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1 **Explosive sequence of La Soufrière St Vincent April 2021: insights into drivers and consequences**
2 **via eruptive products**

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14

15 **Abstract**

16 This paper forensically reconstructs the timings, impacts and processes that drove the sequence of
17 explosive eruptions of La Soufrière, St Vincent in April 2021 using a combination of field-based
18 stratigraphy and textural dissection of the deposit character together with contemporary visual
19 observations.

20 Explosive activity on 9th and early on 10th April involved destruction of almost all of the 2020/2021
21 lava dome, ~ 60% of the 1979 dome and formation of a 600 m diameter crater by 2pm UTC on 10th
22 April. Following the initial explosion, plumes rose to altitudes of ~15 km and pyroclastic density
23 currents (PDCs) formed by column collapse, first occurred on 10th April, only after > 24hrs of
24 explosive activity. Dense PDCs reached the sea only in the Larikai and Roseau Valleys, and dilute
25 PDCs were restricted to within 2.5 km of the Summit Crater rim.

26 The tephra fallout deposits are stratified, composed of numerous layers of both lapilli-rich and ash-
27 rich layers, which we have grouped into at least 7 Units, based on their common characteristics
28 (Units 1 to 7).

29 Volume estimates, using a range of techniques to constrain uncertainties, indicate that the bulk
30 volume of tephra (fallout and PDC) is $1.19 \times 10^8 \text{m}^3$ +/- 20% making this a VEI 4 eruption.

31

32

33

34 **1. Introduction**

35 The island of St Vincent lies in the southern part of the Eastern Caribbean volcanic arc, and La
36 Soufrière volcano sits at the northern end of the island (Fig 1). The volcano rises to 1204 m and 1.5
37 km diameter crater cuts the summit, hereafter referred to as the Summit Crater. It is the most
38 active terrestrial volcano in the region. Having experienced four historical explosive eruptions, in
39 1718, 1812, 1902 and 1979, and at least one solely effusive eruption in 1971 (Robertson 2005).
40 Radiocarbon dating has established that there were at least two prehistoric eruptions in the last
41 1000 years (prehistoric time is < 1700 CE in the Eastern Caribbean), one ~1580 CE, and another
42 ~1440 CE (Cole et al. 2019).

43 All the explosive eruptions at La Soufrière in the last 1000 years have generated pyroclastic density
44 currents (PDCs), however these have varied considerably in their extent. The 1902 eruption
45 generated extensive, broadly radially distributed PDCs, resulting in the deaths of ~1500 people in
46 settlements around the volcano (Anderson and Flett 1903). Also, the 1812 eruption generated PDCs
47 in several valleys, particularly to the southwest, leading to fatalities (Smith, 2011). The 1979 eruption
48 formed much smaller PDCs which, apart from in proximal regions, were confined to valleys to the
49 west and southwest, draining the lowest part of the Summit Crater rim (Shepherd et al. 1979).
50 Tephra fallout was extensive with all explosive eruptions, with at least the 1812, 1902 and 1979
51 eruptions generating ashfall in Barbados 170 km to the east (Anderson and Flett 1903, Shepherd et
52 al. 1979). The prehistoric events in 1580 and 1440 CE were apparently larger and more intense,
53 generating significant lapilli fallout deposits on the island prior to the onset of PDC activity (Cole et al
54 2019).

55

56 **The April 2021 Explosive activity**

57 Eruptive activity at La Soufrière, St Vincent restarted after a > 40 year hiatus on 27th December 2020
58 following a minimal period of precursory seismicity (Joseph et al. 2022, Thompson et al. 2022).

59 Passive extrusion of a basaltic andesite lava dome then took place for ~ 3 months in the
60 southwestern part of the Summit Crater (Stinton et al. this volume). Seismicity changed on 23 March
61 2021 with a short VT (volcano tectonic) earthquake swarm (226 events), a second more intense VT
62 swarm occurred on 5th April, (476 events) followed by banded tremor on 8th April. Explosive activity
63 started on the 9th April 2021 (Joseph et al. 2022), although this commenced with a single explosion
64 at 12:41 UTC, the rapidity with which explosions occurred (~ hourly), together with their semi-
65 continuous nature through the evening of the 9th April and for the following 48 hours made
66 immediate interpretation of the nature of these explosions difficult. Much of the northern part of
67 the island remained in darkness on 10 and 11th April, owing to the presence of extensive, semi

68 continuous ash plumes. Following this, explosions continued at a lower frequency until 22nd April
69 (Joseph et al. 2022).

70 This paper uses a combination of field-based stratigraphy of the tephra sequence, contemporary and
71 visual observations, along with more detailed analysis of the fallout and PDC deposits themselves to
72 reconstruct the changing nature of the explosions and their relative timing. We offer some
73 interpretations of the critical changes that influenced explosion style and impact. The interplay
74 between the initial overburden of the dome, the likely ingress of gassier, more buoyant magma into
75 the conduit system, and the interactions between the vent region, accumulating Summit Crater fill
76 deposits and the prevailing meteorological conditions all influenced the differing character of these
77 explosions.

78

79 **2. DEPOSIT CHARACTER**

80 **The Tephra sequence**

81 Documentation of the tephra deposits was made during three field seasons. Distal products > 4 km
82 from the Summit Crater were documented immediately following cessation of the explosive activity,
83 between 25th April and 10th May 2021. Timed tephra sampling of measured areas was made at a one
84 location on St Vincent and two on Barbados during the explosive activity on 10 - 13th April. Two
85 further field campaigns in early 2022 documented more proximal products between 4 km and the
86 Summit Crater rim. Overall the tephra deposits were investigated at more than 80 locations around
87 the island. In general, the sequence is stratified, composed of numerous layers, defined by variations
88 in the grainsize and nature of the components. The sequence reaches >70 cm in thickness 500m
89 southeast, and > 1 m ~ 800 m southwest of the Summit Crater. Several 'Units' were identified, from
90 1 to 7 from the base upwards, each Unit is composed of a number of layers with similar
91 characteristics that we were able to recognise and correlate around the volcano (Fig 2).

92 Apart from in the Larikai and Roseau valleys (on the West flank) and in the proximal regions < 2.5 km
93 from the Summit Crater rim, where PDCs occurred, deposits comprising all Units described below
94 are considered to be fallout. PDCs were generated contemporaneously with some of these Units,
95 and these products are described in a later section.

96 Below we describe the different features of the various fallout Units. Key observations are
97 summarised in Table 1.

98

100 Unit 1 (U1)

101 The lowermost unit, U1, is a moderate grainsize lapilli deposit with a maximum thickness of 20 cm,
102 350 m southeast of the Summit Crater rim (Fig 2 and 3). At many localities it shows reverse grading,
103 defined by the lowermost third of the unit being slightly finer grained than the upper part. This is
104 particularly evident on the eastern side of the volcano, where the Unit is preferentially dispersed. . A
105 crude stratification, defined by small variations in grainsize of the lapilli was present, such that at
106 least three sub-units could be identified (Fig 3 and 3a). Local horizons of hydrothermally altered
107 fragments (up to ~20 wt%), are found close to the change in grainsize between the lower (finer-
108 grained) and the upper (slightly coarser) parts of the unit. The contact with the overlying Unit 2 is
109 typically defined by a fine grained laminated brown ash, a few mm thick, possibly representing a
110 pause in deposition between Units.

111

112 Unit 2 (U2)

113 This Unit is a notably ash-rich, stratified deposit that reaches a maximum of 22 cm thick, 800 m east
114 of the Summit Crater rim. The stratification is defined by the presence of numerous thin lapilli
115 layers. In distal regions these were sometimes only a few mm thick (Fig 2 and 3). U2 shows a distinct
116 colour change from brown (lower part) to grey (upper part).

117 Although generally ash-rich, at proximal locations the brown lower part of U2 is finer grained,
118 whereas the upper part contains more abundant and coarser lapilli layers that are notably coarser
119 than those lower in this Unit (Fig 2 and 3a). At distal locations > 4 km from the Summit Crater, these
120 layers are typically horizons of lapilli only a clast thick, typically < 1 cm in diameter, however, notably
121 larger lapilli of clasts 1 - 3 cm in size, both of pale vesicular scoria and dense lithologies are locally
122 observed throughout the Unit. Up to seven individual layers were identified within the Unit, which
123 are particularly well-defined at upwind locations (Fig 2 and 3b).

124

125 Unit 3 (U3)

126 This Unit is a distinctive coarse-grained, double lapilli layer couplet (L1 and L2) up to 32 cm thick, 200
127 m from the south-eastern Summit Crater rim, although in localities > 4 km it is typically ~2 cm thick.
128 It forms a key marker horizon within the tephra sequence around much of the island (Fig 2 and 3).

129 In proximal areas, < 1km from the Summit Crater rim, the two lapilli layers are quite distinct (Fig 2
130 and 3c). The lowermost lapilli (L1), was up to 12 cm thick and typically contained a thin fine ash
131 layer up to 1 cm thick, in the upper two thirds of the lapilli. Crude reverse grading is evident across
132 the whole layer. The uppermost lapilli (L2) is a normally graded lapilli layer up to 8 cm thick. An ash
133 layer, up to 7 cm thick, rich in accretionary lapilli separates the two lapilli layers, however in distal
134 regions (> 4 km from the Summit Crater) this ash layer is typically < 0.5 cm thick.

135 This Unit forms one of the coarsest lapilli layers of the sequence with outsized lapilli up to 5 cm in
136 diameter in distal regions that sometimes protruded through the overlying Unit 4 and into Unit 5.
137 (Fig 2 and 3)

138

139 **Unit 4 (U4)**

140 This Unit is a single ash layer up to 12 cm thick in the most proximal locations. At more distal
141 localities > 4 km from the Summit Crater rim this Unit is just a few mm thick. Small aggregates,
142 including accretionary lapilli, up to 8 mm diameter are abundant in this unit (Figs 2 and 3d).
143 Scattered coarser lapilli of both pale scoria and dense lithologies, < 5 mm diameter are also present
144 in this Unit.

145

146 **Unit 5 (U5)**

147 The uppermost distinctive lapilli layer of the tephra sequence, this unit formed the surface carapace
148 lapilli on the eastern (windward) side of the volcano. It is a maximum of 5 cm thick in proximal
149 locations to the southeast, although thicknesses were difficult to estimate on the Eastern flank
150 owing to it being the uppermost, uneven lapilli on the tephra deposit surface. Vesicular scoria lapilli
151 and blocks are typical however, dense glassy non-vesicular clasts are also notable, giving the coarse
152 lapilli an apparently bimodal vesicularity. In the southwestern region U5 is up to 2 cm thick and was
153 overlain by the fine ash of Unit 6 (Fig 2 and 3)

154

155 **Unit 6 (U6)**

156 This unit is found solely on the south-western side (Leeward side) of the volcano and is formed by a
157 number of ash layers. Collectively these form thicknesses of up to 20 cm, 2 km to the southwest of
158 the Summit Crater, but individually these are up to 10 cm thick (Fig 1 and 2). These ash layers are

159 notably fine grained and rich in accretionary lapilli. Individual accretionary lapilli are typically < 1 cm
160 in size.

161 It is evident that some of the thickest and most abundant of these ash layers is close to the Roseau
162 valley and upper Wallibou valleys down which PDCs travelled.

163

164 **Unit 7 (U7)**

165 Similar to U6, this Unit is found only in a few localities on the south-western side of the volcano,
166 such as around the Dry Wallibou valley. It is formed by 3 or 4 thin, relatively fine-grained lapilli layers
167 that are collectively up to 4 cm thick. Individual layers are 0.5-1.5 cm in thickness (Fig 2).

168

169 **Pyroclastic Density currents**

170 Pyroclastic density currents (PDCs) were associated with the explosive activity and entered several
171 valleys draining the Summit Crater. They reached the sea in the Larikai and the Roseau valleys on the
172 western and south-western flank of the volcano only (Fig 4a).

173 PDCs also extended down several of the valleys leading from the southern part of the Summit Crater
174 rim and into the upper Wallibou valley, reaching as far as Trinity falls / Wallibou hot springs,
175 approximately 2.5 km from the Summit Crater rim. PDCs also extended short distances
176 (approximately 1 km) down valleys to the southeast, effectively the head of the Rabacca valley.

177 In proximal regions on ridges and valley sides, up to 2.5 km from the Summit Crater rim, vegetation
178 was removed and trees were extensively felled in directions typically away from the crater (Fig 4a, 5a
179 and b). . Thus, we infer that dilute, low particle concentration PDCs were responsible for this
180 destruction and have used the presence of felled trees to map their extent (Fig 4a). Dissected
181 deposits of the valley-filling PDCs in the Roseau and Larikai valleys, and in proximal areas on the
182 south-eastern flank were documented (Fig 4 b-e).

183

184 **Larikai and Roseau valley PDC deposits**

185 At the mouth of the Larikai Valley PDCs form a fan of deposits, 300 m wide and up to 20 m metres
186 thick (See Fig 4b). Wood contained within the deposits is carbonised and local gas escape structures
187 confirm a primary PDC origin for these deposits. A series of at least six massive PDC units form the
188 Larikai fan. The lowermost unit contains regions locally enriched in coarse clasts, composed of

189 moderately vesicular and dense glassy blocks of lava up to 3 m in diameter. Dissection of these
190 deposits show these concentrations define convex lobate surfaces within the units. The lowermost
191 deposits form a series of four units, without ashfall layers between them. Overlying this, three
192 massive PDC units, interbedded with an accretionary lapilli-rich fallout layer up to 11 cm thick and a
193 series of stratified accretionary lapilli bearing layers, collectively up to 90 cm thick (Fig 4b). A
194 massive poorly sorted layer ~ 1 m thick, overlies the accretionary lapilli-rich fallout layer, and a
195 stratified sequence of accretionary lapilli bearing layers collectively up to 90 cm thick occurs higher
196 in the sequence ('S' on Fig 4b). When traced laterally these layers show notable lateral thickness
197 variations and collectively this sequence forms large wavelength dune-bedforms. These are
198 therefore considered to represent alternating thin PDC and fallout layers. A massive unit, up to 2 m
199 thick, caps the sequence. Approximately 1 km up the valley the total thickness of PDC deposits
200 reach thicknesses of up to 30 m.

201

202 Similar to the Larikai valley, dissection of deposits reveals that the Roseau valley contained several
203 massive flow units (Fig 4c). Up to four separate units, ranging from 2 to 8 m thick individually, are
204 present reaching a maximum of 20 m in thickness, although more typically around 12 m. All these
205 units contain both cauliflower vesicular and dense glassy scoria clasts up to ~50 cm in diameter. A thin
206 15 cm thick accretionary lapilli bearing ash fall layer is interbedded between the flow units ('A' on Fig
207 4c) which we correlate with the Unit 6 of the tephra fallout.

208 Tree branches, trunks and other vegetation contained within these deposits was generally fully
209 carbonised, although locally some wood debris had remained uncharred.

210

211 **Upper Southeastern flank deposits**

212 On the proximal south-eastern flanks of the volcano in the region near Jacobs Well (~0.5 - 1 km from
213 the Summit Crater rim) a series of massive, poorly sorted, valley-filling deposits up to at least 6 m
214 thick, are observed partially filling valley depressions. Critically these massive deposits are
215 interbedded between several tephra fallout layers, identified as Units 3, 4 and 5 (See Fig 4d). Fallout
216 of Units 1 and 2 are present at the base of the sequence below the PDC deposits.

217 Vegetation and wood fragments incorporated within these massive valley-filling deposits were
218 abraded and debarked but generally not carbonised. Nevertheless, these deposits are considered to
219 be primary PDC deposits.

220

221 **Dilute PDC deposits**

222 Deposits formed by the dilute PDCs that caused extensive tree felling above the valley thalwegs (on
223 slopes and ridges) were notably variable. Within 1 km of the southeast of the Summit Crater rim
224 deposits were, < 15 cm thick, composed of fine lapilli, and typically poor in fine ash. These were
225 identified below the U5 lapilli layer and these deposits were relatively continuous, but showed some
226 minor local lateral thickness variations.

227 To the southwest of the Summit Crater rim the deposits on ridges were thicker and more extensive.
228 A series of deposits interbedded with U3, 4 and 5 are individually 10 – 25 cm thick and up to 40 cm
229 thick < 1 km from the Summit Crater rim and show extensive thin < 5 cm thick lenses of ash poor,
230 fine grained lapilli within more ash rich deposits (Fig 5c). Other units are formed by variable
231 thickness ash poor, well-sorted fine lapilli layers. Locally these deposits show crude dune bedforms
232 and cross stratification with marked thickness variations.

233 The numerous trees felled by these dilute PDCs show strong abrasion, typically only on the volcano
234 facing sides. Locally trees with trunks > 50 cm in diameter often remained standing (Fig 5 a and b).
235 Many trees were bent over or snapped at heights of 2-3 m above the base (Fig 5a). Carbonisation of
236 vegetation inundated by passage of these dilute PDCs was absent, although tree fern trunks
237 exhibited a slight blackening of their exterior. Similar lack of carbonisation of trees impacted by PDCs
238 has been reported associated with the 18th May 1980 Mt St Helens blast PDC (Moore and Sission
239 1981), the 2008 eruption of Chaiten (Swanson et al 2013, Major et al 2013) Chile, and at Kelud in
240 Java related to the 2014 eruption (Maeno et al 2019). At Mt St Helens and Chaiten temperatures for
241 uncharred trees were inferred to result from shortlived PDCs < 200°C.

242

243 **3. CHANGING DEPOSIT CHARACTERISTICS**

244 **Grainsize analyses**

245 Particle size analyses were undertaken on ~ 60 samples in order to characterize the grainsize of
246 tephra and its variation through the explosion sequence. Mass fractions were acquired through
247 manual sieving all of clasts down 125 µm, and then using a Retsch Particle Size and Shape Analyzer
248 CAMSIZER X2 for a sub-sample of all material < 125 µm. We focussed on obtaining samples of the
249 different Units through tephra sequences at a range of locations (Fig 6).

250 Cumulative grainsize distributions show a clear transition between U1 and 2, with U1 fallout
251 deposits being notably fines-poor and U2 deposits showing a distinctly more ash-rich character (Fig 6
252 a). Unit 3 deposits (green lines on Fig 6a) have a varied grainsize, generated either by coarser lapilli
253 or fine ash layers. U5 plots on the coarse side of lapilli.

254 The field-based subdivision of deposits into either lapilli or ash hold true in the cumulative grainsize
255 distributions plots (Fig 6b) albeit with some overlap. Similarly, deposits identified as dilute PDCs
256 (yellow lines on Fig 6 b) are better sorted and poorer in fine ash than other deposits.

257

258 Grainsize data through the tephra sequence show a slight coarsening upwards vertically through U1,
259 (Sandy Bay school Md and d) - Fig 6 c) reflecting the visible reverse grading, with continued
260 coarsening through U2. Lapilli layers of U3 or U5 form the coarsest fallout deposits of the sequence.
261 This is corroborated by maximum clast size data (five largest clasts of both vesicular scoria and dense
262 clasts, Figure 6c and d) . There is a general increase in maximum clast size through the sequence,
263 with the coarsest clasts (particularly scoria) occurring either in U3 or U5.

264 Ash aggregates, including accretionary lapilli, were abundant from U3 onwards. Accretionary lapilli
265 were particularly abundant on the leeward (west) side of the volcano. The presence of accretionary
266 lapilli has impacted the grainsize distribution of deposits (Fig 6 c), and is particularly notable in ash-
267 rich deposits on the Leeward trail where peaks at 1 phi fraction in U4 and U6 arise from ash
268 aggregation (Fig 6c).

269

270 **Component Analyses**

271 The 2021 tephra deposits contain a wide range of components which we initially classified in the
272 field as pale scoria (40-60% vesicles), semi vesicular (denser) scoria (20-40% vesicles), dense
273 (sometimes glassy) clasts (<20% vesicles), hydrothermally altered fragments and free crystals. This
274 classification was also used to broadly classify sampled fragments >1mm using the binocular
275 microscope (Fig 7a-d).

276 Pale grey vesicular scoria, representing the juvenile magma, occurs in all units of the tephra
277 sequence in varying quantities. The lowermost parts of U1 contain only 10% pale scoria (>1mm) but
278 this increases to ~ 40 wt% of clasts in the upper part of U1. Within U2 this remains at ~ 40 wt% and
279 in U3, lapilli layers contain up to 60 wt % pale vesicular scoria.

280 Dark coloured, semi- vesicular and dense clasts, (Fig 7 b and c) are most abundant in U1, forming up
281 to 40 and 56 wt % of components > 1mm respectively. Dense clasts were present in all units forming
282 a significant proportion (up to 40%) of U3 and U5. Hydrothermally altered clasts occurred mainly
283 within U1 (Fig 7d). Some horizons of U1 contained up to 20 wt % hydrothermally altered fragments.

284 We also determined the density of sampled vesicular clasts (both pale and denser scoria) in the 16-
285 32 mm range using the Archimedes principle to calculate the bulk density of these clasts (Fig 8).
286 These demonstrate that there are significant variations in both mode and range of vesicularities
287 between the Units. Clasts distinguished in the field or by binocular microscope form a continuum but
288 generally samples classified as denser scoria have vesicularities < 30%. U1 contains a broad range of
289 vesicularities with a mode at 25-30% vesicles. The vesicularity increases markedly to 40-45% in U2
290 and 45-50% vesicles in U3 and U5, which have similar vesicularity ranges.

291 Vesicle textures were further interrogated via quantitative analysis of BSE images for scoriaceous
292 and semi vesicular clasts from U1, U2 and U5, and compared qualitatively with images of two clasts
293 (semi-vesicular and scoriaceous) from U3. BSE images were acquired on a Zeiss Gemini 300 SEM at
294 the University of East Anglia, a nested imaging strategy was applied after Shea et al., (2010) to
295 capture the full range of vesicle sizes (see appendix for image locations and sizes). Key
296 measurements including minimum pixel size are shown in Table 2. Vesicle shape and size was
297 quantified using *Circularity* and *Roundness* parameters as defined by Liu *et al.*, (2015, the aspect
298 ratio of the best fit ellipse and vesicle area (plotted in Fig 9 a - f). These parameters highlight key
299 differences between U1/U2 and U5 and agree with qualitative observations of BSE images. Density
300 plots (the representation of the relative occurrence of measurements) of vesicle area against aspect
301 ratio (Fig. 9a – c) show that U1 and U2 have two modes in their vesicle area populations and extend
302 to (a) smaller areas and (b) higher aspect ratios than U5, though most vesicles across all units are
303 relatively unsheared. Density plots of *Roundness* vs *Circularity* (Fig 9d – f) show more subtle
304 differences between the bubble populations. In U5, *Circularity* and *Roundness* plot much closer to
305 each other than U1 and U2. This indicates that for the U5 clasts analyses surface roughness exerts
306 less of a control on bubble shape than elongation, in contrast to U1 and U2 where the increased role
307 for surface roughness is consistent with a higher pre-existing proportion of microlites on
308 vesiculation. BSE images of bubble textures in U1, U2 and U5 are shown below shape plots (Fig.9 g –
309 i). Images from a semi-vesicular (Fig.9j) and a vesicular (Fig. 9.k) clast from U3 show vesicle textures
310 intermediate between U2 and U5, with the scoriaceous clast closer to U5 and the semi-vesicular
311 clast more closely resembling U2. A similar pattern is seen in the microlite populations of the
312 analysed clasts (Frey *et al.*, this volume). Bubble number densities (BNDs) (corrected to remove
313 phenocryst phases) in 2D were calculated using the analysed images, the BND of U5 is approximately

314 half that of U1 and U2, despite having the highest vesicularity (39% in 2D). This confirms the
315 qualitative observation that U5 has a notably larger vesicle population than either U1 or U2, but a
316 more detailed analysis is provided in Christopher et al., (this volume).

317

318 **Volume of the explosive phase**

319 In order to estimate the volume of the products of the explosive activity three different components
320 were considered: a) tephra fallout deposits from isopach maps b) PDC deposits in valleys outside the
321 Summit Crater and c) the intracrater fill.

322

323 **Tephra fallout volume estimation from isopachs**

324 Because there was no thickness data offshore, automated contouring over the ocean cannot be
325 constrained to obtain closed or even partial isopach coverage. Instead, five of us ('experts') drew
326 isopach maps for the different Units, based on the same field data available on land, but extending
327 contours offshore with each expert providing their own best estimate, judged according to their
328 view of the field data. In most cases, they also plotted corresponding upper and lower credible
329 bound contours to express their assessment of appropriate uncertainties associated with the
330 contouring, given the limited data. With this methodology, the best estimate and lower and upper
331 contours for each Unit are taken to approximate each expert's statistical median, 5th and 95th
332 percentile contour areas, thus allowing elementary uncertainty distributions to be quantified from
333 each expert's judgments. (Examples of Expert 1 isopachs are shown in Figure 10).

334

335 Volumes were calculated for each experts' trio of isopach maps using the Ashcalc tool (Daggitt et al
336 2014) using the three different numerical models: Exponential (Pyle 1989), Power law (Bonadonna
337 and Houghton 2005) and Weibull (Bonadonna and Costa 2011). We averaged the volumes
338 determined by these three different models, with the results corresponding to the five different
339 experts presented in Table 3. Here we note that Figure 10 shows the central "best case" contour
340 drawn by Expert 1. Thus, the volumes indicated for Expert 1 generally fall within the range of
341 volumes from the other experts (see Table 3) and therefore are broadly representative when
342 compared to the other, independently drawn alternatives.

343

344 Pooling these different judgements and uncertainties to create joint volumes was treated as an
345 expert elicitation problem. For this purpose, the Classical Model (Cooke, 1991) combinational
346 algorithm was adopted to aggregate deposit volumes determined from the experts' maps and their
347 uncertainties. These joint estimates were derived via the Classical Model pooling algorithm by
348 equally weighting results obtained from individual experts' maps. On this basis, piece-wise linear
349 distributions were computed at median and 5th and 95th percentiles for the volume of each Unit.
350

351 These combinations capture the experts' uncertainty spreads jointly, thereby synthesising the
352 deposit volume estimates into those of a single "proxy expert", representative of the group as a
353 whole (n.b., the details of each deposit volume joint uncertainty distribution usually differs from
354 those indicated by isopachs drawn by any individual expert).
355

356 Next, the piece-wise linear, equal weights Unit deposit volume uncertainty distributions -- obtained
357 from the isopach maps as described above -- are stochastically sampled using the UNINET* Bayes
358 Net software package. Summing these stochastic samplings of the deposit volume uncertainty
359 distributions, collectively, allows an overall estimate of the total volume in all the Units to be
360 determined from the different isopachs mapped by individual experts (Mean volumes of Units 1-3
361 range from 7.9 -24.2 x 10⁶ m³), with related uncertainties taken into account formally (see Table 4
362 for details). This uncertainty-based approach represents a more informative way of gauging
363 quantitatively the eruption volumes derived from statistical methods. Reporting the eruption
364 volumes with an uncertainty interval is preferred to using just 'best estimate' deposit volumes on
365 their own as it can provide a clearer view of our understanding of the deposit (e.g., Constantinescu
366 et al., 2022).
367

367

368 **Volume of Pyroclastic density currents**

369 The volume of pyroclastic density currents was estimated using the typical maximum thickness
370 measured of the deposits in the different valleys. Thicknesses of PDCs in the Upper Wallibou valleys
371 were not measured directly, therefore we assumed a thickness similar to the other nearby valleys of
372 10 m. We assumed box canyon type cross sections as this is the typical present day morphology of
373 these valleys. We obtain ~ 17 x 10⁶ m³ for the volume of the PDC deposits in the valleys outside the
374 crater and acknowledge the considerable uncertainty in this estimate.

375

376 **Intracrater tephra volume**

377 Estimation of the volume of tephra inside the Summit Crater (see Table 5) was made by differencing
378 of a post eruption Digital elevation model (DEM) made by photogrammetry in June 2021 with a pre-
379 eruption DEM (Pleiades DEM). Almost complete destruction of the 2021 lava dome by the explosive
380 activity means the absence of the 2021 lava dome from the pre-eruption topography does not
381 significantly affect this calculation. This DEM differencing yields a volume of $43 \times 10^6 \text{ m}^3$
382 (uncertainties on this are $\sim \pm 20\%$, so $\pm \sim 10 \times 10^6 \text{ m}^3$).

383

384 The bulk total (non-DRE) volume of tephra is $\sim 119 \times 10^6 \text{ m}^3$ (Table 5). Lava domes form a significant
385 contribution to the tephra deposits, we assume the 2021 lava dome had a volume of $\sim 20 \times 10^6 \text{ m}^3$
386 prior to the explosions and around 60% of the 1979 dome ($\sim 28 \times 10^6 \text{ m}^3$) was destroyed during the
387 explosions. Thus, the fragmented lava domes form $\sim 40\%$ of the bulk volume of the tephra.

388 Therefore, $71 \times 10^6 \text{ m}^3$ of the volume might be new magma-, which converts to $42 \times 10^6 \text{ m}^3$ DRE using
389 a 0.6 conversion based on measured tephra densities of 1500 kgm^{-3} . Here we note that the question
390 of what constitutes “new magma” is not so straightforward as this eruption excavated and
391 incorporated the 2020-2021 lava dome as well as incorporating new magma (see discussion below).

392

393 **Comparison with other volume estimates**

394 Our volume estimates are consistent with two other independent estimates using different kinds of
395 data. Sparks et al. (this volume) used RSAM data and estimates of column heights from satellite data
396 to estimate erupted volumes in each explosive event. Magma supply rates and magma volumes can
397 then be inferred from these data. Their total DRE volume estimate is $37.8 \times 10^6 \text{ m}^3$ (90% credible
398 interval: $[33.5 \dots 42.5] \times 10^6 \text{ m}^3$) which is very similar to the DRE derived from the isopach maps of the
399 tephra deposits (DRE $35.5 \times 10^6 \text{ m}^3$) using a bulk volume of $59.1 \times 10^6 \text{ m}^3$ (Table 4). This apparently
400 close agreement is somewhat misleading because there are uncertainties relating to proportions of
401 non-juvenile clasts in the tephra deposits and excluding the very proximal deposits in the Summit
402 Crater from the isopach volumes and the difficulty in estimating their contribution of heat to the
403 plumes. These uncertainties would push volume estimates in the opposite directions, however, so to
404 some extent cancel one another out. Camejo-Harry et al. (this volume) using ground deformation
405 data estimate a volume change of $50 \times 10^6 \text{ m}^3$ in the first three days of the explosive phase of the
406 eruption and attribute this corresponds to volume (DRE) of erupted magma.

407

408

409 **4. RECONSTRUCTING THE TIMING OF THE UNITS AND THEIR ASSOCIATION WITH EXPLOSIONS**

410 We use multiple strands of evidence to infer the timings of the Units within the explosive cycle, and
411 hence the likely number of explosions or explosive pulses each unit represents. In turn, these timings
412 can help us to reconstruct the impacts and important drivers of the changing explosive sequence.
413 The evidence for these timings is given below and is also summarised in Table 6. We also show the
414 timing of these Units graphically, overlain on real-time seismic amplitude measurement (RSAM) in
415 Figure 11.

416 Re-processed GOES-16 satellite imagery that combines the IR (infrared) anomaly with ash detected
417 in visible light ('ABI RadF ash') was used to determine the timing and distribution pattern of the
418 explosive activity, where distinct individual explosions and matched the associated tephra. These
419 timings correspond broadly with the seismic energy associated with each explosive pulse (expressed
420 via RSAM, Sparks et al., this volume). Observers based on St Vincent, particularly from later on 9th
421 April until the morning of the 11th of April, noted that individual explosive events or plumes were
422 difficult to distinguish even during daylight hours. We have triangulated the remote sensing
423 observations with descriptions from local observers, shared during discussion (from our first field
424 season) or at the time of the eruption via social media, along with our field data.

425

426 **U1**

427 The initial explosion of the eruption occurred at 12:41 UTC, on 9th April and was followed by a
428 second, smaller explosion at 18:59 UTC. Photographic documentation (Fig 12a) and satellite
429 imagery shows that from this point onwards through the night of the 9 /10th April a near continuous
430 pulsatory plume occurred that dispersed tephra towards the ENE. The RSAM (Real Time Seismic
431 Amplitude Measurement) shows continuous seismicity, although a number of distinct peaks can be
432 identified (Fig 11). To be consistent with other papers in this volume and the contemporary seismic
433 analysis (Sparks et al., this volume) we have assigned three events to this period, with a further two
434 more distinct explosions towards the end of the U1 sequence.

435 The continuous pulsatory nature of the explosive activity from 18:59 UTC on 9th April until 04:30 on
436 10th April is consistent with the deposit character of U1, where deposits are crudely stratified, even
437 at relatively proximal locations. The increase in grain-size upwards (See grainsize section for more
438 details) through U1 is associated with the latter explosions forming from higher plumes. Eyewitness

439 accounts from Windward residents on or close to the ENE dispersal axis describe pulse-like venting
440 and continuous noise consistent with the fallout of lapilli-sized tephra on 9th overnight into 10th April.
441 An isopach map shows that U1 had a north-easterly dispersal (Fig 10a). No fallout was reported in
442 Barbados on 9th April, indicating that the plume dispersed to the north of the island supporting this
443 north-easterly dispersal. The presence of ash on the ground at Calliaqua (south coast) at dawn on
444 10th April suggests that larger U1 explosions with more widespread tephra plumes began in the early
445 hours of 10th April.

446

447 Radar imagery (Capella Space) at 14:03 UTC on 10th April showed the presence of a crater 600m in
448 diameter inside the southwestern portion of the old Summit Crater, with almost all of the 2021
449 dome and ~ 60% of the 1979 dome destroyed by formation of this crater. Hereafter we refer to this
450 as the 2021 Crater.

451

452 **U2**

453 The tephra plumes generated from 09:35 UTC onwards on 10th April began to form larger more
454 axisymmetric ABI RadF ash footprint, suggesting near island-wide dispersal, and closely spaced
455 explosive pulses, (interval \leq 70 minutes) with a dispersal axis to the WSW. Photographic
456 documentation also shows a particularly large asymmetrically spreading plume at 09:59 UTC (Fig
457 12b). Given the timing and geometry of this explosion plume we infer that this represents the start
458 of explosive activity responsible for U2 tephra. An isopach map for this unit shows island wide ashfall
459 occurred being dispersed generally to the WSW (Fig 10b).

460

461 **U3**

462 Observers in the Leeward areas all describe an intensification of activity during the late afternoon of
463 the 10th of April – ‘an early night’ at Spring village (Leeward) where significant ashfall was reported
464 between evening of 10th and 11th April (with intense lightning).

465 If we assume the seven layers in U2 correspond with discrete explosive events – the seventh
466 explosion in the U2 sequence occurred at 16:20 UTC on 10th April implying that the explosion at
467 16:30 local time (18:30 UTC) would have been the first of the U3 tephra. However, local

468 observations are insufficiently distinct to distinguish between these two times. RSAM data suggest
469 that the explosion at 18:30 UTC generated a more unusual RSAM peak with longer more diffuse
470 energy and higher frequency (Fig 11) that could be PDC formation, which is associated with this
471 phase. This later explosion is more likely to draw comments about an 'early night' and is associated
472 with fallout in SE of the island. Thus, we suggest that the first part of the U3 sequence and the onset
473 of PDC is associated with the 18:30 UTC explosion. The Isopach map shows a broadly axisymmetric
474 dispersal for this unit on island with preferential dispersal to the east (Fig 10c).

475 We have ascribed three explosions to this Unit, and the third associated with the ash of U4.
476 Atmospheric conditions at this time were wet which may explain the generation of the accretionary
477 lapilli bearing, ash-rich deposit formed.

478

479 **U5**

480 We have assigned four of the explosions to U5, although there is considerable uncertainty about
481 this. An increase in RSAM associated with the explosion-that-cut-the-power overnight (See Fig
482 1104:59 UTC 11th April), is consistent with an eruption that would have the intensity to generate
483 some of the larger scoria, and we suggest that this represents some of the activity that formed the
484 U5 unit.

485 **U6**

486 By early morning on the 11th of April most observers on the Windward (eastern side of the volcano
487 were reporting a clearing atmosphere and very little further ash fell. Thus, we are confident that this
488 is the time when it is most likely that the accretionary lapilli bearing ash layers of U6, which are
489 abundant on the Western side of the volcano was formed from a sequence of explosions. U6
490 accretionary lapilli bearing ash layers are interbedded with PDC deposits in the Larikai and Roseau
491 valleys, indicating that PDCs continued be formed in those valleys, associated with these explosions
492 from 10: 36 UTC on 11th April.

493 The presence of accretionary lapilli is testament to available moisture in the plumes that formed
494 these units. As they the accretionary lapilli –rich ash layers of this Unit are mainly seen in deposits
495 on the south-west side of the volcano (Fig 10b) one possibility is that the ash layers associated with
496 this Unit were formed as a result of PDCs entering the sea in the Larikai and Roseau valleys.

497

498

499 **U7**

500 Following the 11 April activity, explosions had a lower inferred column height (and a lengthening
501 repose between explosion interval) consistent with the deposits of U7 chiefly being observed on the
502 Leeward side of the island (Fig 3) with the greater part of the ash column being transported by the
503 Tropospheric trade winds.

504

505 **Timing and duration of PDCs**

506 Field evidence indicates that the first PDCs to travel out of the Summit Crater were associated with
507 U3 explosions. Satellite imagery and eyewitness observations indicates that U3 commenced before
508 the end of 10th April, perhaps in the later afternoon/ early evening (see table 6 and Fig 11). Partially
509 carbonised trees washed up at Chateaubelair at midday on 11th April also support the occurrence of
510 PDCs earlier that day or on the evening of the 10th April. Evidence also indicates that U5 activity
511 began in the early hours of 11th April and PDCs in the proximal SE flank were clearly associated with
512 these explosions. Radar imagery (Disaster charter imagery) acquired on 11th April 19:56 showed that
513 PDCs had entered several valleys to the south and south-west before that time.

514 Two lines of field evidence clearly demonstrate that PDCs were associated with several discrete
515 explosions, possibly over a number of days: ash fallout layers are interbedded between some PDC
516 flow units in both the Larikai and Roseau valleys; and secondly fallout layers U3, U4 and U5 are
517 interbedded between PDC flow units in the proximal south-eastern area. Although evidence
518 indicates that PDCs continued to be formed associated with U6 and U7 and were probably
519 concentrated in the Larikai and Roseau valleys.

520

521 **5. DISCUSSION**

522 The initial explosive activity between 12:36 UTC on 9th April and 9:35 UTC on 10th April resulted in
523 the destruction of the 2021 lava coulee and ~60% of the 1979 lava dome, and formation of the 600
524 m wide 2021 crater that was observed in radar imagery at 14:03 UTC on 10th April. This activity
525 formed the U1 lapilli deposit that is ash poor and rich in hydrothermally-altered, semi-vesicular and
526 non-vesicular material. It is likely that some of these dense fragments have been sourced from
527 these pre-existing lavas. Crude layering and reverse grading present in U1 together with an increase

528 in grain size and abundance of vesicular scoria, testifies to the pulsatory nature and increasing
529 intensity and our grain type analysis to an increasing proportion of primary vesiculating magma.
530 These observations are consistent with the early stages of explosive eruptions in which near surface
531 overpressures are high, resulting in excavation of a 2021 crater and conduit system (Sparks et al.
532 2006).

533 After the initial explosive phase that formed U1 deposits and the 2021 crater, there was a pause in
534 explosive activity for more than four hours during which a swarm of VT earthquakes occurred, with
535 some evidence that these became deeper with time (Contreras-Arratia pers comm). These coincided
536 with rapid deflation inferred from surface deformation data (Camejo-Harry et al., this volume) and a
537 pulse of SO₂ associated with the initial plume (Esse et al., this volume). We propose that these VTs
538 were associated with the rapid ascent of a new pulse of gas-rich magma that resulted in the
539 character of the deposits associated with Units 2 – 5.

540 Furthermore, our analysis of bubble density and shape (Fig 9) suggests that vesiculation processes
541 were inhibited by the microlite-rich character of the magma at that time, as well as the work to be
542 done excavating the 2021 crater and removing the overlying lava. We interpret the sequence of
543 tephra deposits in terms of a model developed for kimberlite explosive volcanism (Sparks et al.
544 2006) but which is more generally applicable. In this model explosions in an initial overpressured
545 regime excavate a crater and conduit followed by a pressure-adjusted regime which includes infilling
546 of the crater-conduit systems with tephra and clastic materials derived from further instability of the
547 2021 crater and conduit walls.

548 Juvenile magma from U1 shows a notably lower vesicularity than that in U2 (Fig 8 and Table 2).
549 Microtextural studies (Frey et al, this volume) show that U1 juvenile material was distinctly richer in
550 microlites, and contained different phases, than later Units. The U1 magma was likely from a
551 different source to those of later Units. Texturally it is the most distinctive of our erupted magmas,
552 the groundmass is dominated by crystals with a short axis < 5 µm and aspect ratios greater than 1 :
553 3, median vesicle area is the smallest (109 µm²) and it has the lowest BND (167 bubbles/mm²).

554 Activity from 9:30 to 18:50 UTC on 10th April was characterised by closely spaced explosions (<1 – 2
555 hrs apart) and is correlated with the ash-rich U2 deposits. We attribute the change to the influence
556 of an established crater-conduit system in which material falling back into the conduit interacts with
557 erupting magma. The 2021 crater with a tephra rim of up to 40 m thick had formed early part of U2
558 activity. We envisage instability of the unconsolidated tephra rim and crater-conduit walls together

559 with fall back of tephra into the 2021 crater and conduit led to generation of ash through
560 fragmentation of these recycled materials.

561 Field evidence strongly indicates that onset of the first significant PDC activity was associated with
562 U3 activity from 21:30 UTC on 10th April. Proximal tephra sequences show no evidence of PDCs until
563 after deposition of ash-rich U2 tephra fallout. Distinctive U3 lapilli fallout interbedded with PDCs
564 testifies to the onset of PDCs at this time. In addition, particularly large axisymmetric explosion
565 derived plumes causing early darkness in the afternoon of 10th April is coincident with vigorous
566 explosions of U3. We suggest that processes, such as conduit widening (or perhaps when the
567 excavation of looser tephra was more complete) are likely causes of this transition to PDC activity,
568 this seems likely as > 24 hours of semi continuous explosive activity had already occurred. As U3
569 fallout deposits are some of the coarsest, most vesicular of the sequence, we can rule out a
570 decreasing gas content of the magma playing an important role in the switch to collapsing columns.

571 The U3 activity also marks the onset of the appearance of aggregates and accretionary lapilli within
572 the tephra fall deposits. Accretionary lapilli and ash aggregation only need moisture-rich plumes to
573 form. There are several sources of moisture which could have promoted ash aggregation. First,
574 moisture-rich weather systems generating rainfall on the island associated with the explosive activity
575 occurred from 11th April. Another origin for the moisture is from PDCs entering the sea. During the
576 1995-2010 activity at Soufriere Hills, Montserrat accretionary lapilli were formed at numerous times
577 from PDCs entering the sea and generating fallout layers rich in these ash aggregates (Burns et al.
578 2017). Finally, it is possible that ground waters ingressed into the conduit but there is no evidence of
579 hydrovolcanism so we think this is a less likely mechanism. We therefore consider that these
580 accretionary lapilli were formed where either tephra plumes interacted with moisture-rich weather
581 systems or where moisture-rich plumes were formed by PDCs that entered the sea.

582 Accretionary lapilli are abundant in numerous ash layers within the upper part of the sequence.
583 Some of these ash layers are likely formed from elutriation of ash from PDCs, and the abundance of
584 ash layers in sequences on the southwestern flank supports a co-PDC origin. The ash layer that
585 occurs between the two coarse lapilli layers of U3 and the U4 ash layer are both likely to have been
586 co-PDC ash fallout layers, occasional coarse clasts embedded within the U4 ash probably relate to
587 continued minor explosive activity during settling of these ash layers.

588 The implications from the distribution and size of the scoria associated with the U5 explosions are
589 that these were some of the largest and strongest plumes during the course of eruption. This
590 requires some explanation as at this time the explosions had been ongoing for around 40 hours, and

591 are close to the point at which Sparks et al., (this volume) have identified a waning stage for the
592 eruption based on seismic energy and plume height. These scoria have a normal distribution of bulk
593 vesicularities, and the lowest bubble number density and greatest vesicle areas (77 bubbles/mm²).
594 With both U2 and U3 scoria showing wider distributions of vesicularities, we infer from this that U2
595 and U3 explosions were composed of a mixture of the initial magmas as well as driven from behind
596 by the newer magmatic batch, a concept supported by the changing microlite populations identified
597 in Frey *et al.*, (this volume). We postulate that at the point of the U5 explosions the first source was
598 exhausted and U5 explosions are only driven by the comparatively hotter (Frey et al., this volume)
599 new magmatic batch. The U6 and U7 explosions account for the slow depletion of this magma batch
600 and increasing repose periods between explosions until insufficient momentum remained to
601 generate explosions. It also coincides with the period of rapidly declining magma supply rate (Sparks
602 et al., this volume)

603

604 **The character and temperatures of PDCs**

605 It is evident that PDCs were generated by collapsing eruptions columns or fountains. Similar to those
606 formed in other eruptions of this volcano (Hay 1959; Cole et al. 2019). Those that reached the sea at
607 the mouths of the Larikai and Roseau valleys were by that point likely moving at low velocities, as
608 there is no associated dilute PDC component in that region. Dilute PDCs only extended to a
609 maximum distance of 2 km, inundating ridges to the south and west.

610 Field evidence also indicates that dilute PDCs in the proximal regions (< 2 km) had temperatures too
611 low to carbonise vegetation (<250° C). Those PDCs which moved down the Larikai and Roseau valleys
612 were hotter, with temperatures high enough to carbonise most wood fragments incorporated
613 (probably > 300° C).

614 One possibility for these temperature differences is that the PDCs which reached the sea were
615 formed from different explosions that had differing temperatures. A second possibility is that the
616 dilute PDCs entrained significant quantities of air, enough to cool that portion of the PDCs below the
617 carbonisation temperature of ~ 200° C , whereas the dense PDCs that moved down the valleys
618 retained enough heat to carbonise the vegetation incorporated within them. A third explanation is
619 that the duration of the dilute PDCs was brief, perhaps of the order of a few minutes, not long
620 enough to result in carbonisation of the trees, whereas those incorporated in valley-confined PDCs
621 remained engulfed in the hot deposits and were therefore carbonised.

622

623 **Comparison to other eruptions at La Soufriere St Vincent and elsewhere**

624 La Soufriere St Vincent is the most active terrestrial volcano in the Eastern Caribbean. Prior to 2021,
625 there had been at least six explosive eruptions over the last 1000 years (Cole et al 2019). It is
626 therefore of considerable interest how the 2020/2021 eruption compares to these previous
627 eruptions.

628 Our volume estimations indicate that the 2021 explosive eruption was of VEI 4 magnitude. The 1979
629 was considered to be VEI 3, although the PDCs deposits have a relatively similar distribution at least
630 in the Roseau and Larikai valleys (Sigurdsson et al. 1979). Tephra fallout on island associated with
631 the 1979 eruption is notably thinner (Brazier et al. 1982). Although no detailed isopach maps have
632 been constructed for the 1902 eruption) the extensive, radial nature of PDCs around the volcano,
633 and the work of Pyle et al (2018) indicate that the combined output during the 1902 eruptions on
634 the 6-7th of May would put this eruption VEI 5 category. The 1902-03 eruptions were perhaps
635 unique in that following the intense activity over 24 hours on the 6th-7th of May 1902 there were
636 subsequently a further 4 further discrete explosive episodes, the last of which (in March 1903)
637 produced basaltic scoria (Cole et al., 2019).

638 The 1812 eruption lasted for several days from the 27th of April to the 1st of May with a residual
639 explosion on the 6th May (Hugh Perry Keane Accounts, quoted in Smith, 2011). From contemporary
640 accounts the most violent phase was from the 30th April to the 1st of May and although nearby
641 inhabitants were engulfed in darkness and pelted with 'showers of stones & earth and rocks' (Hugh
642 Perry Keane in Smith, 2011) it is clear from these accounts that this consisted of a repetitive series of
643 explosions. Accounts indicate that PDCs generated occurred only after several days of explosive
644 activity that generated tephra fallout (Shepherd 1831 and contemporary Parliamentary Record). This
645 pattern is similar to the 2021 explosive activity, where PDCs only occurred following > 24 hours of
646 significant explosive activity. However, our preliminary geological observations indicate that these
647 1812 PDCs, although not as extensive as 1902, were considerably larger than those of the 2021
648 events, and, as yet there is no written evidence for a preceding dome-forming eruption.

649 Prior to both the 1902 and 1979 a lake was present in the Summit Crater and indeed for both these
650 events hydrovolcanic activity has been invoked for the eruption mechanism of the 1979 explosions
651 (Shepherd et al. 1979; Shepherd and Sigurdsson, 1982), and owing to abundant lithic material, for
652 the opening phases on the 1902 eruption (Cole et al. 2019). The 2020/2021 eruption differs in that it
653 began with three months of lava dome emplacement, and there was no evidence of hydrothermal
654 water involvement or steam-rich plumes during the initial explosive phases. Thus, it seems the 2021

655 explosive eruption falls between 1979 and 1902 in terms of magnitude, but was quite similar in
656 pattern and style to the eruption in 1812.

657 An important feature of the main phase of the 1902 eruption, the accounts of the 1812 eruptions
658 and the 2021 eruption has been the presence of incessant and repetitive explosions that at some
659 point during the eruption also generated PDCs and lahars. Our initial analysis of these deposits prior
660 to their substantial erosion provides a unique record of subtle changes that lead to important
661 changes in eruptive behaviour and impacts, paving the way for more detail study. Comparison of
662 these within the context of the other deposits could provide insights into the critical drivers of
663 eruptive transitions and these repetitive sequences of volcanic explosions.

664 Similar recent eruptions include Kelud in Java, Indonesia, where a short-lived explosive eruption
665 occurred in 2014 of VEI 4 magnitude, generating both PDCs and extensive tephra fallout (Maeno et
666 al. 2019). Tephra fallout generated by the 2008 eruption of Chaiten, Chile despite being rhyolitic, is
667 similar, with multiple layered tephra fallout deposit formed by different phases of the eruption
668 (Alfano et al 2011 and 2012) and associated PDCs (Major et al. 2013). Although Chaiten and Kelud
669 generated blast-like PDCs, for which there is little evidence at La Soufriere St Vincent.

670 In summary, the 2021 eruptions of La Soufrière presented serious hazards to the population
671 (~20,000) living around the volcano. Although PDCs generated were limited, in that they reached the
672 coast only in two valleys to the west, similar to 1979, only a slight increase in magnitude and
673 intensity of future eruptions would result in more extensive and longer runout PDCs as happened in
674 1902.

675 **Conclusions**

- 676 1. Explosive activity between 9th and 22nd April 2021 resulted in a layered tephra deposit. The
677 lowermost deposit, Unit 1 was associated with destruction of almost all of the 2021 lava
678 dome and ~60% of the 1979 lava dome resulting in a 600m diameter 2021 crater.
679
- 680 2. Vesicular scoria representing the juvenile magma is present throughout the tephra
681 sequence, but in varying quantities. Documented variations in the nature of the vesicularity
682 is consistent with different batches of magma rising through the system in the first few days.
683
- 684 3. PDCs were only formed after > 24 hours of explosive activity, contemporaneous with several
685 explosions. The switch from convecting to collapsing plumes is inferred to be related to vent
686 processes, possibly flaring/widening. Dense, concentrated PDCs reached the sea in the

687 Larikai and Roseau valleys only. Dilute PDCs were limited to within 2.5 km of the Summit
688 Crater rim but were distributed across the lower crater rim from west to southeast.

689

690 4. Volume calculations indicate that the explosive phase of this eruption had a bulk volume of
691 $1.19 \times 10^8 \text{ m}^3$ ($7.1 \times 10^7 \text{ m}^3$ DRE) +/- approximately 20% and therefore was a small VEI 4
692 eruption. Approximately one third of the volume of tephra is contained within the pre-
693 existing Summit Crater forming deposits locally > 100m thick.

694

695 5. The changing style and characteristics of the tephra deposits can be attributed to changes in
696 the ascending magma and the evolution of the conduit-crater system during the explosive
697 eruptions. In the first 20 hours a new explosion crater and deeper conduit formed.
698 Thereafter back-filling of the 2021 crater-conduit system by crater wall rock instability and
699 recycling of tephra led to interactions of erupting magma with back-fill resulting in more ash-
700 rich deposits and conditions for column collapse and PDC formation.

701

702 6. Although ash aggregates such as accretionary lapilli were abundant in the upper half of the
703 tephra sequence, there is no evidence for hydrovolcanism, and we infer moisture was
704 derived from weather systems or PDCs entering the sea.

705

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713

714

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816

817 **Figures**

818 Fig 1 The island of St Vincent and location of La Soufriere volcano on the island. Inset are the islands
819 of the Eastern Caribbean arc. The area shaded red represents the volcanic edifice.

820 Fig 2 Measured sections through the 2021 tephra sequence Leeward sections (top) and Windward
821 locations (bottom).

822

823 Fig 3 – Tephra sequence at a) Owia (5 km NE) scale in cm divisions, b) Dry Wallibou mouth (4.5 km
824 SW of Summit Crater rim), c) River Bed 1.8 km SE, Sequence is 30 cm thick in total. d) Tephra fallout
825 sequence at ‘The Bench’ 1.2 km SE of Summit Crater rim, sequence is a total of 45 cm thick. e)
826 Sequence at Loc 38, Dark View falls 6 km SW of Summit Crater rim. Sequence is 3.8 cm thick. Scale is
827 in 1 cm intervals. f) Accretionary lapilli in Unit 4 at Jacobs well (700 m SE of Summit Crater rim). Coin
828 is 2cm across.

829 Fig 4 a) Map showing extent of PDCs, from fieldwork and satellite imagery. Red =dense valley filling
830 PDCs. Pink = dilute PDC; PDC deposits. Yellow dots are sections shown in b-f; b) in the Larikai, c)
831 Roseau, d) section at Jacobs well showing PDCs interbedded with fallout layers, e) Upper SE flank
832 valley (looking South from Jacobs Well) f) Several PDC flow units interbedded between with fallout
833 layers at Jacobs well (Upper SE flank shown in a) and d)

834

835 Fig 5 a) Tree felling ~1km SW of the Summit Crater rim on the Leeward trail. PDCs moved from left to
836 right. Note several trees are broken 2-3 m above their base. b) Detail of trees impacted by PDCs in
837 same region as ‘a’. PDCs moved from right to left obliquely into the plane of the photograph. Note-
838 abrasion of trees on volcano facing (RHS) side and absence of charring of trees. c) Deposits of dilute
839 PDCs in a similar region to a) showing strong lateral thickness variations and crude cross-bedding

840 Current direction is from left to right. Spade handle rests on U2. Pen rests on lowermost PDC
841 deposits and is 14 cm long.

842

843 Fig 6 a) Cumulative grainsize distributions for the different units. U1 and U2 are shown as areas.
844 Units 3 to 5 are depicted as lines for individual grainsize analyses b) cumulative grainsize
845 distributions of the different lithofacies Lapilli and Ash layers shown as shaded areas. PDCs (dilute
846 and concentrated) are plotted as lines of individual grainsizes analyses. Grainsize histograms and
847 statistics through two sequences C) Windward: Mahan ridge and Sandy bay d) Proximal – Jacobs well
848 (700 m SE). Closed symbols on Max clast sizes are dense clasts, open symbols= vesicular scoria.

849 Fig 7 a-d SEM images of component types a) dense b) semi vesicular c) vesicular scoria d)
850 hydrothermally altered. e) Variations in component types > 1mm through three sequences of 2021
851 tephra on the Eastern (Windward) side of the volcano.

852

853 Fig 8 Vesicularity variations in juvenile clasts 16 - 32 mm in four different Units. Clast bulk densities
854 were calculated using the Archimedes principle after Shea et al., 2010 and converted to vesicularity
855 using a DRE value of 2.79 g/cm³ – as calculated using whole rock (XRF) data and the method of
856 Lange and Carmichael (1987) In brackets, n = number of clasts analysed from each unit. Pie charts
857 show the proportion of field classified vesicular and semi-vesicular clasts in the different measured
858 vesicularity ranges.

859

860 Figure 9: Density plots of bubble shape and size from Units 1, 2 and 5 (A – F), dashed red line marks
861 boundary at which roundness = circularity. Backscattered electron images showing changing bubble
862 textures between Units 1, 2 and 5 (G – I) and Unit 3 (J and K). SV = clast categorised as semi-
863 vesicular, S = clast categorised as scoriaceous. Numbers in brackets refer to 3D bulk vesicularities
864 acquired using the Archimedes method following Shea *et al.*, (2010). *Circularity* is sensitive to
865 deviations from a perfect circle via either surface roughness (e.g., protrusions caused by crystal
866 interference or preservation of coalescence features), or elongation. In contrast, *Roundness* is a
867 measure is less sensitive to protrusions on vesicle walls (Liu *et al.*, 2015). If elongation is the
868 dominant factor, lower values of *Circularity* will be approximately equal to *Roundness* (Liu *et al.*,
869 2015)

870

871 Fig 10 Hand-drawn isopach maps for Expert 1 for a) U1, b) U2, c) U3, d) U4-7, e) total tephra
872 thickness and f) interpreted distal thickness including Barbados island. Thicknesses values are in
873 millimetres.

874

875 Fig 11 Timeline showing Real time seismic amplitude (RSAM) for (a) the whole explosive phase and
876 (b) a detailed of RSAM and seismic frequency spectra for the first 100 hours of explosive activity. Our
877 interpretation of the timing of the different Units (see also table 6) is superimposed on this, start
878 times of each Unit given in Local time and UTC in parentheses. U4 is not shown simply owing to
879 space issues. Fig 12 a) Tephra plume at 5:15 LT (21:15 UTC) on 9th April 2021 viewed from boat just
880 north of Kingstown approximately 19 km southwest of the volcano. Photo credit: Kai Best b) Large
881 axisymmetric spreading plume at 5:59 LT (09:59 UTC) viewed from nr Calliaqua, close to the
882 southernmost point of the island, 22.5 km south of the volcano. This plume likely corresponds to the
883 start of the Unit 2 phase. Photo Credit: Jenny Trumble

884 **Tables**

885 Table 1 Summary of key features of different Units identified. N.G=normal grading. R.G. = reverse
886 grading. S= vesicular scoria, SV= semi vesicular, D= Dense, H = hydrothermal

887 Table 2: Key measurements from 2D image analysis of vesicles and micro/phenocryst phases for
888 Units 1, 2 and 5.

889

890 Table 3 Bulk volumes of the different Units calculated from isopach maps. Volumes in millions of
891 cubic metres (to the nearest million). 'Best Case' = in bold, 95 and 5% estimates in parentheses

892

893 Table 4 Results of UNINET stochastic sampling of the EqWt Unit bulk volume piece-wise linear
894 uncertainty distributions from EXCALIBUR. Volumes are 10^6m^3

895

896 Table 5 Bulk volumes of the different components of the explosive activity.

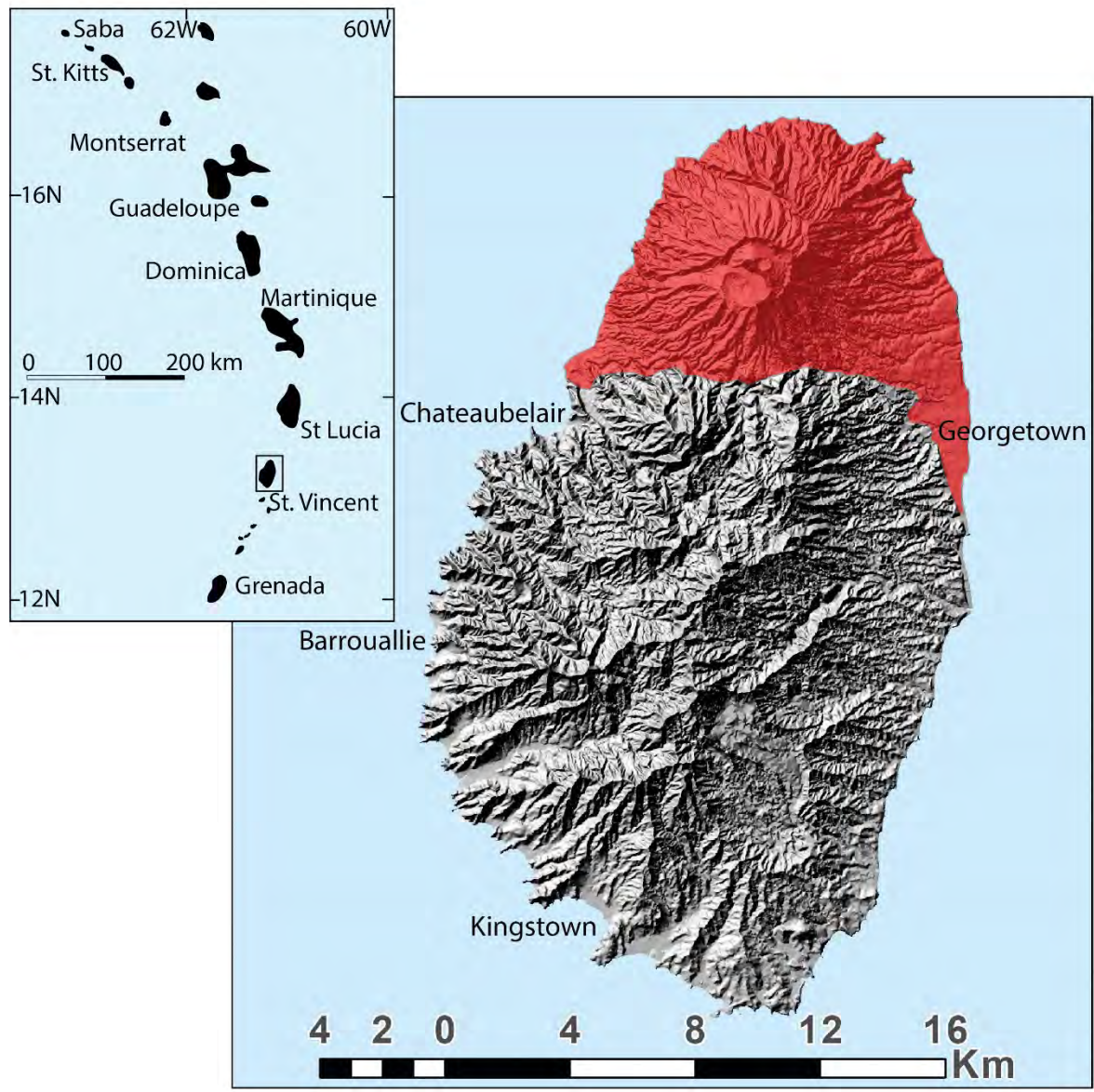
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898 Table 6: (1) Explosion number – explosion assignment from Robertson et al., this volume (2) Seismic
899 (RSAM data) to define onset on explosions and durations of RSAM signal. Data used here are RSAM
900 Spike determinations by Sparks et al., this volume but see also Fig 10. (3) Times used here are
901 derived from satellite data as described in Sparks et al., (this volume). Dark grey shading indicated
902 discrete explosions less than two hours apart, light grey from 2-4 hours apart. Thick black line
903 indicates high degree of certainty on boundary timing, lighter grey lines indicate lower degrees of

904 certainty.

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906 **Fig 1**



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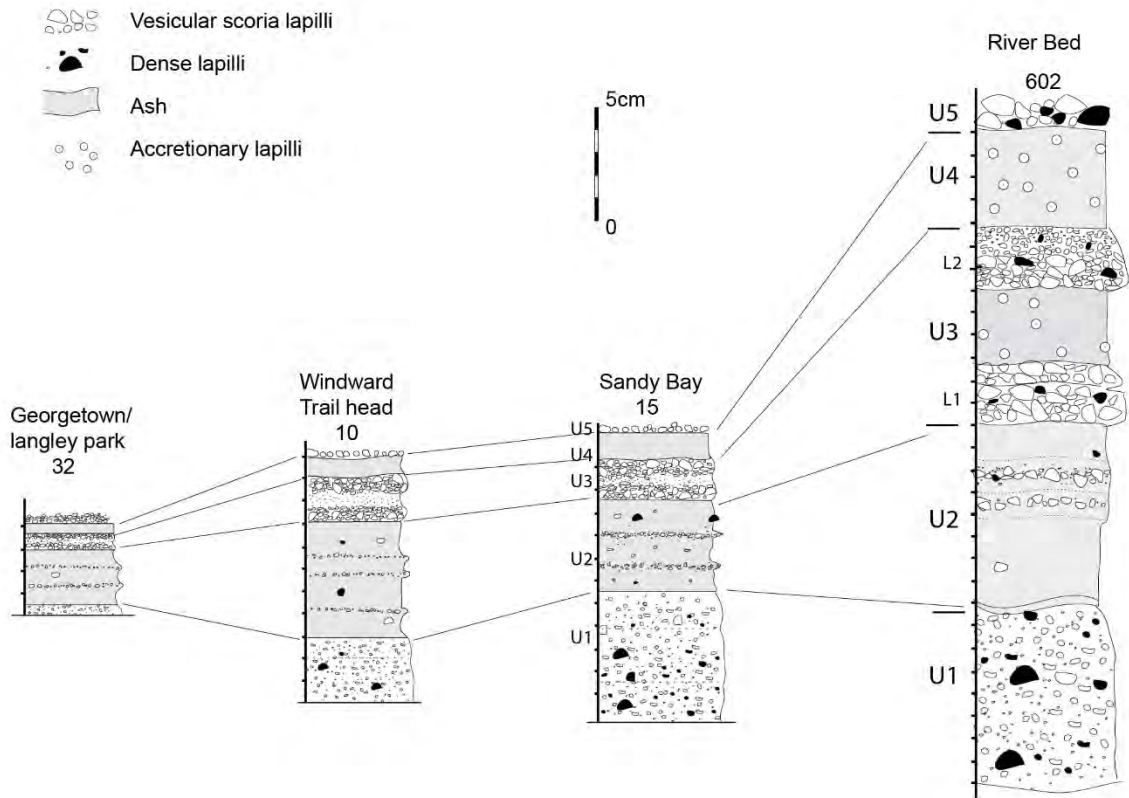
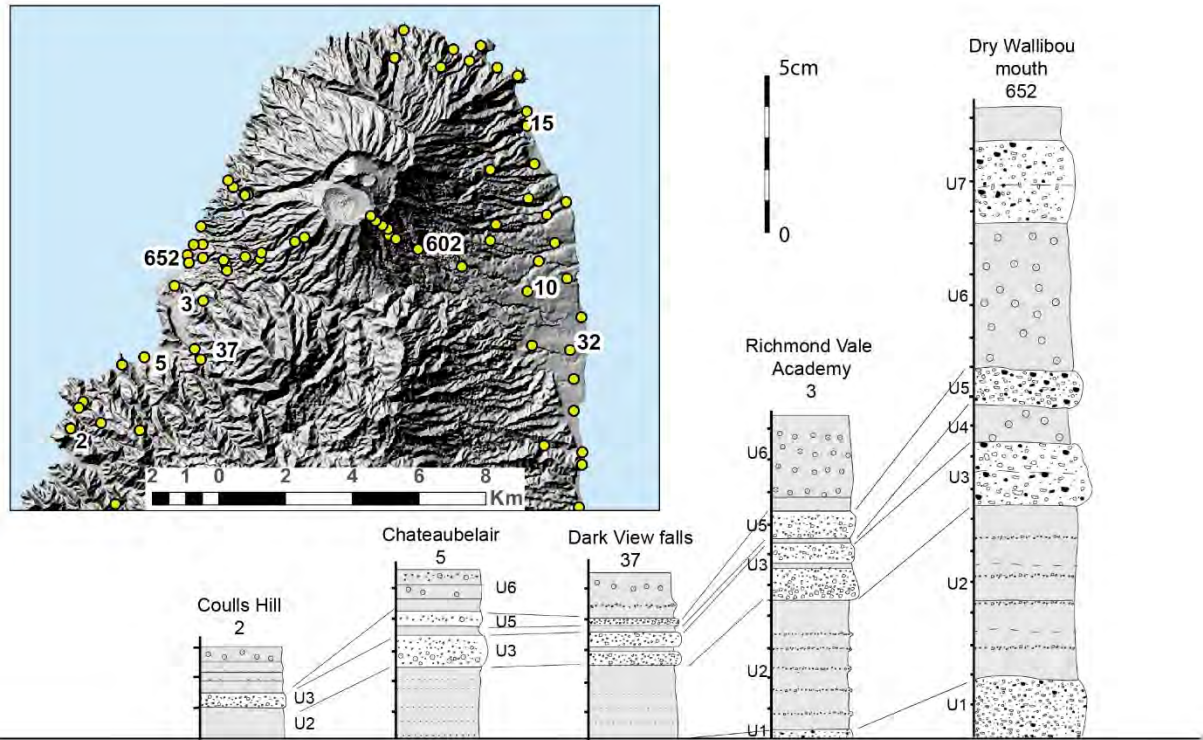
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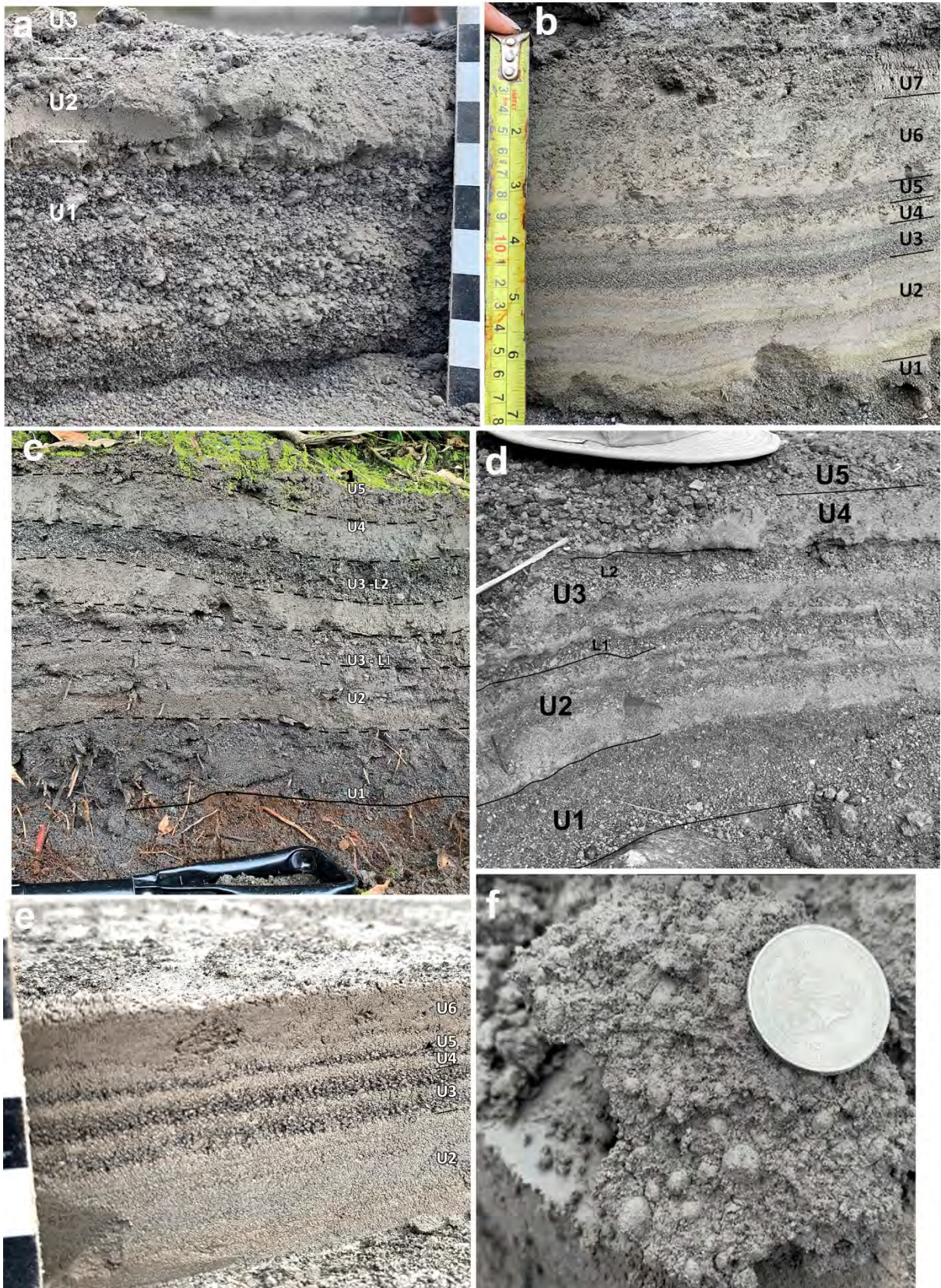
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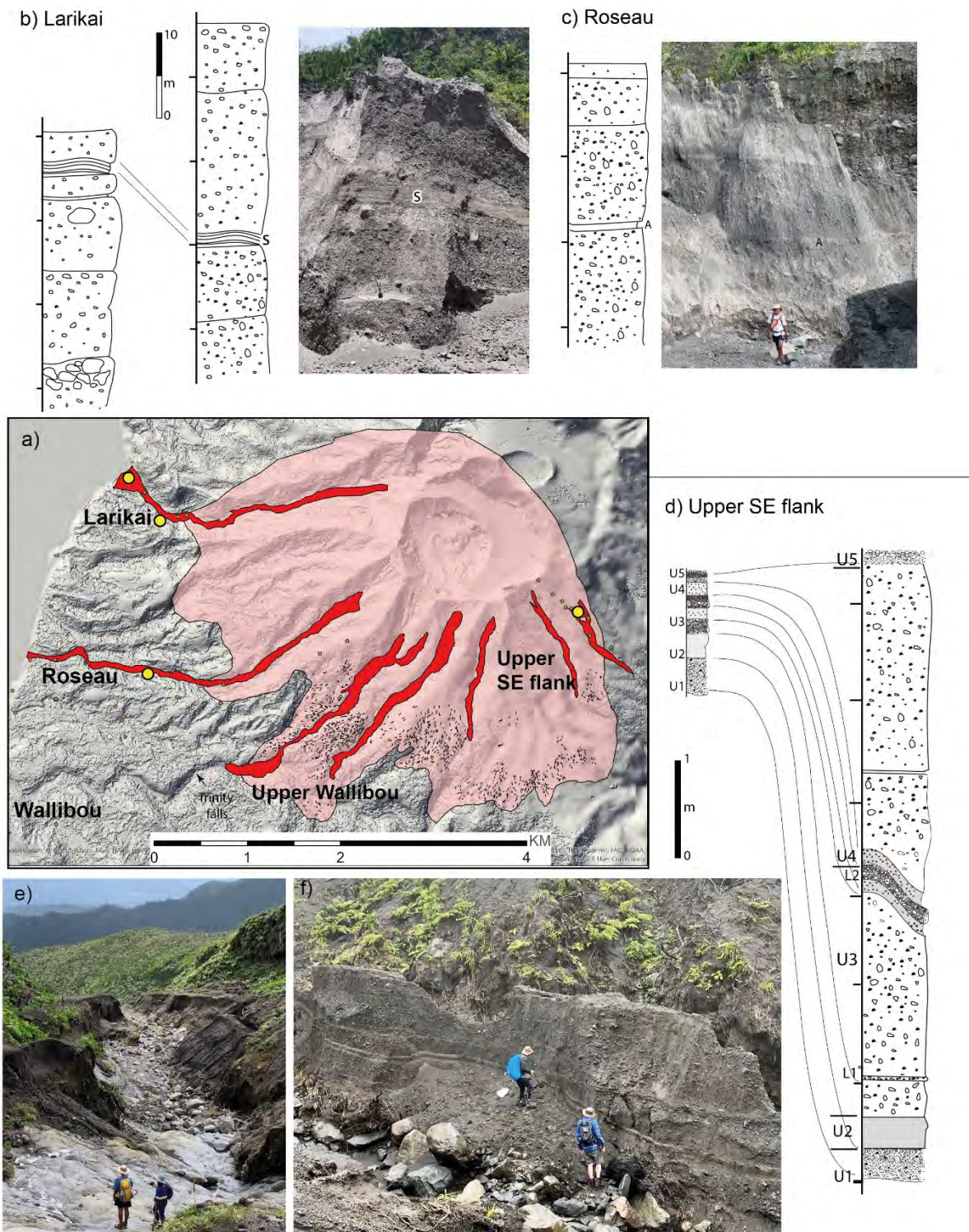
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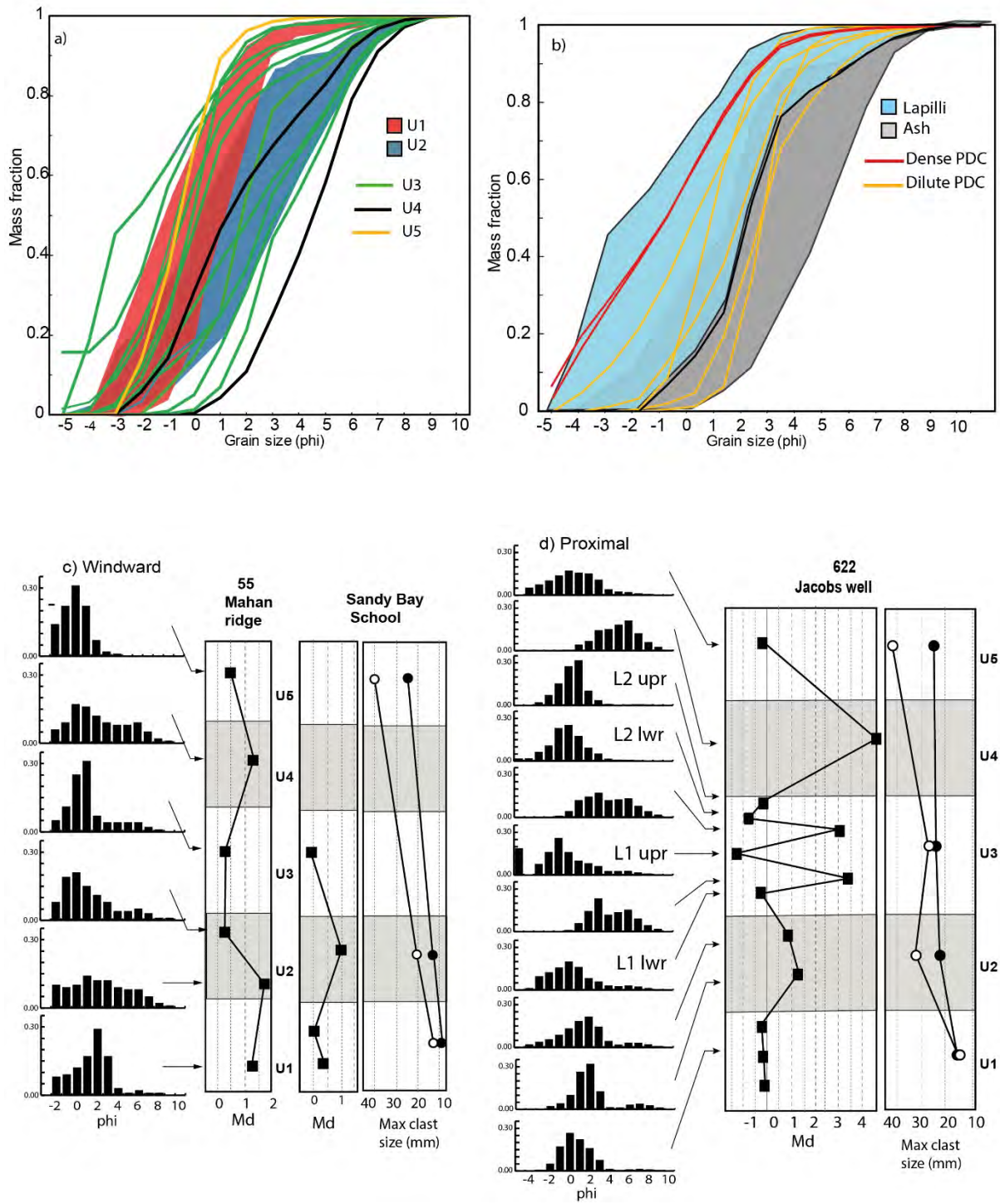
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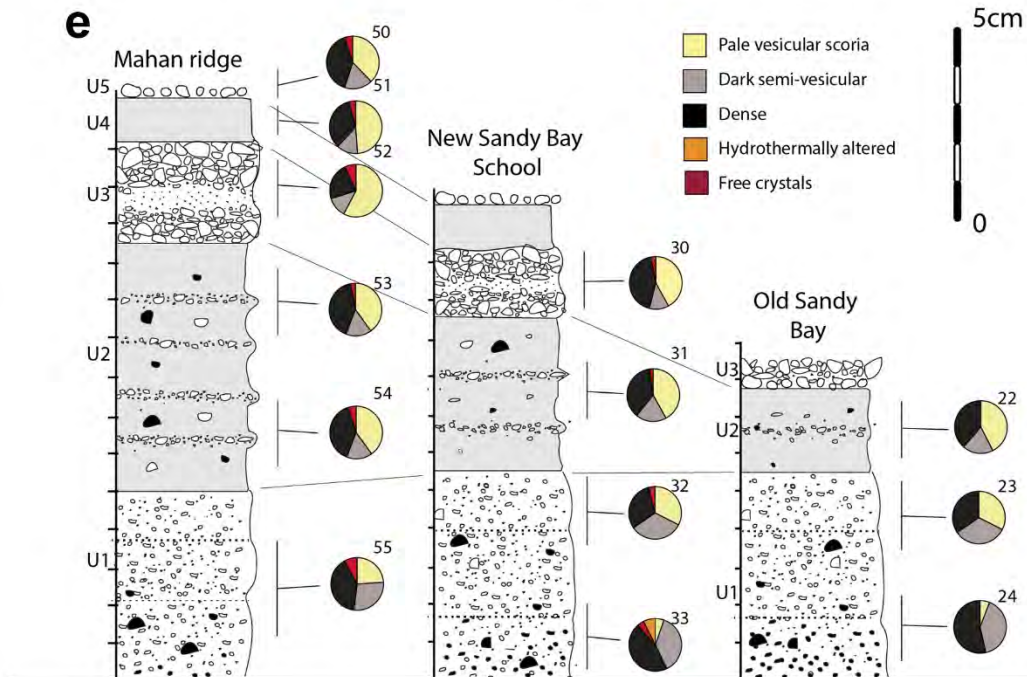
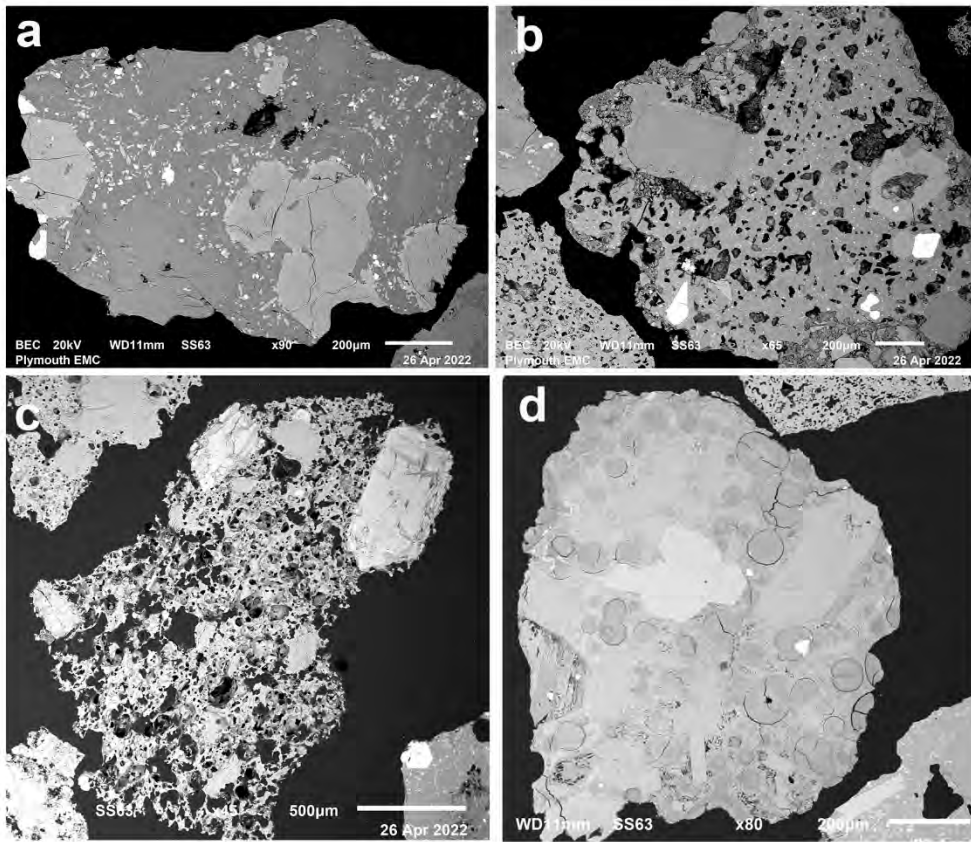
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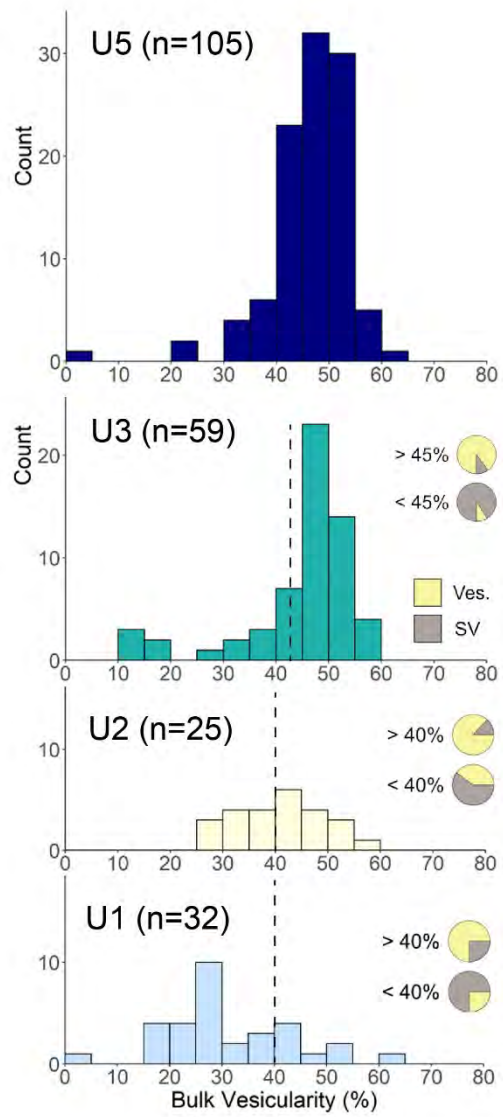
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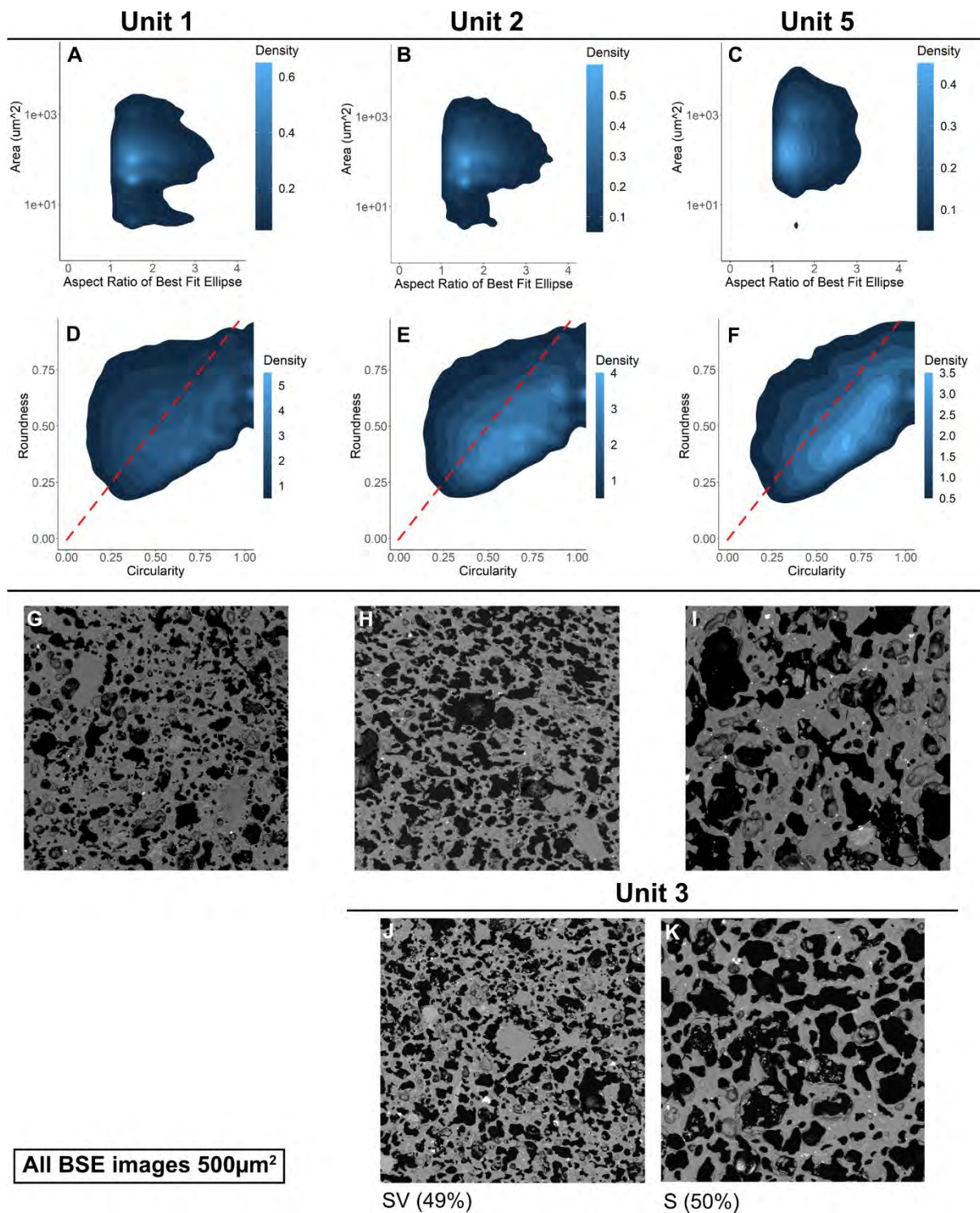
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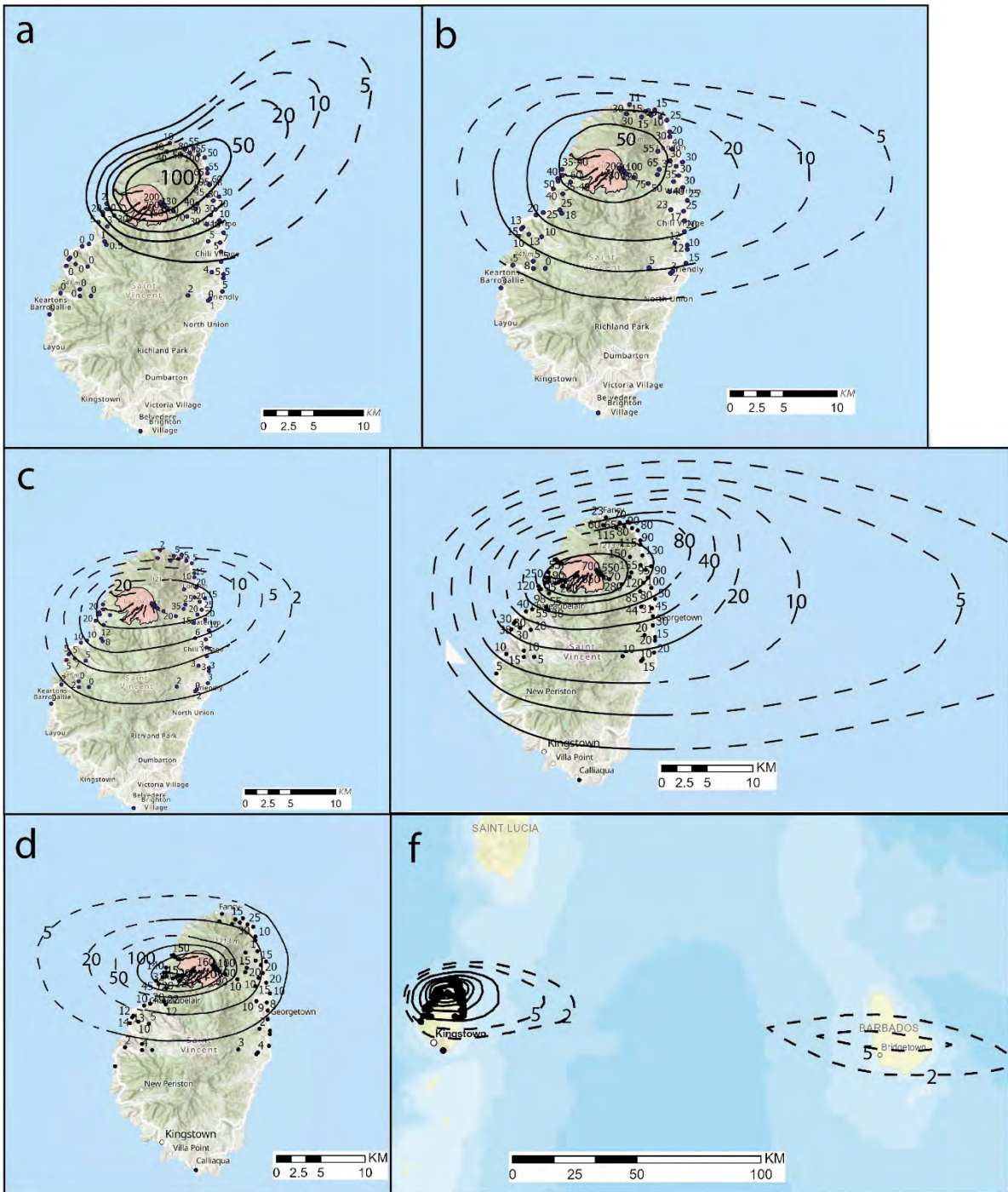
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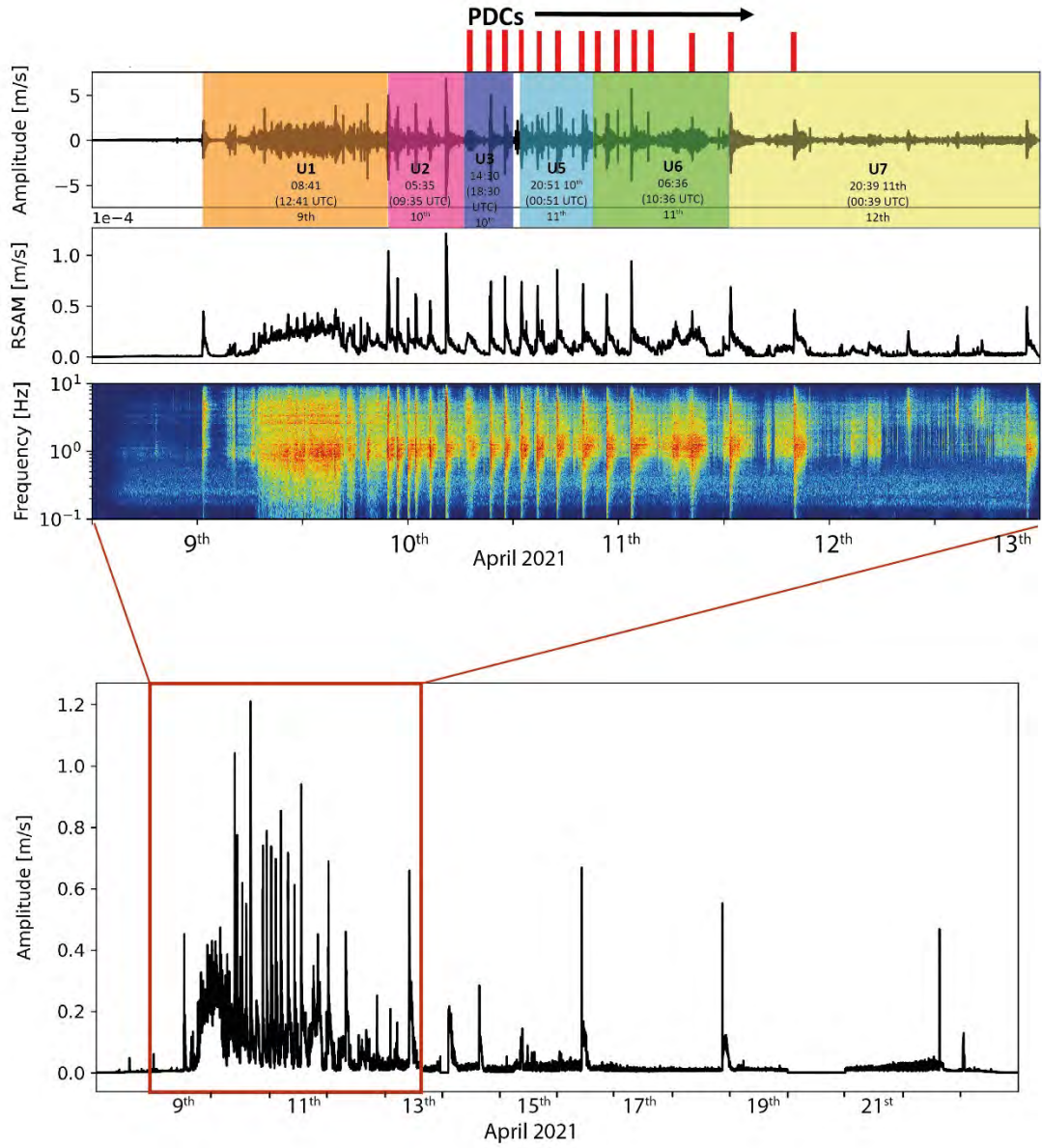
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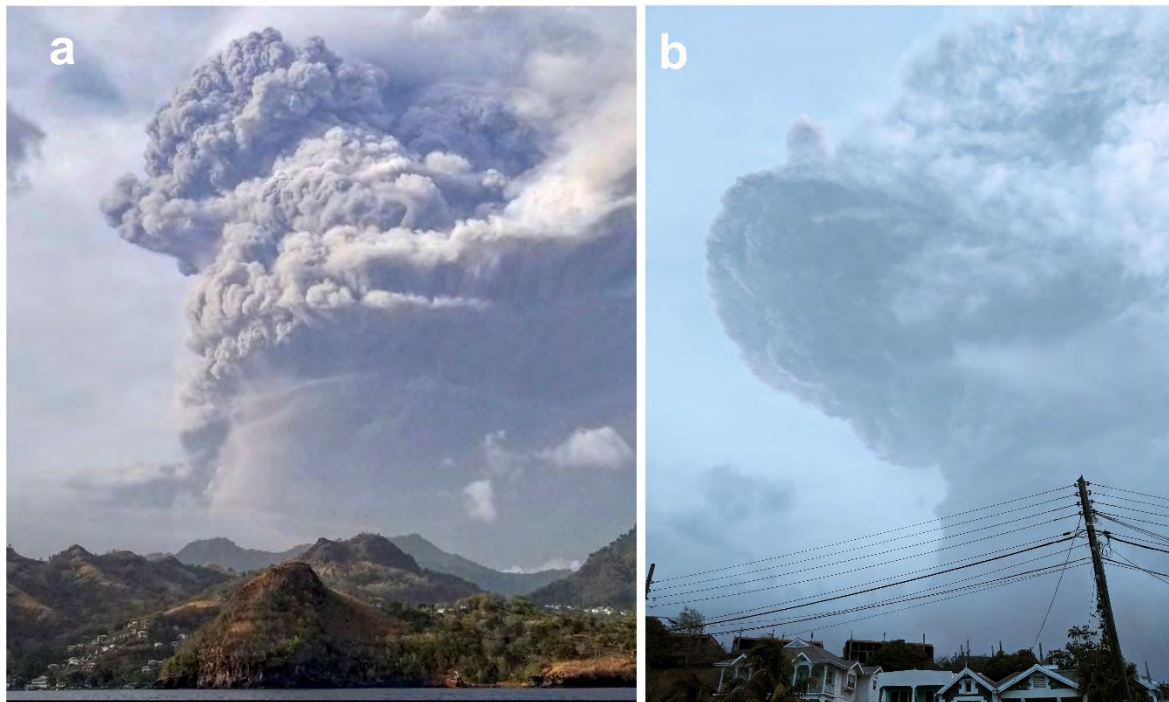
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965 Table 1

Unit	Max thickness (location)	Comments/features	Accretionary lapilli	Components
U1	20 cm (700m SE)	Crudely stratified, moderate GS lapilli (R.G.) Horizons rich in hydrothermally altered clasts	No	S ~10% at base, to 40% at top. Rich in SV clasts, H-rich horizons
U2	20 cm (700m SE)	Ash-rich, up to seven individual layers, Coarser lapilli toward top of unit	No	S ~40-50 wt % clasts
U3	31 cm (600m SE)	Double lapilli, (upper N.G.). Ash layer between lapilli	Yes	S clasts up to 60 wt %)
U4	8 cm (700m SE)	Single ash layer, some diffuse/ scattered lapilli	Yes, abundant	Sparse coarse clasts, mostly D and S.
U5	6 cm (700m SE)	Coarse lapilli, uppermost deposit to East	No	Rich in S, glassy D clasts also prominent
U6	10 cm (2 km SW)	several ash-rich layers	Yes, abundant	
U7	5 cm (4 km SW)	Thin fine grained ash and lapilli	Yes	

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969 **Table 2**

	UNIT 1	UNIT 2	UNIT 5
Total area analysed (cm²)	2.19	1.55	1.65
% phenocrysts/microcrysts	24.4	22.6	18
% vesicularity	10	16	32
% vesicularity (crystal free)	27	26	39
No. analysed	32914	22816	10399
Crystal corrected area (mm²)	197	131	135
2D BND (per mm²)	167	174	77
Average vesicle area (µm²)	537	916	4358
Median vesicle area (µm²)	109	121	252
Min vesicle area*	3.78	3.76	2.93
Max vesicle area (mm²)	0.85	2.80	2.55
Average Elongation	0.3	0.3	0.29
Median Elongation	0.29	0.29	0.28
Pixel size (µm²)	0.66	0.86	0.76

970 *Constrained by minimum pixel size

971 **Table 3**

	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Unit 1	15 (12,22)	11 (5,14)	15 (8,20)	18 (14,57)	10
Unit 2	19 (16,29)	15 (12, 16)	16 (12,18)	28 (18, 53)	24
Unit 3	6 (4,12)	5 (4,6)	6 (4,7)	9 (7,16)	-
Unit 4-7	15 (13,18)	12 (11,17)	8 (5,12)		
Total Thickness (From whole tephra thickness isopach)	44 (35,98)	37 (24,82)	31 (29,90)	44 (30,99)	74

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980 Table 4

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	5%ile	Median	95%ile	Mean	+/- StDev
Unit 1	4.6	14.5	51.2	21.6	+/- 15.3
Unit 2	12.2	17.2	47.1	24.2	+/- 12.5
Unit 3	3.8	6.0	15.1	7.9	+/- 3.7
Units 4-7	5.1	12.1	17.7	11.8	+/- 4.0
Summed Units	37.2	63.3	102.4	65.4	+/- 20.4
Total isopach map volume	25.6	42.3	98.0	52.7	+/- 24.3
Mean of Summed and Total				59.1	

992

993 Table 5

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995

	Volume (x10⁶m³) to nearest million
Tephra fallout from isopachs	59 +/- 20
PDC deposits (in valleys outside the Summit Crater)	
Larikai	(6) +/-1.5
Roseau	(4) +/- 1
Upper Wallibou (3 valleys)	(6) +/-1.5
Upper South East flank (upper Rabacca)	(1) +/-0.25
	17 +/-3.5
Intracrater fill (DEM differencing)	43 +/- 10
Total bulk volume	119 +/-24

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1002 Table 6

Event # ⁽¹⁾	Day (April 2021)	RSAM Spike Time ⁽²⁾ (UTC)	Spike Duration (minutes)	Plume emergence ⁽³⁾ (UTC)	Unit	Visual/Stratigraphic observations and correlation with other geophysical datasets
1	9 th	12.41	11	12.50	U1	Distinctive explosion and plume, widely observed
2,3,4	9 th	18.59		19.00 (start)	U1	Deposit lapilli-rich/ash poor on island with slight coarsening upwards in sequence but individual pulses difficult to differentiate until last 2 explosions shown here. Following the initial pulse at 19:00 RadiF ash imagery shows near continuous pulsatory plume dispersed ENE, with some distinct pulses towards end of sequence consistent with RSAM spikes at 06:37 and 07:24 UTC.
					U1	
					U1	
	10 th				04:30 (End)	
5	10 th	06:37	11		U1	
6	10 th	07:24	3	07:50	U1	Minor (ash) fallout in SE. island between midnight and 05:30 (09:30 UTC) inferred to be from last two explosions.
7	10 th	09.35	23	09.50	U2	Begins with distinct plume seen in SE island at dawn (05:35 LT, 09:35 UTC), with visible fallout. Axisymmetric plume in RadiF. Plume travels ESE. Minor ashfall begun across Barbados mid-morning, then intensifies, ashfall in Kingstown during day. Boundary uncertainty: Distinctive ash-rich deposits but with 7 discrete coarse pulses evident in medial locations (six explosions here)
8	10 th	10.47	8	11.00	U2	
9	10 th	12.02	12	12.10	U2	
10	10 th	12.54	13	13.00	U2	
11	10 th	14.27	14	14.40	U2	
12	10 th	16.20	23	16.30	U2	
13	10 th	18.30	13	18.50	U3	Distinctive distal expression as coarse lapilli couplet separated by fine ash. Proximal localities have fallout separated by PDC (and co-PDC ash). Distinctive RSAM peak consistent with the first PDC generation at 18:30 (consistent with proximal stratigraphy). Ash fallout in S. Leeward begins at this time. N. Leeward Observers describe 'an early night' around this time. Some rain in S. Island. Windward observers describe diminishing continuity or intensity of activity.
14	10 th	21.20	19	21.30	U3	

15	10 th	23.02	20	23.10	U4	Ash-rich layer with some coarser lapilli. Although U4 could be predominantly from PDC fallout, distributed across island. Boundary uncertainty: lower peak energy (RSAM) explosions could imply PDC or lower intensity ash generation
16	11 th	00.51	21	01.00	U5	Coarse scoria-rich deposits. Prominent in deposits across island, forming carapace on Windward sequences. 3 rd Explosion in this sequence cuts power across the island. Early morning rain in Barbados, combined with continued ash fall. Boundary Uncertainty: nature of U5 deposit (large scoria lodged in finer ash) makes precise no. of explosions harder to determine. Daylight visual observations more consistent with U6 explosions.
17	11 th	02.44	16	02.50	U5	
18	11 th	04.59	11	05.10	U5	
19	11 th	07.55	13	08.10	?U5	
20	11 th	10.36	13	10.50	U6	Number of fine-grained ash layers, rich in accretionary lapilli. Limited to Western flanks of volcano. PDC generation continues at this time. Eruption columns predominantly carried to Leeward in lower atmospheric winds from this time (below windshear). Rainfall on Windward side of island (lahars) – little further ash deposition on this side of island & ‘clearing air’ during morning. Steaming in Rabacca reported at this point.
21	11 th	13.24	22	13.40	U6	
22	11 th	18.11	11	18.20	U6	
23	11 th	20.22	12	20.20	U6	
24	12 th	00.39	18	00.50	U7?	Majority of this sequence is manifest in fine indistinct ash sequence of U7 (when present at all – only found proximal to volcano). N. Leeward observers report no ash by 13 th April. PDCs still observed. Rainfall continues on 12 th and 13 th April. Ashfall in Barbados now negligible. We infer that there would be almost no fallout visible in our sequence from the last three explosions.
25	12 th	07.59	20	08.10	U7 ?	
26	12 th	20.53	24	21.30	U7?	
27	13 th	10.23	24	10.40	U7?	
28	14 th	02.27	17	02.40	U7 ?	
29	14 th	15.31	10	15.40	U7?	
30	16 th	10.16	5	10.50	-	
31	18 th	20.49	10	21.00	-	
32	22 nd	15.09	9		-	

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