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1 The thermal conductivity of unlithified granular volcanic materials: the influence  
2 of hydrothermal alteration and degree of water saturation

3

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15

16 **Highlights**

- 17 • Thermal properties of volcanic rocks are typically higher than for unlithified volcanic materials.
- 18 • Thermal conductivity and diffusivity of unlithified volcanic material decreases with alteration.
- 19 • Thermal conductivity of unlithified volcanic material increases with water saturation degree.
- 20 • Thermal conductivity of saturated unlithified volcanic material can be higher than that for dry volcanic  
21 rocks.
- 22 • Lithification (rock versus powder), alteration, and water saturation degree are important considerations  
23 for heat flux calculations.

24

25 **Abstract**

26 The thermal properties of volcanic materials are required for modelling and for understanding volcanic  
27 surface heat fluxes and timescales for cooling magma. However, compared to volcanic rocks, there are relatively  
28 few thermal property data for unlithified granular volcanic materials. Here, we measured the thermal properties of  
29 a suite of hydrothermally altered powders from La Soufrière de Guadeloupe (Eastern Caribbean) as a function of

30 water saturation degree. Our data show, under dry conditions, that thermal conductivity and thermal diffusivity  
31 decrease, and that specific heat capacity does not change systematically, as a function of the degree of alteration  
32 of the unlithified granular material. For example, thermal conductivity decreases from  $\sim 0.3$  to  $\sim 0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as  
33 the quantity of alteration minerals in the samples increases from  $\sim 10$  to  $\sim 70$  wt%. We interpret the decrease in  
34 thermal conductivity with increasing alteration as the result of the lower thermal conductivity of the alteration  
35 mineral assemblage relative to the unaltered assemblage. Our data also show that thermal conductivity increases  
36 from  $\sim 0.2\text{--}0.3$  to  $\sim 0.8\text{--}1.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as saturation degree increases from dry to at, or close to, complete  
37 saturation, due to the higher thermal conductivity of water compared to air. We show that an empirical model for  
38 variably saturated granular media is in general agreement with our data and provides a framework to predict the  
39 thermal conductivity of unlithified granular volcanic materials as a function of saturation degree. The data and  
40 modelling provided herein can help improve heat flux calculations designed to inform on volcanic and geothermal  
41 processes.

42

43 **Keywords:** volcano; thermal conductivity; thermal diffusivity; specific heat capacity; porosity; La Soufrière de  
44 Guadeloupe; hydrothermal alteration; saturation; heat flux

45

## 46 **1 Introduction**

47 The fragmentation and granulation of magma and volcanic rock is a consequence of the energetic  
48 phenomena that often typify active volcanoes. First, explosions, explosive eruptions, directed blasts, and lava  
49 fountains, create and expel pyroclasts at various velocities and to various distances (Heiken and Wohletz, 1991;  
50 Kueppers et al., 2006) and/or form breccia-filled conduits and brecciated conduit margins (Rust et al., 2004; Goto  
51 et al., 2008; Kolzenburg et al., 2014; Kennedy et al., 2020). Even effusive silicic volcanism is thought to be rooted  
52 in fragmentation (Wadsworth et al., 2020). Second, the collapse of a lava dome or volcanic flank can form  
53 pyroclastic density currents, mixtures of pyroclasts and gas, that sweep across the landscape (Branney et al., 2002;  
54 Dufek et al., 2015). These phenomena, and others, can create thick and voluminous layers of granular material that  
55 either remain unlithified or, if the pyroclasts are glassy and remain hot, can weld to reform rock (Pyle, 1989; Brown  
56 and Andrews, 2015). The net result is a volcanic environment characterised by both lithified rock (lavas and welded  
57 granular rocks) and unlithified loose granular material.

58 The heat from subsurface magma is transported to the surface by hot convecting fluids (hydrothermal  
59 systems), the conduction of heat through the edifice (rock and unlithified granular material), and the upward

60 movement of the magma itself. As a result, active volcanoes are often associated with regions of high surface heat  
61 flux (Wright and Flynn, 2004) and, because surface heat flux changes are indicative of the subsurface movement  
62 of magma and/or hydrothermal fluids, an increase in surface heat flux can indicate volcanic unrest and perhaps  
63 impending eruptive activity (Girona et al., 2021). It is for this reason that surface heat flux is widely used as a  
64 monitoring tool at active volcanoes worldwide (Harris et al., 1997; Wooster and Rothery, 1997; Harris et al., 2001;  
65 Dehn et al., 2000; Wright et al., 2004; Chiodini et al., 2005; Stevenson and Varley, 2008; Bloomberg et al., 2014;  
66 Chiodini et al., 2015; Mannini et al., 2019; Jessop et al., 2020). Understanding the thermal properties of the  
67 volcanic edifice, and the processes that can influence these properties, is important for the interpretation of surface  
68 heat flux data and can therefore help improve the reliability of volcano monitoring. The thermal properties of  
69 volcanic materials are also required in a variety of models designed to estimate timescales for the cooling of magma  
70 bodies, dykes, sills, lavas, and ignimbrites (Irvine, 1970; Norton and Knight, 1977; Carrigan, 1984; Bruce and  
71 Huppert, 1989; Carrigan et al., 1992; Fialko and Rubin, 1999; Wooster et al., 1997; Annen et al., 2008; Nabelek  
72 et al., 2012; Heap et al., 2017; Annen, 2017; Mattsson et al., 2018; Tsang et al., 2019).

73 Experimental studies have provided values for the thermal properties of volcanic rocks for modelling  
74 (Horai et al., 1970; Fujii and Osako, 1973; Robertson and Peck, 1974; Bagdassarov and Dingwell, 1994;  
75 Whittington et al., 2009; Romine et al., 2012; Mielke et al., 2015, 2016, 2017; Vélez et al., 2018; Heap et al., 2020;  
76 Weydt et al., 2021; Heap et al., 2022a). These studies, and others, have shown that porosity plays a first-order role  
77 in dictating thermal properties of volcanic rocks. For example, the thermal conductivity of basalt from Hawai'i  
78 (USA) decreased from  $\sim 1.7 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at a porosity of 0.05 to  $\sim 0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at a porosity of 0.85 (Robertson  
79 and Peck, 1974). The thermal properties of volcanic rocks are also influenced by factors such as temperature,  
80 saturation with water, and hydrothermal alteration. For example, the thermal diffusivity of rhyolite decreased from  
81  $\sim 2.0$  to  $\sim 0.7 \text{ mm}^2\cdot\text{s}^{-1}$  as temperature was increased from  $\sim 260$  to  $\sim 850 \text{ K}$  (Whittington et al., 2009). The thermal  
82 conductivity of andesite from Ruapehu (New Zealand) with a porosity of  $\sim 0.3$  was increased from  $\sim 0.8$  to  $\sim 1.3$   
83  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  upon complete saturation with water (Heap et al., 2020), and hydrothermal alteration has been shown  
84 to either increase or decrease the thermal properties of volcanic rocks, depending on whether the alteration was  
85 manifest as (1) dissolution and/or replacement or (2) the precipitation of minerals within the void space within the  
86 rock (Heap et al., 2022a).

87 Although data exist for volcanic rocks, much less is known as to the thermal properties of un lithified  
88 granular volcanic deposits. McCombie et al. (2017) found that the thermal conductivity of pozzolana from Rome  
89 (Italy) increased from  $\sim 0.2$  to  $\sim 1.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as the saturation degree increased from dry to fully saturated. The

90 thermal conductivity, thermal diffusivity, and specific heat capacity of dry unlithified volcanic deposits from the  
91 lava dome at La Soufrière de Guadeloupe (Eastern Caribbean) were measured to be  $0.15\text{--}0.20\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ,  
92  $0.17\text{--}0.24\text{ mm}^2\cdot\text{s}^{-1}$ , and  $0.68\text{--}1.04\text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ , respectively (Heap et al., 2022a). The average dry and water-  
93 saturated thermal conductivity of volcanic soils from Hokkaido (Japan) was measured to be 0.14 and 0.52  
94  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , respectively (Tarnawski et al., 2019). Finally, dry rhyolitic and basaltic ash from Kamchatka (Russia)  
95 was found to have a thermal conductivity of  $\sim 0.2\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , which increased to  $\sim 1.0\text{--}1.2\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  upon  
96 complete saturation with frozen water (Kuznetsova, 2017).

97 More thermal property data for unlithified granular volcanic materials, and a better understanding of  
98 factors that can influence these properties, can help improve models designed to interpret heat flux data and model  
99 heat loss from magma. In particular, there remains no constitutive material model that can be used to predict  
100 thermal properties of unlithified granular volcanic materials as a function of saturation degree, the state of particle  
101 packing, or the mineralogy and alteration. Here, therefore, we report findings from a laboratory study designed to  
102 better understand the thermal properties of unlithified granular volcanic materials, including the influence of  
103 hydrothermal alteration and degree of water saturation. Finally, we encapsulate our dataset in an empirical model  
104 framework (Johansen, 1975) for general use.

105

## 106 **2 Materials and Methods**

107 The materials used for this study were collected from La Soufrière de Guadeloupe, hereafter called La  
108 Soufrière, an active andesitic stratovolcano located on the French island of Guadeloupe in the Eastern Caribbean  
109 (Moretti et al., 2020; Figure 1). In total, 19 rock blocks were collected from different locations around the volcano  
110 (sampling locations are shown in Figure 1). These blocks have been previously used in recent studies focused on  
111 the influence of hydrothermal alteration on the compressive and tensile strength (Heap et al., 2021, 2022b, 2022c)  
112 and the thermal properties (Heap et al., 2022a) of volcanic rocks.

113 Of the 19 rock blocks collected, nine blocks were taken from the collapse scar of the 2009 landslide (H2A,  
114 H2B, H3, H4A, H5A, H6, H25, H29, and H30). Five blocks were collected from the dome summit: four blocks  
115 were taken from the lava spines of the 1530 CE dome (two blocks from Cratère Sud Central, H19 and H20, and  
116 two blocks from an adjacent site, H21 and H22), and one block was taken from the Lacroix Supérieur outgassing  
117 fracture (H18). We also collected blocks from the West wall of the fault “Faille 30 Août” (H14 and H15), the  
118 collapse scar of the landslide triggered by the 21 November 2004 Les Saintes magnitude Mw 6.3 regional  
119 earthquake (Feuillet et al., 2011) (WP1285), and from a lava adjacent to the Galion waterfall (H32). The final

120 block, a volcanic bomb from the 1976–1977 eruption, was taken from the roof of a small disused thermal bathhouse  
121 to the South of the dome (WP1317). These blocks are characterised by advanced argillic alteration, the result of  
122 the efficient circulation of acidic sulfate-chloride-rich fluids (below 350 °C, and down to 150–200 °C; pH < 4)  
123 (Heap et al., 2021).

124 Offcuts of each of the blocks were crushed and powdered by hand using a pestle and mortar. The  
125 powdered materials were then sieved to a grain diameter <1 mm and dried in a vacuum-oven at 40 °C for at least  
126 48 h. The solid density of each powdered sample  $\rho_s$  was then measured using the mass and volume, measured by  
127 a helium pycnometer, of an aliquot of the oven-dry powder.

128 The thermal conductivity  $\lambda$  and thermal diffusivity  $D$  of the powders were measured using a Hot Disk®  
129 TPS 500 Thermal Constants Analyser using the transient plane source (TPS) method (Gustafsson, 1991; Harlé et  
130 al., 2019; Heap et al., 2020, 2022a). The TPS method uses a resistive sensor (the transient plane source)  
131 sandwiched between two samples to measure the increase in resistance as it heats the samples using an electrical  
132 current pulse. Because the geometry of the sensor is known, the average temperature increase as a function of time  
133 can be calculated, which can be then used to determine thermal conductivity and thermal diffusivity. The resistive  
134 sensor is therefore used as both the heat source and the temperature sensor.

135 Thermal conductivity and thermal diffusivity were measured using a sensor consisting of two 10  $\mu\text{m}$ -  
136 thick nickel foil spirals (radius of 3.189 mm) that are encased and insulated by 30  $\mu\text{m}$ -thick Kapton (Figure 2a).  
137 The powdered samples were measured using a sample holder of known volume supplied by Hot Disk®. The mass  
138 of the powder was first measured. Half of the powder was then spooned into the lower part of the sample holder.  
139 The powder in the sample holder was then manipulated using the spoon so that the surface of the powder was flat.  
140 The sample holder containing the powder was then placed underneath the sensor (Figure 2a). The top part of the  
141 sample holder was then placed on top of the lower part, and the remaining powder was spooned on top of the  
142 sensor and manipulated using the spoon to ensure a flat surface (Figure 2b). A metal plate was then placed on top  
143 of the sample assembly, and the entire sample assembly was compacted using a 3.5 kg weight (Figure 2c). The 3.5  
144 kg weight ensured (1) a similar compaction from sample to sample (and therefore a similar porosity), (2) a good  
145 contact between the powder and the sensor, and (3) that the sensor was flat during the measurements. The bulk  
146 sample volume was calculated by measuring the height of the powder in the sample holder following compaction  
147 under a weight of 3.5 kg. The bulk sample density  $\rho_b$  was then calculated using the mass and volume of the powder.  
148 Finally, the total porosity of the powder  $\phi_t$  was calculated using  $\phi_t = 1 - (\rho_b/\rho_s)$ .

149 Because temperature influences the measurements, the ambient room temperature adjacent to the sample,  
150 measured using a thermocouple, was inputted into the Thermal Constants Analyser prior to starting each  
151 measurement. In order to measure the thermal conductivity and thermal diffusivity of the samples, an electrical  
152 current of known power and for a fixed duration was passed through the sensor, which then recorded the increase  
153 in sample temperature as a function of time. The output power and test duration used were 70 mW and 20 s,  
154 respectively. Four consecutive measurements were performed on each powder, and we report herein the mean and  
155 standard error of these four measurements. Each measurement was performed at least five minutes apart to ensure  
156 that the sample had cooled back to the ambient temperature. The sensor measured the temperature drift of the  
157 sample for 40 seconds prior to each measurement to check whether the sample was in thermal equilibrium. If the  
158 sample temperature was not constant during this 40 second period, the data were not considered and the  
159 measurement was repeated. The specific heat capacity at constant pressure  $C_p$  of each sample was calculated using  
160  $C_p = \lambda/(\rho_b D)$ . All measurements were conducted in a far-field environment that was at ambient laboratory  
161 temperature and pressure.

162 To provide an assessment of the precision of the Hot Disk® TPS 500 Thermal Constants Analyser, we  
163 measured the thermal conductivity and thermal diffusivity of the same pair of sandstone samples 100 times. The  
164 power and duration of each measurement was 180 mW and 5 s, respectively, and we waited at least 10 minutes  
165 between individual measurements. We used two discs, 40 mm in diameter and 20 mm in length, of Rothbach  
166 sandstone, a sandstone with a connected porosity of 0.2 and an average grain radius of 110  $\mu\text{m}$  (Louis et al., 2007).  
167 The mineral composition of Rothbach sandstone is 68% quartz, 16% feldspar, 3% oxides and micas, and about  
168 6% clays (Louis et al., 2007). The mean and standard error for the thermal conductivity are 2.878 and 0.007  
169  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , respectively, and the mean and standard error for the thermal diffusivity are 1.884 and 0.027  $\text{mm}^2\cdot\text{s}^{-1}$ ,  
170 respectively (all the data are provided in a Microsoft Excel spreadsheet that accompanies this contribution as  
171 Supplementary Material).

172 We additionally measured the thermal conductivity of the powders as a function of the degree of water  
173 saturation. The degree of water saturation  $S$  is defined here as the fraction of the porosity filled with water such  
174 that  $S = \bar{V}_w/\phi_t$ , where  $\bar{V}_w$  is the volume ratio of water to sample. Therefore,  $S = 0$  denotes a dry sample and  $S = 1$   
175 denotes a completely water-saturated sample with all of the porosity filled with water. We used the same Hot  
176 Disk® device described above, although the procedure differed in the following ways. Following the compaction  
177 of the dry powder under a weight of 3.5 kg, the weight and metal plate were removed and 5 ml of water was added  
178 to the sample using a syringe. The water was applied homogeneously throughout the top surface of the sample.

179 The metal plate and weight were placed back on the sample and we waited 10 min before starting the measurement  
180 to ensure that the water was evenly distributed throughout the sample (pilot experiments, in which we varied the  
181 volume of water and wait time and cut the partially-saturated powdered sample in half to visually inspect the cross  
182 section of the sample, suggested that 10 min was sufficient to ensure a uniform water distribution). The  
183 measurements were then performed as described above (output power and durations varied from 80–180 mW and  
184 5–20 s, respectively). Once the measurements for a given saturation degree were complete, another aliquot of  
185 water was added (2–5 ml) and the procedure was continued until the sample was completely or almost-completely  
186 saturated.

187 The mineral phases present in each block was identified by a combination of optical microscopy, Raman  
188 spectroscopy, and X-ray powder diffraction (XRPD). Quantitative phase analysis was then performed using the  
189 XRPD data and the Rietveld approach. These data were previously published in (Heap et al., 2021, 2022a). The  
190 blocks contain primary plagioclase, pyroxene (clinopyroxene and orthopyroxene), and magnetite, and an alteration  
191 assemblage of secondary minerals consisting of variable quantities of kaolinite, alunite or natro-alunite, silica  
192 polymorphs (quartz, cristobalite, tridymite, and opal-A), hematite, pyrite, gypsum, and talc (Heap et al., 2021,  
193 2022a). The alteration intensity of each block was quantified as the weight percentage (wt%) of secondary minerals  
194 (these values are provided in Table 1).

195

### 196 **3 Results**

#### 197 3.1 Thermal properties of the dry volcanic powders

198 We first note that the total porosity of our powdered samples was essentially constant in the range 0.47–  
199 0.51 (Table 1), which speaks to the homogeneity of the powdered samples in terms of grainsizes, as well as the  
200 reproducibility of the packing-and-weight approach (Figure 2). Our data for the thermal conductivity, thermal  
201 diffusivity, and specific heat capacity for all the dry powdered samples are plotted as a function of alteration in  
202 Figure 3 (data available in Table 1). Figure 3a shows that thermal conductivity exhibits a modest decrease as a  
203 function of increasing alteration. Thermal conductivity decreases from  $\sim 0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at an alteration of  $\sim 10$   
204 wt% to  $\sim 0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at an alteration of  $\sim 70$  wt% (Figure 3a). Figure 3b shows that thermal diffusivity also  
205 decreases as a function of increasing alteration. Thermal diffusivity decreases from  $\sim 0.27 \text{ mm}^2\cdot\text{s}^{-1}$  at an alteration  
206 of  $\sim 10$  wt% to  $\sim 0.22 \text{ mm}^2\cdot\text{s}^{-1}$  at an alteration of  $\sim 70$  wt% (Figure 3b). Specific heat capacity, however, does not  
207 appear to change systematically as a function of alteration (Figure 3c). Specific heat capacity varies between 0.6  
208 and  $0.9 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$  (Figure 3c).



209

### 210 3.2 Thermal conductivity as a function of water saturation degree

211 Thermal conductivity is plotted as a function of the degree of saturation with water in Figure 4 (data  
212 available in Table 2). The colour of the symbols and lines on Figure 4 indicates the alteration, where red and yellow  
213 indicate low and high alteration, respectively. Figure 4 shows that the thermal conductivity of the powders  
214 increases as a non-linear function of saturation degree. In general, thermal conductivity increases from  $\sim 0.2\text{--}0.3$   
215  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at a saturation degree of  $S = 0$  up to  $\sim 0.8\text{--}1.1 \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at a saturation degree of  $S \approx 0.7$ , and remains  
216 more-or-less constant up to the maximum saturation degree of  $S = 1$  (Figure 4). This suggests that the effect of  
217 increasing saturation degree is most pronounced at relatively low values of  $S$ , tailing off as the sample becomes  
218 completely saturated (Figure 4).

219 Figure 4 also shows that the increase in thermal conductivity as a function of saturation degree appears  
220 to depend on the alteration intensity. The increase in thermal conductivity per unit saturation is, in general, lower  
221 for the highly altered samples (in yellow and orange) than for the relatively unaltered samples (in red) (Figure 4).  
222 Further, the thermal conductivity at, or close to, complete saturation is lower as alteration increases (Figure 4).  
223 Highly altered samples (in yellow and orange) have a thermal conductivity of  $\sim 0.8\text{--}1.0 \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at, or close to,  
224 complete saturation, compared to  $\sim 1.0\text{--}1.2 \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for the relatively unaltered samples (in red) (Figure 4).

225

## 226 4 Discussion

### 227 4.1 Influence of alteration on the thermal properties of dry volcanic powders

228 Our data show that the thermal conductivity of dry un lithified volcanic material varies from  $\sim 0.2\text{--}0.3$   
229  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  (Table 1). These values are in broad agreement with previously published studies, who report thermal  
230 conductivities for dry un lithified volcanic material of  $0.15\text{--}0.20 \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  (McCombie et al., 2017; Kuznetsova,  
231 2017; Tarnawski et al., 2019; Heap et al., 2022a).

232 Our data also show that thermal conductivity and thermal diffusivity of volcanic powders decrease as a  
233 function of alteration (Figure 3), in agreement with data collected for volcanic rock samples (Heap et al., 2022a).  
234 Heap et al. (2022a) found, for rock samples prepared from the same blocks studied herein, that thermal  
235 conductivity decreased from  $\sim 1.5$  to  $\sim 0.6 \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as alteration increased from 6 to  $>70$  wt%. However, these  
236 data for volcanic rocks are also influenced by their varying porosities, another factor that is known to greatly  
237 influence thermal conductivity (Robertson and Peck, 1974; Heap et al., 2020). Heap et al. (2022a) then used an  
238 effective medium approach—the Maxwell equation (Zimmerman, 1989)—to estimate the thermal conductivity of

239 the solid groundmass (i.e., without porosity)  $\lambda_0$  and found that  $\lambda_0$  decreases as a function of alteration, from  $\sim 1.8$   
240  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at an alteration of  $\sim 10$  wt% to  $\sim 1.25 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  at an alteration of  $>70$  wt%. The thermal property  
241 data measured here (Figure 3) are unaffected by the influence of porosity (since the porosities of the powders are  
242 essentially equal; Table 1) and therefore indicate that the thermal conductivity and thermal diffusivity of unlithified  
243 granular volcanic materials are indeed reduced as a result of increasing alteration. This can be explained by the  
244 lower thermal conductivity and thermal diffusivity of the alteration assemblage compared to the primary mineral  
245 assemblage. For example, the thermal conductivity of kaolinite, a common secondary mineral in the dome rocks  
246 from La Soufrière (Heap et al., 2021, 2022a), is lower than that of plagioclase (Horai, 1971; Brigaud and Vasseur,  
247 1989).

248 If we compare our values of thermal conductivity  $\lambda$  at a saturation degree of zero (i.e.,  $\lambda|_{S=0}$ ; the data  
249 shown in Figure 3a), hereafter termed  $\lambda_d$ , with the values for the solid groundmass  $\lambda_0$  (from Heap et al., 2022a),  
250 we find that the degree to which the dry, but porous, conductivity of the powder  $\lambda_d$  depends on alteration is similar  
251 to the degree to which  $\lambda_0$  depends on alteration (Figure 5a). The empirical linear regressions to the  $\lambda_d$  and  $\lambda_0$  data  
252 as a function of alteration have very similar slopes (dashed lines on Figure 5a), albeit with different intercepts that  
253 reflect the porous vs. non-porous nature of  $\lambda_d$  and  $\lambda_0$ , respectively (Figure 5a). The covariance of  $\lambda_d$  and  $\lambda_0$  is  
254 linear and an excellent fit ( $r^2 = 0.987$ ) with an imposed intercept of 0 (dashed line on Figure 5b). This suggests  
255 that, at constant porosity, the thermal conductivity of the non-porous groundmass  $\lambda_0$  is the first order control on  
256 the conductivity of the unlithified granular material  $\lambda_d$  at  $S = 0$ . This can be further confirmed by applying the  
257 geometric mean model  $\lambda_d = \lambda_0^{1-\phi} \lambda_p^\phi$  (Judge, 1973), where  $\lambda_p$  is the conductivity of the pore fluid. In our case,  
258  $\lambda_p \approx 0.0367 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  for air at the experimental temperature. When we use this value to predict  $\lambda_d$  as a function  
259 of  $\lambda_0$  as described, and assuming  $\phi = 0.47$ , we find further good agreement with our data (solid line on Figure  
260 5b).

261

#### 262 4.2 Influence of water saturation degree and alteration on the thermal conductivity of volcanic powders

263 Our data show that thermal conductivity of volcanic powders increases as a function of the degree of  
264 water saturation (Figure 4). The thermal conductivity of rocks and unlithified granular materials has been  
265 previously seen to increase as a function of water saturation degree, and is due to the higher thermal conductivity  
266 of water compared to air (e.g., Clauser and Huenges, 1995; Côté and Konrad, 2005; Balland and Arp, 2005; Lu et  
267 al., 2007; Smits et al., 2010; Nagaraju and Roy, 2014; Barry-Macaulay et al., 2015; Zhang and Wang, 2017; Harlé  
268 et al., 2019; Heap et al., 2020). Our data are very much in agreement with the data provided by McCombie et al.

269 (2017) for pozzolana (pyroclastic soil) from Rome. These authors showed that thermal conductivity increased from  
 270  $\sim 0.2$  to  $\sim 1.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as the saturation degree increased from dry to fully saturated, very similar to the data  
 271 presented herein (Figure 4).

272 To better understand our data, we use a model for the conductivity of variably saturated media (Johansen,  
 273 1975) that predicts that  $\lambda$  is linearly dependent on  $\log_{10} S$  and is:

274

$$275 \lambda = \lambda_d + (\lambda_s - \lambda_d)(1 + \log_{10} S), \quad (1)$$

276

277 where  $\lambda_s$  is the conductivity of the fully saturated sample (i.e.,  $\lambda|_{S=1}$ ). Although various models exist to model the  
 278 thermal conductivity of variably saturated media, we chose here the model of Johansen (1975) due to its  
 279 widespread use in the study of soils and granular media (e.g., Côté and Konrad, 2005; Balland and Arp, 2005; Lu  
 280 et al., 2007; Smits et al., 2010; Barry-Macaulay et al., 2015; Zhang and Wang, 2017). Equation (1) cannot be valid  
 281 at low  $S$  because it predicts that  $\lambda < 0 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as  $S \rightarrow 0$ . For this reason, it is clearly valid only for moderate  
 282 to high values of  $S$ . Specifically,  $\lambda$  will be greater than zero for  $S > 10^{[\lambda_d/(\lambda_s - \lambda_d)] - 1}$ . Equation (1) can be rendered  
 283 dimensionless, and therefore universal for all powder types (i.e., for all alteration values) by rearranging as:

284

$$285 \frac{\lambda - \lambda_d}{\lambda_s - \lambda_d} = 1 + \log_{10} S, \quad (2)$$

286

287 where we define the dimensionless conductivity as  $\bar{\lambda} \equiv (\lambda - \lambda_d)/(\lambda_s - \lambda_d)$ . This normalisation has the desirable  
 288 property that at  $\bar{\lambda} \rightarrow 0$ ,  $\lambda \rightarrow \lambda_d$ , and at  $\bar{\lambda} \rightarrow 1$ ,  $\lambda \rightarrow \lambda_s$  such that all of our data should be bounded  $0 \leq \bar{\lambda} \leq 1$ . In  
 289 both Equations (1) and (2),  $\lambda_d$  is directly measured herein (see Figure 3a and Table 1). To find  $\lambda_s$  we can apply  
 290 one of two approaches. First, we predict  $\lambda_s$  using the same approach as applied in Figure 5b for the dry case where  
 291 the pore fluid is air:  $\lambda_s = \lambda_0^{1-\phi} \lambda_p^\phi$ . Here we simply exchange the value of  $\lambda_p$  that is valid for air, for the value valid  
 292 for water  $\lambda_p = 0.599 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ . This result is given in Figure 6a and, while it captures the general trend of the  
 293 data, clearly the data are not bounded between 0 and 1 as expected, and the data  $\bar{\lambda} > 1$  imply that  $\lambda_s$  may be  
 294 incorrect (i.e.  $\lambda_s = \lambda_0^{1-\phi} \lambda_p^\phi$  performs poorly with our saturated data at  $S = 1$ ). Therefore, second, we can reduce  
 295 the total dataset to just those samples for which  $\lambda$  was measured at  $S = 1$  (samples H2B, H15, H21, and H30; see  
 296 Table 2). These four samples cover a range of alteration from 41 to 74.6 wt% (Table 1). Now, when we use the  
 297 measured  $\lambda_s$  values in Equation (2), we find excellent agreement between our data and the model without the need

298 for empirical adjustment or fitting (Figure 6b). In Figure 6b, it is clear that all data are well-bounded by  $0 \leq \bar{\lambda} \leq 1$   
299 as predicted. Using the data for these four samples, we can now specify the lower value of  $S$  below which Equation  
300 (1) or (2) is not valid. As stated, that lower limit is  $S = 10^{[\lambda_d/(\lambda_s - \lambda_d)]^{-1}}$ , which is  $S \approx 0.05$  according to the values  
301 of  $\lambda_d$  and  $\lambda_s$  that we measure (here taking approximately  $\lambda_d = 0.25$  and  $\lambda_s = 1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ , respectively). Given  
302 the normalisation  $\bar{\lambda}$ , it is clear that while Equation (1) provides positive, and therefore sensible, values of  $\lambda$  for  
303  $S > 10^{[\lambda_s/(\lambda_d - \lambda_s)]}$ , Equation (2) shows that the normalised values  $\bar{\lambda}$  will only be positive for  $S > 10^{-1}$  (i.e.,  $S >$   
304  $0.1$ ). This implies that in the region  $0.05 \lesssim S \lesssim 0.1$ , Equation (2) will predict positive  $\lambda$  values but at  $\lambda < \lambda_d$ .

305 The result given in Figure 6b suggests that across the range of alteration present in the four samples  
306 analysed (i.e., 41–74.6 wt%), there is no discernible effect of alteration on their thermal conductivity at different  
307 saturation degrees. This observation suggests that the dominant effect of alteration is captured in the end member  
308 values  $\lambda_d$  and  $\lambda_s$ , and can thus be deconvolved from the effect of saturation degree. Hence, by applying  $\bar{\lambda}$ , alteration  
309 does not enter into the saturation-conductivity model given by Equation (2).

310 In Figure 7 we show the dimensional data from Figure 6b along with the dimensional version of the model  
311 (i.e., Equation (1)). When compared with Figure 6a, it is clear that using the measured  $\lambda_d$  and  $\lambda_s$  far out-performs  
312 using the predicted  $\lambda_s$  value. The effect of alteration that is captured by these four datasets is limited compared  
313 with the apparent effect seen in Figure 4. And given the efficacy of the correlations in Figure 5, we anticipate that  
314 the dominant effect of alteration is in changing  $\lambda_d$  and  $\lambda_s$ . While the effect of alteration on  $\lambda_d$  is clearly attributable  
315 to the effect of alteration on the groundmass  $\lambda_0$  (Figure 5), the effect of alteration on  $\lambda_s$  remains unexplained. This  
316 effect could also be related to  $\lambda_0$ . Although, we additionally hypothesise that the effect of alteration on  $\lambda_s$  could  
317 be the result of the higher wt% of kaolinite in the altered samples (Heap et al., 2021, 2022a), which can adsorb  
318 water (Croteau et al., 2009). Therefore, for the altered samples, some of the water may adsorb to the surface of  
319 mineral grains rather than residing within the void space, which may result in a lower  $\lambda_s$ .

320

#### 321 4.3 Implications for the modelling of heat transport in a volcano or volcanic geothermal reservoir

322 Values for the thermal properties of volcanic rocks and unlithified granular volcanic materials are  
323 required in models designed to interpret surface heat flux data and model heat loss from magma. We provide three  
324 take-home points, based on the results of this study, to help those tasked with modelling heat transport within a  
325 volcano.

326 First, our study shows that, due to the potentially large difference in thermal properties between volcanic  
327 rocks and unlithified granular volcanic materials, it is important to know the proportions and/or locations of rock

328 and unlithified materials when modelling heat transport within a volcano. To emphasise, the thermal conductivity  
329 of rocks from La Soufrière was measured to be  $\sim 0.5\text{--}1.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  (Heap et al., 2022a), whereas the thermal  
330 conductivity of powders prepared from the same rocks was measured to be  $\sim 0.2\text{--}0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  (Figure 3).

331         Second, our study shows that it is important to know the alteration state of the rocks and unlithified  
332 materials. The thermal conductivity and thermal diffusivity of unlithified granular volcanic materials (Figure 3)  
333 and volcanic rocks (Heap et al., 2022a) are reduced following hydrothermal alteration.

334         Finally, our study also shows that it is important to know the saturation degree of the rocks and unlithified  
335 granular materials. This is especially important for the unlithified granular materials, which see larger increases in  
336 thermal conductivity upon saturation (Figure 4) than rocks (Heap et al., 2020). Indeed, thermal conductivity values  
337 for saturated powders can be similar to those for dry porous rocks (porosity  $> 0.2$ ; Heap et al., 2022a) and even  
338 some water-saturated porous rocks (porosity  $> 0.5$ ; Heap et al., 2020) (Figure 8). The empirical model proposed  
339 by Johansen (1975) for variably saturated granular media is in general agreement with our data, and provides a  
340 means to model the thermal conductivity of unlithified granular volcanic materials as a function of saturation  
341 degree (Figures 6 and 7). The importance of saturation degree on the thermal conductivity of volcanic rocks and  
342 powders (Figure 8) suggests that geophysical methods able to map subsurface saturation, such as electrical  
343 tomography (Rosas-Carbajal et al., 2016; Gresse et al., 2017; Byrdina et al., 2017; Ahmed et al., 2018; Ghorbani  
344 et al., 2018), could be used to improve heat flux calculations and modelling designed to inform on volcanic and  
345 geothermal processes.

346

## 347 **5 Conclusions**

348         The thermal properties of volcanic rocks and unlithified granular volcanic materials are required for  
349 modelling and understanding surface heat fluxes at volcanoes, which can inform on growing volcanic unrest and  
350 impending eruptive activity, and for models designed to estimate timescales for the cooling of magma. There are  
351 comparatively few data for unlithified granular volcanic materials, however, which served as the motivation for  
352 this contribution.

353         Our study has shown that the thermal properties of unlithified granular volcanic materials are low when  
354 compared to rocks ( $\sim 0.2\text{--}0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  compared to  $\sim 0.5\text{--}1.5 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ; Figure 3; Heap et al., 2022a) and that  
355 they are influenced by alteration and saturation with water (Figures 3 and 4). We show that thermal conductivity  
356 decreases from  $\sim 0.3$  to  $\sim 0.2 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and thermal diffusivity decreases from  $\sim 0.27$  to  $\sim 0.22 \text{ mm}^2\cdot\text{s}^{-1}$  as alteration  
357 is increased from  $\sim 10$  to  $\sim 70$  wt% (Figures 3a and 3b). We interpret this to be the result of the lower thermal

358 conductivity and thermal diffusivity of the secondary mineral assemblage. Specific heat capacity, however, does  
359 not appear to change systematically as a function of alteration (Figure 3c).

360 We also show that thermal conductivity increases from  $\sim 0.2\text{--}0.3$  to  $\sim 0.8\text{--}1.1$   $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  as the saturation  
361 degree is increased from dry to near-complete saturation (Figure 4), due to the higher thermal conductivity of water  
362 compared to air. We find that an empirical model for variably saturated granular media (Johansen, 1975) is in  
363 general agreement with our data (Figures 6 and 7), and provides a framework to predict the thermal conductivity  
364 of unlithified granular volcanic materials as a function of saturation degree. We also find that, when saturated, the  
365 thermal conductivity of altered unlithified materials is lower than that of unaltered unlithified materials (Figure 4).  
366 We interpret this latter point to be dominantly due to the effect of alteration on the groundmass conductivity (Figure  
367 5), although we also suggest that this could also be due to the ability of kaolinite, abundant in the altered materials,  
368 to adsorb water. Finally, we show that saturated unlithified materials can have higher thermal conductivities than  
369 dry rocks (Figure 8), highlighting the importance of understanding the saturation state prior to performing heat  
370 flux calculations and modelling designed to inform on volcanic and geothermal processes.

371 It is our hope that the data and modelling presented in this study will assist those tasked with modelling  
372 heat transport within a volcano or volcanic geothermal reservoir. Improved models will help better assess volcanic  
373 hazards and mitigate risk and help optimise geothermal energy exploitation. Finally, we note that, although the  
374 blocks studied herein were collected to capture the breadth of alteration seen at La Soufrière, and so likely capture  
375 the range in expected thermal properties for La Soufrière, care should be taken to ensure that the type of alteration  
376 (advanced argillic alteration) is similar if these data are to be used for other volcanoes or volcanic systems. Because  
377 the thermal properties of unlithified granular volcanic materials depend on the thermal properties of the constituent  
378 minerals, the thermal properties of altered deposits with different secondary mineral assemblages may differ from  
379 those reported herein.

380

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391

#### 392 **Declaration of competing interest**

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

395

#### 396 **CRediT author statement**

397 **Michael Heap:** Conceptualisation; Investigation; Resources; Writing – Original Draft; Visualisation; Project  
398 administration; Funding acquisition. **Fabian Wadsworth:** Formal analysis; Writing – Review & Editing. **David**

399 **Jessop:** Writing – Review & Editing.

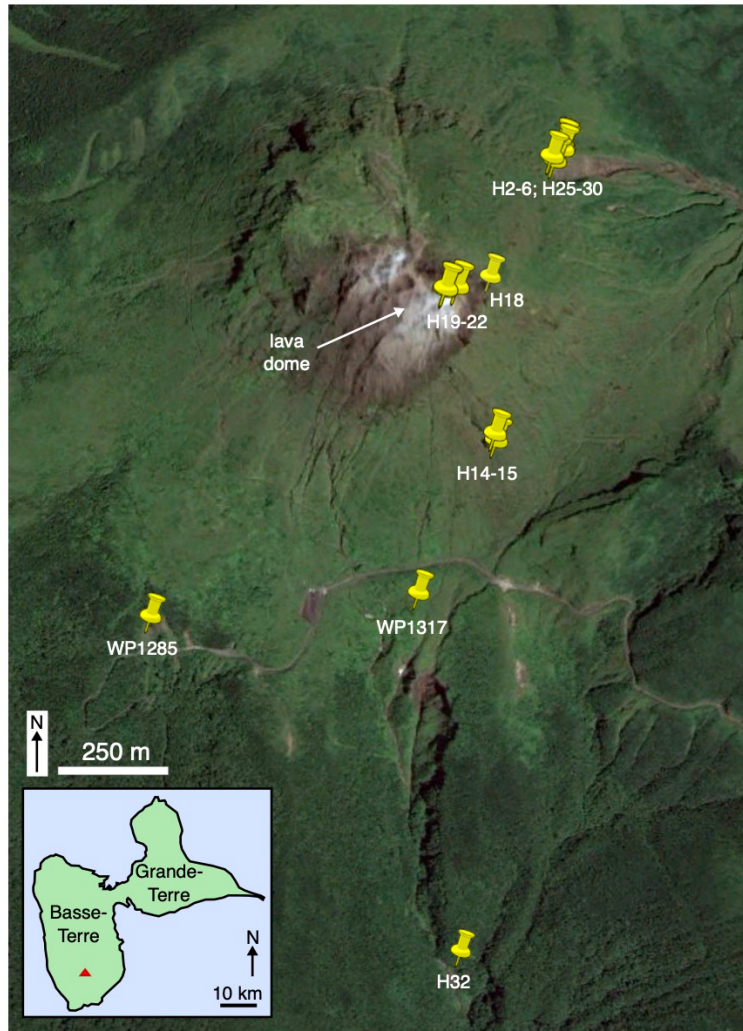
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#### 401 **Supplementary Material**

402 We provide a Microsoft Excel spreadsheet containing all the data collected for this study.

403

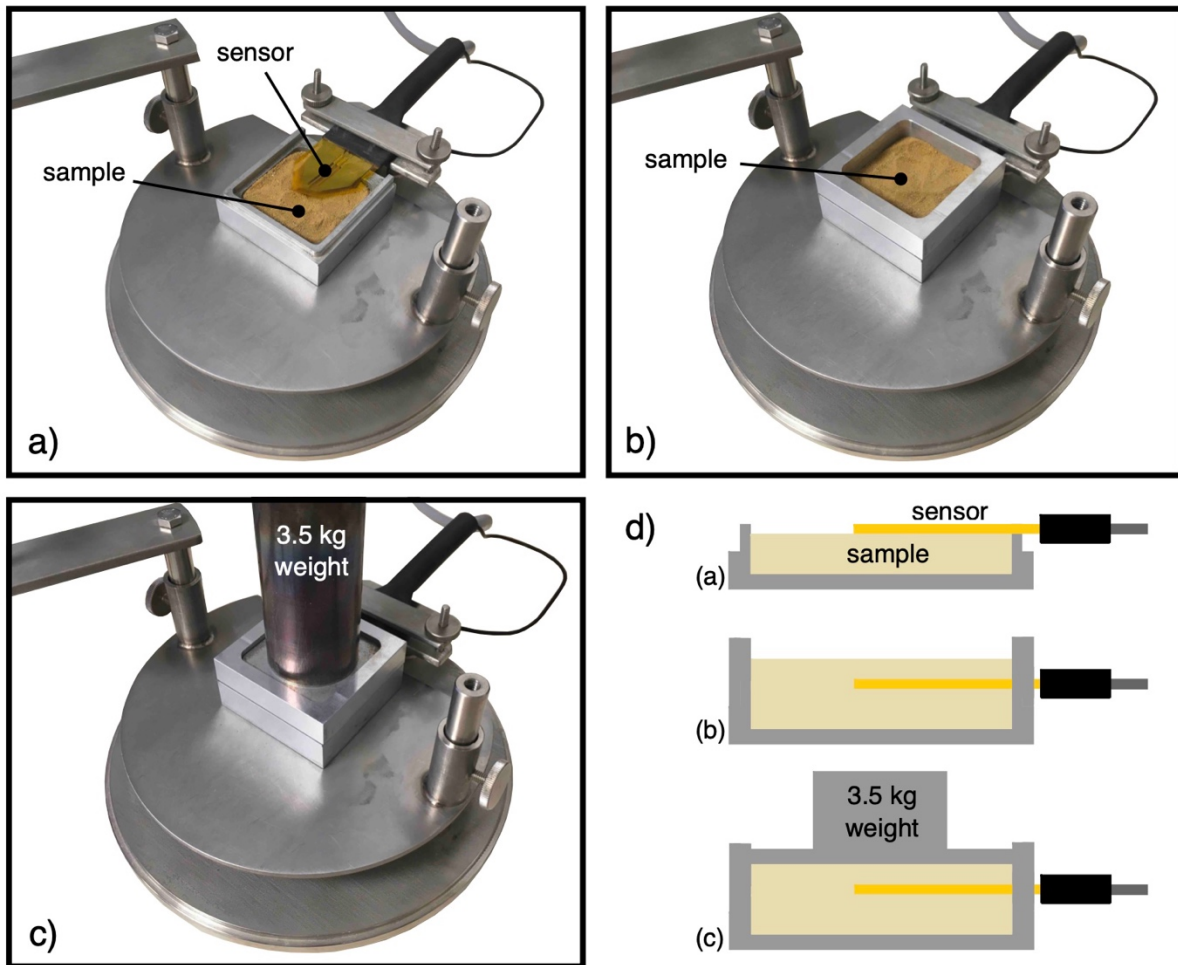
404 **Figure 1.** Map image of La Soufrière de Guadeloupe (Eastern Caribbean) showing the sample collection sites.  
405 Inset shows a map of Guadeloupe (with the location of the volcano given as a red triangle). Image data ©2019  
406 Google.



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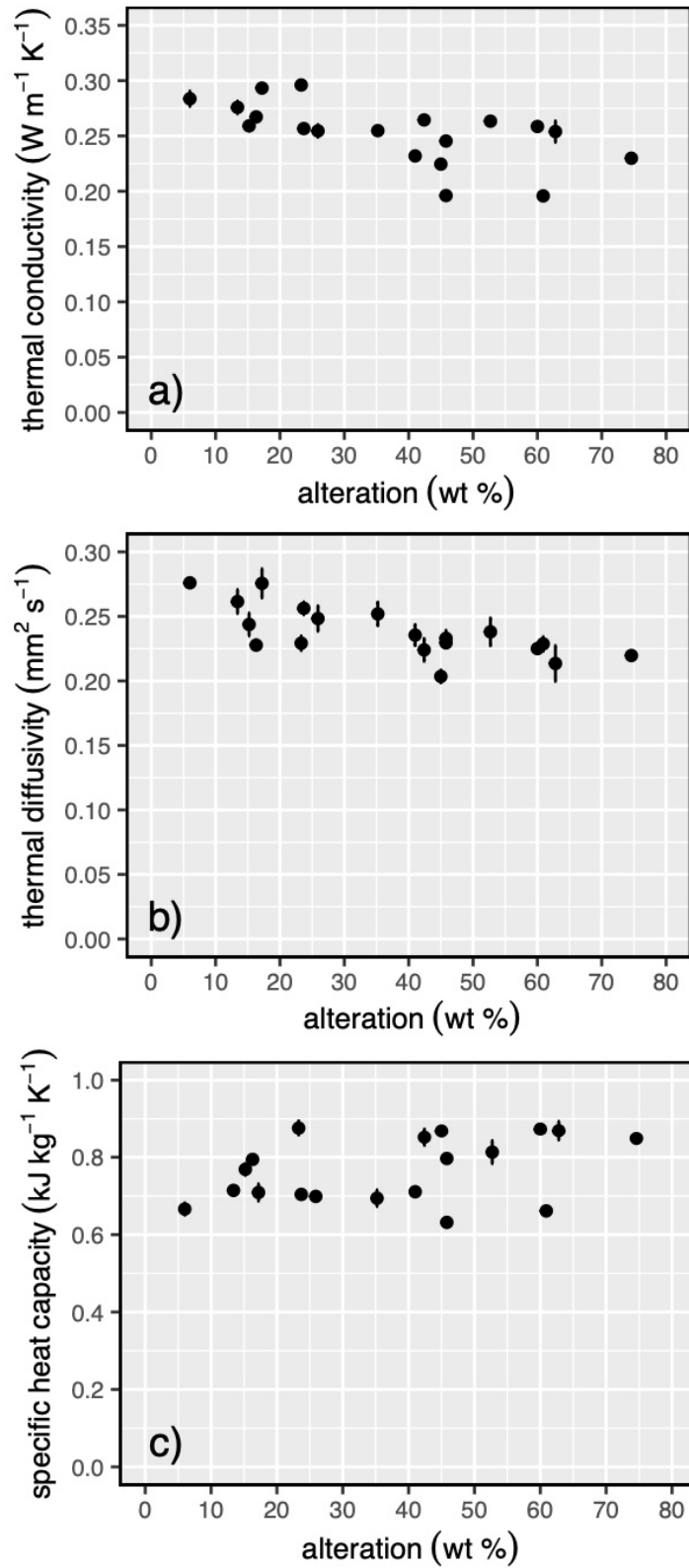


409 **Figure 2.** Photographs and a schematic diagram showing the procedure for measuring the powdered samples. (a)  
410 The powder was first spooned into the lower part of the holder, underneath the sensor. (b) The upper part of the  
411 holder was placed onto the lower part and powder was spooned over the sensor. (c) The top of the holder (a flat  
412 metal piece) was placed on top of the powder and a 3.5 kg weight was placed on top of the setup to ensure  
413 reproducible compaction (and therefore a similar porosity) and a good contact between the sensor and the powder.  
414 (d) Schematic (not-to-scale) diagrams showing a side-on view of the experimental steps shown in panels (a), (b),  
415 and (c).



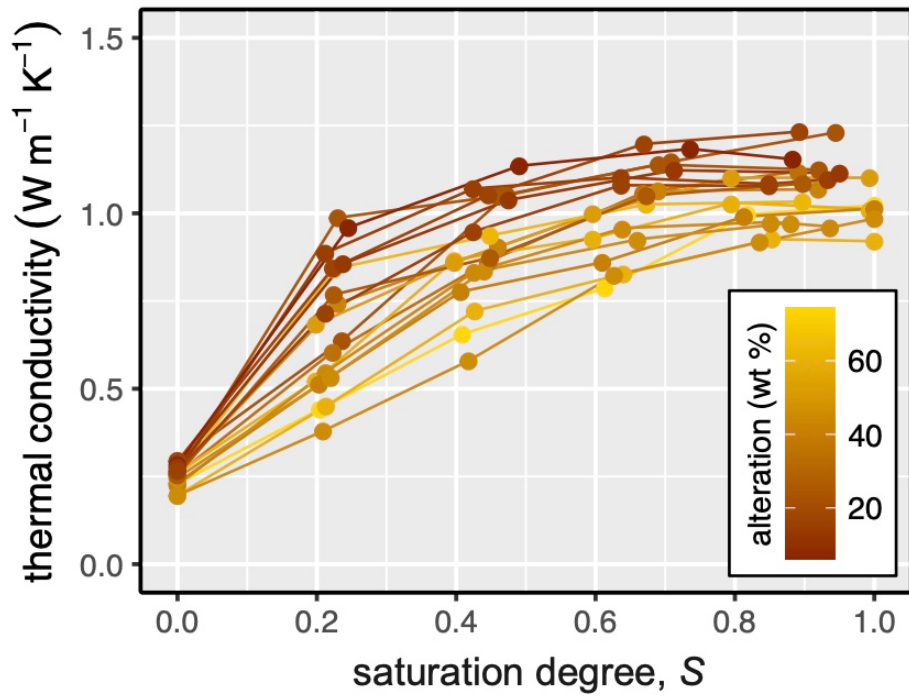
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418 **Figure 3.** Thermal conductivity (a), thermal diffusivity (b), and specific heat capacity (c) as a function of alteration  
419 (the wt% of secondary minerals) for dry powders from La Soufrière de Guadeloupe (Eastern Caribbean). Data  
420 provided in Table 1.



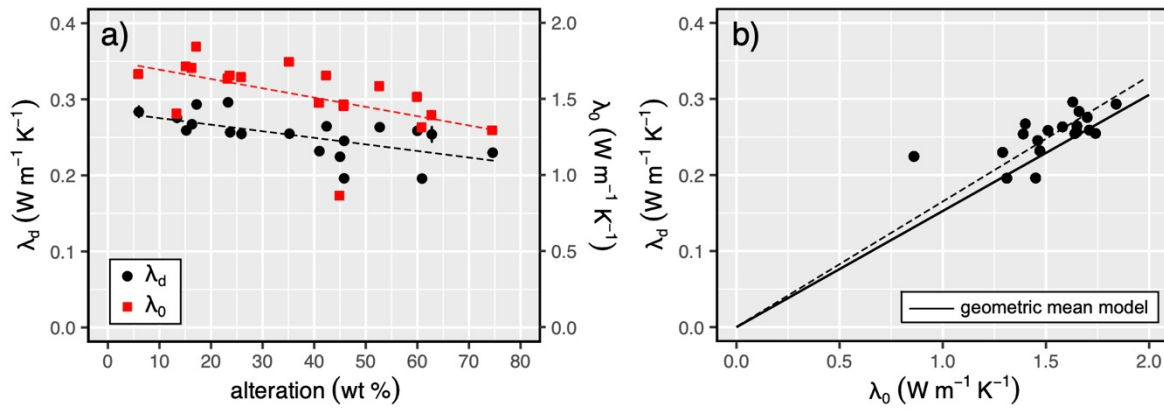
421

422 **Figure 4.** Thermal conductivity of powders from La Soufrière de Guadeloupe (Eastern Caribbean) as a function  
423 of water saturation degree  $S$ . Colour of the symbols and lines indicates the alteration (the wt% of secondary  
424 minerals), where red and yellow indicate low and high alteration, respectively.



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426

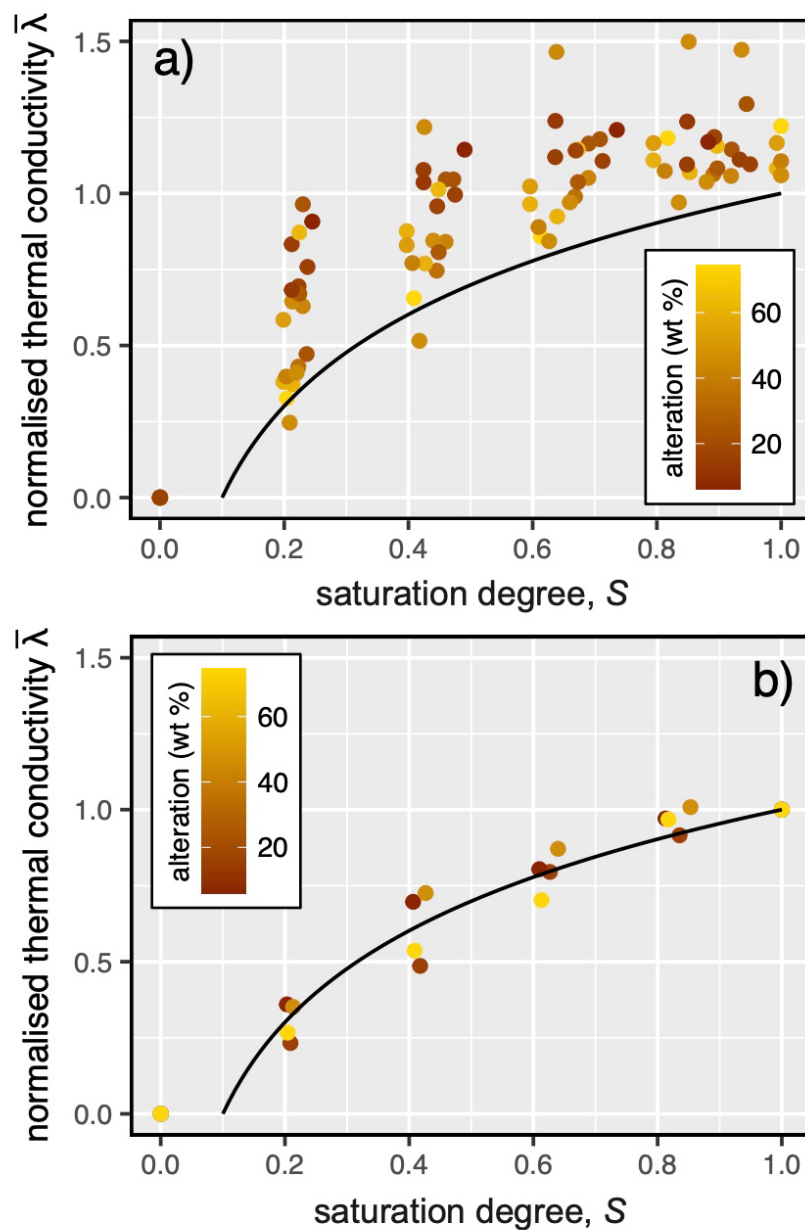
427 **Figure 5.** (a) The porosity-free groundmass conductivity  $\lambda_0$  (red squares) and the conductivity of the dry powders  
 428 at zero saturation ( $S = 0$ )  $\lambda_d$  (black circles) as a function of alteration (the wt% of secondary minerals). Dashed  
 429 lines are empirical linear fits to the data. (b) The conductivity of the dry powders at zero saturation ( $S = 0$ )  $\lambda_d$  as  
 430 a function of the porosity-free groundmass conductivity  $\lambda_0$ . The dashed line is an empirical linear fit to the data  
 431 with an imposed intercept of 0. The solid curve is the theoretical trend following  $\lambda_d = \lambda_0^{1-\phi} \lambda_p^\phi$  with  $\lambda_p = 0.0367$   
 432  $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$  and  $\phi = 0.47$ .



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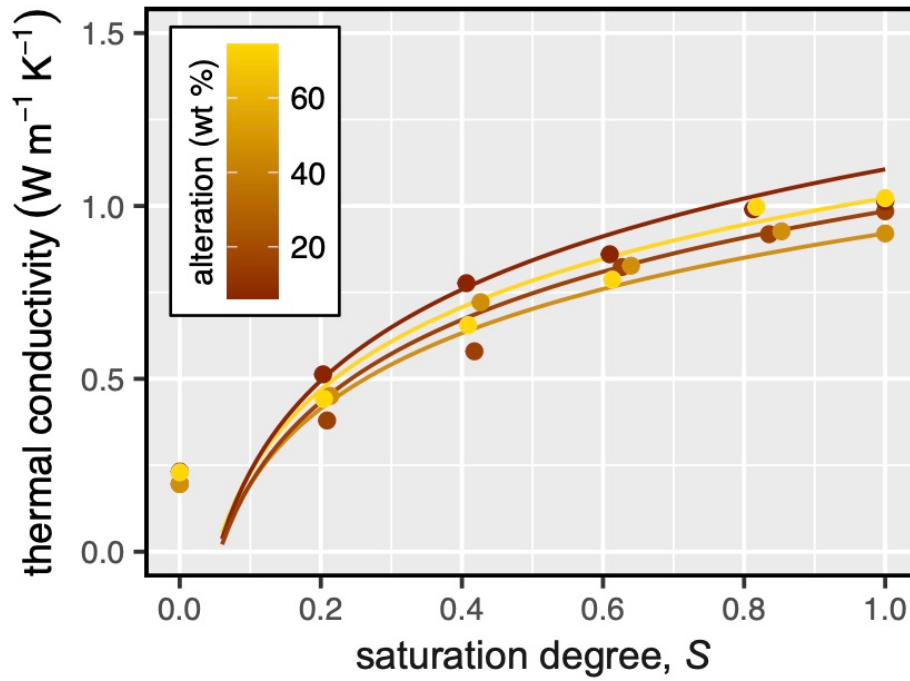
434

435 **Figure 6.** (a) Dimensionless conductivity,  $\bar{\lambda} \equiv (\lambda - \lambda_d)/(\lambda_s - \lambda_d)$ , as a function of saturation degree  $S$  for all the  
 436 data (Table 2). Black solid line is the modelled curve using Equation (2), in which the saturated conductivity is  
 437 predicted using  $\lambda_s = \lambda_0^{1-\phi} \lambda_p^\phi$ . (b) Dimensionless conductivity,  $\bar{\lambda} \equiv (\lambda - \lambda_d)/(\lambda_s - \lambda_d)$ , as a function of saturation  
 438 degree  $S$  for the data that reached complete saturation ( $S = 1$ ; samples H2B, H15, H21, and H30). Black solid line  
 439 is the modelled curve using Equation (2), in which  $\lambda_s$  is measured directly (see Table 2). In both panels, the model  
 440 provides  $\lambda$  values valid above  $S \approx 0.05$  (note that  $\lambda \rightarrow 0$  occurs at  $\bar{\lambda} < 0$  because  $\lambda = 0$  is at  $\lambda < \lambda_d$ , which is why  
 441 the solid curves in this figure approach  $\bar{\lambda} = 0$  at  $S \approx 0.1$ ). Colour of the symbols indicates the alteration (the wt%  
 442 of secondary minerals), where red and yellow indicate low and high alteration, respectively.



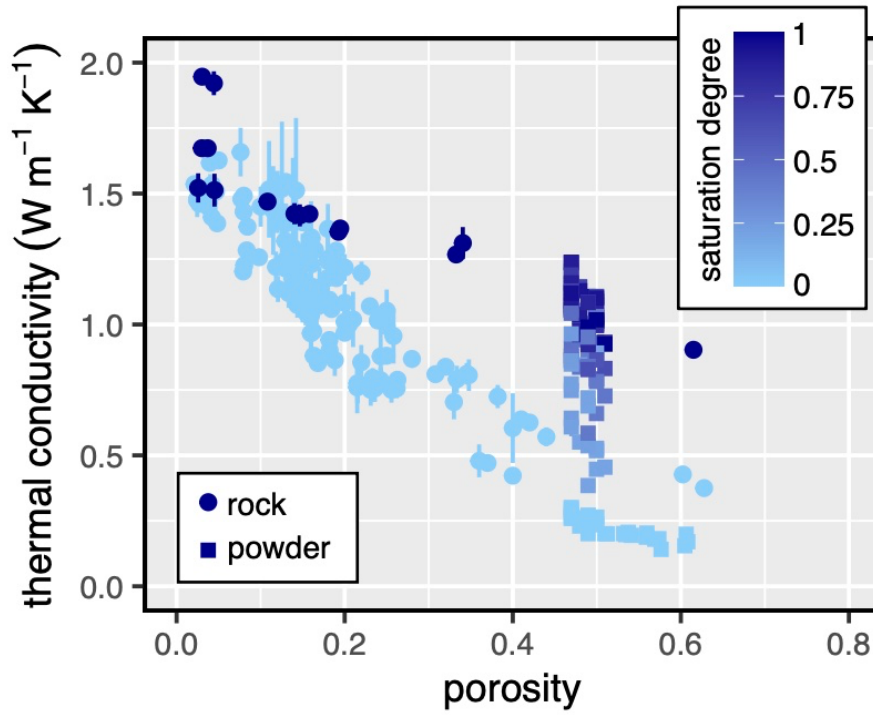
443

444 **Figure 7.** Dimensional thermal conductivity as a function of water saturation degree  $S$  for the four samples for  
445 which both the dry  $\lambda_d$  and saturated  $\lambda_s$  are measured values. The curves are given by Equation (1) with the  
446 measured values input (i.e., no fitting parameters). The model is valid above  $S \approx 0.05$ .



447  
448

449 **Figure 8.** Thermal conductivity as a function of porosity for volcanic rocks (circles; data from Heap et al., 2020,  
450 2022a) and unlithified granular volcanic materials (squares; data from Heap et al., 2022a and this study). Colour  
451 of the symbols indicates the water saturation degree, where light blue and dark blue indicate low and high  
452 saturation degree, respectively.



453

Block	Alteration (wt%)	Total porosity	Thermal conductivity [ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ]	Thermal diffusivity [ $\text{mm}^2\cdot\text{s}^{-1}$ ]	Specific heat capacity [ $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ]
H2A	23.3	0.47	$0.296 \pm 0.001$	$0.229 \pm 0.006$	$0.876 \pm 0.019$
H2B	74.6	0.50	$0.230 \pm 0.001$	$0.220 \pm 0.002$	$0.849 \pm 0.007$
H3	35.2	0.47	$0.255 \pm 0.001$	$0.252 \pm 0.009$	$0.694 \pm 0.021$
H4A	60.0	0.50	$0.259 \pm 0.001$	$0.225 \pm 0.003$	$0.873 \pm 0.008$
H5A	42.4	0.47	$0.264 \pm 0.004$	$0.224 \pm 0.009$	$0.852 \pm 0.021$
H6	52.7	0.49	$0.263 \pm 0.003$	$0.238 \pm 0.011$	$0.813 \pm 0.029$
H14	23.7	0.48	$0.257 \pm 0.002$	$0.256 \pm 0.005$	$0.704 \pm 0.008$
H15	60.9	0.51	$0.196 \pm 0.002$	$0.229 \pm 0.006$	$0.661 \pm 0.008$
H18	15.2	0.50	$0.259 \pm 0.004$	$0.244 \pm 0.009$	$0.769 \pm 0.015$
H19	62.8	0.48	$0.254 \pm 0.010$	$0.214 \pm 0.014$	$0.869 \pm 0.024$
H20	45.0	0.48	$0.225 \pm 0.003$	$0.203 \pm 0.005$	$0.868 \pm 0.009$
H21	41.0	0.50	$0.232 \pm 0.004$	$0.236 \pm 0.008$	$0.711 \pm 0.012$
H22	17.2	0.47	$0.293 \pm 0.004$	$0.276 \pm 0.011$	$0.709 \pm 0.022$
H25	45.8	0.49	$0.245 \pm 0.002$	$0.230 \pm 0.003$	$0.797 \pm 0.009$
H29	25.9	0.47	$0.255 \pm 0.006$	$0.248 \pm 0.010$	$0.699 \pm 0.012$
H30	45.8	0.49	$0.196 \pm 0.003$	$0.233 \pm 0.006$	$0.632 \pm 0.008$
H32	6.0	0.47	$0.284 \pm 0.007$	$0.276 \pm 0.002$	$0.666 \pm 0.016$
WP1285	13.4	0.47	$0.276 \pm 0.006$	$0.261 \pm 0.009$	$0.714 \pm 0.011$
WP1317	16.3	0.49	$0.267 \pm 0.001$	$0.228 \pm 0.004$	$0.794 \pm 0.012$

456

457 **Table 1.** Thermal properties (thermal conductivity, thermal diffusivity, and specific heat capacity) of the 19 dry  
458 powders from La Soufrière de Guadeloupe (Eastern Caribbean). Also provided are their alteration intensities (the  
459 wt% of secondary minerals) and their total porosities. The thermal properties of each sample were measured four  
460 times and we report the mean and standard error of these four measurements (all the data are provided in a  
461 Microsoft Excel spreadsheet that accompanies this contribution as Supplementary Material).

462

Block	Alteration (wt%)	Total porosity	Saturation degree, $S$	Thermal conductivity [ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ]
H2A	23.3	0.47	0.00	$0.296 \pm 0.001$
H2A	23.3	0.47	0.24	$0.637 \pm 0.018$
H2A	23.3	0.47	0.47	$1.052 \pm 0.002$
H2A	23.3	0.47	0.71	$1.147 \pm 0.011$
H2A	23.3	0.47	0.94	$1.231 \pm 0.005$
H2B	74.6	0.50	0.00	$0.230 \pm 0.001$
H2B	74.6	0.50	0.20	$0.442 \pm 0.005$
H2B	74.6	0.50	0.41	$0.655 \pm 0.005$
H2B	74.6	0.50	0.61	$0.787 \pm 0.005$



H2B	74.6	0.50	0.82	0.997 ± 0.006
H2B	74.6	0.50	1.00	1.023 ± 0.014
H3	35.2	0.47	0.00	0.255 ± 0.001
H3	35.2	0.47	0.22	0.604 ± 0.036
H3	35.2	0.47	0.45	0.860 ± 0.006
H3	35.2	0.47	0.67	1.057 ± 0.003
H3	35.2	0.47	0.89	1.116 ± 0.003
H4A	60.0	0.50	0.00	0.259 ± 0.001
H4A	60.0	0.50	0.20	0.522 ± 0.004
H4A	60.0	0.50	0.40	0.865 ± 0.005
H4A	60.0	0.50	0.60	0.927 ± 0.006
H4A	60.0	0.50	0.79	1.027 ± 0.002
H4A	60.0	0.50	0.99	1.008 ± 0.011
H5A	42.4	0.47	0.00	0.264 ± 0.004
H5A	42.4	0.47	0.23	0.743 ± 0.009
H5A	42.4	0.47	0.46	0.904 ± 0.007
H5A	42.4	0.47	0.69	1.064 ± 0.008
H5A	42.4	0.47	0.92	1.069 ± 0.011
H6	52.7	0.49	0.00	0.263 ± 0.003
H6	52.7	0.49	0.20	0.684 ± 0.007
H6	52.7	0.49	0.40	0.860 ± 0.028
H6	52.7	0.49	0.60	0.999 ± 0.018
H6	52.7	0.49	0.79	1.101 ± 0.008
H6	52.7	0.49	0.99	1.102 ± 0.005
H14	23.7	0.48	0.00	0.257 ± 0.002
H14	23.7	0.48	0.23	0.987 ± 0.014
H14	23.7	0.48	0.46	1.049 ± 0.009
H14	23.7	0.48	0.69	1.139 ± 0.019
H14	23.7	0.48	0.92	1.124 ± 0.005
H15	60.9	0.51	0.00	0.196 ± 0.002
H15	60.9	0.51	0.21	0.450 ± 0.004
H15	60.9	0.51	0.43	0.722 ± 0.018
H15	60.9	0.51	0.64	0.827 ± 0.014
H15	60.9	0.51	0.85	0.927 ± 0.022
H15	60.9	0.51	1.00	0.920 ± 0.015
H18	15.2	0.50	0.00	0.259 ± 0.004
H18	15.2	0.50	0.21	0.886 ± 0.008
H18	15.2	0.50	0.42	1.070 ± 0.017
H18	15.2	0.50	0.64	1.102 ± 0.017
H18	15.2	0.50	0.85	1.084 ± 0.009
H18	15.2	0.50	0.93	1.096 ± 0.002
H19	62.8	0.48	0.00	0.254 ± 0.010
H19	62.8	0.48	0.22	0.841 ± 0.013
H19	62.8	0.48	0.45	0.937 ± 0.019
H19	62.8	0.48	0.67	1.026 ± 0.012
H19	62.8	0.48	0.90	1.033 ± 0.009
H20	45.0	0.48	0.00	0.225 ± 0.003

H20	45.0	0.48	0.21	0.546 ± 0.017
H20	45.0	0.48	0.43	0.832 ± 0.010
H20	45.0	0.48	0.64	0.955 ± 0.011
H20	45.0	0.48	0.85	0.972 ± 0.005
H20	45.0	0.48	0.94	0.958 ± 0.012
H21	41.0	0.50	0.00	0.232 ± 0.004
H21	41.0	0.50	0.20	0.513 ± 0.008
H21	41.0	0.50	0.41	0.777 ± 0.010
H21	41.0	0.50	0.61	0.860 ± 0.028
H21	41.0	0.50	0.81	0.991 ± 0.025
H21	41.0	0.50	1.00	1.013 ± 0.007
H22	17.2	0.47	0.00	0.293 ± 0.004
H22	17.2	0.47	0.22	0.844 ± 0.007
H22	17.2	0.47	0.45	1.052 ± 0.006
H22	17.2	0.47	0.67	1.198 ± 0.021
H22	17.2	0.47	0.89	1.233 ± 0.004
H25	45.8	0.49	0.00	0.245 ± 0.002
H25	45.8	0.49	0.22	0.532 ± 0.002
H25	45.8	0.49	0.44	0.835 ± 0.005
H25	45.8	0.49	0.66	0.923 ± 0.015
H25	45.8	0.49	0.88	0.970 ± 0.006
H29	25.9	0.47	0.00	0.255 ± 0.006
H29	25.9	0.47	0.22	0.768 ± 0.004
H29	25.9	0.47	0.45	0.874 ± 0.015
H29	25.9	0.47	0.67	1.050 ± 0.026
H29	25.9	0.47	0.90	1.085 ± 0.014
H30	45.8	0.49	0.00	0.196 ± 0.003
H30	45.8	0.49	0.21	0.380 ± 0.021
H30	45.8	0.49	0.42	0.580 ± 0.020
H30	45.8	0.49	0.63	0.823 ± 0.002
H30	45.8	0.49	0.84	0.918 ± 0.004
H30	45.8	0.49	1.00	0.985 ± 0.030
H32	6.0	0.47	0.00	0.284 ± 0.007
H32	6.0	0.47	0.25	0.959 ± 0.011
H32	6.0	0.47	0.49	1.135 ± 0.010
H32	6.0	0.47	0.74	1.184 ± 0.007
H32	6.0	0.47	0.88	1.154 ± 0.001
WP1285	13.4	0.47	0.00	0.276 ± 0.006
WP1285	13.4	0.47	0.24	0.856 ± 0.012
WP1285	13.4	0.47	0.48	1.038 ± 0.011
WP1285	13.4	0.47	0.71	1.123 ± 0.020
WP1285	13.4	0.47	0.95	1.115 ± 0.012
WP1317	16.3	0.49	0.00	0.267 ± 0.001
WP1317	16.3	0.49	0.21	0.715 ± 0.011
WP1317	16.3	0.49	0.42	0.947 ± 0.011
WP1317	16.3	0.49	0.64	1.080 ± 0.006
WP1317	16.3	0.49	0.85	1.079 ± 0.006

464 **Table 2.** Thermal conductivity of the 19 powders from La Soufrière de Guadeloupe (Eastern Caribbean) at  
465 different degrees of water saturation. Also provided are their alteration intensities (the wt% of secondary minerals)  
466 and their total porosities. The thermal properties of each sample were measured four times and we report the mean  
467 and standard error of these four measurements (all the data are provided in a Microsoft Excel spreadsheet that  
468 accompanies this contribution as Supplementary Material).

469

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