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1 The tensile strength of hydrothermally altered volcanic rocks

2

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22

23 **Abstract**

24 The tensile strength of volcanic rocks is an important parameter for understanding and
25 modelling a wide range of volcanic processes, and in the development of strategies designed to

26 optimise energy production in volcanic geothermal reservoirs. However, despite the near-
27 ubiquity of hydrothermal alteration at volcanic and geothermal systems, values of tensile
28 strength for hydrothermally altered volcanic rocks are sparse. Here, we present an experimental
29 study in which we measured the tensile strength of variably altered volcanic rocks. The
30 alteration of these rocks, quantified as the weight percentage of secondary (alteration) minerals,
31 varied from 6 to 62.8 wt%. Our data show that tensile strength decreases as a function of
32 porosity, in agreement with previous studies, and as a function of alteration. We fit existing
33 theoretical constitutive models to our data so that tensile strength can be estimated for a given
34 porosity, and we provide a transformation of these models such that they are a function of
35 alteration. However, because porosity and alteration influence each other, it is challenging to
36 untangle their individual contributions to the measured reduction in tensile strength. Our new
37 data and previously published data suggest that porosity exerts a first-order role on the tensile
38 strength of volcanic rocks. Based on our data and observations, we also suggest that (1)
39 alteration likely decreases tensile strength if associated with mineral dissolution, weak
40 secondary minerals (such as clays), and an increase in microstructural heterogeneity and (2)
41 alteration likely increases tensile strength if associated with pore- and crack-filling mineral
42 precipitation. Therefore, we conclude that both alteration intensity and alteration type likely
43 influence tensile strength. To highlight the implications of our findings, we provide discrete
44 element method modelling which shows that, following the pressurisation of a dyke, the
45 damage within weak hydrothermally altered host-rock is greater and more widespread than for
46 strong hydrothermally altered host-rock. Because the rocks in volcanic and geothermal settings
47 are likely to be altered, our results suggest that future modelling should consider the tensile
48 strength of hydrothermally altered volcanic rocks.

49

50 **Keywords:** La Soufrière de Guadeloupe; Merapi; Chaos Crags; porosity; alteration

51

52 **Highlights:**

- 53 • Tensile strength decreases as a function of porosity and alteration.
- 54 • Constitutive models provide tensile strength estimates for a given porosity or alteration.
- 55 • Alteration intensity and alteration type likely influence tensile strength.
- 56 • Numerical models show that alteration influences the damage surrounding a dyke.
- 57 • Volcano and geothermal modelling should consider the tensile strength of altered rocks.

58

59 **1 Introduction**

60 Hot hydrothermal fluids within a volcanic system can permanently change the rocks
61 through which they pass, both physically and chemically (Browne, 1978). Hydrothermal
62 alteration is thought to compromise the stability of a volcanic dome or flank, increasing the
63 likelihood of potentially devastating collapse hazards (Day, 1996; van Wyk de Vries et al.,
64 2000; Reid et al., 2001; Voight et al., 2002; Reid, 2004; Cecchi et al., 2004; Ball et al., 2015,
65 Rosas-Carbajal et al., 2016; Ball et al., 2018; Mordensky et al., 2019; Heap et al., 2021a, b;
66 Harnett and Heap, 2021; Darmawan et al., 2022). Indeed, hydrothermal alteration is prominent
67 in both the matrix and coherent blocks within debris avalanche deposits resulting from partial
68 edifice collapse (e.g., Salaün et al., 2011). Alteration is also considered to inhibit the outgassing
69 of magmatic volatiles through the dome or conduit and/or restrict fluid movement, promoting
70 erratic explosive behaviour (Boudon et al., 1998; Edmonds et al., 2003; Montanaro et al., 2016;
71 Mayer et al., 2017; de Moor et al., 2019; Heap et al., 2019; Kennedy et al., 2020; Mick et al.,
72 2021; Kanakiya et al., 2021).

73 Despite the importance and common presence of hydrothermal alteration at volcanic
74 systems, few laboratory studies have sought to better understand the influence of hydrothermal
75 alteration on the physical and mechanical properties of volcanic rocks. The need for more

76 experimental studies is further emphasised by the seemingly contradictory influence of
77 alteration on the physical and mechanical properties of volcanic rocks. For example,
78 experimental studies have shown that hydrothermal alteration can increase (Marmoni et al.,
79 2017; Heap et al., 2020, 2021b) or decrease (del Potro and Hürlimann, 2009; Frolova et al.,
80 2014; Wyering et al., 2014; Mayer et al., 2016; Farquharson et al., 2019; Heap et al., 2021a)
81 the strength, and increase (Mayer et al., 2016; Farquharson et al., 2019) or decrease (Heap et
82 al., 2017, 2019, 2020; Kennedy et al., 2020; Kanakiya et al., 2021) the permeability of volcanic
83 rocks. It was also recently shown that hydrothermal alteration can increase or decrease the
84 thermal properties (thermal conductivity, thermal diffusivity, specific heat capacity) of volcanic
85 rocks (Heap et al., 2022). These studies, and others, have suggested that whether alteration
86 increases or decreases a certain petrophysical property depends on (1) whether the alteration
87 increases or decreases the porosity of the rock (e.g., through mineral dissolution or porosity-
88 filling mineral precipitation, respectively), a factor known to exert a first-order control on rock
89 physical properties (see review by Heap and Violay, 2021) and (2) whether the secondary
90 (alteration) minerals are characterised by a lower or higher value of the petrophysical property
91 of interest (e.g., in terms of strength, whether the secondary minerals are weaker or stronger
92 than the primary mineral assemblage).

93 The tensile strength of volcanic rocks is required for analytical or numerical estimates
94 of (1) the magma overpressure required for magma chamber rupture and dyke propagation, (2)
95 the limits on magma chamber volume (see reviews by Gudmundsson, 2006, 2020; Acocella,
96 2021), and (3) magma under-pressure leading to the generation of collapse-related structures
97 (Folch and Marti, 2004; Holohan et al., 2013). A refined knowledge of the tensile strength of
98 volcanic rocks is also fundamental to improve our understanding of volcanotectonic seismicity
99 during unrest and eruptions (Roman and Cashman, 2018). Volcano stability modelling
100 performed using the finite element method (FEM; Heap et al., 2014; Chen et al., 2017) and the

101 discrete element method (DEM; Holohan et al., 2015, 2017; Harnett et al., 2018, 2020; Heap
102 and Harnett, 2021), designed to better understand the mechanical behaviour of volcanic rocks
103 and structures, require the tensile strength or the ratio between the compressive and tensile
104 strength as inputs. The tensile strength of volcanic rocks and magmas also exerts crucial control
105 over their fragmentation behaviour (McBirney and Murase, 1970; Alidibirov, 1994; Zhang,
106 1999; Spieler et al., 2004; Koyaguchi et al., 2008) and is considered a controlling factor in the
107 stability of lava domes (Kilburn, 2018; Harnett et al., 2019). Finally, understanding the tensile
108 strength of volcanic rocks, and in particular altered volcanic rocks, is important for the appraisal
109 and operation of geothermal energy resources in volcanic regions (e.g., Iceland and New
110 Zealand; Arnórsson, 1995; Friðleifsson and Elders, 2005; McNamara et al., 2016; Wilson and
111 Rowland, 2016).

112 Although experimental studies have shown that the tensile strength of volcanic rocks
113 decreases nonlinearly as a function of porosity (Heap et al., 2012; Lamb et al., 2017; Hornby et
114 al., 2019; Harnett et al., 2019; Kendrick et al., 2021; Heap and Violay, 2021; Heap et al., 2021c;
115 Weydt et al., 2021), and can be influenced by temperature (Hornby et al., 2019; Weaver et al.,
116 2020), the influence of hydrothermal alteration is comparatively understudied. For example,
117 Pola et al. (2014) found that the tensile strength of five lava samples collected from Solfatara
118 (Italy) was reduced from ~12 to ~2 MPa as degree of alteration (determined using the chemical
119 index of alteration, CIA) increased from fresh to completely altered. Mayer et al. (2016) found
120 that the tensile strength of ignimbrites and fall deposits (six blocks in total) from Solfatara and
121 Pisciarelli (Italy) was reduced from ~4.5 to ~0.5 MPa as a function of increasing alteration
122 (determined using the CIA). Despite these initial findings, values of tensile strength for
123 hydrothermally altered rocks are sparse and, to the authors' knowledge, there are no
124 experimental studies that have systemically explored the influence of hydrothermal alteration
125 on the tensile strength of volcanic rocks.

126 Here, therefore, we present the results of an experimental study in which we performed
127 laboratory tensile experiments on well characterised suites of variably altered volcanic rocks.
128 We first present the experimental material, methods, and results. We then discuss the influence
129 of porosity and alteration on tensile strength, aided by existing theoretical and semi-empirical
130 constitutive models, and discuss the influence of different types of alteration (porosity-
131 increasing dissolution and porosity-decreasing precipitation) on tensile strength. Finally, we
132 highlight the implications of our new data using DEM modelling in which we model fracture
133 localisation following dyke pressurisation within hydrothermally altered host-rock.

134

135 **2 Materials and Methods**

136 A total of 25 variably altered blocks (typically about $30 \times 30 \times 30$ cm in size) collected
137 from La Soufrière de Guadeloupe (Eastern Caribbean, France), Chaos Crags (California, USA),
138 and Merapi volcano (Indonesia) were used for this study. The collection sites for the blocks are
139 shown on Fig. 1.

140 A suite of 15 blocks were collected from La Soufrière de Guadeloupe (Fig. 1a), an active
141 andesitic stratovolcano located on the French island of Guadeloupe in the Eastern Caribbean
142 (Komorowski et al., 2005; Moretti et al., 2020). Seven blocks were taken from the collapse scar
143 of the 2009 landslide on the eastern flank of the dome (blocks H2A, H3, H4A, H5A, H6, H29,
144 and H30). Three blocks were collected from the lava spines on the summit of the current lava
145 dome (which formed in 1530 CE): one block from Cratère Sud Central (H19) and two blocks
146 from an adjacent site (H21 and H22). Blocks were also collected from the west wall of the fault
147 “Faille 30 août” (H14 and H15) that cuts the 1530 CE dome, from the scar of an earthquake-
148 triggered landslide (WP1285), and from a lava adjacent to the Galion waterfall (H32). The final
149 block, a volcanic bomb from the 1976–1977 eruption, was taken from the roof of a small
150 disused thermal bathhouse to the south of the dome (WP1317). The blocks from La Soufrière

151 de Guadeloupe, previously described by Heap et al. (2021a, 2022), are andesites characterised
152 by a porphyritic texture comprising phenocrysts (often a few hundred microns long, but
153 occasionally as large as 1–2 mm) of dominantly plagioclase and pyroxene (orthopyroxene and
154 clinopyroxene) within a crystalline groundmass (Figs. 2a and 2b; Table 1). All samples contain
155 variable quantities of secondary minerals, such as kaolinite, alunite or natro-alunite, silica
156 polymorphs (quartz, cristobalite, tridymite, and opal- A), hematite, pyrite, gypsum, and talc
157 (Table 1).

158 Five blocks were collected from Chaos Crags (Fig. 1b), a suite of dacitic to rhyodacitic
159 lava domes in the Lassen Volcanic Center (California, USA; Heiken and Eichelberger, 1980;
160 Clynne and Muffler, 2017). All five blocks were collected from Dome C, which collapsed ~350
161 years ago (Clynne and Muffler, 2017). One block was taken from the tongue-shaped Chaos
162 Jumbles collapse deposit (block CCC), and four blocks were taken from the altered carapace of
163 the dome that now forms the collapse scar (blocks CC3, CC4A, CC4B, and CC10). The blocks
164 from Chaos Crags, previously described by Ryan et al. (2020) and Heap et al. (2021b), are
165 porphyritic rhyodacites containing phenocrysts of dominantly plagioclase, K-feldspar, and
166 quartz within a crystalline groundmass (Figs. 2c and 2d; Table 1). All samples contain variable
167 quantities of secondary minerals (cristobalite, hematite, smectite, and kaolinite; Table 1).

168 Five blocks were collected from Merapi volcano (Fig. 1c), an active stratovolcano
169 located on the island of Java in Indonesia (Voight et al., 2000; Surono et al., 2012). These blocks
170 (blocks M-U, M-SA1, M-SA2, M-HA1, and M-HA2) were collected from the 1902 dome, ~100
171 m to the northeast of the currently active dome. The blocks from Merapi volcano, previously
172 described in Heap et al. (2019) and Darmawan et al. (2022), are variably altered basaltic-
173 andesites with a porphyritic texture comprising phenocrysts of dominantly plagioclase and
174 pyroxene within a crystalline groundmass (Figs. 2e and 2f; Table 1). All samples contain

175 variable quantities of secondary minerals (natro-alunite, alunite, quartz, hematite, cristobalite,
176 gypsum, and various amorphous phases; Table 1).

177 Because we are interested in exploring the influence of hydrothermal alteration on the
178 tensile strength of volcanic rocks, the alteration assemblage was identified and the alteration
179 intensity of each block was quantified by the weight percentage (wt%) of secondary (i.e.
180 alteration) minerals. The mineral phases present in each block were identified by a combination
181 of optical microscopy, Raman spectroscopy, and X-ray powder diffraction (XRPD).
182 Quantitative phase analysis was then performed using the XRPD data and the Rietveld approach
183 (Bergmann et al., 1998) (Table 1). The data presented in Table 1 were taken from Heap et al.
184 (2019, 2021a, 2022). Backscattered scanning electron microscope (SEM) images of the least-
185 and most-altered blocks from each volcano are provided in Fig. 2. These images, especially
186 those for the samples from La Soufrière de Guadeloupe and Merapi volcano, show that the
187 most-altered samples have much more complex and heterogeneous microstructures (Fig. 2).

188 Multiple cylindrical samples were cored in the same orientation from each of the rock
189 blocks to a diameter of 20 or 40 mm (based on the volume of material available), and then cut
190 and precision-ground to a nominal length of 20 mm. The rock blocks contained no obvious pore
191 or crystal shape preferred orientation and so the coring direction in each block was selected to
192 maximise the number of cylindrical samples. The samples were washed and then dried in a
193 vacuum-oven at 40 °C for at least 48 h. The connected porosity of each sample was calculated
194 using the bulk sample volume and the skeletal (solid) sample volume measured by a helium
195 pycnometer (an AccuPyc II by Micromeritics©). Measurements of total porosity, determined
196 using the density of a powdered aliquot of each sample (measured using the pycnometer),
197 showed that there is little to no isolated porosity in any of the studied materials. Dry indirect
198 tensile strength was measured on oven-dry samples in a uniaxial loading frame (a LoadTrac II
199 load frame by Geocomp©; Griffiths et al., 2018) using the Brazil disc technique, a method in

200 which samples are deformed diametrically in compression (Fig. 3; Perras and Diederichs,
201 2014). Samples were deformed under ambient laboratory pressure and temperature at a constant
202 displacement rate of 0.025 mm. s⁻¹ until the formation of the first macrofracture, which
203 typically occurred during the first 30 s of the experiment. Samples were deformed in a loading
204 platen with curved loading jaws, and a hemispherical ball and seat were used ensure that there
205 was no misalignment (Fig. 3). Axial displacement and axial load were measured using a linear
206 variable differential transducer (LVDT) and a load cell (45 kN maximum), respectively (Fig.
207 3). Indirect tensile strength, σ_t , was then calculated using (Ulusay, 2014):

208

$$209 \quad \sigma_t = \frac{2F}{\pi DL}, \quad (1)$$

210

211 where F is the applied force at the propagation of the first macrofracture, and D and L are the
212 diameter and length of the discs, respectively. The tensile strength data for block CCC from
213 Chaos Crag, and the tensile strength data for four of the five blocks from Merapi volcano
214 (blocks M-U, M-SA1, M-SA2, and M-HA1), were previously published in Heap et al. (2021c).

215

216 **3 Results**

217 Representative force-displacement curves are provided in Fig. 4 for three samples from
218 La Soufrière de Guadeloupe (with high, medium, and low tensile strength), and the tensile
219 strength of the rocks from La Soufrière de Guadeloupe, Chaos Crag, and Merapi volcano are
220 plotted as a function of porosity and alteration in Fig. 5 (all data available in Table 2). In Figs.
221 5a and 5c, the different symbols and colours differentiate the data from the different volcanoes.
222 In Figs. 5b and 5d, the colour of the symbol (where red and yellow indicate low and high values,
223 respectively) indicates the alteration and porosity of the sample, respectively.

224 The data show that tensile strength is reduced as a function of increasing porosity. For
225 example, tensile strength decreases from ~14 to ~2 MPa as porosity is increased from ~0.05 to
226 almost 0.35 (Fig. 5a). The change in tensile strength as a function of increasing alteration varies
227 between the different sample suites (Fig. 5c). The tensile strength of the andesites from La
228 Soufrière de Guadeloupe decreases as a function of increasing alteration: tensile strength
229 decreases from ~14 to ~4 MPa as alteration is increased from ~6 to ~60 wt% (Fig. 5c). A notable
230 outlier exists in the La Soufrière de Guadeloupe dataset (sample H29_T3; Table 2). This sample
231 has a very low tensile strength of 0.9 MPa, but is not characterised by a high alteration intensity
232 (25.9 wt%). The relative weakness of sample H29_T3 is likely the result of its anomalously
233 high porosity of 0.33 (the porosity of the other samples prepared from this block are 0.27–0.28;
234 Table 2). The tensile strengths of the rhyodacites from Chaos Crags and the basaltic-andesites
235 from Merapi volcano, however, do not appear to vary systematically with increasing alteration
236 (Fig. 5c). For the rocks from Chaos Crags and Merapi volcano, the samples with the lowest
237 tensile strengths are not the most altered samples, and the samples with the highest tensile
238 strengths are not the least altered samples (Fig. 5c).

239

240 **4 Discussion**

241 4.1 Influence of porosity on the tensile strength of volcanic rocks

242 New mechanical data show that the tensile strength of variably altered volcanic rocks
243 from La Soufrière de Guadeloupe, Chaos Crags, and Merapi volcano decreases as a function of
244 increasing porosity (Fig. 5a), in accordance with previous studies on volcanic rocks (Heap et
245 al., 2012; Lamb et al., 2017; Hornby et al., 2019; Harnett et al., 2019; Kendrick et al., 2021;
246 Heap and Violay, 2021; Weydt et al., 2021; Heap et al., 2021c).

247 We compare our new data with those previously published for volcanic rocks (andesites,
248 basalts, dacites, and pyroclastic rocks) in Fig. 6, which shows that our new data are in broad

249 agreement with those previously published. When all the data are considered, the range of
250 tensile strength for a given porosity can be up to 20–25 MPa (Fig. 6). This range is the result of
251 sample-scale discontinuities (low-porosity samples with a low tensile strength likely contained
252 fractures, for example), microstructural differences (pore diameter, pore aspect ratio, and pore
253 orientation have been shown to influence tensile strength; Heap et al., 2021c), and differences
254 in their degree and type of alteration, as discussed in the next section.

255 We can further explore the influence of porosity on tensile strength using existing
256 theoretical constitutive models. Constitutive models exist to estimate the critical pressure drop
257 required to rupture bubbly magma (McBirney and Murase, 1970; Alidibirov, 1994; Zhang,
258 1999; Spieler et al., 2004; Koyaguchi et al., 2008). These micromechanical models describe the
259 tensile bursting of an array of gas-filled solid elastic shells under a given external tensile
260 pressure. However, Heap et al. (2021c) suggested that this critical threshold decompression
261 pressure could be interpreted as akin to the critical bulk tensile strength of porous rock, T , and
262 recast the equations as follows:

263

$$264 \quad T \approx \frac{T_0}{\phi} \quad (2a)$$

265

$$266 \quad T \approx \frac{T_0(1 - 1.7\phi)^{\frac{1}{2}}}{\phi} \quad (2b)$$

267

$$268 \quad T \approx \frac{2T_0(1 - \phi)}{1 + 2\phi} \quad (2c)$$

269

$$270 \quad T \approx \frac{2T_0(1 - \phi^n)}{a\phi^n} \quad (2d)$$

271

272
$$T \approx \frac{2T_0(1 - \phi)}{3\phi\sqrt{\phi^{-1/3} - 1}}, \quad (2e)$$

273

274 where T_0 is an effective characteristic tensile strength (see Koyaguchi et al., 2008), ϕ is the
 275 porosity, and a and n are defined constants (Alidibirov (1994) found $a = 1$ and $n = 1/3$, and
 276 Koyaguchi et al. (2008) found $a = 3$ and $n = 1$). Using a compiled dataset for volcanic rocks,
 277 Heap et al. (2021c) assumed that $\sigma_t = T$, and provided best-fit values of T_0 to each of the
 278 models given by Eq. (2), found by varying T_0 in such a way as to minimise the sum of square
 279 residuals between the logarithm of the data and the logarithm of each model result at the same
 280 porosity (Table 3).

281 In Fig. 7a we show the tensile strength of the rocks from La Soufrière de Guadeloupe,
 282 Chaos Crags, and Merapi volcano as a function of porosity, alongside the modelled curves using
 283 Eq. (2) and the values of T_0 determined from the previously compiled dataset in Heap et al.
 284 (2021c) (Table 3). The modelled curves shown in Fig. 7a underestimate the tensile strength of
 285 the rocks measured herein. This underestimation may be due to the numerous low-porosity
 286 samples with a low tensile strength in the compiled dataset (Fig. 6). As discussed above, these
 287 low-strength samples likely contained sample-scale discontinuities such as fractures, features
 288 not present in the samples measured in this study.

289 We have performed the same fitting procedure described above to provide best-fit
 290 values of T_0 for the andesites from La Soufrière de Guadeloupe, the most abundant dataset. Fig.
 291 7b shows the tensile strength of the andesites from La Soufrière de Guadeloupe as a function
 292 of porosity, alongside the modelled curves using Eq. (2) and the best-fit values of T_0 for the La
 293 Soufrière de Guadeloupe rocks (Table 3). Based on the good description of Eqs. (2d) and (2e)
 294 to the La Soufrière de Guadeloupe data (the sums of the square residuals are provided in Table
 295 3), we conclude that these models can be used to estimate the tensile strength of rocks from La

296 Soufrière de Guadeloupe, and perhaps other similarly-altered andesites (using the best-fit values
297 of T_0 provided in Table 3).

298 The similarity between the tensile strength of volcanic rocks and the critical threshold
299 decompression pressure measured from shock-tube experiments (see Heap et al., 2021c)
300 suggests that, in the absence of shock-tube data, the tensile strength data presented herein (Fig.
301 5; Table 2), and/or Eq. (2) and the best-fit values of T_0 (Table 3), can be used to estimate the
302 fragmentation threshold of the studied materials below a porosity of 0.3. Above a porosity of
303 0.3, tensile strength data deviate from fragmentation threshold data from shock-tube
304 experiments due to overpressure leakage (Mueller et al., 2008; Heap et al., 2021c).

305

306 4.2 Influence of alteration on the tensile strength of volcanic rocks

307 New mechanical data show that the tensile strength of the andesites from La Soufrière
308 de Guadeloupe decreases as a function of increasing alteration (Fig. 5c), in accordance with
309 sparse published data for volcanic rocks (Pola et al., 2014; Mayer et al., 2016). However, the
310 tensile strength data for the rocks from Chaos Crags and Merapi volcano do not appear to vary
311 systematically with alteration (Fig. 5c). We highlight that there are fewer samples in the Chaos
312 Crags and Merapi volcano datasets than in the La Soufrière de Guadeloupe dataset, and that the
313 range of alteration intensity measured for the samples from Chaos Crags is smaller than for the
314 other two datasets (Fig. 5c), limitations that could serve to obscure a clear trend in these data.

315 It is unfortunately not possible to replot the compiled data of Fig. 6 as a function of
316 alteration, as the vast majority of studies did not report detailed mineralogical information for
317 their studied materials. Further, because this compilation consists of a combination of unaltered
318 samples, altered samples, and samples for which there is no information, it is challenging to
319 assess the role of alteration using the compiled dataset, or by comparing our new data with the
320 compiled data. Aided by ancillary data, microstructural observations, and comparisons with

321 published data, we will now discuss the influence of alteration on the three suites of rocks
322 measured herein.

323 Our new data for the rocks from La Soufrière de Guadeloupe are in agreement with the
324 conclusions of previous studies, which suggest that alteration decreases the tensile strength of
325 volcanic rocks (Pola et al., 2014; Mayer et al., 2016). We also note that the uniaxial compressive
326 strength, a strength parameter that is typically 10 or 12 times higher than the tensile strength
327 (Cai, 2010), of these same rocks from La Soufrière de Guadeloupe was also found to decrease
328 as a function of increasing alteration (Heap et al., 2021a).

329 One possible reason for the measured reduction in the tensile strength of the samples
330 from La Soufrière de Guadeloupe as a function of alteration is that the secondary mineral
331 assemblage is likely weaker than the primary mineral assemblage. Indeed, it was argued by
332 Heap et al. (2021a) that the reduction in compressive strength of these rocks as a function of
333 alteration was the result of the relative weakness of the secondary mineral assemblage and, in
334 particular, the presence of clay minerals. Clay minerals, abundant in these rocks (Table 1), have
335 been previously considered by several authors to reduce the overall strength of volcanic rocks
336 (del Potro and Hürlimann, 2009; Nicolas et al., 2020; Opfergelt et al., 2006; Watters and
337 Delahaut, 1995).

338 Another possible reason for the measured reduction in the tensile strength is that
339 hydrothermal alteration has increased the microstructural heterogeneity of the rocks (as shown
340 in the SEM images of Figs. 2 and 8). Microstructural heterogeneity has been previously shown
341 to reduce the strength of rocks (Tang et al., 2007; Villeneuve et al., 2012; Heap et al., 2016;
342 Peng et al., 2017; Xu et al., 2020).

343 A final possible reason for the reduction in the tensile strength of the samples from La
344 Soufrière de Guadeloupe as a function of alteration is that the alteration could have increased
345 porosity the samples, a factor known to greatly influence tensile strength (Fig. 6; Heap et al.,

346 2012; Lamb et al., 2017; Hornby et al., 2019; Harnett et al., 2019; Kendrick et al., 2021; Heap
347 and Violay, 2021; Weydt et al., 2021; Heap et al., 2021c). Indeed, the porosity of the andesites
348 from La Soufrière de Guadeloupe increases as a function of alteration (Fig. 9; see also Figs. 5c
349 and 5d). However, a microstructural inspection of the andesites from La Soufrière de
350 Guadeloupe shows that the alteration is characterised by both porosity-increasing alteration
351 (mineral dissolution leading to the formation of pores), especially in plagioclase crystals (Figs.
352 8a and 8b), and porosity-decreasing alteration (pore- and crack-filling mineral precipitation by
353 Na-alunite and silica polymorphs; Fig. 8c). Therefore, it is unclear from these data and
354 observations whether the alteration has increased the porosity of the samples from La Soufrière
355 de Guadeloupe (as suggested by Fig. 9), or whether the more porous samples are simply more
356 altered due to their higher fluid-rock ratios. As a result, it is challenging to separate the influence
357 of porosity and alteration on tensile strength and draw firm conclusions as to the influence of
358 alteration. Studies that alter volcanic rocks under controlled laboratory conditions and then
359 measure their tensile strengths would be required to separate the contributions of porosity and
360 alteration on the tensile strength of volcanic rocks. For example, Farquharson et al. (2019),
361 altered samples in the laboratory by immersing them in a bath of sulphuric acid and found that
362 alteration increased the porosity and decreased the uniaxial compressive strength of andesite.

363 Although we cannot draw firm conclusions as to influence of alteration on the tensile
364 strength of the andesites from La Soufrière de Guadeloupe, because of the aforementioned link
365 between porosity and alteration, we speculate that hydrothermal alteration has reduced their
366 tensile strength due to the relative weakness of the secondary mineral assemblage (Table 1) and
367 the increase in microstructural heterogeneity that accompanies hydrothermal alteration (Figs. 2
368 and 8).

369 The tensile strength of the basaltic-andesites from Merapi volcano does not appear to
370 vary systematically with alteration (Fig. 5c). The block with the highest tensile strength (~10

371 MPa; block M-SA2) is not the least altered block, and the block with the lowest tensile strength
372 (~2–3 MPa; block M-SA1) is not the most altered block (Fig. 5c; Table 2). The high tensile
373 strength of block M-SA2 is likely due a combination of its low porosity (Table 2) and an
374 alteration assemblage that is not dominated by low-strength secondary minerals (Table 1), and
375 the low tensile strength of block M-SA1 can be explained by its high porosity (Table 2). Similar
376 to the andesites from La Soufrière de Guadeloupe, although the porosity of the basaltic-
377 andesites from Merapi volcano appears to increase as a function of increasing alteration (Fig.
378 9), they are characterised by both porosity-increasing (Fig. 8h) and porosity-decreasing (Figs.
379 8f and 8g) alteration. It is also unclear, as for the andesites from La Soufrière de Guadeloupe,
380 whether the alteration has increased the porosity of the samples from Merapi volcano, or
381 whether the more porous samples are simply more altered. Because of the similarities in
382 alteration assemblage and microstructure between the rocks from La Soufrière de Guadeloupe
383 and Merapi volcano, we anticipate, if more data were available, that the rocks from Merapi
384 volcano would also show a similar trend of decreasing tensile strength as a function of
385 alteration. Indeed, Darmawan et al. (2022) concluded that the uniaxial compressive strength of
386 altered rocks from Merapi volcano, including some of the samples tested here, decreased as a
387 function of increasing alteration due to the relative weakness of the secondary mineral
388 assemblage.

389 The tensile strength of the rhyodacites from Chaos Crags also does not appear to vary
390 systematically with alteration (Fig. 5c). The block with the highest tensile strength (~7–8 MPa;
391 block CC4A) is not the least altered block, and the block with the lowest tensile strength (~3–
392 4 MPa; block CC4B) is not the most altered (Fig. 5c; Table 2; although some samples from
393 blocks CC3 and CC10 also have a tensile strength of ~3–4 MPa). In a previous study, Heap et
394 al. (2021b) found that the uniaxial compressive strength of block CC4A was considerably
395 higher than for the other rocks from Chaos Crags (~120–140 MPa, compared to ~40–55 MPa).

396 These authors suggested that pore- and crack-filling alteration in sample CC4A (Fig. 8d and
397 8e) was responsible for the observed increase in uniaxial compressive strength (Heap et al.,
398 2021b). Unlike the rocks from La Soufrière de Guadeloupe and Merapi volcano, block CC4A
399 from Chaos Crag does not contain abundant porosity-increasing alteration (i.e. mineral
400 dissolution). Therefore, we conclude here that the high tensile strength of block CC4A is likely
401 to be the result of pore- and crack-filling alteration (Fig. 8d and 8e), which has reduced the
402 porosity of this block (Table 2). As discussed above, this same conclusion was drawn to explain
403 the higher compressive strength of block CC4A in Heap et al. (2021b).

404 Although it is difficult to draw firm conclusions as to the influence of alteration on the
405 tensile strength of volcanic rocks, because porosity and alteration influence each other, we
406 conclude that it is likely that hydrothermal alteration has modified the tensile strength of the
407 rocks collected from La Soufrière de Guadeloupe, Chaos Crag, and Merapi volcano, and in
408 different ways. The alteration of the rocks from La Soufrière de Guadeloupe and Merapi
409 volcano, which we consider to have reduced tensile strength, manifests as both porosity-
410 increasing (dissolution) and porosity-decreasing (pore- and crack-filling mineral precipitation)
411 alteration (Fig. 8), and is characterised by a relatively weak secondary mineral assemblage
412 consisting of minerals such as clays (Table 1) and an increase in microstructural heterogeneity
413 (Figs. 2 and 8). The alteration of one of the blocks from Chaos Crag, which we consider to
414 have increased tensile strength, is characterised by pore- and crack-filling mineral precipitation
415 and an absence of the dissolution textures that typify the samples from La Soufrière de
416 Guadeloupe and Merapi volcano (Fig. 8). We conclude, therefore, that not only does alteration
417 likely influence the tensile strength of volcanic rocks, but also that the type of alteration
418 (porosity-increasing or porosity-decreasing alteration, and the alteration minerals involved)
419 likely dictates whether the alteration decreases or increases the tensile strength.

420 The constitutive models presented in Eq. (2) provide estimates for the tensile strength
421 when the porosity and an effective characteristic tensile strength, T_0 , is known. However, some
422 volcano monitoring methods, such as remote sensing (Kereszturi et al., 2020; Mueller et al.,
423 2021), provide the extent and intensity of hydrothermal alteration. To assist volcano monitoring
424 efforts, we can adapt Eq. (2) so that tensile strength can be estimated for a given degree of
425 alteration, rather than for a given porosity. To do so, we focus on the data for the andesites from
426 La Soufrière de Guadeloupe, the most abundant dataset. The relationship between porosity and
427 alteration (Fig. 9) can be described by a simple power law of the form $\phi = c_1 A^{c_2}$, where A is
428 the alteration (in wt%). We fit for the two constants c_1 and c_2 using a least squares minimization
429 of the power law $\gamma = f(A)$ to the La Soufrière de Guadeloupe subset of the data in Fig. 9. By
430 this method, we find that $c_1 = 0.0252$ wt.% and $c_2 = 0.5660$, respectively, for the data for La
431 Soufrière de Guadeloupe. The term $c_1 A^{c_2}$ can then be substituted for ϕ in Eq. (2) to yield a
432 sequence of expressions for T that depend on A and the constants T_0 , c_1 , and c_2 , all of which
433 are found independently,

434

$$435 \quad T \approx \frac{T_0 A^{-c_2}}{c_1} \quad (3a)$$

436

$$437 \quad T \approx \frac{T_0 A^{-c_2} (1 - 1.7 A^{c_2})^{\frac{1}{2}}}{c_1} \quad (3b)$$

438

$$439 \quad T \approx T_0 \left(\frac{3}{2c_1 A^{c_2} + 1} - 1 \right) \quad (3c)$$

440

$$441 \quad T \approx \frac{2T_0 ((c_1 A^{c_2})^{-n} - 1)}{a} \quad (3d)$$

442

443
$$T \approx \frac{2T_0 A^{-c_2} (1 - c_1 A^{c_2})}{3c_1 \sqrt{(c_1 A^{c_2})^{-1/3} - 1}}. \quad (3e)$$

444

445 We show in Fig. 10 the experimental data for La Soufrière de Guadeloupe alongside the
 446 modelled curves for Eq. (3). As for Fig. 7b, we use the best-fit values of T_0 for the La Soufrière
 447 de Guadeloupe data, provided in Table 3. Based on the good description of these models to the
 448 La Soufrière de Guadeloupe data, we conclude that it is also possible to provide tensile strength
 449 estimates for andesites from La Soufrière de Guadeloupe using the degree of alteration, rather
 450 than the porosity (using the best-fit values of T_0 provided in Table 3 and c_1 and c_2 found via
 451 Fig. 9). It is recommended here that Eqs. (3d) and (3e) are used preferentially, due to their low
 452 sum of square residuals to the data (provided in Table 3). As discussed above, Eq. (3) and the
 453 best-fit values of T_0 (Table 3) could also be used to estimate the fragmentation threshold of the
 454 studied materials below a porosity of 0.3. We again highlight that the outlier on Fig. 10 (sample
 455 H29_T3), which has a very low tensile strength compared to its alteration intensity, is likely the
 456 result of its anomalously high porosity (see Table 2 and the discussion above).

457

458 4.3 Implications

459 Our experimental study provides values of tensile strength for hydrothermally altered
 460 volcanic rocks (Fig. 5). As noted above, the tensile strength of volcanic rocks is required for
 461 estimates of (1) the magma overpressure required for magma chamber rupture and dyke
 462 propagation, (2) the limits on magma chamber volume, (3) magma under-pressure leading to
 463 the generation of collapse-related structures, and (4) process-based models of the nature and
 464 dynamics of volcanotectonic seismicity during unrest and eruptive phases. Because the rocks
 465 adjacent to a magma chamber or dyke are likely to be hydrothermally altered (e.g., Goto et al.,
 466 2008; Salaün et al., 2011; Mordensky et al., 2018; Yilmaz et al., 2021), we propose that the
 467 tensile strengths of altered volcanic rocks, documented here, are perhaps the most suited to

468 provide estimates of dyke and magma chamber overpressure and magma chamber volume.
469 Similarly, the volcanic rocks in geothermal reservoirs are also often hydrothermally altered
470 (e.g., Browne, 1978; Marks et al., 2010; Siratovich et al., 2014; Cant et al., 2018; Lévy et al.,
471 2018; Heap et al., 2020) and so we propose that modelling designed to, for example, guide
472 reservoir stimulation strategies should also consider tensile strength values for hydrothermally
473 altered volcanic rocks.

474 FEM (Heap et al., 2014; Chen et al., 2017) and DEM (Holohan et al., 2017; Harnett et
475 al., 2018, 2020; Heap and Harnett, 2021) models designed to better understand the mechanical
476 behaviour of volcanic rocks and structures also require a robust value for the tensile strength of
477 volcanic rock. However, it is more common to use a laboratory-measured uniaxial compressive
478 strength and then assume a ratio, typically 10 or 12, between the compressive and tensile
479 strength. To assist such modelling, we provide here the range of compressive to tensile strength
480 ratios for our studied materials (Table 4; Fig. 11a) and investigate whether this ratio varies
481 systematically as a function of porosity (Fig. 11b) or alteration (Fig. 11c).

482 We find that the ratio of compressive to tensile strength for the volcanic rocks studied
483 here is between ~ 5 and ~ 20 , and that uniaxial compressive strength increases as a function of
484 tensile strength (Fig. 11a; Table 4). This ratio range is similar to that provided by Cai (2010),
485 who showed that it varied from 4 to 40 for a range of rock types (with a mode ratio of 14). Fig.
486 11 shows that the ratio of compressive to tensile strength does not vary systematically as a
487 function of porosity or alteration. Nevertheless, our data (Table 4) show that (1) the accuracy
488 of FEM and DEM models could be improved by using laboratory-measured values for both
489 uniaxial compressive and tensile strength and (2) if tensile strength is unknown, there is
490 justification for running models using a wide range of compressive to tensile strength ratios.

491 The above discussion prompts the following questions. (1) How do changes in the
492 tensile strength of hydrothermally altered volcanic rocks influence large-scale volcanic

493 processes? (2) How are the predictions from large-scale modelling influenced by changing the
494 ratio of compressive to tensile strength? To tackle these questions, we developed two-
495 dimensional DEM models in Particle Flow Code (PFC; Itasca Consulting Group, Inc.) capable
496 of reproducing solid and brittle rock behaviour and deformation. The aim of the models is to
497 investigate host-rock damage accumulation and distribution in response to the pressurisation of
498 a dyke-like magma body. A packed particle assemblage was created following the procedure
499 outlined by Potyondy and Cundall (2004), after which contact bonds were installed between
500 the particles forming the host-rock (coloured grey in the resultant figures) to create a bonded
501 particle assemblage capable of reproducing solid rock behaviour (Potyondy and Cundall, 2004;
502 Potyondy, 2012). The dyke, a 700 m-long and 100 m-wide penny-shaped crack, was located at
503 a depth of 300 m within a homogeneous host-rock. The particles within the dyke (coloured red
504 in the resultant figures) remained unbonded, to simulate fluid-like properties. The assemblage
505 was then settled under a gravitational acceleration of 9.81 m/s^2 , following the procedure
506 outlined in Holohan et al. (2011). Dyke pressurisation was implemented within the model by
507 increasing the radii of the particles within the dyke by a set factor, leading to a constant
508 incremental area increase (an area increase of 1% was used for the models presented here).
509 Damage accumulation in the host-rock is visualised in the models by examining interparticle
510 bond breakage. Bond breakage (shown by black lines in the resultant figures) occurs when local
511 stresses exceed the cohesive or tensile strength of the individual contacts between particles. We
512 can then quantify this damage as a proportion of the still-bonded contacts in the model. We
513 highlight that our modelling does not consider temperature-induced changes to the physical and
514 mechanical properties of the host-rock adjacent to the dyke. High-temperatures can promote
515 thermal microcracking and/or chemical or phase transformations that can reduce, for example,
516 strength and Young's modulus (Heap and Violay, 2021).

517 To address the first question above, and as guided by our laboratory data and
518 observations, the mechanical properties of the homogeneous host-rock were chosen to simulate
519 three key scenarios: (1) weak hydrothermally altered host-rock, (2) unaltered or intact rock, and
520 (3) strong hydrothermally altered host-rock. To ensure that the bulk behaviour of the particle-
521 based model accurately represents the laboratory data, we performed an iterative calibration
522 procedure (further outlined in Holohan et al., 2011; Potyondy, 2016; Harnett and Heap, 2021),
523 details of which can be found in the Supplementary Material. The input parameters (the target
524 input parameters and those resulting from the calibration procedure) for the modelling are
525 provided in Table 5.

526 We show the model results for each of the three scenarios (“intact”, “altered weak”, and
527 “altered strong”) in Fig. 12. We can quantify the damage accumulated due to dyke
528 pressurisation in each case by calculating the number of broken contacts as a proportion of
529 initial bonded contacts in the gravitationally stable model. We find the following proportions
530 of damage in each scenario: (1) 2.9% microcracking in the intact host-rock (Fig. 12b), (2) 6.5%
531 microcracking in the weak hydrothermally altered host-rock (Fig. 12a), and (3) 1.6%
532 microcracking in strong hydrothermally altered host-rock (Fig. 12c). In other words, weak
533 hydrothermally altered host-rock will be more pervasively damaged than unaltered host-rock,
534 and strong hydrothermally altered host-rock will be less damaged than unaltered host-rock. We
535 highlight that our modelling assumes that the host-rock is brittle and that weak hydrothermally
536 altered host-rock could reduce the number of microcracks relative to the unaltered case if the
537 rock is able to deform in a ductile manner (Mordensky et al., 2019). Our modelling also shows
538 that (1) the damage is more widespread in the weak hydrothermally altered host-rock (Fig. 12a),
539 and, conversely, damage is more localised in the strong hydrothermally altered host-rock (Fig.
540 12c) and (2) the number of fractures that reach the surface increases when the host-rock is weak,
541 and decreases when the host-rock is strong (Fig. 12).

542 To address the second question, the ratio of compressive to tensile strength of the
543 homogeneous host-rock was varied between 5 and 20 (guided by our experimental data; Table
544 4), whilst maintaining a constant Young's modulus of 30 GPa and a constant uniaxial
545 compressive strength of 100 MPa (i.e. we only varied the tensile strength). A compressive to
546 tensile strength ratio of 10 represents the same host-rock properties as the "intact" state shown
547 in Fig. 12. We again performed an iterative calibration procedure, details of which can be found
548 in the Supplementary Material. The input parameters (the target input parameters and those
549 resulting from the calibration procedure) for the modelling are provided in Table 6. The model
550 results are presented in Fig. 13. We find the following proportions of damage in each scenario:
551 (1) 0.9% microcracking in the host-rock with a ratio of 5 (Fig. 13a), (2) 2.9% microcracking in
552 the host-rock with a ratio of 10 (Fig. 13b), and (3) 7.8% microcracking in the host-rock with a
553 ratio of 20 (Fig. 13c). In other words, increasing the ratio of compressive to tensile strength (i.e.
554 decreasing the tensile strength) results in a more pervasively damaged host-rock. Our modelling
555 also shows that (1) damage is more widespread as the ratio of compressive to tensile strength
556 increases and (2) the number of fractures that reach the surface remains the same for ratios
557 tested here (Fig. 13).

558 Taken together, our DEM modelling shows that the extent and spatial distribution of
559 damage surrounding a pressurised source is different for weak and strong hydrothermally
560 altered host-rock (Figs. 12 and 13), with implications for the nature and dynamics of
561 volcanotectonic seismicity during unrest and eruptive phases (Roman and Cashman, 2008). For
562 example, the hundreds of shallow (i.e. within the hydrothermal system), low-magnitude
563 earthquakes at La Soufrière de Guadeloupe each month (Moretti et al., 2020) could be, in part,
564 due to the alteration of the rock hosting the hydrothermal system. We also note that a weak
565 hydrothermally altered host-rock may also provide a greater number of paths to the surface,
566 which could be used for, for example, the escape of hydrothermal fluids (e.g., as fumaroles).

567 Improving the circulation of hydrothermal fluids may increase the efficiency and extent of the
568 alteration, further influencing the physical and mechanical properties of the host-rocks. A
569 greater number of larger fractures may also help create viable geothermal and epithermal
570 mineral resources by increasing permeability and channelising the flow of hydrothermal fluids,
571 respectively (Rowland and Simmons, 2012; Heap et al., 2020). Taken together, these models
572 suggest that alteration induced changes to tensile strength should be considered in the large-
573 scale modelling of volcanic and geothermal systems.

574

575 **5 Conclusions and future work**

576 Motivated by the common occurrence of hydrothermal alteration at volcanic and
577 geothermal systems, the need for reliable values of tensile strength for modelling, and the
578 paucity of laboratory data, we performed a systematic study designed to (1) provide values for
579 the tensile strength of hydrothermally altered volcanic rocks and (2) to explore the influence of
580 alteration on the tensile strength of volcanic rocks. Our study shows that the tensile strength of
581 volcanic rocks decreases as a function of porosity (Figs. 5a and 5b), in accordance with previous
582 studies (Fig. 6), and as a function of alteration (Figs. 5c and 5d). However, it is challenging to
583 separate the influence of porosity and alteration on tensile strength, because the initial porosity
584 influences the alteration intensity due to the higher fluid-rock ratio, and the alteration influences
585 the porosity (Fig. 8). While the influence of porosity on the tensile strength of volcanic rocks is
586 well-established (Fig. 6), we use our new data and observations to speculate on the influence
587 of alteration on the tensile strength of volcanic rocks. Taken together, our data and observations
588 suggest that hydrothermal alteration could increase or decrease tensile strength, depending on
589 the type of alteration. Decreases in tensile strength following alteration are thought to be the
590 result of mineral dissolution, the replacement of primary minerals with weak secondary
591 minerals (such as clays), and an increase in microstructure heterogeneity. Increases in tensile

592 strength following alteration are thought to be the result of pore- and crack-filling mineral
593 precipitation.

594 Large-scale simulations using DEM models, guided by our experimental results, shows
595 that the tensile strength of hydrothermally altered volcanic rocks influences the extent and
596 spatial distribution of damage surrounding a pressurised source (Figs. 12 and 13). Our
597 modelling therefore emphasises that the tensile strengths of altered volcanic rocks should be
598 used in models designed to better understand volcanic processes and in the development of
599 strategies designed to increase the efficiency of volcanic geothermal reservoirs, systems often
600 characterised by pervasive hydrothermal alteration.

601 To conclude, our study suggests that mapping the extent and evolution of hydrothermal
602 systems is important to inform modelling endeavours (using, for example, electrical methods;
603 Rosas-Carbajal et al., 2016; Byrdina et al., 2017; Ghorbani et al., 2018; Soueid Ahmed et al.,
604 2018), and that future research should focus on understanding and modelling the geophysical
605 and geochemical signatures of alteration associated with rock weakening and rock
606 strengthening. Future experimental studies should focus on (1) measuring the tensile strength
607 of volcanic rocks that have been altered in the laboratory to preserve different alteration
608 intensities and (2) determining the influence of water-saturation and temperature on the tensile
609 strength of hydrothermally altered volcanic rocks, factors known to influence the mechanical
610 behaviour of volcanic rocks (Heap and Violay, 2021).

611

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634

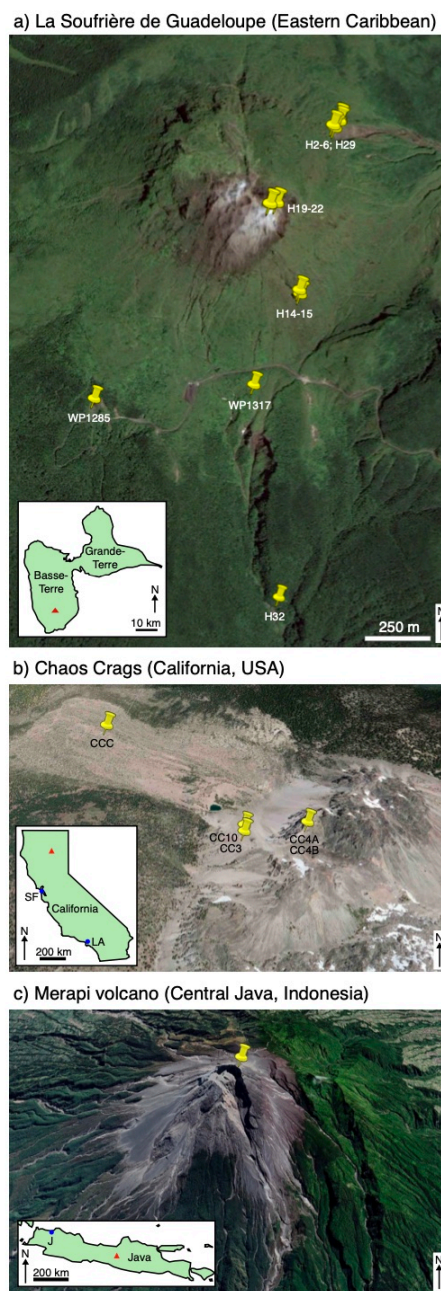
635 **CRedit author statement**

636 **Michael J. Heap:** Conceptualization; Methodology; Formal analysis; Investigation; Resources;
637 Writing - Original draft; Visualization; Supervision; Project administration; Funding
638 acquisition

639 **Claire Harnett:** Conceptualization; Methodology; Software; Formal analysis; Writing -
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642 Editing
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- 653 **Roberto Moretti:** Resources; Project administration; Writing - Review & Editing
654

655 **Fig. 1.** Sample collection sites. Images of (a) La Soufrière de Guadeloupe (Eastern Caribbean,
656 France), (b) Chaos Crags (California, USA), and (c) Merapi volcano (Java, Indonesia)
657 showing the location of the sample collection sites (from Earth data ©2019 Google). Insets
658 show maps of Guadeloupe, California, and Java, respectively, with the volcanoes indicated by
659 red triangles. Global Positioning System (GPS) coordinates for the sampling sites are
660 provided in the Supplementary Material.

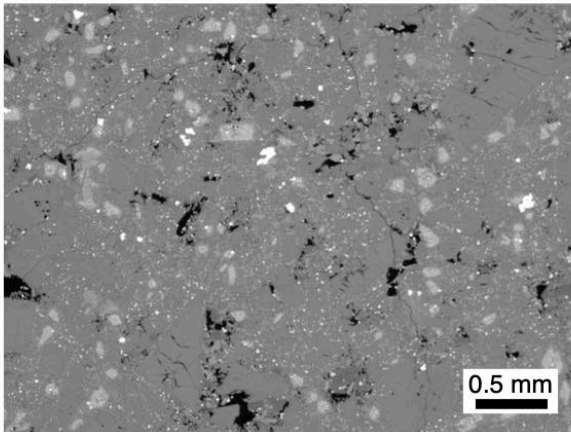


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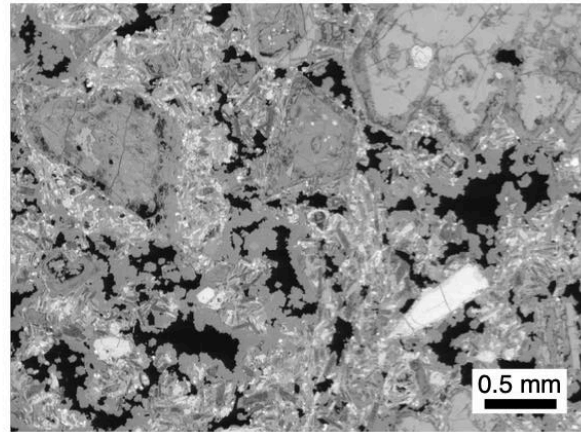
662

663 **Fig. 2.** Backscattered scanning electron microscope (SEM) of the least- and most-altered rocks
664 from each volcano (based on the weight percentage of secondary minerals, indicated above
665 each image). La Soufrière de Guadeloupe – H32 (least altered) and H19 (most altered); Chaos
666 Crags – CCC (least altered) and CC4A (most altered); Merapi volcano – M-U (least altered)
667 and M-HA2 (most altered).

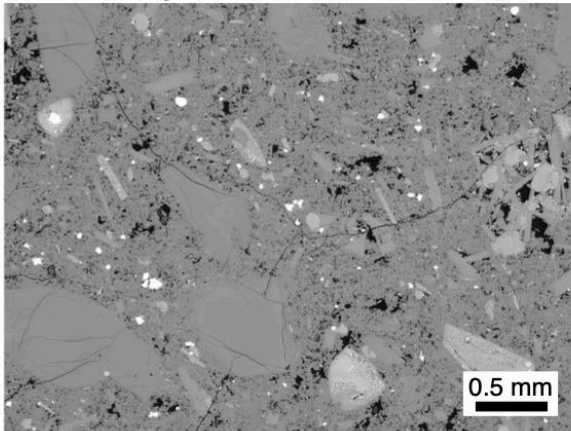
(a) La Soufrière (H32; alteration = 6.0 wt.%)



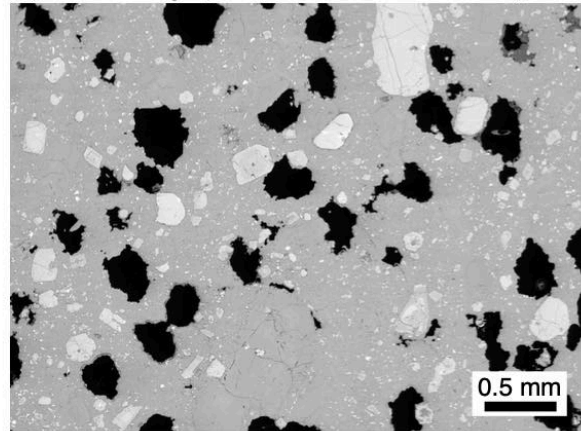
(b) La Soufrière (H19; alteration = 62.8 wt.%)



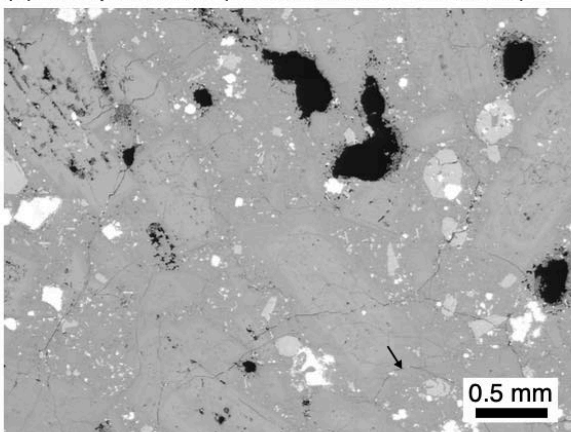
(c) Chaos Crags (CCC; alteration = 6.4 wt.%)



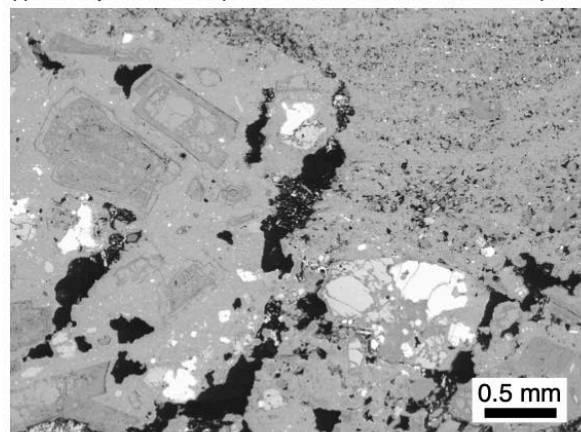
(d) Chaos Crags (CC3; alteration = 24.8 wt.%)



(e) Merapi volcano (M-U; alteration = 7.5 wt.%)

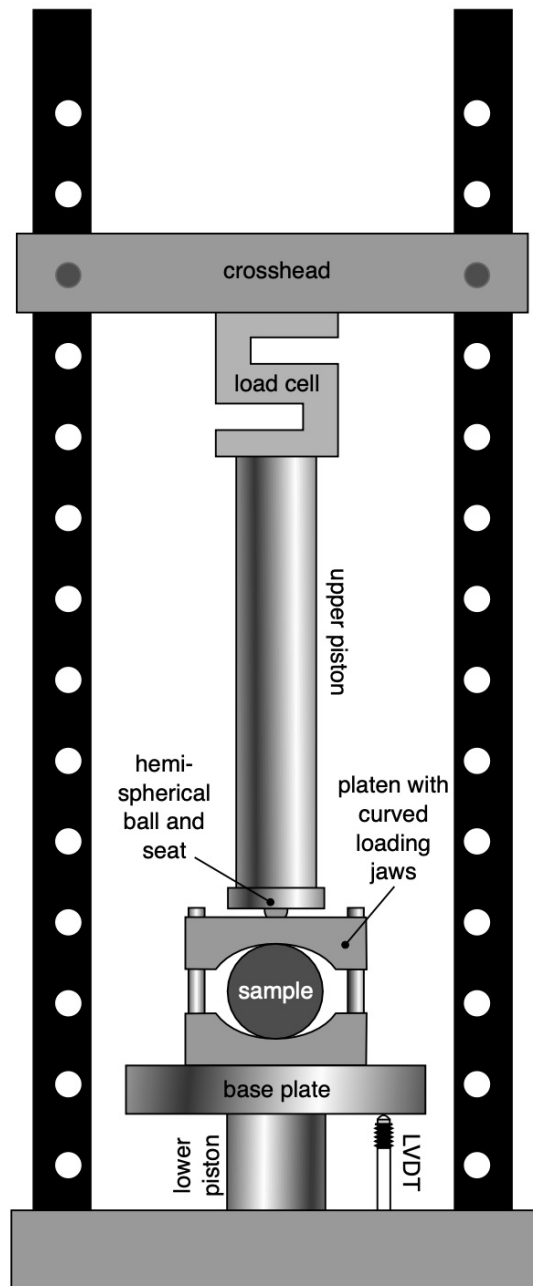


(f) Merapi volcano (M-HA2; alteration = 62 wt.%)



668

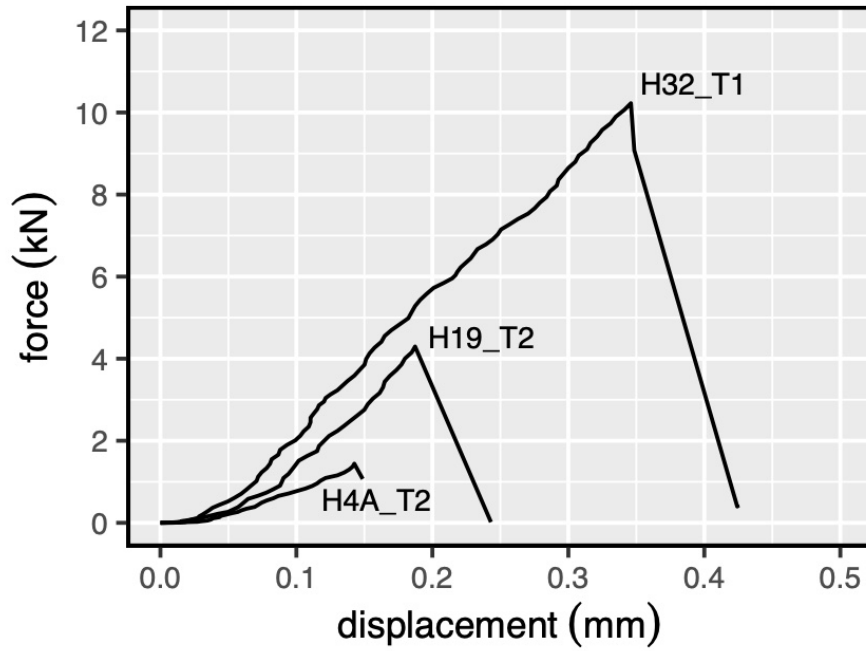
669 **Fig. 3.** Schematic diagram of the experimental setup to measure the tensile strength of rocks
670 (not to scale). LVDT – linear variable differential transducer. The setup is approximately 2 m
671 in height.



672

673

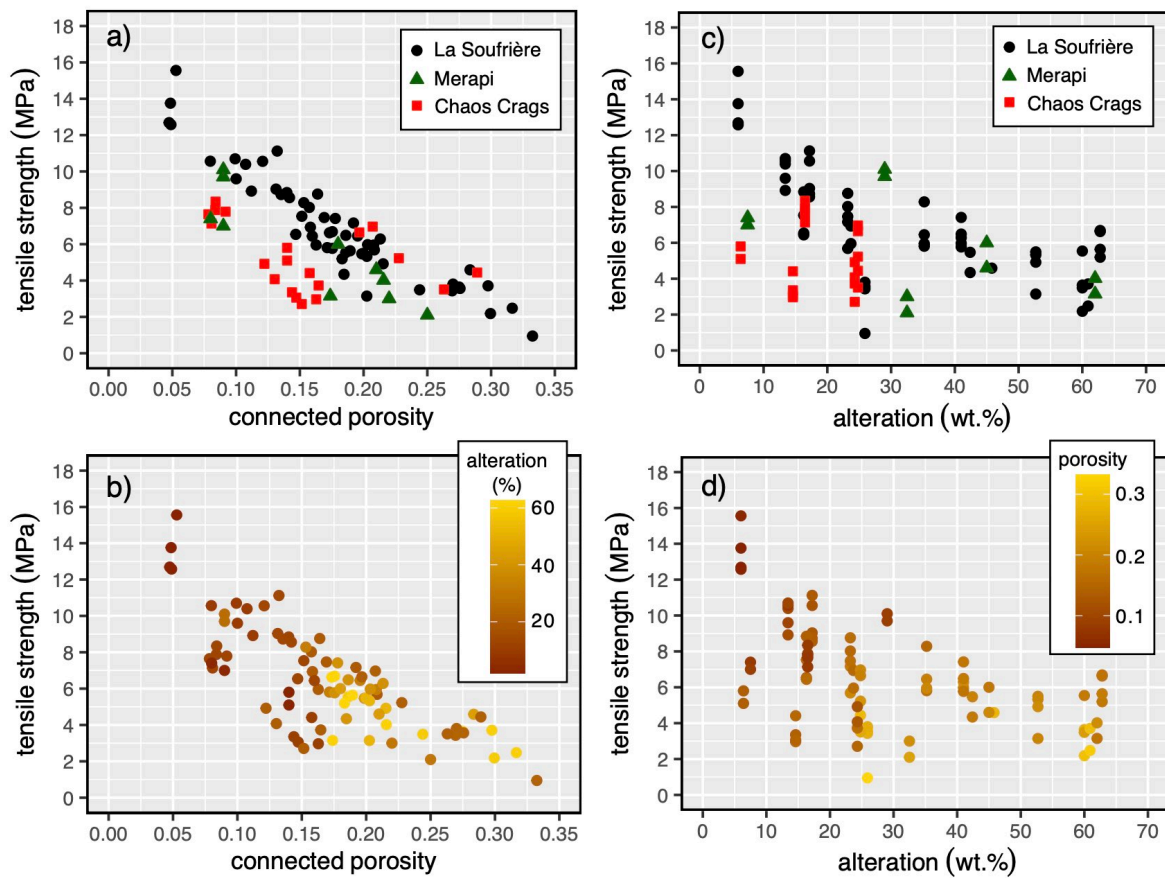
674 **Fig. 4.** Representative force-displacement curves for three of the samples (all from La Soufrière
675 de Guadeloupe; Table 2) deformed for this study.



676

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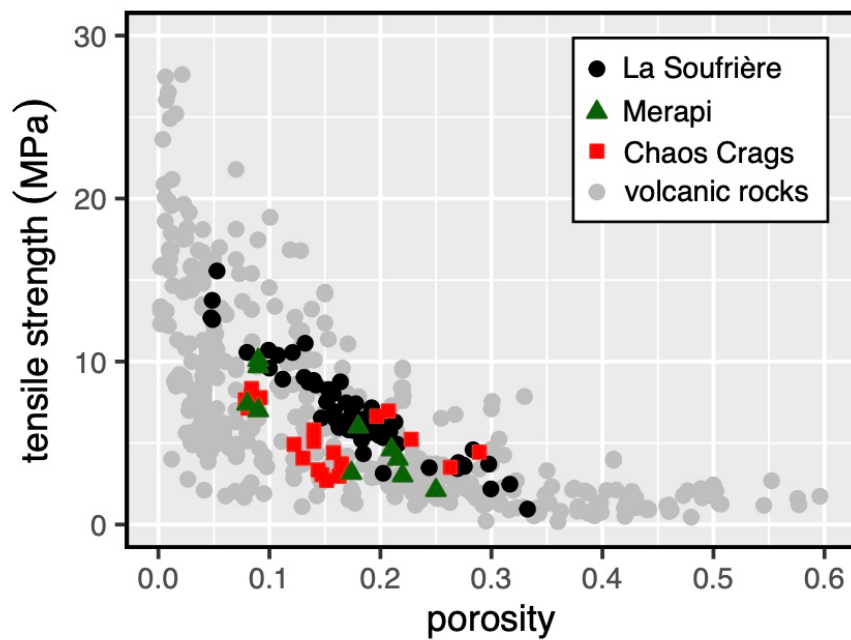
678 **Fig. 5.** Panels (a) and (b) show the tensile strength as a function of porosity. Panels (c) and (d)
679 show the tensile strength as a function of alteration (the weight percentage of secondary
680 minerals). For panels (a) and (c), La Soufrière de Guadeloupe – black circles; Chaos Crags –
681 red squares; Merapi volcano – green triangles. For panels (b) and (d), the colour of the symbol
682 indicates the alteration and porosity, respectively. Experimental errors for the measurements of
683 porosity and tensile strength are $< 1\%$ (i.e. within the symbol size). Relative errors for the
684 weight percentages are 5–10%.



685

686

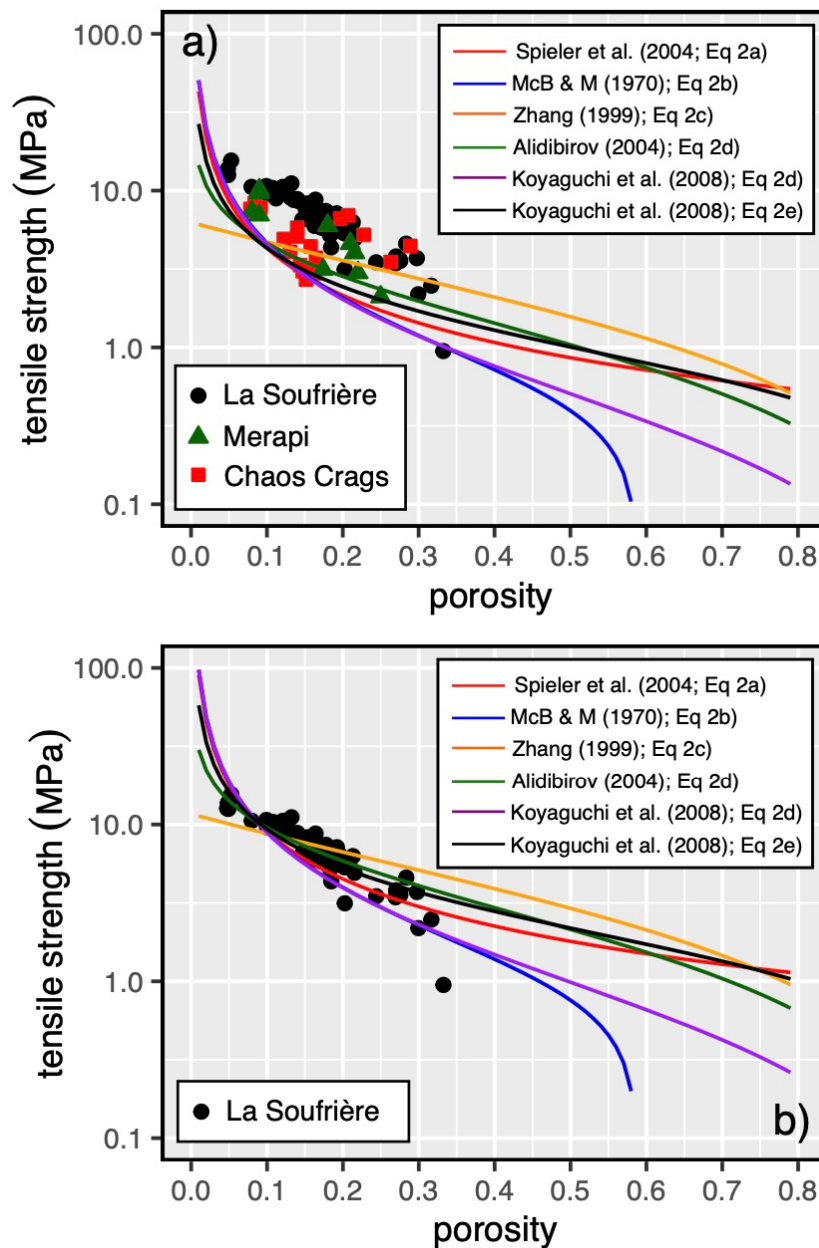
687 **Fig. 6.** Tensile strength as a function of porosity for andesites from La Soufrière de Guadeloupe
688 (black circles), rhyodacites from Chaos Crags (red squares), basaltic-andesites from Merapi
689 volcano (green triangles), and compiled data from the literature (andesites, basalts, dacites, and
690 pyroclastic rocks; grey circles). Literature data from: Tuğrul and Gürpınar (1997), Gupta and
691 Rao (2000), Chen et al. (2004), Ersoy and Atici (2007), Kılıç and Teymen (2008), Nara et al.
692 (2010), Kahraman and Yeken (2010), Graue et al. (2011), Lavallée et al. (2012), Heap et al.
693 (2012), Wedekind et al. (2013), Karakuş and Akatay (2013), Hashiba and Fukui (2015),
694 Siratovich et al. (2015), Fener and Ince (2015), Ündül and Er (2017), Yavuz et al. (2017), Lamb
695 et al. (2017), Malik et al. (2017), Aldeeky and Al Hattamleh (2018), Zorn et al. (2018), Hornby
696 et al. (2019), Harnett et al. (2019), Moon and Yang (2020), Yasar and Komurlu (2020),
697 Kendrick et al. (2021), Heap et al. (2021c), and Weydt et al. (2021).



698

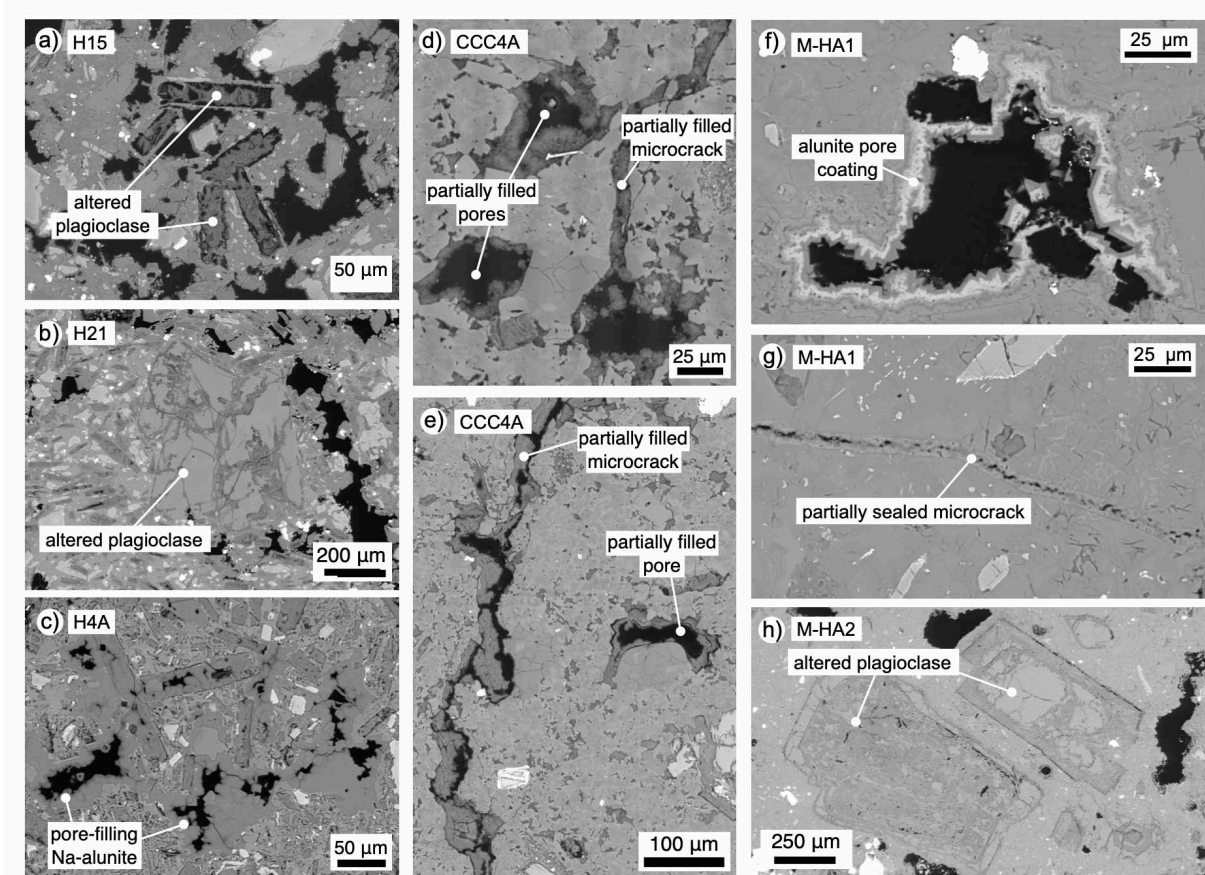
699

700 **Fig. 7.** (a) Tensile strength as a function of porosity for andesites from La Soufrière de
 701 Guadeloupe (black circles), rhyodacites from Chaos Crags (red squares), and basaltic-andesites
 702 from Merapi volcano (green triangles). Modelled curves are provided using Eq. (2), using the
 703 best-fit T_0 for a previously compiled dataset (Table 3). (b) Tensile strength as a function of
 704 porosity for andesites from La Soufrière de Guadeloupe (black circles). Modelled curves are
 705 provided using Equation (2), using an updated best-fit T_0 for the rocks from La Soufrière de
 706 Guadeloupe (Table 3).



707

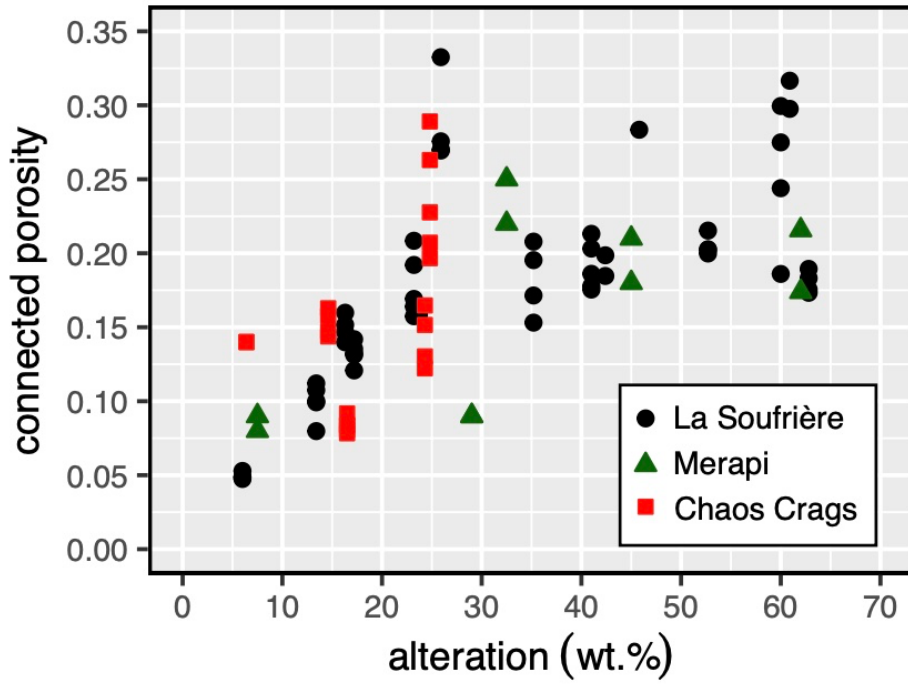
708 **Fig. 8.** Backscattered scanning electron microscope (SEM) images of samples from La
709 Soufrière de Guadeloupe (a-c), Chaos Crags (d-e), and Merapi volcano (f-h) showing examples
710 of porosity-increasing (e.g., the dissolution of plagioclase crystals causing “sieve” textures) and
711 porosity-decreasing (crack- and pore-filling precipitation) alteration.



712

713

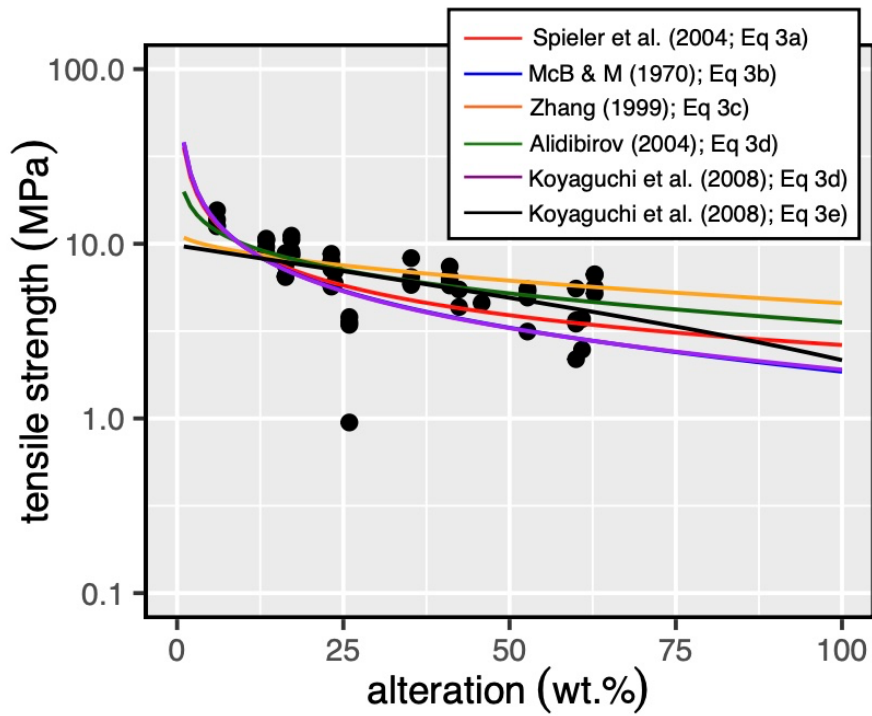
714 **Fig. 9.** Connected porosity as a function of alteration (the weight percentage of secondary
715 minerals). La Soufrière de Guadeloupe – black circles; Chaos Crags – red squares; Merapi
716 volcano – green triangles.



717

718

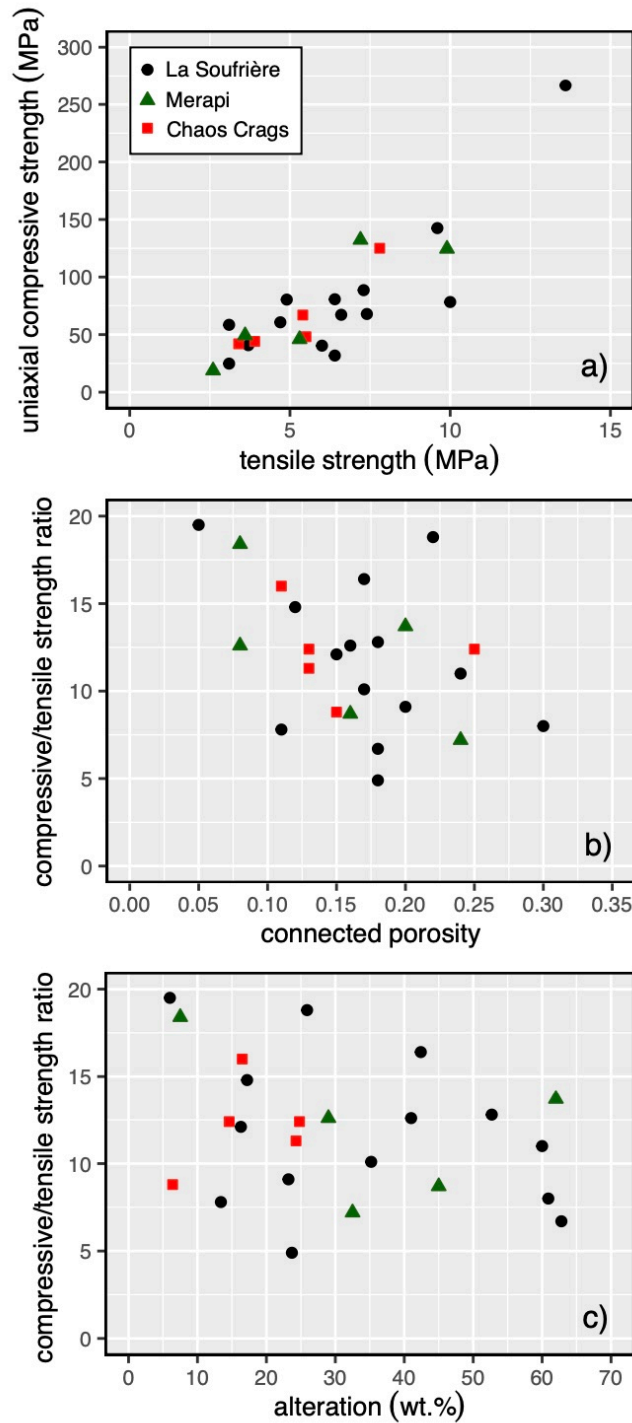
719 **Fig. 10.** Tensile strength as a function of alteration (weight percentage of secondary minerals)
720 for andesites from La Soufrière de Guadeloupe (black circles). Modelled curves are provided
721 using Equation (3), which is a modified version of the equations provided in the referenced
722 studies, using the best-fit T_0 for the rocks from La Soufrière de Guadeloupe (Table 3).



723

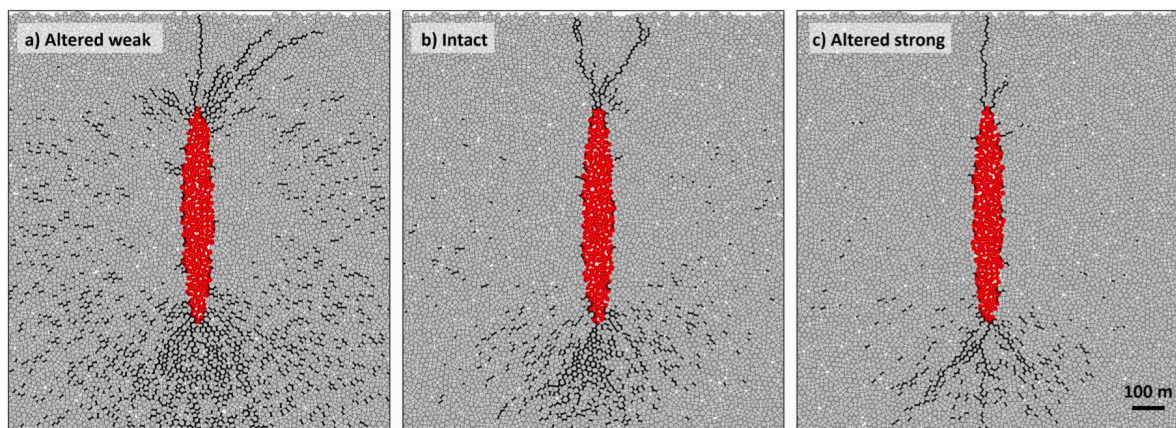
724

725 **Fig. 11.** (a) Uniaxial compressive strength as a function of tensile strength for rocks from La
 726 Soufrière de Guadeloupe, Chaos Crags, and Merapi volcano. (b) The ratio of compressive to
 727 tensile strength as a function of average connected porosity. (c) The ratio of compressive to
 728 tensile strength as a function of alteration (the weight percentage of secondary minerals). Data
 729 available in Table 4.



730

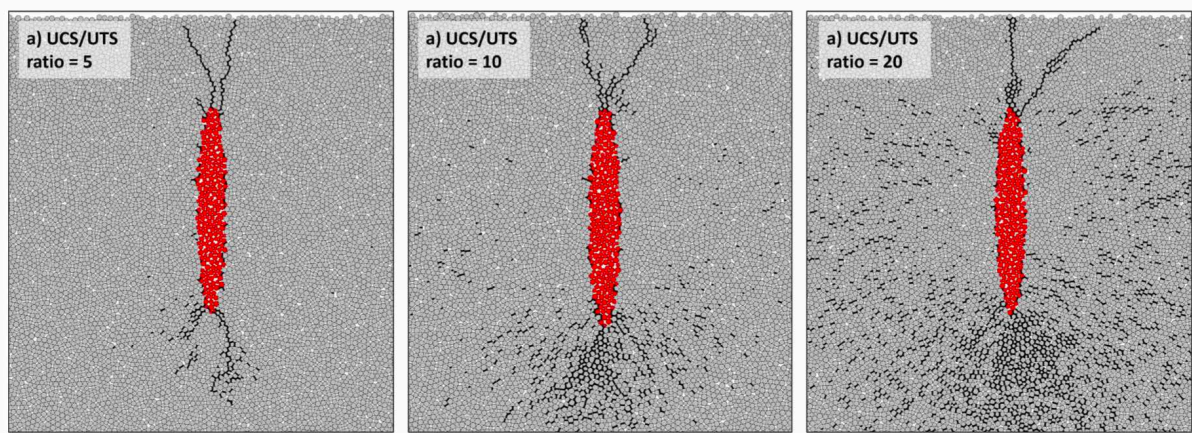
731 **Fig. 12.** Discrete element method models using Particle Flow Code 2D to show the influence
732 of homogeneously altered host rock in response to pressurisation of a magma-filled dyke. Host
733 rock properties correspond to the following scenarios: (a) weak hydrothermally altered host-
734 rock, (b) unaltered intact host-rock, (c) strong hydrothermally altered host-rock. The
735 mechanical properties for these scenarios can be found in Table 5. Red particles show unbonded
736 fluid magma; grey particles show bonded host-rock; and black lines show bond breakage,
737 indicating microcracking of the host-rock and damage accumulation.



738

739

740 **Fig. 13.** Discrete element method models using Particle Flow Code 2D to show the influence
741 of homogeneously altered host rock in response to pressurisation of a magma-filled dyke. Host
742 rock properties correspond to the following scenarios: (a) low UCS/UTS ratio = 5, (b)
743 intermediate UCS/UTS ratio = 10 (equivalent to the intact properties in Fig. 12), (c) high
744 UCS/UTS ratio = 20. The mechanical properties for these scenarios can be found in Table 6.
745 Red particles show unbonded fluid magma; grey particles show bonded host-rock; and black
746 lines show bond breakage, indicating microcracking of the host-rock and damage accumulation.



747

748

749 **Tables**

750

751 **Table 1.** Mineral contents, measured by X-ray powder diffraction and refined using Raman
 752 spectroscopy and optical microscopy, of the 15 blocks from La Soufrière de Guadeloupe
 753 (sampling locations shown in Fig. 1a), the five blocks from Chaos Crags (sampling locations
 754 shown in Fig. 1b), and the five blocks from Merapi volcano (sampling location shown in Fig.
 755 1c). Values in wt%. Data from Heap et al. (2019, 2021a, 2022). Pl – plagioclase, Kfs – K-
 756 feldspar, Cpx – clinopyroxene, Opx – orthopyroxene, Mag – magnetite, Bt – biotite, Hbl –
 757 hornblende, Qtz – quartz, Crs – cristobalite, Trd – tridymite, O-A – opal-A, AP – amorphous
 758 phases, Hem – hematite, Py – pyrite, Alu – alunite, Na-Alu – Na-alunite, Gp – gypsum, Kln –
 759 kaolinite, Smc – smectite, Tlc – talc. Unless otherwise stated, the relative errors in the
 760 quantification are 5–10% (Heap et al., 2021a, 2022).

761

	Pl	Kfs	Cpx	Opx	Mag	Bt	Hbl	Qtz	Crs	Trd	O-A	AP	Hem	Py	Alu	Na-Alu	Gp	Kln	Smc	Tlc
H2A	56.7	-	8.7	10.8	0.7	-	-	1.0	11.3	-	-	-	-	3.5	-	1.4	-	6.0	-	-
H3	46.6	-	5.6	11.8	0.8	-	-	0.6	10.6	-	-	-	-	3.8	-	2.8	-	17.4	-	-
H4A	23.3	-	4.9	11.8	-	-	-	0.6	11.8	-	-	-	-	2.3	-	1.3	0.7	43.3	-	-
H5A	41.3	-	5.2	11.1	-	-	-	0.5	13.0	-	-	-	-	-	-	5.4	-	23.5	-	-
H6	30.0	-	6.4	10.8	-	-	-	0.5	11.1	-	-	-	-	-	-	5.1	-	36.0	-	-
H14	60.7	-	6.3	8.6	0.8	-	-	1.7	13.5	-	-	-	3.4	-	-	5.1	-	<1	-	-
H15	22.5	-	7.3	9.2	-	-	-	0.7	10.2	-	-	-	0.7	-	-	15.0	-	34.3	-	-
H19	22.0	-	5.0	10.2	-	-	-	1.7	9.5	-	30.0	-	2.4	-	-	14.2	-	2.0	-	-
H21	24.2	-	12.4	19.3	3.1	-	-	0.2	11.7	-	-	-	0.4	-	-	0.5	1.2	2.0	-	-
H22	59.5	-	8.9	13.6	0.8	-	-	0.6	10.6	-	-	-	3.1	-	-	-	-	<1	-	2.9
H29	62.4	-	7.8	11.2	2.7	-	-	0.4	12.4	-	10.0	-	3.1	-	-	-	-	-	-	-
H30	8.9	-	2.5	3.3	-	-	-	0.9	9.0	-	10.0	-	4.3	-	-	25.6	-	35.6	-	-
H32	64.4	-	9.5	15.1	4.9	-	-	0.3	5.7	-	-	-	-	-	-	-	-	-	-	-
WP 1285	64.7	-	5.2	13.2	3.5	-	-	0.2	-	13.2	-	-	-	-	-	-	-	-	-	-
WP 1317	61.6	-	5.9	15.6	0.7	-	-	0.7	-	13.2	-	-	-	-	2.4	-	-	-	-	-
CCC	52.6	16.8	2.3	-	0.3	2.5	1.0	17.8	5.2	-	-	-	1.2	-	-	-	-	-	-	-
CC3	47.1	7.0	6.5	13.2	-	-	-	1.4	-	-	-	23.8	1.0	-	-	-	-	-	-	-
CC4 A	36.3	14.6	1.7	-	0.6	3.1	1.7	25.4	9.8	-	-	-	0.6	-	-	-	-	4.8	1.3	-
CC4 B	42.9	16.7	2.2	-	0.5	3.5	1.8	17.8	8.7	-	-	-	0.8	-	-	-	-	4.2	0.9	-
CC10	58.9	10.5	-	-	1.0	0.2	1.0	4.0	22.2	-	-	-	2.1	-	-	-	-	-	-	-
M-U	54 ± 3	19 ± 3	16 ±2		3 ± 0.5	-	-	1 ± 0.5	6 ± 0.5	-	-	-	0.5 ± 0.5	-	-	-	-	-	-	-
M- SA1	47 ± 3	9 ±3	13 ±2		2 ± 0.5	-	-	1.5 ± 0.5	-	-	-	24 ± 4	2 ± 0.5	-	-	1 ± 0.5	0.5 ± 0.5	-	-	-
M- SA2	38 ± 3	13 ± 3	14 ±2		2.5 ± 0.5	-	-	0.5 ± 0.5	-	-	-	19 ± 4	0.5 ± 0.5	-	-	8.5 ± 2	5 ± 0.5	-	-	-
M- HA1	38 ± 3	6 ±3	11 ±2		<1 ±0.5	-	-	1 ± 0.5	-	-	-	25 ± 4	3 ± 0.5	-	-	11 ± 2	5 ± 0.5	-	-	-
M- HA2	19 ± 3	10 ± 3	8 ±2		<1 ±0.5	-	-	0.5 ± 0.5	2.5 ± 0.5	-	-	28 ± 4	1 ± 0.5	-	-	24 ± 2	6 ± 0.5	-	-	-

762

763 **Table 2.** Summary of the experimental data collected for this study (*data from Heap et al.,
764 2021c). Experimental errors for the measurements of porosity and tensile strength are < 1%.
765 Relative errors for the weight percentages are 5–10%.
766

Volcano	Sample	Connected porosity	Weight percentage of secondary minerals	Indirect tensile strength (MPa)
La Soufrière	H2A_T1	0.16	23.2	8.8
La Soufrière	H2A_T2	0.19	23.2	7.2
La Soufrière	H2A_T3	0.21	23.2	5.7
La Soufrière	H2A_T4	0.17	23.2	7.5
La Soufrière	H2A_T5	0.16	23.2	8.0
La Soufrière	H3_T1	0.20	35.2	6.5
La Soufrière	H3_T2	0.15	35.2	8.3
La Soufrière	H3_T3	0.17	35.2	5.8
La Soufrière	H3_T4	0.21	35.2	6.0
La Soufrière	H4A_T1	0.27	60	3.6
La Soufrière	H4A_T2	0.30	60	2.2
La Soufrière	H4A_T3	0.24	60	3.5
La Soufrière	H4A_T4	0.19	60	5.5
La Soufrière	H5A_T1	0.18	42.4	4.3
La Soufrière	H5A_T2	0.20	42.4	5.5
La Soufrière	H6_T1	0.20	52.7	5.5
La Soufrière	H6_T2	0.20	52.7	5.3
La Soufrière	H6_T3	0.20	52.7	3.1
La Soufrière	H6_T4	0.22	52.7	4.9
La Soufrière	H14_T1	0.16	23.7	6.9
La Soufrière	H14_T2	0.16	23.7	6.0
La Soufrière	H15_T1	0.32	60.9	2.5
La Soufrière	H15_T2	0.30	60.9	3.7
La Soufrière	H19_T1	0.18	62.8	5.2
La Soufrière	H19_T2	0.17	62.8	6.6
La Soufrière	H19_T3	0.18	62.8	6.7
La Soufrière	H19_T4	0.19	62.8	5.6
La Soufrière	H21_T1	0.18	41	7.4
La Soufrière	H21_T2	0.20	41	6.0
La Soufrière	H21_T3	0.21	41	6.3
La Soufrière	H21_T4	0.19	41	6.5
La Soufrière	H21_T5	0.18	41	5.8

La Soufrière	H22_T1	0.14	17.2	8.6
La Soufrière	H22_T2	0.13	17.2	9.0
La Soufrière	H22_T3	0.14	17.2	8.7
La Soufrière	H22_T4	0.12	17.2	10.6
La Soufrière	H22_T5	0.13	17.2	11.1
La Soufrière	H29_T1	0.27	25.9	3.4
La Soufrière	H29_T2	0.28	25.9	3.6
La Soufrière	H29_T3	0.33	25.9	0.9
La Soufrière	H29_T4	0.27	25.9	3.8
La Soufrière	H30_T1	0.28	45.8	4.6
La Soufrière	H32_T1	0.05	6	15.6
La Soufrière	H32_T2	0.05	6	13.8
La Soufrière	H32_T3	0.05	6	12.6
La Soufrière	H32_T4	0.05	6	12.7
La Soufrière	WP1285_T1	0.11	13.4	10.4
La Soufrière	WP1285_T2	0.08	13.4	10.6
La Soufrière	WP1285_T3	0.10	13.4	10.7
La Soufrière	WP1285_T4	0.11	13.4	8.9
La Soufrière	WP1285_T5	0.10	13.4	9.6
La Soufrière	WP1317_T1	0.15	16.3	6.5
La Soufrière	WP1317_T2	0.16	16.3	6.4
La Soufrière	WP1317_T3	0.15	16.3	7.5
La Soufrière	WP1317_T4	0.14	16.3	8.8
Chaos Crags*	CCC	0.14	6.4	5.8
Chaos Crags*	CCC	0.14	6.4	5.1
Chaos Crags	CC3_T1	0.29	24.8	4.4
Chaos Crags	CC3_T2	0.26	24.8	3.5
Chaos Crags	CC3_T3	0.23	24.8	5.2
Chaos Crags	CC3_T4	0.21	24.8	7.0
Chaos Crags	CC3_T5	0.20	24.8	6.6
Chaos Crags	CC4A_T1	0.09	16.5	7.8
Chaos Crags	CC4A_T2	0.08	16.5	8.3
Chaos Crags	CC4A_T3	0.08	16.5	7.9
Chaos Crags	CC4A_T4	0.08	16.5	7.1
Chaos Crags	CC4A_T5	0.08	16.5	7.6
Chaos Crags	CC4B_T1	0.16	14.6	3.0
Chaos Crags	CC4B_T2	0.14	14.6	3.4
Chaos Crags	CC4B_T3	0.16	14.6	4.4
Chaos Crags	CC4B_T4	0.15	14.6	3.1
Chaos Crags	CC10_T1	0.12	24.3	4.9
Chaos Crags	CC10_T2	0.16	24.3	3.7
Chaos Crags	CC10_T3	0.13	24.3	4.1

Chaos Crags	CC10_T4	0.15	24.3	2.7
Merapi*	MU	0.08	7.5	7.4
Merapi*	MU	0.09	7.5	7.0
Merapi*	MSA1	0.22	32.5	3.0
Merapi*	MSA1	0.25	32.5	2.1
Merapi*	MSA2	0.09	29.0	9.7
Merapi*	MSA2	0.09	29.0	10.1
Merapi*	MHA1	0.18	45.0	6.0
Merapi*	MHA1	0.21	45.0	4.6
Merapi	MHA2	0.17	62.0	3.1
Merapi	MHA2	0.22	62.0	4.0

767

768 **Table 3.** Best-fit values for the effective characteristic tensile stress, T_0 , for the compiled dataset
769 in Heap et al. (2021c) and for the variably altered andesites from La Soufrière de Guadeloupe
770 (data from this study). Note: the goodness of fit values quoted in Heap et al. (2021c) were the
771 linear residual ratios, rather than the formal R^2 values shown here.
772

Model	Best-fit T_0 for the compiled dataset (from Heap et al., 2021c) in MPa	Goodness of fit (from Heap et al., 2021c)*	Best-fit T_0 for the variably altered andesites from La Soufrière de Guadeloupe	Goodness of fit for the La Soufrière de Guadeloupe dataset*
Spieler et al. (2004) Eq. 2a	0.43	0.26	0.90	0.6414
McBirney and Murase (1970) Eq. 2b	0.51	0.13	0.98	0.4870
Zhang (1999) Eq. 2c	3.14	0.57	5.84	0.4724
Alidibirov (1994) Eq. 2d	2.00	0.44	4.12	0.7068
Koyaguchi et al. (2008) Eq. 2d	0.76	0.45	1.48	0.4743
Koyaguchi et al. (2008) Eq. 2e	0.77	0.13	1.67	0.7211

773 * The goodness of fit R^2 is computed in the standard way, but using the $\log(T_m)$, $\log(T_p)$, and
774 the mean of $\log(T_m)$, where T_m is the measured tensile strength and T_p is the predicted tensile
775 strength.

776 **Table 4.** Average ratios of compressive to tensile strength for the rocks from La Soufrière de
777 Guadeloupe, Chaos Crags, and Merapi volcano. Also shown are the average porosities,
778 alteration (percentage of secondary minerals), and the average uniaxial compressive and tensile
779 strength. Data for the uniaxial compressive strength of the rocks from La Soufrière de
780 Guadeloupe, Chaos Crags, and Merapi volcano are published in Heap et al. (2021a), Heap et
781 al. (2021b), and Darmawan et al. (2022). Experimental errors for the measurements of porosity,
782 tensile strength, and uniaxial compressive strength are < 1%. Relative errors for the weight
783 percentages are in the order of 5–10%. Standard deviations are provided for the average
784 connected porosities and average compressive strengths. Data are too few to provide standard
785 deviations for the average tensile strengths.

786

Volcano	Block	Average connected porosity	Weight percentage of secondary minerals	Average compressive strength (MPa)	Average indirect tensile strength (MPa)	Ratio of compressive to tensile strength
La Soufrière	2A	0.20 ± 0.04	23.2	67.9 ± 8.1	7.4	9.1
La Soufrière	2B	0.42 ± 0.02	74.6	6.9 ± 1.6	-	-
La Soufrière	3	0.17 ± 0.02	35.2	67.2 ± 4.9	6.6	10.1
La Soufrière	4A	0.24 ± 0.02	60.0	40.8 ± 2.5	3.7	11.0
La Soufrière	5A	0.17 ± 0.02	42.4	80.4 ± 8.4	4.9	16.4
La Soufrière	6	0.18 ± 0.01	52.7	60.7 ± 6.3	4.7	12.8
La Soufrière	14	0.18 ± 0.02	23.7	31.8 ± 19.5	6.4	4.9
La Soufrière	15	0.30 ± 0.03	60.9	24.8 ± 2.2	3.1	8.0
La Soufrière	18	0.12 ± 0.01	15.2	99.3 ± 9.2	-	-

La Soufrière	19	0.18 ± 0.03	62.8	40.4 ± 4.8	6.0	6.7
La Soufrière	20	0.37 ± 0.02	45.0	4.7 ± 0.9	-	-
La Soufrière	21	0.16 ± 0.01	41.0	80.7 ± 10.7	6.4	12.6
La Soufrière	22	0.12 ± 0.00	17.2	142.5 ± 6.2	9.6	14.8
La Soufrière	25	0.16 ± 0.03	45.8	92.4 ± 7.1	-	-
La Soufrière	29	0.22 ± 0.03	25.9	58.5 ± 9.8	3.1	18.8
La Soufrière	30	0.25 ± 0.11	85.4	-	4.6	-
La Soufrière	32	0.05 ± 0.00	6.0	266.6 ± 8.7	13.6	19.5
La Soufrière	WP1285	0.11 ± 0.02	13.4	78.3 ± 9.4	10.0	7.8
La Soufrière	WP1317	0.15 ± 0.02	16.3	88.6 ± 13.9	7.3	12.1
Chaos Crags	CCC	0.15 ± 0.00	6.4	48.2 ± 2.6	5.5	8.8
Chaos Crags	CC3	0.25 ± 0.02	24.8	67.0 ± 1.3	5.4	12.4
Chaos Crags	CC4A	0.11 ± 0.03	16.5	125.0 ± 8.0	7.8	16.0
Chaos Crags	CC4B	0.13 ± 0.01	14.6	42.0 ± 5.0	3.4	12.4
Chaos Crags	CC10	0.13 ± 0.01	24.3	44.1 ± 4.6	3.9	11.3
Merapi	M-U	0.08 ± 0.00	7.5	132.3 ± 11.3	7.2	18.4
Merapi	M-SA1	0.24 ± 0.02	32.5	18.8 ± 6.9	2.6	7.2
Merapi	M-SA2	0.08 ± 0.00	29.0	124.5 ± 13.1	9.9	12.6
Merapi	M-HA1	0.16 ± 0.01	45.0	46.0 ± 6.9	5.3	8.7
Merapi	M-HA2	0.20 ± 0.03	62.0	49.3 ± 21.5	3.6	13.7

788 **Table 5.** Target bulk properties (Young’s modulus, uniaxial compressive strength (UCS),
789 uniaxial tensile strength (UTS), and UCS/UTS ratio) for each of the three strength scenarios
790 considered. Target bulk properties for each scenario are guided by the laboratory data presented
791 here. Resultant bulk properties are achieved by an iterative model calibration process within
792 Particle Flow Code 2D. Averages (plus/minus one standard deviation) are given from 10
793 simulated tests, each with different random particle packing arrangements to account for the
794 variation in packing that occurs in the large-scale models.

795

	Strength scenario	Young’s modulus (GPa)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	UCS/UTS ratio
Target bulk properties	Intact	30	100	10	10
	Altered weak	25	50	5	10
	Altered strong	35	150	15	10
Resultant bulk properties	Intact	30.0 ± 0.2	99.5 ± 5.7	10.2 ± 0.9	9.9 ± 1.3
	Altered weak	24.9 ± 0.2	49.9 ± 3.1	4.8 ± 0.4	10.6 ± 1.4
	Altered strong	35.2 ± 0.3	150.6 ± 8.1	15.3 ± 1.4	10.0 ± 1.2

796

797 **Table 6.** Target bulk properties (Young’s modulus, uniaxial compressive strength (UCS),
798 uniaxial tensile strength (UTS), and UCS/UTS ratio) for each of the three UCS/UTS ratio
799 scenarios considered. Target bulk properties for each scenario are guided by the laboratory data
800 presented here. Resultant bulk properties are achieved by an iterative model calibration process
801 within Particle Flow Code 2D. Averages (plus/minus one standard deviation) are given from
802 10 simulated tests, each with different random particle packing arrangements to account for the
803 variation in packing that occurs in the large-scale models.
804

	Strength scenario	Young’s modulus (GPa)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	UCS/UTS ratio
Target bulk properties	Intermediate UCS/UTS ratio	30	100	10	10
	Low UCS/UTS ratio	30	100	20	5
	High UCS/UTS ratio	30	100	5	20
Resultant bulk properties	Intermediate UCS/UTS ratio	30.0 ± 0.2	99.5 ± 5.7	10.2 ± 0.9	9.9 ± 1.3
	Low UCS/UTS ratio	30.2 ± 0.2	100.2 ± 3.1	19.7 ± 1.8	5.2 ± 0.6
	High UCS/UTS ratio	30.3 ± 0.2	99.5 ± 9.3	5.1 ± 0.5	19.6 ± 2.9

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