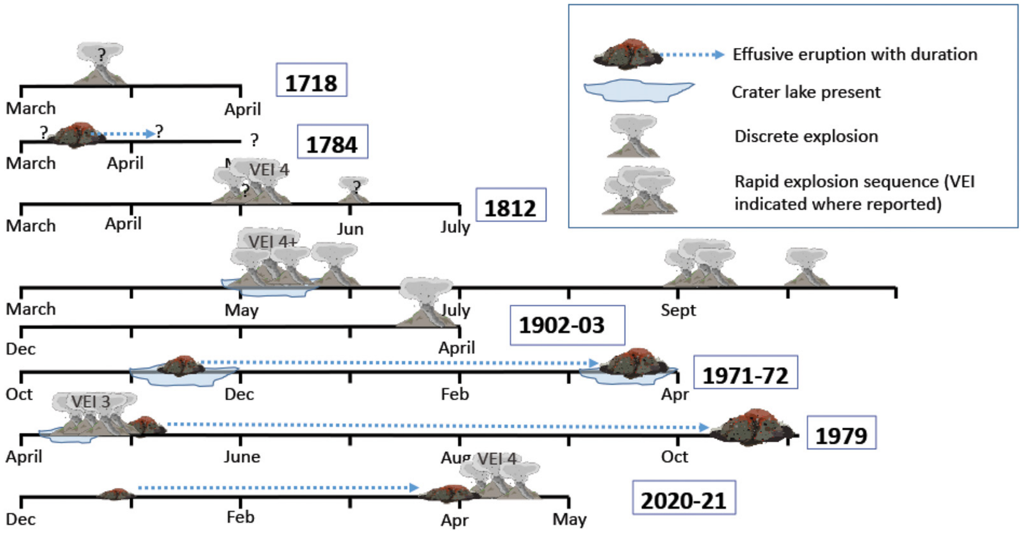

Fig. 3. Summary timelines of historical eruptions of La Soufrière Volcano. Note that explosive events typically represent a repetitive series of explosions rather than one 'paroxysmal' event. Volcanic Explosivity Index (VEI) of integrated total is represented.

Evolution of the Soufrière Volcano monitoring network

The evolution of volcano monitoring and scientific research on La Soufrière Volcano can be traced back to the devastating eruption of 1902–03, which prompted initial studies (Anderson and Flett 1903; Lacroix 1949; Hay 1959*a*, *b*) and subsequent ongoing surveillance and scientific investigations by a varied assemblage of local individuals and overseas-based scientists (Robertson *et al.* 2003; Dondin *et al.* 2019). The establishment of the Seismic Research Unit (now UWI-SRC) in 1952 led to deployment of monitoring instruments and a sustained volcano monitoring programme that has evolved in response to both changes in technology (e.g. use of single-component short-period seismometers and analogue communications to broadband three-component seismometers using satellite communication) and to changes in the state of the volcano. Major developments resulted from responses to eruptions, such as development of a PC-based network following the 1979 eruption, as well as grant funding from external aid agencies (e.g. United States Agency for International Development (USAID)-sponsored establishment of satellite communications infrastructure). Funding for the monitoring programme is provided by the government of SVG through contributions made to UWI-SRC and recurrent funding to the operations of a local unit (SMU), established after the 1979 eruption.

The geophysical monitoring network evolved during the 2020–21 eruption, which began with effusive dome growth in late December 2020 (Joseph *et al.* 2022*a*). Limitations on the movement of UWI-SRC staff due the global pandemic from 2020 onwards exacerbated the already challenging resource-constrained environment within which UWI-SRC had been operating. There had been insufficient maintenance of the pre-existing monitoring network, such that at the onset of eruptive activity, the network had been reduced to a single seismic station located ~9 km from the volcano summit. This was augmented by periodic visits to the summit for visual observations. In response to eruptive activity, the volcano monitoring network (Fig. 1) rapidly evolved during the first 2 months to consist in February 2022 of a seven-station seismograph network, a ground deformation network (four continuous GPS (cGPS), one electronic distance measurement (EDM) line), volcanic gas monitoring (UV spectrometers and multi-gas meter) and lava extrusion surveillance with remote cameras, drones (aerial surveys) and visual observations.

During the eruption, previous research undertaken on the volcano, as well as experience and understanding of the volcanic system, supplemented data obtained from the monitoring network to guide prognosis for decision-making authorities (Joseph *et al.* 2022*a*). The scientific team consisted of scientists and technicians drawn from UWI-SRC staff (based in Trinidad at UWI-SRC headquarters and in Montserrat at the Montserrat Volcano Observatory). They were well supported by a large group of scientists drawn from among long-standing collaborators of UWI-SRC and new collaborations developed during and after the eruption.

Chronology of the volcanic crisis

The following records the chronology of available information and interpretations at that time and builds on the briefer description provided in Joseph *et al.* (2022*a*). It provides the framework into which the subsequent analysis presented in this volume can be considered. All times used throughout are local times (−4 hours UTC). To help guide the narrative, Figure 4 provides a pictorial summary of the events associated with the eruption while Figure 5 (adapted from Joseph *et al.* 2022*a*), presents monitoring data and changes in Alert Level over the course of the eruption.

Precursory activity at La Soufrière has varied markedly during past eruptions from short duration, low-level seismicity such as that experienced prior to the 1971–72 and 1979 eruptions, to several months to years of felt earthquakes as occurred prior to the 1902–03 eruption. The 1979 eruption began with <24 hours of instrumentally recorded precursory seismicity. Activity prior to the start of the 2020–21 eruption was more akin to what occurred in 1971–72, although the explosive phase was preceded by 3 months of lava extrusion.

Activity during October–December 2020

During this period there was a single station (SVB, the Belmont Observatory Seismic Station, ~9 km from the volcano). On 1 and 8 October 2020, volcanic earthquakes were recorded, one on each day. These were similar in duration and intensity to another period of elevated seismicity in June–July 2019. Between these two periods no seismicity was detected. On 18 October eight earthquakes were recorded and elevated seismic activity continued at variable levels up until 23 December 2020 with a peak of 11 events recorded on 16 November. The largest event in the sequence, of 3.3 M_t (duration magnitude), occurred at 10:29 p.m. on 16 December. Some of the events had the signature of rockfalls but others had signatures of both hybrid and volcano-tectonic (VT) earthquakes (see **Latchman and Aspinall 2023** for a detailed analysis of seismic data).

Fig. 4. A timeline of events of the 2020–21 eruption of La Soufrière Volcano showing key volcanic activity, communication products and information used by The UWI Seismic Research Centre (UWI-SRC) during the volcanic crisis to update the public about events happening at the volcano. Source: graphic representation by Nadia Huggins for the Volcano Ready Communities Project administered by UWI-SRC.

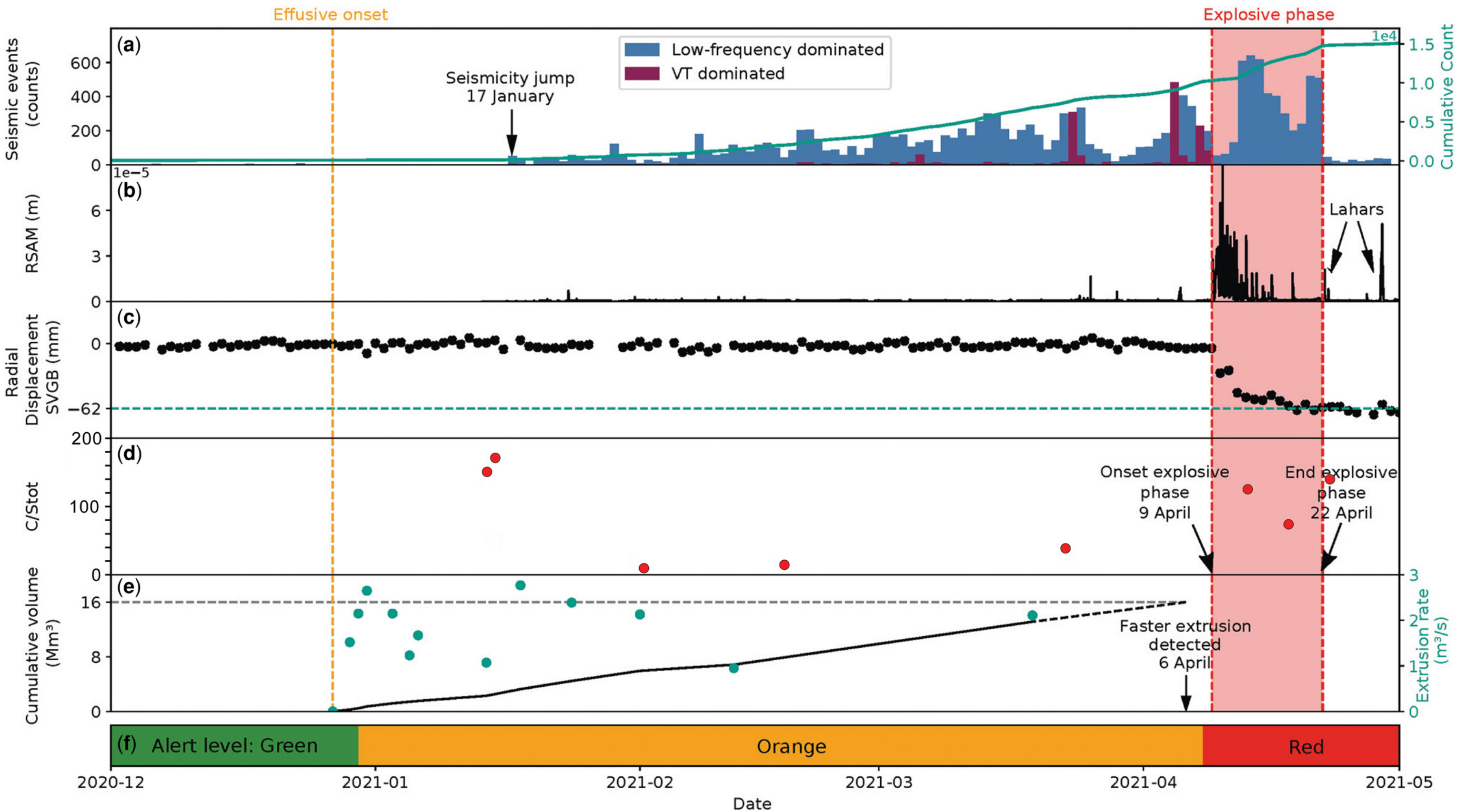

Fig. 5. Monitoring data and changes in Alert Level over the course of the 2020–21 eruption of La Soufrière Volcano. (**a**) Daily (bars) and cumulative (teal line) seismicity observed during the eruption. (**b**) Real-time Seismic Amplitude Measurement (RSAM) calculated with 1minute windows and no overlap. (**c**) Radial extension from the vent observed at the continuous GPS station located at Belmont Observatory (station SVGB, see Fig. 1 for location). (**d**) C/Stot (CO_2/H_2S) concentration rations in ppm in the plume from MultiGAS measurements. (**e**) Lava extrusion rate (teal dots) and cumulative volume increase (black line). (**f**) Volcano Alert Level for each day. VT, volcano-tectonic. Source: adjusted from Joseph *et al.* (2022*a*, fig. 2).

Following recommendations made by UWI-SRC, a site visit was made by members of SMU on 16 December 2020. Fumarolic activity on the crater floor was marginally more extensive in some areas and there was a slight increase in the size of the small lake located on the eastern crater floor. Both changes were within variations expected of background activity at the volcano, although the possibility that the earthquakes indicated incipient unrest precursory to more significant activity was noted in the Scientific Advisory (Joseph *et al.* 2022*b*).

On 27 December an image collected by NASA Fire Information for Resource Management System as part of routine observations for hotspots across the globe, indicated a thermal anomaly (hotspot) inside the summit crater of La Soufrière. On 29 December, additional satellite images indicated an extension of this hotspot. Visual observations shared on social media by a resident of Rose Hall village ~9 km SW of La Soufrière, indicated greyish-white emissions being seen above the general area of the crater. An SMU team visited the crater on 29 December and reported the presence of a small dome on the SE of the 1979 dome (Fig. 6). Strong gas emissions were visible and the small crater lake on the eastern crater floor had almost dried out. With confirmation that an effusive eruption had begun, the Volcano Alert Level was increased by NEMO from Green to Orange on 29 December (Fig. 7) and the national Volcanic Emergency Plan put into effect. A three-person monitoring team (the first of many that followed in the upcoming months), was mobilized by UWI-SRC to travel to St Vincent on 31 December to restore network strength, undertake additional monitoring, provide near real-time advice to the local authorities and assist with education and outreach activities. These resident teams were coordinated by a Scientist-in-Charge and rotated every ~4 weeks.

A series of photographs acquired during the period 29–31 December indicated hemispherical dome growth, 1.5–2.6 $m^3 s^{-1}$, a radius of approximately 70 m and volume of $0.72 \times 10^6 m^3$ (see **Stinton 2023** for a full discussion of the growth and evolution of the dome and coulée during the eruption). Satellite imagery obtained through the MOUNTS (Monitoring Unrest from Space) project indicated that the dome had become detectable by orbiting earth satellites.

Activity during January–February 2021

During January 2021, the scientific effort focused on strengthening the monitoring network, tracking the growth of the lava dome, and providing regular updates on activity to disaster management officials and the public. During the first week of January daily radio briefings, given by the Scientist-in-Charge of the resident monitoring team, were added to the regular Scientific Advisories (sent every other day by UWI-SRC). A structured elicitation process was initiated on 7 January 2021 amongst monitoring scientists to assist in estimating quantitative probabilities of different eruption scenarios (Joseph *et al.* 2022*a*). Monitoring scientists were asked on a weekly or biweekly basis to provide their estimated

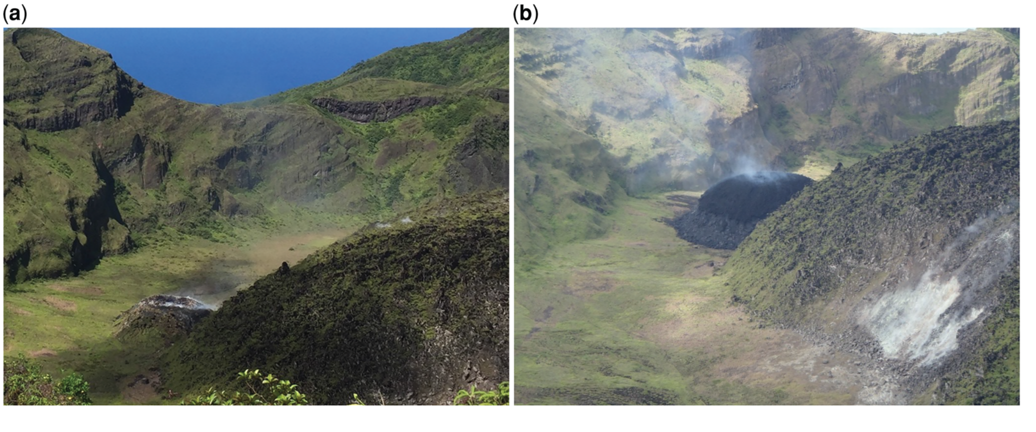

Fig. 6. (**a**) The nascent dome on 27 December 2020 taken by Melanie Grant who had fortuitously made a visit to the crater but did not realize at the time that there was new growth of a lava dome. (**b**) The new lava dome growing WSW of the 1979 lava dome on the SW edge of the summit on 29 December 2020 taken by Kemron Alexander (of the Soufrière Monitoring Unit) confirming the start of the effusive phase of the 2020–21 eruption. The accompanying gas and steam emission from the top of the dome was visible from communities located to the SW of the volcano. Sources: Melanie Grant and National Emergency Management Organisation.

Alert Level	Symptoms	Action Scientist	Action: Civil Authorities
Green	Volcano is quiescent (quiet): seismic and fumarolic (steam vent) activities are at or below the historical level at this volcano. No other unusual activity has been observed.	Normal monitoring	Undertake ongoing public awareness campaign and work on volcanic emergency plans.
Yellow	Volcano is restless: seismic or fumarolic activity or both are above the historical level at this volcano or other unusual activity has been observed (this activity will be specified at the same time that the alert level is raised).	Monitoring system will be brought up to full capability. Civil authorities alerted.	Undertake ongoing public awareness campaigns and work on volcanic emergency plans. Advise vulnerable communities of evacuation procedures in the event of an emergency.
Orange	Highly elevated level of seismicity or fumarolic activity or both or other highly unusual symptoms. Eruptions may occur with less than 24 hours notice.	Monitoring system continuously manned. Regular visual inspection of potential vent areas. Continuous ground deformation and hydrothermal monitoring. Daily assessment reports to civil authorities.	Coordinate evacuation (if necessary) based on hazard zones. Entry to the restricted access zone by scientist will be permitted after evacuation on a case-by-case basis. Organize regular radio and television announcements.
Red	Eruption is in progress or may occur without further warning	Measurements as permitted by safety condition. Civil authorities advised continuously.	Coordinate continued evacuation as necessary. Organize regular radio and television announcements.

Fig. 7. Volcano Alert Level System for La Soufrière Volcano, St Vincent that was used to guide emergency response during the 2020–21 eruption. The figure caters for unrest at the volcano leading to an explosive eruption and so posed several challenges to its application during the first 3 months of the 2020–21 eruption which was entirely effusive.

probability of three possible outcomes for the next stage of volcanic activity: (i) effusive activity continuing; (ii) the eruption ending; and (iii) escalation to explosive activity. Elicitations done during January to early March consistently favoured continuation of effusive activity (Joseph *et al.* 2022*b*).

The monitoring network was augmented with the installation of new seismic stations at Wallibou (5 January), Georgetown (9 January), Owia (17 January), Volcano Summit (20 January) and Fancy (21 January), as well as cGPS stations at Georgetown (6 January). Web cameras, providing views of the volcano, were installed at the Belmont Observatory (3 January) and at the NEMO Warehouse in Georgetown (8 January), and aerial surveillance from a fixed wing aircraft was carried out on 30–31 January.

A visit to the volcano summit on 5 January, as well as analysis of satellite imagery, indicated that as growth was confined by the 1979 dome, the initial dome had developed an elliptical shape (with dimensions 200 × 160 × 70 m) and was expanding in a westerly direction (see Fig. 8 and **Stinton 2023**). Strong gas emissions from the lava vent, visible as a greyish-white, weak plume seen above the crater, were being channelled towards the SW by local winds. Traverses from helicopter with a UV spectrometer on 16 January 2021 failed to detect sulfur dioxide (SO_2), although carbon dioxide (CO_2) and hydrogen sulfide (H_2S) were detected by MultiGAS (see also Joseph *et al.* 2022*a*). A distinct brown discoloration of the vegetation, first noted on the SW crater walls, became visible at the upper rim of the

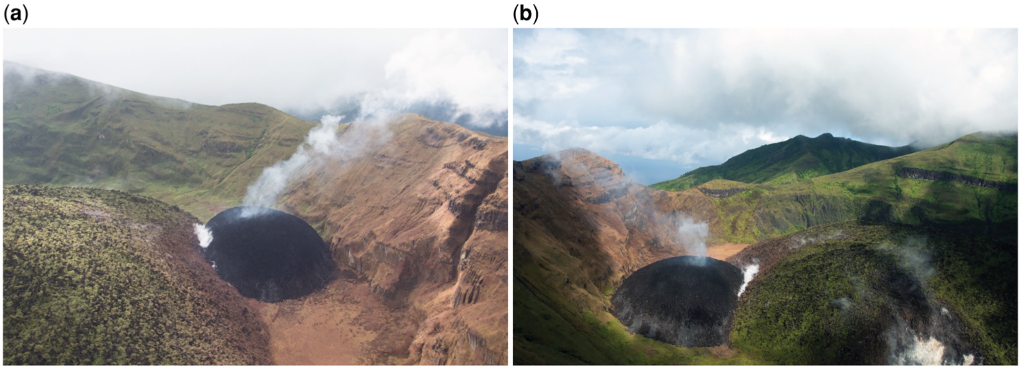

Fig. 8. Oblique aerial views of the new lava dome taken (**a**) from the north and (**b**) from the south on 6 January 2021 by Kemron Alexander of the Soufrière Monitoring Unit during an aerial reconnaissance of the crater. The images show the actively growing northwestern and southeastern faces of the dome as it transitioned towards an ellipsoidal shape expanding along the crater floor restricted by the twin barriers of the 1979 dome (to the NE) and the crater wall (to the SW). The brown discoloration of the vegetation on the 1979 dome and crater walls is caused by the chemical (acidic gases) and thermal impact of the lava dome. Source: National Emergency Management Organisation.

crater and began advancing further downslope (Fig. 9).

Visual observations of the dome on 14 January confirmed that it had increased in height to 80 m, approximately three-quarters of the height of the 1979 dome. The most active gas emissions were occurring at the contact areas between the pre-existing 1979 dome and the 2020–21 dome, as well as the top of the new dome. The fumarolic area on the 1979 dome had become more active than prior to the eruption. Cracks on the eastern side of the crater floor had developed with weak venting observed. At this stage, the initial dome was confined by the crater wall and the 1979 dome and the lava grew as a coulée rather than a classical dome (**Stinton 2023**). Photogrammetry surveys commenced on 18 January.

Rock samples were collected and a temperature of 590°C was recorded on the western side of the actively growing, leading edge of the dome on 16 January (Fig. 10). During the evening of 16 January there were reports of a strong glow emanating from the crater of the volcano. Aerial surveillance from a helicopter on 17 January indicated that this was most likely due to a forest fire that had occurred on the western parts of the crater floor. This resulted in a black irregular deposit on the crater floor leading from the edge of the dome (Fig. 11).

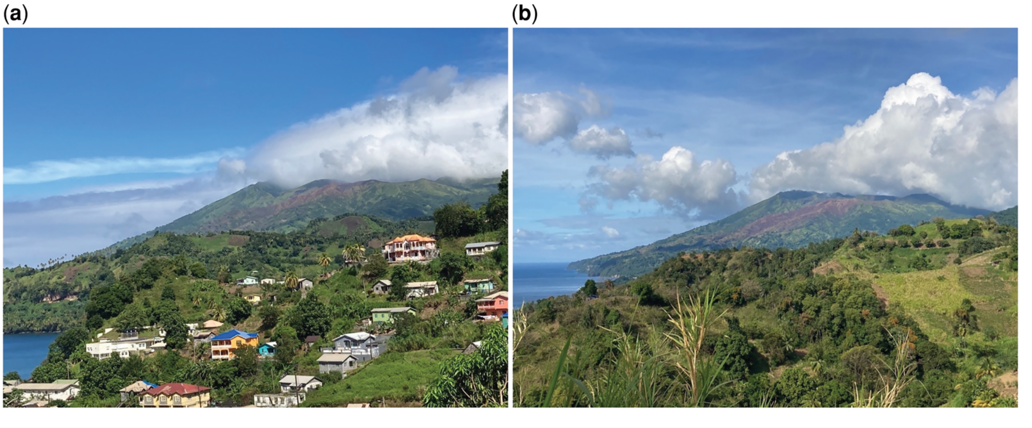

Fig. 9. Profile view of La Soufrière Volcano from the Belmont Observatory located ~ 9 km away taken on (**a**) 12 January 2021 and (**b**) 19 March 2021. It shows the expansion downslope of an area with damaged vegetation that is visible as a brown stain along the southwestern flank of the volcano. This resulted from by acid burn due to volcanic gases emitted by the volcano. Source: The UWI Seismic Research Centre.

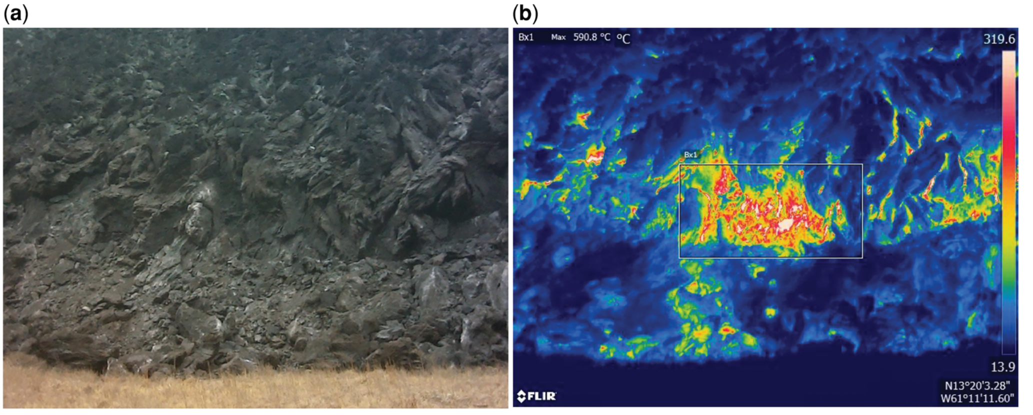

Fig. 10. Frontal view of the western side of the actively growing, leading edge of the lava dome taken from the crater floor by Adam Stinton on 16 January 2021. (**a**) A colour-corrected image of the base of the lava dome. (**b**) A thermal FLIR (Forward-Looking InfraRed) image of the same area which had maximum temperatures of 590.8°C. Rock samples of the lava dome were collected from this area at the same time. Source: The UWI Seismic Research Centre.

By the end of January, SW coulée growth was restricted by the crater wall. It had a steep, south-facing side and a gentler sloping side towards the north. The monitoring network had by this time been upgraded to consist of: four cGPS stations, a nine-prism EDM reflector and seven seismic stations; aerial surveillance of lava growth with unmanned drones; visual observations from the summit and fixed wing aircraft overflights; remote cameras at the summit and Belmont Observatory, and analysis of satellite imagery (Sentinel-1, -2 & -5P).

Since the installation of seismic stations at Wallibou (on the lower flank of the volcano) on 8 January and at the summit on 18 January, 652 earthquakes were recorded up to 2 February. These events were of very low magnitude (<1 M_t) and considered to be earthquakes directly related to dome/coulée emplacement (Joseph *et al.* 2022*a*; Fig. 5). Notably,

Fig. 11. Oblique aerial view of the new lava dome from the north taken by Adam Stinton on 18 January 2021. The black irregular shape on the crater floor spreading out from the base of the dome traces the path of burnt vegetation resulting from a fire that occurred during the night of 16 January. The first was possibly caused by hot rock falls from the actively growing dome front which was sampled earlier that day. Two white circular discs put in to help calibrate the rate of dome growth are visible within the black mass. Source: The UWI Seismic Research Centre.

Fig. 12. Close-up oblique aerial view of the summit of the new lava dome taken from a helicopter by Adam Stinton on 16 January 2021. It shows the most active areas of gas emissions: a small circular area at the top of the dome and the interface between the new dome and the pre-existing 1979 dome. Source: The UWI Seismic Research Centre.

the number pattern of events recorded at the long-standing Belmont Observatory station, located 9 km from the volcano summit, remained unchanged throughout this period.

The lava continued to advance during early February with lateral spreading towards both the north and south but with preferred northward growth observed. The most active areas of gas emissions were now the interface between the new dome and the pre-existing 1979 dome and a small circular area at the top of the dome (Fig. 12). The fumarolic area on the 1979 dome continued to be more active than it was prior to the start of dome growth.

Analysis of Sentinel-1 imagery from December 2020 indicated that a possible 10 cm line-of-sight displacement had occurred during the period 19–31 December 2020. The limited deformation zone and poor coherence made it difficult to constrain the magnitude and source of the deformation, but analysis of similar data acquired in January found no deformation between 31 December 2020 and 12 January 2021. Analysis of data from the cGPS network done at this time indicated that there had been no significant deformation signals related to lava emplacement (see **Camejo-Harry *et al.* 2023** for more recent analysis).

A visit to the summit on 1 February revealed that another bush fire had occurred in the northern part of the crater floor with signs of burnt vegetation on the crater wall. Two circular target discs placed on the crater floor as reference scales for tracking dome growth had been destroyed by the fire. During this visit the first ground-based gas measurements, using a MultiGAS instrument, showed that water vapour, CO_2 and H_2S were still present, but SO_2 was detected for the first time. This observation indicated either the presence of new volatile-rich magma, or that SO_2 was no longer being 'scrubbed' by the hydrothermal system, suggesting a drying out of the water in the hydrothermal aquifer located in the crater. Analysis of the gas data, when compared to MultiGAS data collected on 2 May 2018, indicated that the signature of the gas composition had moved from a hydrothermal-dominated to a deep hydrothermal-magmatic signature.

The ongoing communications effort by NEMO and UWI-SRC became more coordinated and focused during late January and continuing into February with several efforts being made to effect communications to the public through face-to-face meetings, within the constraints caused by the Covid-19 pandemic. Drive-by community meetings with Red and Orange Zone residents using loudspeakers were used to update them of the latest activity at the volcano as well as of plans for emergency response. Public service announcements were prepared and disseminated by radio and via WhatsApp groups. Regular radio updates given by the Scientist-in-Charge of the resident monitoring team increased to three times per week and virtual community meetings, media call-in and Facebook Live programmes were arranged with UWI-SRC and NEMO staff.

The new lava continued to advance towards the NW and SW with the areas of most active emissions remaining unchanged (Fig. 13). Analysis indicated that the overall rate of growth since onset of lava extrusion was $\sim 1.85\ m^3\ s^{-1}$ (**Stinton *et al.* 2023**)

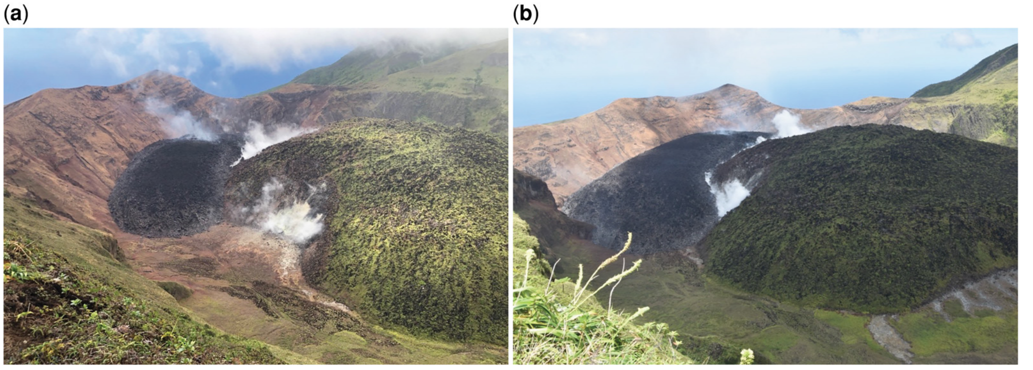

Fig. 13. Growth of the new lava dome at Soufrière St Vincent from (**a**) 12 February to (**b**) 1 April 2021. The dome expanded >170 m across the crater floor between both photographs, to overcome the pre-existing area of fumarolic activity located on the 1979 dome. White gas-and-steam emissions are visible along the contact area with the 1979 dome and at the top of the dome. Source: The UWI Seismic Research Centre.

with short-term variations of between 0.95 $m^3 s^{-1}$ and 2.6 $m^3 s^{-1}$ (see **Stinton 2023** for more recent analysis). Seismic stations on the volcanic crater recorded several dome emplacement events, the majority of which (~98.5%) were small and fluctuated. There was one brief period on 14 February when a subtle change in their magnitude was observed. This was short-lived but was followed by a 2-day increase in the number of events, which then had a sharp drop off on 18 February. One M_t 1.6 earthquake located at 15 km depth beneath the southeastern flank of the volcano was recorded on 18 February.

Activity during March–early April 2021

This low-level pattern of seismic activity continued until 23 March, when at about 10:30 a.m., a 45-minute period of elevated VT earthquakes occurred. Again at 4:52 p.m. on 23 March and continuing at a diminishing level, until 26 March, the network recorded a swarm of VT earthquakes. The largest event was of M_t 3.1 with >95% of the located events at depths shallower than 5 km.

The level of VT activity and dome emplacement events subsided after 26 March and was markedly diminished by 29 March. Events thought to be related to lava extrusion rose sharply following the 29 March low, until 5 April at 6:38 a.m., when activity transitioned to an intense swarm of VT earthquakes that steadily increased in numbers until about 8:30 a.m. The largest events were felt in communities located on or near to the La Soufrière Volcano as far south as Chateaubelair (Fig. 1). VT activity levelled off and started to decline at about 2:00 p.m., but during the period 2–5 April over 598 events were recorded. The earthquakes were located 6 km beneath the volcano, slightly deeper than the VT swarm recorded during 23–25 March which was in the depth range of 3–5 km. The earthquake swarm was also more intense (larger and more events) than in March. Several of the earthquakes were of M_t 3.0 or greater but the largest VT earthquake (M_t 3.9) occurred at 2:16 p.m. on 5 April.

Adverse weather conditions and some technical difficulties prevented unmanned aerial vehicle (UAV) surveys to be completed of the lava during April but analysis of optical satellite imagery from 24 March and 1 and 2 April, as well as from Sentinel-1 imagery from 24 and 31 March, indicated that overall, since 19 March, there had been between 35 and 40 m of lateral advancement over the crater floor. Growth continued to occur at both the northern and southern fronts of the lava.

Seismic activity changed significantly at 3 a.m. on 8 April when the seismic station located closest to the summit began recording low-level seismic tremor. Six separate bands of tremor with slowly increasing magnitude were recorded during the day at intervals of 2.5 hours and accompanied by elevated and continuous gas venting. Long-period earthquakes (five events) were recorded during the second and fourth band of tremor. In addition, two brief swarms of small VT earthquakes occurred between the bands of tremor.

The summit camera indicated that the dome height had increased significantly during the day with incandescence visible on the central raised parts of the dome (Fig. 14). **Dualeh *et al.* (2023)** have shown that there was a marked increase in lava discharge rate to an estimated 17.5 $m^3 s^{-1}$ in the 1–2 days prior to onset of explosive activity on 9 April.

Elicited estimates for transition to explosive activity increased with the escalation of volcanic activity in late March. With the onset of banded tremor on 8 April, elicited probabilities of explosive

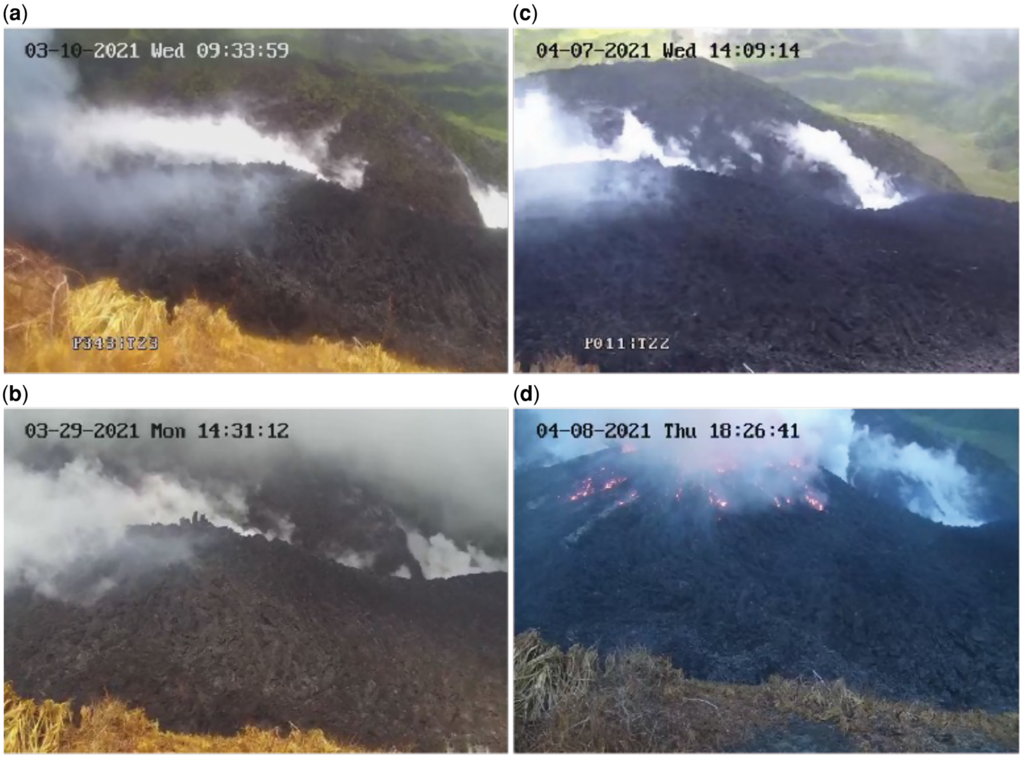

Fig. 14. Sequence of images taken with a webcam located on the southern crater rim overlooking the growing lava dome which show the changes that occurred over the period (**a**) 10 March 2021 to (**d**) 8 April 2021 (especially between (**c**) 7 April and (d) 8 April), inclusive of (**b**) 29 March 2021. Full details of the growth and evolution of the lava dome and coulée can be found in Stinton (2023). Source: The UWI Seismic Research Centre.

activity tripled to a media value of ~60% (Joseph *et al.* 2022*a*).

Regular and frequent communications with the disaster management authorities of SVG had been ongoing throughout the eruption. They were therefore informed of the elevation in activity observed from late March onwards. By 8 April several briefings were given during the day on the state of activity at the volcano and, based on this advice, the government declared a disaster alert at 1 p.m. as a prelude to an evacuation order. The Volcano Alert Level at the volcano was increased by NEMO to Red and evacuation of communities located in the Red Zone on the volcano began soon after the declaration of an evacuation order by the Prime Minister at 4:00 p.m. on 8 April 2021.

Explosive eruptive sequence 9–23 April 2021

A seventh band of tremor occurred at about 8 p.m. on 8 April and was followed by a VT earthquake swarm after which the volcano went into continuous tremor. The UV spectrometer detected SO_2 for the first time from a boat traverse on 8 April, albeit with a comparatively low flux (Joseph *et al.* 2022*b*). The amplitude of the tremor gradually increased, peaking at 3:30 a.m. on 9 April before decreasing slightly over the next few hours. The steam and gas venting, which had been associated with periods of tremor, became more persistent and eventually continuous with a well-defined plume developing above the volcano. Incandescence from the lava became visible directly from the Belmont Observatory overnight.

At about 8:37 a.m. on 9 April the amplitude of the tremor increased rapidly by several orders of magnitude and audible sounds of explosion were heard. However, the summit of the volcano was obscured by low-level cloud, and it was not until about 8:40 a.m. that an expanding eruption column was observed rising through the cloud cover at the top of the volcano signalling the start of explosive activity (Fig. 15). High-amplitude tremor, generated by the explosive activity, continued for about 40 minutes before slowly declining in amplitude.

Seismic activity began to increase again at about 11:30 a.m. with a swarm of earthquakes dominated

Fig. 15. The first ash plume from La Soufrière St Vincent taken from the Belmont Observatory at 8:44 a.m. on Friday 9 April 2021. The plume rose to 8 km altitude and drifted ENE. It signalled the start of the explosive phase of the eruption. Source: The UWI Seismic Research Centre.

by VT events accompanied by many small, long-period and hybrid earthquakes. The swarm continued up to 2:40 p.m. increasing slowly in intensity and followed at about 2:45 p.m. with voluminous and energetic ash venting visible from the Belmont Observatory. Continuous seismic tremor started again at 3 p.m., increasing in amplitude whenever the ash venting was most vigorous. Seismic tremor generated by voluminous energetic venting continued overnight. The amplitude of the tremor peaked between 8 p.m. and midnight on 9 April and then slowly declined over the next few hours. A small number of VT, long-period and hybrid earthquakes were recorded during the tremor. Audible rumblings accompanied by ash venting occurred throughout the night and ashfall was reported over the entire island (Fig. 16).

The seismic network began to record banded tremor again at about 3:30 a.m. on 10 April. The tremor episodes initially lasted 20–30 minutes with gaps of 1–3 hours. They were associated with explosive activity that generated heavy ashfall in the northern parts of the island. Thunder and lightning were experienced during periods of explosive activity. Steaming (inferred at the time to be associated with possible PDCs or lahars) was observed for the first time in the upper parts of the Rabacca Valley at midday on 11 April, although this also followed periods of overnight rainfall. Radar imagery acquired by Capella Space on 10 April at

Fig. 16. Ash covering most surfaces and continuing to fall (white hazy background) because of the intense period of ash venting and explosive activity that occurred during the first 2 days of the eruption. (**a**) Taken at 2:53 p.m. on 10 April in the community of Georgetown located ~8.7 km SE of the volcano. (**b**) Taken at 10:33 a.m. on 11 April in Rose Bank located ~9 km SW of the volcano. Source: The UWI Seismic Research Centre.

12:10 a.m., indicated that a summit crater had formed in place of the 1979 dome and the 2020–21 dome had been destroyed. Analysis of satellite imagery (TerraSAR-X) taken of the volcano on 11 April at 8:19 a.m. indicated the explosive eruptions had largely destroyed the pre-existing domes (the 1979 and 2020–21 domes) and created an 825 × 750 m-wide new crater within which the current explosions were being sourced.

The time between episodes of explosive activity and accompanying high-amplitude seismic tremor lengthened after midday on 11 April to 5–8 hours, and at this point field teams were able to travel to sample the tephra sections deposited. At 4:15 a.m. observations of incandescence from the Belmont Observatory provided visual confirmation that PDCs were being generated and had entered multiple valleys surrounding the volcano. Small long-period earthquakes were recorded from about 6 p.m. on 11 April.

The pattern of seismic activity changed on 12 April with the end of the episodes of high-amplitude tremor 2–8 hours apart. Starting at 6 a.m., two episodes of lower-amplitude tremor were recorded followed at 5 p.m. by one episode of high-amplitude tremor. These episodes continued to be associated with either enhanced venting or explosive activity.

Reconnaissance of the north coast from Chateaubelair (west coast) to Georgetown (east coast) on 12 April from the sea, confirmed that PDCs had descended several valleys on the southern and west flanks of the volcano. They had reached the sea at Roseau Bay and Larikai Bay (Fig. 17). Extensive damage was observed to vegetation along the entire west coast of the island extending from Larikai Bay to Turner Bay. Coastal areas along the eastern flank of the volcano had been affected by heavy ashfall.

At 1:30 a.m. on 13 April, long-period earthquakes steadily increased in frequency. Audible venting was heard associated with some periods of tremor and long-period earthquake activity. The period of increasing long-period earthquakes changed with an explosive vulcanian eruption that began at 6:30 a.m. (Fig. 18). The explosions pulsed for about 30 minutes and produced PDCs that were observed from the Belmont Observatory to have descended several valleys along the west and SW flanks of the volcano. The explosions were accompanied by high-amplitude tremor and followed by >3 hours of lower-amplitude continuous seismic tremor.

Another episode of explosive activity started at 8:30 p.m. on 14 April accompanied by over 40 minutes of pulsatory activity, producing PDCs down most valleys on the west coast and some on the east. By the 14 April, the eruption plumes had become less dense and more gas-rich and did not rise as energetically as previous explosions. The intervals between the bands of tremor with associated episodes of explosive activity had increased to 14 hours apart, separated by small, long-period earthquakes.

The pattern of activity changed on 15 April as the last of the series of bands of tremor ended at about 5:40 a.m. and, unlike previous bands, did not have any ash venting or explosive activity associated. After this time, the seismic network began to record a near-constant swarm of long-period and hybrid earthquakes with brief periods of low-level tremor lasting several minutes to hours that were often associated with an increase in venting (shorter periods) or explosive activity (longer periods of venting). Further explosions were registered on 16 April (about 6:15 a.m.) and 18 April (4:49 p.m.).

New measurements of SO_2 flux from the volcano on 15 April yielded an average SO_2 flux of 809 tons/

Fig. 17. Oblique view of the Larikai River Valley taken just off the west coast of the island showing thick tephra deposits produced by multiple pyroclastic density currents (PDCs) that have extended the pre-existing coastline into the sea. A weak, water-rich plume is seen rising above the summit crater of La Soufrière Volcano in the background. Vegetation damaged by heavy ash fall and the passage of PDCs are visible within the valley and on the intervening headland. Source: The UWI Seismic Research Centre.

day. Measurements, continued in subsequent days, remained at similar levels but began to drop by the second week.

Long-period and hybrid earthquakes continued to occur, but their rate dropped significantly on 16 April and then returned to a near-constant rate. No episode of tremor was recorded after 16 April, but occasional, small VT earthquakes were recorded on the network.

The final explosion of the eruption occurred on 22 April, lasted 20 minutes and generated a vertical plume up to ~5 km above the crater rim. PDCs were observed moving down the western side of the volcano during the initial stages of the explosion. About 2 hours of ash venting and tremor continued after the initial explosion (see **Cole *et al.* 2023** for explosion timings).

Post-eruptive hazards and geomorphological change

There was some syn-eruptive lahar activity during the explosive period but the first signal from a lahar was recorded by a seismic station close to the Rabacca River on the eastern side of the volcano at 4 p.m. on 20 April. Following intense rains there were several intense periods of lahar activity in the few weeks following the explosive sequence. These and their impacts are explored in **Phillips *et al.* (2023)**. Trees brought down by the lahars were observed as floating logs that posed a hazard to small craft near to the shoreline along the east and west coast.

The combined action of the PDCs meant that many valleys around the volcano were infilled to flat plains and others had an abundance of loose material at their head with weakened and damaged vegetation. Post-eruptive rainfall rapidly mobilized this material and there was particularly rapid incision and geomorphological evolution. The first events contained large boulders that rapidly descended all the river valleys draining the volcano and resulted in extensive damage in some of the villages on the eastern flank of the volcano. The rapid topographic change in and around the Wallibou Valley was previously documented by Hovey following the 1902 eruptions (Hovey 1902).

The explosive eruptions resulted in the creation of an explosion crater and development of multiple fumaroles within and outside this crater. Venting of white steam from several areas of the crater floor has continued, including a linear feature that extends from the WNW to ESE of the crater floor.

Fig. 18. A rising ash plume above La Soufrière Volcano taken from the Belmont Observatory at 6:35 a.m. on 13 April 2021. The explosion occurred on the anniversary of the 1979 eruption with the plume eventually rising to >14 km and drifting towards the east. Source: The UWI Seismic Research Centre.

Discussion: new information and future challenges

This chronology offers some lessons for monitoring science and disaster risk management. There was an acute and very specific challenge here associated with the global pandemic. The eruption began during a period when vaccines were not yet widely available and so the restriction of movement was the only viable mitigative action. This restricted movement not only impacted the state of the long-term network but also severely challenged planning around evacuations. This was compounded by border closures of islands in the Eastern Caribbean, with no commercial flights being available for movement of monitoring personnel.

This doubly emphasized the value of pre-eruption planning and preparedness, and long-term engagement, which created the teamwork and partnerships necessary to cope. In this context the national and international partnerships described above that fuelled the local and remote monitoring were critical to the success of provision of timely advice and warnings (Joseph *et al.* 2022*b*). Our chronology demonstrates the critical importance of the multiparametric dataset in anticipating the course of the eruption, particularly when interpreted in the context of the detailed pre-existing historical knowledge of past eruptions (Robertson 2005; Pyle *et al.* 2018). During the eruption our detailed and close observation enabled us to build considerably on the past datasets, generating a canonical dataset for this type of activity.

The material in this volume represents the synthesis, analysis and further work carried out on these and other new data gathered since the eruption. Here, we introduce the key findings from these papers, and other associated works to date, while also signposting areas ripe for further research to improve response in the future. This volume is not only a significant contribution to the knowledge of the La Soufrière eruptive system, but also provides important insights into the ways and means by which volcanic eruptions of this type impact on populations at risk, and detailed insights into the most effective communication processes through this type of crisis.

Understanding the subsurface system and its relation to eruptive activity

Previous experimental, petrological and geophysical research had shown that La Soufrière has a well-developed plumbing system with vertically extensive, crystal-mush-dominated reservoirs typical of the arc (e.g. Melekhova *et al.* 2017, 2019). Interrogation of the eruptive products and the geophysical datasets has now revealed important insights into the system across an eruptive episode. By combining cGPS and retrospective analysis of InSAR data, **Camejo-Harry *et al.* (2023)** recognized pre-eruptive inflation in the far field from July to December 2020, which continued during the effusive phase of eruption, with near-field deformation detected via InSAR images collected in late 2020 and early 2021, followed by rapid syn-eruptive deflation in the first 24 hours following the first explosion. Using Mogi modelling they infer that this inflation was driven by deep-seated changes in the magmatic plumbing system (16–20 km depth), and the inferred pressurization source transitioned to shallower depths as the eruption progressed towards its explosive phase. Following the initial explosion on 9 April, the post-explosion deflation represented a rapid depressurization of the conduit and transport system centred around 6–10 km. **Latchman and Aspinall (2023)** also found a hint of a zone of reduced seismicity at 7–8 km during this period, perhaps indicative of an ephemeral shallow storage region, but they did not uncover unambiguous evidence for time-related shallowing of VT earthquakes consistent with slow rise of material prior to the explosive sequence.

These depths are also consistent with the geothermobarometry of **Weber *et al.* (2023)** for the phenocryst assemblage in both the sampled dome and a sample of scoria, suggesting crystallization depths of between 8 and 13 km for the clinopyroxene cargo. Based on an absence of petrological evidence for mafic recharge or a change in volatile content they suggest that an andesitic–dacitic melt pocket was disrupted and entrained mush in the lead up to the eruption, which is also consistent with **Latchman and Aspinall's (2023)** suggestion that an ephemeral magma system reached a critical metastable state, setting in motion events that led to the initial extrusion of the coulée. **Latchman and Aspinall (2023)** also tentatively offer the perturbation associated with regional seismic events as a tipping point which triggered the subsurface movements determined through 2020 and early 2021. They also note the overlap (within uncertainty) between the calculated volume of the eruption (**Cole *et al.* 2023**) and their calculated injection volumes based on the seismic moment of the VT swarms in March 2021, suggesting that this represents the injection of the eruptible volume towards shallower depths in the system.

The precise origin of the magma erupted during the effusive phase remains more enigmatic, partly due to the limited opportunity for sampling and the constraints imposed by a network impacted by resource and the pandemic, during the pre-eruptive and early phases of the eruption. Analysis of gas emissions suggest either that the effusive magma was already thoroughly degassed (**Esse *et al.* 2023**; **Stinton *et al.* 2023**) or that much of the primary gas phases were scrubbed via the hydrothermal system (Joseph *et al.* 2022*a*). There is limited evidence of a gas signature consistent with origin at depth during the effusive stage (Joseph *et al.* 2022*a*). One possibility suggested by **Stinton *et al.* (2023)** is that this initial volume could have been remobilized material from previous eruptions. Also, **Sparks *et al.* (2023)** and **Stinton (2023)** use rheological analysis to infer that the rapid change in extrusion rates immediately prior to the explosions (**Dualeh *et al.* 2023**) is consistent with the extrusion of a remnant degassed magma, pushed from behind by a laterally rapidly rising batch of gas-rich magma. Evidence from the remotely sensed gas data (**Esse *et al.* 2023**) also corroborates this view, along with the differences in microlite cargo associated with the effusive–explosive transition and different phases of the explosive cycle (**Frey *et al.* 2023**). However, steady aseismic ascent of a similar magma from a deeper reservoir throughout the unrest period cannot be completely ruled out: **Weber *et al.* (2023)** and **Frey *et al.* (2023)** agree that the clinopyroxene and plagioclase macrocrystal population in both the explosive scoria and dome are similar, suggesting entrainment and storage of this assemblage at the same depth. Preliminary olivine (ol) diffusion profiles on three crystals in scoria (representing disintegration and entrainment from surrounding mush) imply timescales between entrainment at depth and eruption (**Weber *et al.* 2023**) from 7 months to 8 years on two, and only 1–14 days on a third crystal magmatic movement across the storage region for some time. In contrast, using heating and oxidation experiments, **Morrison-Evans *et al.* (2023)** concluded that the oxidation-exsolution reactions can occur relatively quickly, and that textures observed in the dome rock developed at the surface during dome emplacement rather than during long-term magma subsurface storage prior to eruption.

The precise reason for eruption initiation requires further work, with low initial sulfur emissions combined with little petrological evidence for perturbation with new melt or heating of the system. **Weber *et al.* (2023)** suggest that the initial magma was remobilized from around 10 km depth (to explain the lack of disequilibrium textures in the macrocrystal assemblage) with perturbation likely coming from a deeper more buoyant melt, also evidenced in the ol and high-An plagioclase microlite assemblage in the initial explosive products (**Frey *et al.* 2023**).

Subsequently, a further critical question for these new analyses is the extent to which their interpretation can improve forecasting of the onset of a new eruption, and the anticipation of the likely size and duration of any explosive activity. This is a critical insight for a volcano capable of producing eruptions with large variations in the size and impact of explosions, despite a monotonous bulk composition. The lessons learned thus far from these papers is the value of an active multiparametric monitoring network in interpreting subsurface activity. Further, more detailed work that expands the analysis of the geospeedometry with the seismic and deformation datasets could provide critical insights into the changes in subsurface geometries and movement of materials in the lead up to and the early stage of the eruption, particularly in comparison with the other historical activity.

Anticipating explosive–effusive transitions and explosive behaviour

As detailed here and in Joseph *et al.* (2022*a*), the likelihood of a transition to explosive activity was recognized via the monitoring data ‘just-in-time’ (where the monitoring team recommended an Alert Level change with sufficient time to have initiated and theoretically to have completed evacuation before the first explosion). Nonetheless, the extent and size of the explosions could not be anticipated during the eruption, and this is a critical question for eruptions of this type worldwide (Cassidy *et al.* 2018). Subsequent work in this volume has considerably advanced understanding of the drivers of these explosions, and the reason why they ceased, and how this might be recognized in monitoring data in the future. Comparison of local observations, with the detailed on-island stratigraphy and the satellite record of explosive eruptions, recognized several different phases of activity, as the rising magma excavated and removed the overlying domes, and as magma supply and character changed (**Cole *et al.* 2023**). This corresponds well with the three phases of acceleration, peak and then an exponentially waning stage determined via analysis of satellite-derived plume heights and seismic energies (**Sparks *et al.* 2023**). This implies that the reservoir of magma represented by the quasi steady-state of the peak eruption sequence was not replenished from depth at least after the first 24 hours of the explosive phase, an observation corroborated by the detailed analysis of the microlites from the stratigraphically constrained samples by **Frey *et al.* (2023)**, where monotonous bulk compositions and phenocryst cargos suggest a common source, but the microlite cargo suggest subtly different conditions of magmatic storage and pathways of ascent and overpressurization in the shallow system. Notably, their more detailed analysis points to differing batches of magma arriving through both the accelerating and the early stages of the peak explosive activity identified by **Sparks *et al.* (2023)**. The dominance of this last (hotter, and perhaps most rapidly ascended) magma batch accounts for the relatively large and buoyant explosions associated with the final explosion of the peak stage (**Cole *et al.* 2023**). At this point the exponential decay of inferred energies for the remaining events, along with the absence of seismic events associated with further magma movement demonstrate the exhaustion of this source.

The total volume of tephra (fallout and PDC) is $1.19 \times 10^8\ m^3 \pm 20\%$ (**Cole *et al.* 2023**), equivalent to VEI 4, although this was constructed via the outputs from at least 32 discrete events. The good fit between estimated intrusive volume via seismic moment (**Latchman and Aspinall 2023**), and the inferred erupted volumes from **Constantinescu *et al.* (2023)**, **Cole *et al.* (2023)** and **Sparks *et al.* (2023)**, suggest that the analysis from this sequence has now created a canonical dataset of both monitored signals, carefully tied in with erupted deposits and inferred conditions of storage and ascent via petrology. Deposits from historical eruptions, of differing durations and intensity, can be further analysed and interpreted against this framework to improve our understanding and anticipation of eruptive size and transition in the system.

We do not yet fully understand the extent to which the initial eruption was pushed by the influx of a specific volume of (gas-rich) juvenile magma from depth or whether sudden failure was initiated by overpressurization via the overlying dome and conduit and shallow surface conditions, or some combination of the two. Further studies focused on these aspects of the system braced via the datasets described here could generate a significant advance in anticipating eruptive transitions at this and similar systems worldwide.

Flow regimes

Like most of the historical eruptions at La Soufrière, the 2020–21 eruptive sequence was notable for producing viscous lava flows (coulées), PDCs and lahars. The detailed analysis of the dome growth (**Stinton 2023**) not only provided input into the monitoring at the time but has created a basis on which the drivers behind both the effusive and explosive stages of the eruption can be understood. Comparison with the well-documented 1971–72 and 1979 eruptions provides a contrasting case, and some insights into the impacts of confinement on the evolution of lava domes (**Stinton 2023**). The rheological analysis of **Stinton *et al.* (2023)** demonstrates that the rheology of the magma changed significantly through this transition and that the extrusion rate could be modelled via a constricted pathway from a pressurized shallow body.

Although critical for life safety (Brown *et al.* 2017), the point at which the explosive sequence began to generate PDCs was not clearly understood during the eruption. The evacuated population and low ash visibility meant that contemporary direct observation was often not possible. Later analysis of satellite imagery and the stratigraphic reconstruction suggest this happened during the early stages of the 'peak eruption', after the overlying dome had been largely removed (**Cole *et al.* 2023**). This initial analysis suggests that PDCs were associated with several explosions from this point onwards, their character being that of collapsing eruption columns, perhaps due to some change in conduit radius. There is need for further work to understand more carefully the causes of the generation of PDCs and the conditions for their generation relative to other historical eruptions.

To support ongoing hazard assessment, **Gueugneau *et al.* (2023)** generated rapid scenario-based PDC invasion maps during the explosive phase of the eruption. These were later compared with simulations based on field-based deposit maps and shown to mimic the observed valley-confined PDCs, although the dilute PDCs were overestimated. The results indicate the potential of such simulations for rapid hazard assessment purposes and the utility of field-based data in improving them.

A further complication in the geophysical identification of PDCs was the occurrence of co-eruptive rainfall that led to the generation of lahars. Lahars were also rapidly mobilized in the immediate aftermath of the eruption and created a rapid topographic change in the Wallibou River that closely followed the patterns observed by Hovey (1902). The analysis of the first year of lahar activity following the eruption has identified some critical thresholds for the generation of lahars and the characteristic most important to their management in the longer term (**Phillips *et al.* 2023**).

Environmental and social impacts and the communication of risk

The explosive phase of the eruption ejected sufficient ash into the environment to be of concern in terms of harm to respiratory health and pointed to the need for the implementation of monitoring networks to determine potential impacts on water supply and particle re-suspension after the eruption (**Horwell *et al.* 2023**). The need for a more thorough assessment of the local and regional impact of ash is still unfulfilled despite the conclusion by **Horwell *et al.* (2023)** that the greatest hazard to respiratory health was not the silica content (which was <5 wt%), but the large quantity of respirable particles in the ash.

The 2020–21 eruption is noted for having resulted in no loss of life, but it caused the evacuation of ~16 000 people from the northern third of the island. Residents of the Red and Orange zones indicated that they were willing to evacuate if given the information needed beforehand to guide their decision-making (**Ferdinand and Badenock 2023**). Some of the issues of most concern were: (i) the safety and security of their property (house, land and animals); (ii) if they had a place to stay; and (iii) the support, especially food supplies, they would receive (**Ferdinand and Badenock 2023**). These considerations confirm the strong role that sustaining livelihoods and wellbeing play in decision-making and actions that endanger life during volcanic crises (Barclay *et al.* 2019).

Detailed analysis of the efficacy of various creative and adaptive communication campaigns implemented during the eruption has provided unique new evidence about the value of tailored information (**Graham *et al.* 2023**). It challenged widely held paradigms about the value and influence of religion and demonstrated the value of sustained community relations in crisis response (**Graham *et al.* 2023**; **Mani *et al.* 2023**). Traditional media (i.e. radio) held sway as the most important communication tool for reaching a wide audience, but one-on-one communication and use of groups that worked within or were part of communities were more important in areas closest to the volcano (**Graham *et al.* 2023**; **Mani *et al.* 2023**).

Acknowledgements The tremendous support of all members of staff of The University of the West Indies Seismic Research Centre and the Montserrat Volcano Observatory, and long-standing colleagues and other members of the regional and global scientific community who assisted in the emergency response to the 2020–21 eruption is sincerely appreciated.

We would like to thank David Boyt, Caroline Astley, Danielle Tremeer and Jo Armstrong of the Geological Society Publishing House for their support in bringing this volume to fruition, and all of the contributing authors for their patience throughout the process.

We are particularly grateful to all our reviewers for their efforts in getting the papers fit for your reading: Alvaro Aravena, Teresa Amijos, Willy Aspinall, Amelia Bain, Olivier Bernard, Juliet Biggs, Hannah Buckland, Mike Burton, Katherine Cashman, Danielle Charlton, Annemarie Christophersen, Fidel Costa, Natalia Deligne, Amy Donovan, Marie Edmonds, Samantha Engwell, Jamie Ian Farquharson, Jonathan Fink, Holli Frey, Josh Hayes, Richard Herd, Madeleine Humphreys, Chris Kilburn, Stephan Kolzenburg, Jean-Christophe Komorowski, Nina Kristiansen, Martin Mangler, Steve McNutt, Severine Mourne, Jorge Eduardo Romero Moyana, Madison Myers, Sarah Ogburn, Matthew Pritchard, David Pyle, Jazmin Scarlett, Thomas Sheldrake, Carmen Solana, Roberta Spallanzani, Randell A. Stephenson, Mylene Villegas and Emily Wilkinson.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **REAR**: conceptualization (lead), methodology (equal), visualization (lead), writing – original draft (lead), writing – review & editing (lead); **JB**: conceptualization (equal), methodology (equal), visualization (supporting), writing – original draft (equal), writing – review & editing (equal); **EPJ**: writing – original draft (supporting), writing – review & editing (supporting); **RSJS**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

Anderson, T. and Flett, J.S. 1903. Report on the Eruption of the Soufrière of St. Vincent in 1902 and on a Visit to Montagne Pelé in Martinique. Part I. *Philosophical Transactions of the Royal Society A*, **200**, 353–553.

Aspinall, W.P., Sigurdsson, H. and Shepherd, J.B. 1973. Eruption of Soufrière Volcano on St. Vincent Island, 1971–72. *Science (New York, NY)*, **181**, 117–124, https://doi.org/10.1126/science.181.4095.117

Barclay, J., Few, R. *et al.* 2019. Livelihoods, wellbeing and the risk to life during volcanic eruptions. *Frontiers in Earth Science*, **7**, https://doi.org/10.3389/feart.2019.00205

Barclay, J., Robertson, R., Scarlett, J.P., Pyle, D.M. and Armijos, M.T. 2022. Disaster aid? Mapping historical response to volcanic eruptions from 1800 to 2000 in the Eastern Caribbean: their role in creating vulnerabilities. *Disasters*, **46**, S10–S50, https://doi.org/10.1111/disa.12537

Bouysse, P. and Guennoc, P. 1983. Données sur la structure de l'arc insulaire des petites Antilles, entre Ste-Lucie et Anguilla. *Marine Geology*, **53**, 131–166, https://doi.org/10.1016/0025-3227(83)90038-5

Bouysse, P., Westercamp, D. and Andreieff, P. 1990. The Lesser Antilles Island Arc. *Proceedings of the Ocean Drilling Program, Science Results*, **110**, 29–44.

Briden, J.C., Rex, D.C., Faller, A.M. and Tomblin, J.F. 1979. K–Ar geochronology and palaeomagnetism of volcanic rocks in the Lesser Antilles Island Arc. *Philosophical Transactions of the Royal Society of London A*, **291**, 485–528.

Brown, S.K., Jenkins, S.F., Sparks, R.S.J., Odbert, H. and Auker, M.R. 2017. Volcanic fatalities database: analysis of volcanic threat with distance and victim classification. *Journal of Applied Volcanology*, **6**, 15, https://doi.org/10.1186/s13617-017-0067-4

Camejo-Harry, M., Pascal, K. *et al.* 2023. Monitoring volcano deformation at La Soufrière, St Vincent during the 2020–21 eruption with insights into its magma plumbing system architecture. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-270

Cassidy, M., Manga, M., Cashman, K. and Bachmann, O. 2018. Controls on explosive–effusive volcanic eruption styles. *Nature Communications*, **9**, 2839, https://doi.org/10.1038/s41467-018-05293-3

Cole, P.D., Robertson, R.E.A., Fedele, L. and Scarpati, C. 2019. Explosive activity of the last 1000 years at La Soufrière, St. Vincent, Lesser Antilles. *Journal of Volcanology and Geothermal Research*, **371**, 86–1000, https://doi.org/10.1016/j.jvolgeores.2019.01.002

Cole, P., Barclay, J. *et al.* 2023. Explosive sequence of La Soufrière St Vincent April 2021: insights into drivers and consequences via eruptive products. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-292

Constantinescu, R., White, J.T., Connor, C., Cole, P., Fontijn, K., Barclay, J. and Robertson, R. 2023. Estimation of eruption source parameters for the 2021 La Soufrière eruption (St Vincent): implications for quantification of eruption magnitude on volcanic islands. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2023-38

Dondin, F.J.-Y., Lynch, L. *et al.* 2019. The University of the West Indies-Seismic Research Centre Volcano Monitoring Network: Evolution since 1953 and Challenges in Maintaining a State-of-the-Art Network in a Small Island Economy. *Geosciences*, **9**, 71, https://doi.org/10.3390/geosciences9020071

Druitt, T.H. and Kokelaar, B.P. (eds) 2002. *The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to*

1999. Geological Society, London, Memoirs, **21**, https://doi.org/10.1144/GSL.MEM.2002.021.01.32
Dualeh, E.W., Ebmeier, S.K. *et al*. 2023. Rapid pre-explosion increase in dome extrusion rate at La Soufrière, St. Vincent quantified from synthetic aperture radar backscatter. *Earth and Planetary Science Letters*, **603**, 117980, https://doi.org/10.1016/j.epsl.2022.117980
Esse, B., Burton, M. *et al*. 2023. SO2 emissions during the 2021 eruption of La Soufrière St Vincent, revealed with back-trajectory analysis of TROPOMI imagery. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-77
Ferdinand, I. and Badenock, K. 2023. Emergency shelters – fleeing La Soufrière: a case study from April 2021 volcanic eruption. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-288
Ferdinand, I., O'Brien, G., O'Keefe, P. and Jayawickrama, J. 2012. The double bind of poverty and community disaster risk reduction: a case study from the Caribbean. *International Journal of Disaster Risk Reduction*, **2**, 84–94, https://doi.org/10.1016/j.ijdrr.2012.09.003
Frey, H., Manon, M. *et al*. 2023. Petrology of the explosive deposits from the April 2021 eruption of La Soufrière volcano, St Vincent: a time-series analysis of microlites. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-291
Graham, O., Thomas, T., Hicks, A., Edwards, S., Juman, A., Ramroop, A. and Robertson, R. 2023. Facts, faith and Facebook: science communication during the 2020–2021 La Soufrière, St Vincent volcanic eruption. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-289
Gueugneau, V., Charbonnier, S., Miller, V., Cole, P., Dualeh, E. and Grandin, R. 2023. Modelling pyroclastic density currents of the April 2021 La Soufrière, St Vincent eruption: from rapid invasion maps to field-constrained numerical simulations. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-290
Hay, R.I. 1959*a*. Formation of the crystal-rich glowing avalanche deposits of St. Vincent B.W.I. *Journal of Geology*, **67**, 540–562, https://doi.org/10.1086/626606
Hay, R.I. 1959*b*. Origin and weathering of late Pleistocene ash deposits on St. Vincent, B.W.I. *Journal of Geology*, **67**, 65–87, https://doi.org/10.1086/626558
Horwell, C., Damby, C.J. *et al*. 2023. Physicochemical hazard assessment of ash and dome rock from the 2021 eruption of La Soufrière, St Vincent, for the assessment of respiratory health impacts and water contamination. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2023-46
Hovey, E.O. 1902. Martinique and St. Vincent: a preliminary report upon the eruptions of 1902. *Bulletin of the American Museum of Natural History*, **16**, 333–372.
Joseph, E.P., Robertson, R., Contreras-Arratia, R. and Stewart, R. 2022*a*. *Scientific Advisories of the 2020–2021 eruption of La Soufrière volcano, St. Vincent*. SRC Open File Report **OFR 22-01**.
Joseph, E.P., Camejo-Harry, M. *et al*. 2022*b*. Responding to eruptive transitions during the 2020–2021 eruption of La Soufrière volcano, *St Vincent. Nature Communications*, **13**, https://doi.org/10.1038/s41467-022-31901-4
Lacroix, A. 1949. Sur des enclaves endopolygenes de Saint Vincent. *Bulletin de la Société française de Minéralogie et de Cristallographie*, **72**, 571–590, https://doi.org/10.3406/bulmi.1949.4686
Latchman, J. and Aspinall, W. 2023. La Soufrière volcano, St Vincent, eruption 2020–21: assessing unrest and eruptive states from limited volcano-seismic data. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-223
Lipman, P.W. and Mullineaux, D.R. (eds) 1981. *The 1980 Eruptions of Mount St. Helens, Washington*. US Geological Survey Professional Paper, **1250**.
Mani, L., Edwards, S., Joseph, E., Juman, A. and Thomas, T. 2023. Evaluating the crisis communications campaign during the 2020–21 eruption of La Soufrière, St Vincent. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-297
Martin-Kaye, P.H.A. 1969. Summary of the Geology of the Lesser Antilles. *Overseas Geology & Mineral Resources*, **10**, 172–206.
Melekhova, E., Blundy, J., Martin, R., Arculus, R. and Pichavant, M. 2017. Petrological and experimental evidence for differentiation of water-rich magmas beneath St. Kitts, Lesser Antilles. *Contributions to Mineralogy and Petrology*, **172**, 98, https://doi.org/10.1007/s00410-017-1416-3
Melekhova, E., Schlaphorst, D., Blundy, J., Kendall, J.-M., Connolly, C., McCarthy, A. and Arculus, R. 2019. Lateral variation in crustal structure along the Lesser Antilles arc from petrology of crustal xenoliths and seismic receiver functions. *Earth and Planetary Science Letters*, **516**, 12–24, https://doi.org/10.1016/j.epsl.2019.03.030
Morrison-Evans, B., Melekhova, E. and Blundy, J. 2023. Experimental insight into basaltic andesite lava dome oxidation textures at La Soufrière, St Vincent. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-298
Newhall, C.G. and Punongbayan, R.S. (eds) 1996. *Fire and mud: Eruptions and lahars of Mount Pinatubo, Philippines*. Philippine Institute of Volcanology and Seismology, Quezon City and University of Washington Press, Seattle.
Phillips, J., Barclay, J., Cole, P., Johnson, M., Miller, V. and Robertson, R. 2023. Impacts and prospective hazard analysis of rainfall-triggered lahars on St Vincent 2021–22. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-313
Pyle, D.M., Barclay, J. and Armijos, M.T. 2018. The 1902–3 eruptions of the Soufrière, St Vincent: impacts, relief and response. *Journal of Volcanology and Geothermal Research*, **356**, 183–199, https://doi.org/10.1016/j.jvolgeores.2018.03.005
Robertson, R.E.A. 2005. St. Vincent. *In*: Lindsay, J.M., Robertson, R.E.A., Shepherd, J.B. and Ali, S. (eds) *2005: Volcanic Hazard Atlas of the Lesser Antilles*. Seismic Research Unit, The University of the West Indies, Trinidad and Tobago, WI, 240–261.
Robertson, R.E.A., Samuel, A., Shepherd, J., Lynch, L. and Latchman, J. 2003. Monitoring volcanic activity at the Soufrière volcano – a model for volcano monitoring operations in small-island nations. *Proceedings of the*

Conference on Beyond Walls: Multi-Disciplinary Perspectives, 22–24 May 2003, Kingstown, St. Vincent and the Grenadines, the School of Continuing Studies, U.W.I.

Sigurdsson, H. 1981. *Geological Observations in the Crater of Soufrière Volcano, St. Vincent*. Internal Report, Seismic Research Unit, St. Augustine, Trinidad.

Sparks, R.S.J., Aspinall, W.P., Barclay, J., Renfrew, I.A., Contreras-Arratia, R. and Stewart, R. 2023. Analysis of magma flux and eruption intensity during the 2021 explosive activity at La Soufrière, St Vincent, West Indies. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-286

Stinton, A. 2023. Growth and evolution of the lava dome and coulée during the 2020–21 eruption of La Soufrière, St Vincent. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-304

Stinton, A., Sparks, R., Stephen, J. and Huppert Herbert, E. 2023. Analysis of magma rheology from lava spreading and explosive activity during the 2020–21 eruption of La Soufrière, St Vincent, with implications for eruption dynamics. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-284

Wadge, G., Robertson, R.E.A. and Voight, B. (eds) 2014. *The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010*. Geological Society, London, Memoirs, **39**, https://doi.org/10.1144/M39.0

Weber, G., Blundy, J. *et al*. 2023. Petrology of the 2020–21 effusive to explosive eruption of La Soufrière volcano, St Vincent: insights into plumbing system architecture and magma assembly mechanism. *Geological Society, London, Special Publications*, **539**, https://doi.org/10.1144/SP539-2022-177

Wilkinson, E., Lovell, E., Carby, B., Barclay, J. and Robertson, R.E.A. 2016. The dilemmas of risk-sensitive development on a small Volcanic Island. *Resources*, **5**, 21, https://doi.org/10.3390/resources5020021