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1 Conservation and restoration of St. George's church (Nördlingen,
2 Germany), a 15th century Gothic church built using suevite from
3 the Ries impact crater

4

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24 **Abstract**

25 An asteroid impact in southwest Germany ca. 15 Ma left a >20 km-diameter
26 blanket of poorly sorted clastic rock, called suevite. In the 15th century, the suevite was
27 used to construct a Gothic church (St. George's church, Nördlingen). Visual inspection
28 of the church highlights its strong weathering susceptibility. We investigate whether
29 the suevite used to construct the church and the rocks used in its restoration (suevite
30 and sandstone) are weaker when saturated with water, important for conservation
31 strategies. We additionally assess, by comparing their physical properties, the
32 suitability of the replacement stones. We show that the strength of the suevite used to
33 build the church is reduced by half when water-saturated, considered here a
34 consequence of its high smectite content. This helps explain the prevalent weathering
35 of the stones forming the outer walls of the church. The replacement suevite has a
36 higher wet/dry strength ratio than the original suevite and is therefore more resistant to
37 weathering. Not only does the replacement sandstone have a low ratio of wet/dry
38 strength, but also its physical properties are different from the original suevite, which
39 has almost identical physical properties to those of the replacement suevite. Based on
40 these results, and the appearance of the stones, we recommend that, where possible,
41 natural suevite stones be used to replace the weathered blocks of suevite at St. George's
42 church and at buildings built using suevite within the region.

43

44 **Keywords:** suevite; conservation; porosity; permeability; uniaxial compressive
45 strength

46 **1 Introduction**

47 An asteroid impacted a 600-700 m thick layer of sedimentary rocks overlying a
48 crystalline basement (Pohl et al., 1977; von Engelhardt, 1990; Stöffler et al., 2013) in
49 southwest Germany ca. 15 Ma (Rocholl et al., 2018) (Fig. 1a). In the aftermath of the
50 impact, “clouds” of hot debris and gas dispersed radially (Siegert et al., 2017) forming
51 a subcircular blanket of poorly sorted clastic material that subsequently welded to form
52 a rock called suevite. Two layers of suevite exist: (1) “crater suevite”, which is up to
53 300 m thick and covered by Miocene lake sediments and (2) “outer suevite”, which is
54 only up to 25 m thick and outcrops up to 22 km from the centre of the structure (Stöffler
55 et al., 2013). The Ries impact crater, a double-layer rampart crater (Sturm et al., 2013),
56 has an inner- and outer-ring diameter of ca. 12 and 24 km, respectively (Wünnemann
57 et al., 2005; Fig. 1b). The suevite contains centimetric-sized clasts of impact melt glass
58 (aerodynamically shaped bombs and angular fragments; Stähle, 1972; Osinski, 2003)
59 and crystalline and sedimentary rocks (Graup, 1981; von Engelhardt, 1990, 1997).
60 These clasts are hosted within a matrix of clays (and sometimes zeolites) that formed
61 as a result of post-deposition hydrothermal alteration, impact melt glass, rock and
62 mineral fragments, and crystallites (Newsom et al., 1986; von Engelhardt, 1990, 1997;
63 Osinski, 2005; Osinski et al., 2010; Muttik et al., 2010, 2011; Sapers et al., 2017).
64 Coesite is also present (Stöffler, 1966; Stähle et al., 2008), the mineral that confirmed
65 the impact origin of these deposits (Shoemaker and Chao, 1961). Diamond and other
66 high-pressure minerals have also been identified (Stöffler et al., 2013).

67 The town of Nördlingen (Fig. 1) was founded within the impact crater and
68 suevite was used in its construction. Parts of the city hall, the city fortifications (walls
69 and gates), and the impressive 15th century Gothic church (St. George’s church; Fig.
70 1c) were constructed using suevite. A visual inspection of St. George’s church, and

71 other buildings constructed using suevite, highlights its strong weathering
72 susceptibility. There is evidence of alveolisation (detachment of clasts/fragments),
73 scaling, exfoliation, and disaggregation (Fig. 2a) and, as a result, many of the suevite
74 dimension stones of St. George's church have been recently (starting from the 1970s)
75 replaced with blocks of synthetic and natural suevite and a white sandstone (Fig. 2b
76 and 2c).

77 Laboratory experiments on clay-bearing sandstones (Dyke and Dobereiner,
78 1991; Hawkins and McConnell, 1992; Shakoor and Barefield, 2009; Wasantha and
79 Ranjith, 2014; Verstryngge et al., 2014; Heap et al., 2018a, 2019) and tuffs (e.g., Zhu et
80 al., 2011; Heap et al., 2018b) suggest that clays may promote rock weakening in the
81 presence of water. The metric "water-weakening", the ratio of the wet to dry strength
82 of a material, is often used to describe this affect, where low values (close to zero)
83 indicate a strong water-weakening effect and values at or close to unity indicate that
84 there is little or no water-weakening. The high clay content of the suevite (Newsom et
85 al., 1986; Osinski, 2005; Muttik et al., 2010, 2011; Sapers et al., 2017) may therefore
86 help explain its high susceptibility to weathering (Fig. 2).

87

88 **2 Research aim**

89 Our objective is twofold. First, to inform on the suitability of the replacement
90 stones (Přikryl, 2007), we assess the physical properties of the suevite originally used
91 in the construction of the church and the replacement suevite and sandstone. Second,
92 to better understand the observed weathering susceptibility (Fig. 2), we assess the
93 water-weakening of the original suevite and the replacement stones.

94

95 **3 Materials and methods**

96 The two suevite blocks used in this study were sourced from the quarries at
97 Altenbürg (thought to be the quarry from where the rock for the church was sourced;
98 Fig. 1b) and Seelbronn (the quarry from where the suevite used to restore the church is
99 sourced; Fig. 1b; see also Poschlod et al., 2017). Although the Altenbürg quarry is
100 thought to be the source site for the suevites used in the original construction, it cannot
101 be definitively ruled out that some blocks were sourced from other quarries.
102 Nevertheless, we consider that the block we collected from Altenbürg well represents
103 the colour and therefore alteration of the blocks used in the original construction. The
104 sandstone used in the restoration of the church is Schönbrunn sandstone (from
105 Schönbrunn-Hermannsberg quarry in Bavaria, Germany).

106 Both suevites are poorly sorted clastic rocks that contain millimetric and
107 centimetric-sized clasts of glass (aerodynamically shaped bombs and angular
108 fragments), crystalline rocks (Variscan granites and pre-Variscan gneisses and
109 amphibolites), and sedimentary rocks within a fine-grained matrix (von Engelhardt,
110 1990, 1997; Stöffler et al., 2013). Macroscopically, the only observable difference
111 between the blocks is that the suevite blocks from Seelbronn and Altenbürg are blue-
112 grey and yellow-green in colour, respectively (Figs. 2 and 3). The replacement
113 sandstone is very well sorted and contains faint bedding-parallel laminations.

114 A total of 62 cylindrical samples were cored from the three blocks: 20 samples
115 of Schönbrunn sandstone (SBS), 20 samples of suevite from Seelbronn (SEEL), and 22
116 samples of suevite from Altenbürg (ALT). The sandstone samples were cored to a
117 diameter of 20 mm and cut and precision-ground to a nominal length of 40 mm. Due to
118 the heterogeneity of the suevite blocks, the suevite samples were prepared to a diameter
119 of 25 mm and cut and precision-ground to a nominal length of 60 mm. The suevite
120 samples were cored so as to avoid centimetric-sized clasts. Although these sample

121 dimensions do not conform to standard guidelines, such as those outlined by the
122 International Society for Rock Mechanics and Rock Engineering (ISRM; Ulusay,
123 2014), we highlight that (1) the grain size of our materials is significantly smaller than
124 our sample diameters and (2) a recent study has shown that the uniaxial compressive
125 strength (UCS) of small (diameter = 8-9 mm) samples was very similar to that
126 determined from standard-sized samples (Van Stappen et al., 2019).

127 The connected porosity of each sample was then determined using the skeletal
128 (connected) volume of the sample given by a helium pycnometer and the bulk volume
129 calculated using the sample dimensions. The permeability of select samples was
130 measured using a benchtop nitrogen-gas permeameter (see Farquharson et al., 2016;
131 Heap and Kennedy, 2016). Permeability measurements were performed at room
132 temperature under a confining pressure of 1 MPa (for more information on such
133 measurements, see Heap et al., 2017).

134 Finally, the samples were deformed in a uniaxial loadframe at a strain rate of
135 $1.0 \times 10^{-5} \text{ s}^{-1}$ until macroscopic failure. The UCS of a material is a commonly used
136 strength metric in engineering geoscience. Half of each sample suite was deformed
137 “wet” (vacuum-saturated in deionised water and deformed in a water bath) and the other
138 half deformed “dry” (dried in a vacuum-oven for at least 48 hours prior to deformation).
139 The water saturation procedure for the samples deformed wet consisted of two steps.
140 First, the vacuum-dried samples were placed inside a belljar that was then evacuated
141 for at least 12 hours. Second, degassed deionised water was introduced into the bell jar
142 whilst under vacuum. This procedure ensured that the void space within the rock was
143 completely water-saturated.

144 The mineral content of the studied materials was quantified using X-ray powder
145 diffraction (XRPD). Crushed sample pieces were ground in isopropanol with a

146 McCrone micronizing mill using agate cylinders, and 10 wt.% ZnO was added (internal
147 standard). The analyses were performed on side-loaded powder mounts using a PW
148 1800 X-ray diffractometer (Cu-Ka, 40 kV, 30 mA, automatic divergence slit, irradiated
149 length 10 mm, 2θ 2 θ , step width 0.02°, counting time 1 s per step, graphite
150 monochromator). The mineral phases were quantified using the Rietveld program
151 BGMN (Bergmann et al., 1998). To identify the clay minerals, we also separated < 2
152 μm fractions by gravitational settling and prepared oriented mounts that were X-rayed
153 in an air-dried and ethylene-glycolated state. The carbonate contents of the suevite
154 samples were additionally quantified using a Hecatech EURO elemental analyser.

155 To complement our XRPD analyses, thermo-gravimetric (TG) analyses were
156 performed using a Netzsch STA 449 C thermobalance apparatus. Powdered samples
157 were heated in an argon atmosphere at a rate of 10 °C/min up to a temperature of 1000
158 °C and then cooled back to room temperature at the same rate.

159 A thin section (~30 μm -thick) of each the suevite blocks was prepared and their
160 microstructure was examined using a TESCAN VEGA II XMU scanning electron
161 microscope (SEM) (using a beam voltage of 150 kV and a working distance of 23 mm).
162 Minerals were identified during our SEM analyses using energy-dispersive X-ray
163 spectroscopy.

164

165 **4 Results**

166 4.1 Mineral content and microstructure

167 Schönbrunn sandstone is a feldspathic sandstone that contains small quantities
168 of muscovite and chlorite (Table 1). The suevites from Seelbronn and Altenbürg are
169 both principally composed of amorphous phases, smectite, and plagioclase, with minor
170 quantities of quartz, coesite, K-feldspar, calcite, biotite, and hematite (Table 1). The

171 only noteworthy differences are that Seelbronn suevite contains more plagioclase than
172 Altenburg suevite (27 and 18 wt.%, respectively; Table 1) and that Altenburg suevite
173 contains more calcite (13 ± 1 and 2.1 ± 0.2 wt.%, respectively; Table 1). The calcite
174 content of both suevite samples was determined by the elemental analyser to be $14.0 \pm$
175 0.1 and 2.11 ± 0.06 wt.%, respectively, confirming the results of the XRPD analyses.
176 The mineralogical composition of our suevites is in agreement with previous studies
177 (Engelhardt, 1997; Osinski, 2005; Sapers et al., 2017).

178 The results of the TG analysis (Fig. 4a) corroborate our XRPD data. The mass
179 loss seen at ~ 700 - 750 °C in both suevites, associated with the decomposition of calcite
180 (Samtani et al., 2002), is much more pronounced for the Altenburg suevite than for the
181 Seelbronn suevite. The mass loss < 700 °C in both suevites is associated with the
182 dehydration (~ 100 - 150 °C) and dehydroxylation (~ 400 - 600 °C) of smectite (Girgis et
183 al., 1987), abundant in these materials (Table 1). The mass loss in Schönbrunn
184 sandstone between ~ 500 - 550 °C is associated with the dehydroxylation of chlorite
185 (Ross and Kodama, 1976).

186 Backscattered SEM images of the thin sections prepared from the two suevite
187 blocks are provided in Fig. 3. The suevite blocks are microstructurally complex,
188 containing poorly sorted angular fragments (of quartz, calcite, K-feldspar, plagioclase)
189 within a fine-grained matrix. The images also show that both suevites are pervasively
190 microcracked.

191

192 4.2 Petrophysical data

193 The average connected porosities of Altenburg suevite, Seelbronn suevite, and
194 Schönbrunn sandstone are 0.238, 0.245, and 0.163, respectively (Table 2). The average

195 permeability of both suevites is $\sim 2 \times 10^{-15} \text{ m}^2$, and the permeability of a sample of
196 Schönbrunn sandstone was measured to be $4.69 \times 10^{-16} \text{ m}^2$ (Table 2).

197 Our mechanical data show that the suevite from the Seelbronn quarry is stronger
198 than that from Altenbürg, and that the sandstone is much stronger (about twice as
199 strong) than both suevites (Fig. 4b; Table 2). The average dry and wet strengths of the
200 suevites from Seelbronn and Altenbürg are 34.2 (standard deviation, s. d., 11.2 MPa)
201 and 29.2 (s. d. 5.8 MPa) MPa and 24.2 (s. d. 6.2 MPa) and 16.3 (s. d. 4.1 MPa) MPa,
202 respectively (Fig. 4b). We consider the difference in strength between samples cored
203 from the same block (standard deviations shown in Fig. 4b) to be a result of natural
204 sample-to-sample variability. The average dry and wet strength of the sandstone is 59.3
205 (s. d. 2.4 MPa) and 30.6 (s. d. 0.5 MPa) MPa, respectively. The ratio of wet to dry
206 strength is 0.71, 0.56, and 0.52, respectively, for Seelbronn suevite, Altenbürg suevite,
207 and Schönbrunn sandstone.

208

209 **5 Discussion**

210 5.1 Weathering of the suevite at St. George's church

211 The study of Heap et al. (2019) compiles the available data for water-weakening
212 in sandstone and shows that the ratio of wet to dry strength in sandstone decreases as
213 clay content is increased. The water-weakening of sandstone was considered by these
214 authors to be the result of a reduction in fracture surface free energy in the presence of
215 water and that, due to the ability of clays to adsorb water, higher clay contents ensured
216 that more water was adsorbed on the surface of growing microcracks. We similarly
217 conclude here that the presence of clays within the rock matrix ($\sim 25 \text{ wt.}\%$; Table 1) is
218 largely responsible for the observed water-weakening in the studied suevites. We
219 additionally conclude that the lower ratio of wet to dry strength in the Altenbürg

220 suevite, compared to the Seelbronn suevite, is a result of the slightly higher wt.% of
221 smectite (Table 1) and the higher wt.% of calcite (Table 1), another mineral considered
222 to weaken in the presence of water (Baud et al., 2009, 2016) (although we anticipate
223 that clay contributes more to the observed water-weakening than calcite). Due to the
224 absence of clay, the very low ratio of wet to dry strength of 0.52 for Schönbrunn
225 sandstone is unexpected (Fig. 4c). Possible reasons for the observed water-weakening
226 include: (1) the presence of minor (4 wt.%; Table 1) chlorite (a hydrated phyllosilicate
227 mineral), (2) a reduction in the fracture toughness of feldspar, which is relatively
228 abundant (35 wt.%; Table 1), and (3) a decrease in capillary pressure or an increase in
229 pore pressure (e.g., Verstryngne et al., 2014); however, we highlight that a permeability
230 of $\sim 5 \times 10^{-16} \text{ m}^2$ (Table 2) is likely high enough to ensure drained deformation. More
231 data are required to forward a definitive reason for the high water-weakening observed
232 in Schönbrunn sandstone.

233 The suevite from Seelbronn has a higher ratio of wet to dry strength than
234 Altenbürg suevite (0.71 and 0.56, respectively; Fig. 4b; Table 2) and could help explain
235 the observed weathering susceptibility (Fig. 2). Some of the outer walls however, such
236 as the wall on the east side, are noticeably less weathered and likely reflect variations
237 in stone alteration and environmental factors. Variation in the alteration of the stones
238 used is not only visible by the different colours of the blocks (Fig. 2), but also expected
239 due the preferential selection of medium-sized (typically 2-3 m in size) blocks
240 (“bollen”), regardless of their degree of alteration, by medieval stonemasons. In the
241 absence of modern cutting tools, these 2-3 m-sized blocks were easier to manage for
242 medieval stonemasons. It is possible therefore that the blocks forming the east side of
243 the church were sourced from a part of the quarry that was less altered (or even that
244 they were sourced, or partly sourced, from another quarry). Nowadays, cuboids are cut

245 from larger bollen (as large as 5-10 m), allowing stonemasons to assess the extent of
246 alteration and therefore stone quality. Environmental factors could have also influenced
247 the variation in weathering seen on different church faces. Swelling clays (Table 1) and
248 micropores (Fig. 3), for example, can lead to building stone deterioration during
249 wetting/drying cycles (Wangler and Scherer, 2008; Wrangler et al., 2011; Ruedrich et
250 al., 2011; Colas et al., 2011). In the case of St. George's church, it is the south-facing
251 side that will, on average, receive the most sunlight and is therefore most prone to solar-
252 induced rock weathering (Eppes et al., 2016). Since the prevailing wind direction is
253 from west, as deduced from yearly weather reports for Nördlingen, it is the west-facing
254 side that should receive more wind-driven rainfall. Freeze-thaw damage (average
255 minimum temperatures are below 0 °C in the winter months) should also affect the
256 sides of the church that receive the most precipitation and the least sunlight. We note
257 that the tensile strength of materials, often invoked as the principal metric in, for
258 example, freeze-thaw weathering (Nicholson and Nicholson, 2000), is typically a tenth
259 or a twelfth of the UCS (Paterson and Wong, 2005), the strength metric reported herein.

260

261 5.2 The use of replacement stones at St. George's church

262 Some of the original suevite blocks forming St. George's church (Fig. 1c) have
263 been recently replaced with synthetic and natural suevite and sandstone (Fig. 2). It is
264 recommended that damaged or weathered stones be replaced by new stones sourced
265 from the same quarry or, if this is not possible, using stone with similar petrophysical
266 properties is strongly advised (Přikryl, 2007). It is further recommended, from an
267 aesthetic and cultural point of view, that the replacement stones have a similar
268 appearance (colour and texture) to the original stones (Přikryl, 2007). To this end, there
269 are many studies that have investigated the physical properties (e.g., porosity, saturation

270 and capillary absorption coefficients, elastic wave velocity, compressive and flexural
271 strengths) of replacement stones for monuments and buildings of historical significance
272 (Nijland et al., 2010; Graue et al., 2011; Quist et al., 2013; De Kock et al., 2013, 2015).
273 Our petrophysical assessment shows that the Schönbrunn sandstone is less porous,
274 about an order of magnitude less permeable, and more than twice as strong (in dry
275 conditions; Fig. 4b) than the original suevite used in the construction of the church
276 (Table 2). We also note that the Schönbrunn sandstone is very different in appearance
277 to the original suevite (Fig. 2). By contrast, the physical properties and appearance of
278 the original suevite and the natural suevite used in the restoration of the church are very
279 similar (Table 2). Based on our petrophysical analyses, and a visual assessment of the
280 appearance of the stones, we recommend, where possible, that the original damaged or
281 weathered suevite stones be replaced with natural suevite from the currently active
282 Seelbronn quarry.

283

284 **6 Conclusions**

285 We provide herein experimental data to better understand (1) the observed
286 weathering susceptibility of suevite and (2) the suitability of the replacement stones
287 used in the restoration of St. George's church in Nördlingen. We find that the strength
288 of the suevite originally used to build the church is reduced by about half when water-
289 saturated, considered here as a result of its high smectite content. This helps explain the
290 prevalent weathering of the stones forming the outer walls of the church. Due to its low
291 ratio of wet to dry strength, large differences between its physical properties and those
292 of the original suevite dimension stone, and visual differences, Schönbrunn sandstone
293 is not considered here as an ideal replacement stone. By contrast, the suevite
294 replacement stone from the quarry at Seelbronn is more resistant to weathering when

295 water-saturated and has a similar appearance and similar physical properties to the
296 original suevite. We therefore recommend that, where possible, natural suevite stones
297 be used to replace the weathered blocks of original suevite at St. George's church and
298 at buildings built using suevite within the area.

299

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306

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461 **Table 1.** Quantitative bulk mineralogical composition, determined using X-ray powder
 462 diffraction (XRPD), for the three materials used in this study. The error associated with
 463 the estimation of the content of amorphous phases is a conservative estimate (it has not
 464 been calculated).

465

Mineral	Altenbürg suevite (values in wt.%)	Seelbronn suevite (values in wt.%)	Schönbrunn sandstone (values in wt.%)
Quartz	9 ± 1	10 ± 1	57 ± 2
Coesite	1.7 ± 0.3	1.4 ± 0.3	-
K-feldspar	3.1 ± 0.5	1.7 ± 0.5	18 ± 2
Plagioclase	18 ± 2	27 ± 3	17 ± 2
Calcite	13 ± 1	2.1 ± 0.2	-
Smectite	25 ± 3	23 ± 3	-
Muscovite	-	-	4 ± 1
Chlorite	-	-	4 ± 1
Biotite	2.0 ± 0.5	1.9 ± 0.5	-
Hematite	0.2 ± 0.1	0.2 ± 0.1	-
Amorphous phases	28 ± 5	33 ± 5	-

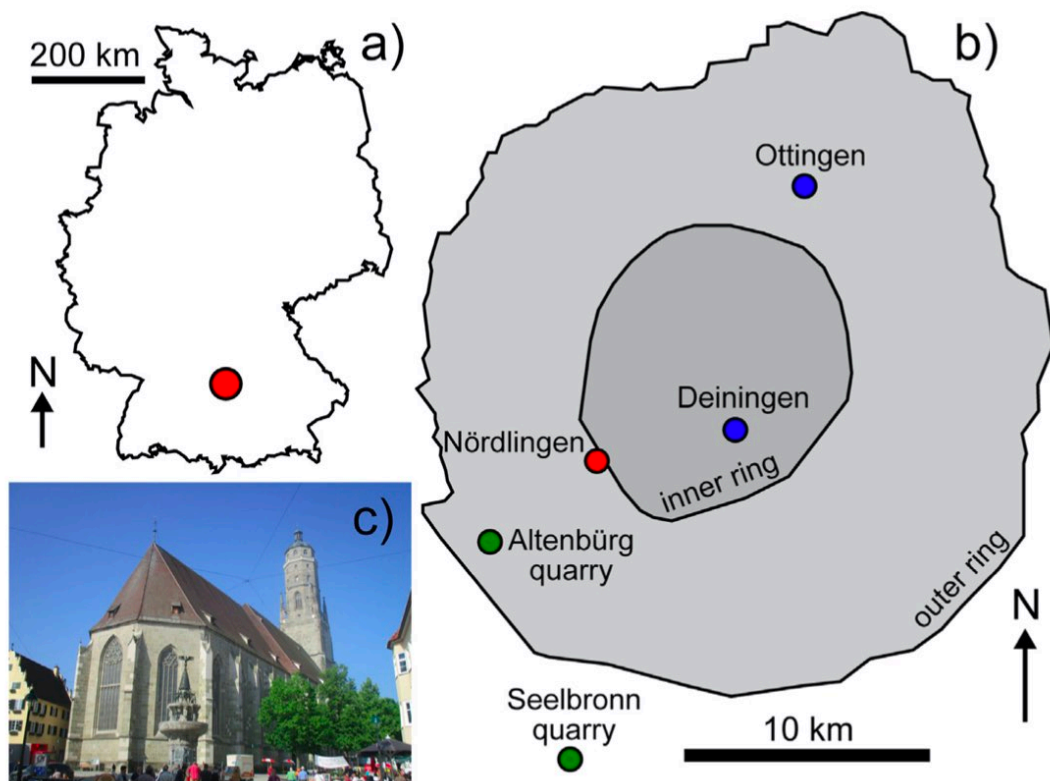
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467 **Table 2.** Experimental summary. SBS—Schönbrunn sandstone. ALT—Altenbürg
 468 suevite. SEEL—Seelbronn suevite. Wet—vacuum-saturated in deionised water (see
 469 text for details). Dry—dried in a vacuum oven at 40 °C for at least 48 h.

470

Sample	Connected porosity	Uniaxial compressive strength [MPa]	Experimental condition	Permeability [m ²]
SBS-1	0.16	31.7	Wet	-
SBS-2	0.16	62.6	Dry	-
SBS-3	0.16	30.0	Wet	-
SBS-4	0.16	30.8	Wet	-
SBS-5	0.16	60.2	Dry	4.69×10^{-16}
SBS-6	0.16	30.5	Wet	-
SBS-7	0.16	59.1	Dry	-
SBS-8	0.16	31.2	Wet	-
SBS-9	0.16	29.9	Wet	-
SSB-10	0.16	30.8	Wet	-
SBS-11	0.16	30.6	Wet	-
SBS-12	0.16	55.0	Dry	-
SBS-13	0.16	62.0	Dry	-
SBS-14	0.16	30.3	Wet	-
SBS-15	0.16	60.8	Dry	-
SBS-16	0.16	59.8	Dry	-
SBS-17	0.17	58.4	Dry	-
SBS-18	0.16	58.5	Dry	-
SBS-19	0.17	30.5	Wet	-
SBS-20	0.17	56.2	Dry	-
ALT-1	0.24	31.7	Dry	1.02×10^{-15}
ALT-2	0.26	31.6	Dry	2.54×10^{-15}
ALT-3	0.26	13.4	Wet	2.44×10^{-15}
ALT-4	0.23	25.3	Dry	3.13×10^{-15}
ALT-5	0.24	18.3	Wet	1.76×10^{-15}
ALT-6	0.26	17.7	Dry	3.16×10^{-15}
ALT-7	0.24	21.0	Wet	1.19×10^{-15}
ALT-8	0.26	22.5	Dry	1.84×10^{-15}
ALT-9	0.26	18.1	Wet	2.13×10^{-15}
ALT-10	0.23	33.0	Dry	9.54×10^{-16}
ALT-11	0.18	-	-	-
ALT-12	0.24	34.8	Dry	-
ALT-13	0.22	33.6	Dry	-
ALT-14	0.24	34.6	Dry	-
ALT-15	0.25	26.9	Dry	-
ALT-16	0.14	-	-	-
ALT-17	0.25	14.3	Wet	-
ALT-18	0.24	18.6	Wet	-
ALT-19	0.23	9.9	Wet	-

ALT-20	0.22	16.2	Wet	-
ALT-21	0.26	10.9	Wet	-
ALT-22	0.25	22.2	Wet	-
SEEL-1	0.27	18.4	Dry	6.33×10^{-15}
SEEL-2	0.23	48.6	Dry	6.22×10^{-16}
SEEL-3	0.27	-	-	5.68×10^{-15}
SEEL-4	0.25	21.7	Dry	7.40×10^{-16}
SEEL-5	0.22	42.2	Dry	9.53×10^{-16}
SEEL-6	0.21	31.1	Wet	1.08×10^{-15}
SEEL-7	0.23	30.9	Wet	1.47×10^{-15}
SEEL-8	0.23	32.8	Dry	6.32×10^{-16}
SEEL-9	0.27	17.4	Wet	1.47×10^{-15}
SEEL-10	0.23	43.3	Dry	5.84×10^{-16}
SEEL-11	0.26	-	-	-
SEEL-12	0.23	32.8	Dry	-
SEEL-13	0.22	31.0	Wet	-
SEEL-14	0.25	16.3	Wet	-
SEEL-15	0.25	22.7	Wet	-
SEEL-16	0.25	-	-	-
SEEL-17	0.26	20.4	Wet	-
SEEL-18	0.21	25.1	Wet	-
SEEL-19	0.23	24.3	Wet	-
SEEL-20	0.23	34.1	Dry	-



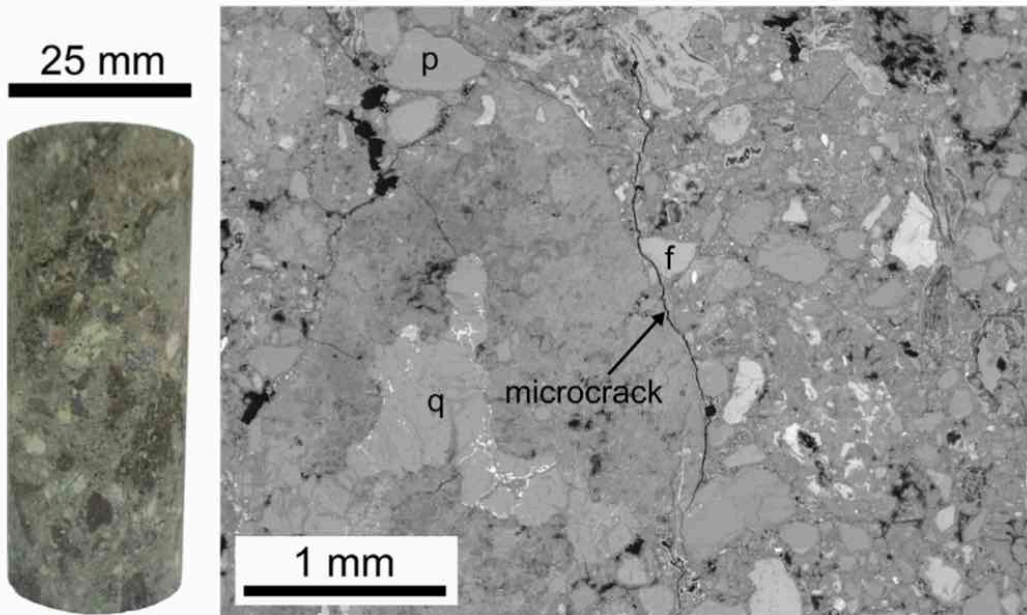
475 **Fig. 1.** (a) Map of Germany showing the location of Nördlingen (red circle). (b) Outline
476 of the Ries impact crater showing the position of Nördlingen (red circle), neighbouring
477 towns (blue circles), and the suevite quarries (green circles). (c) Photograph of St.
478 George's church (Nördlingen, Germany).



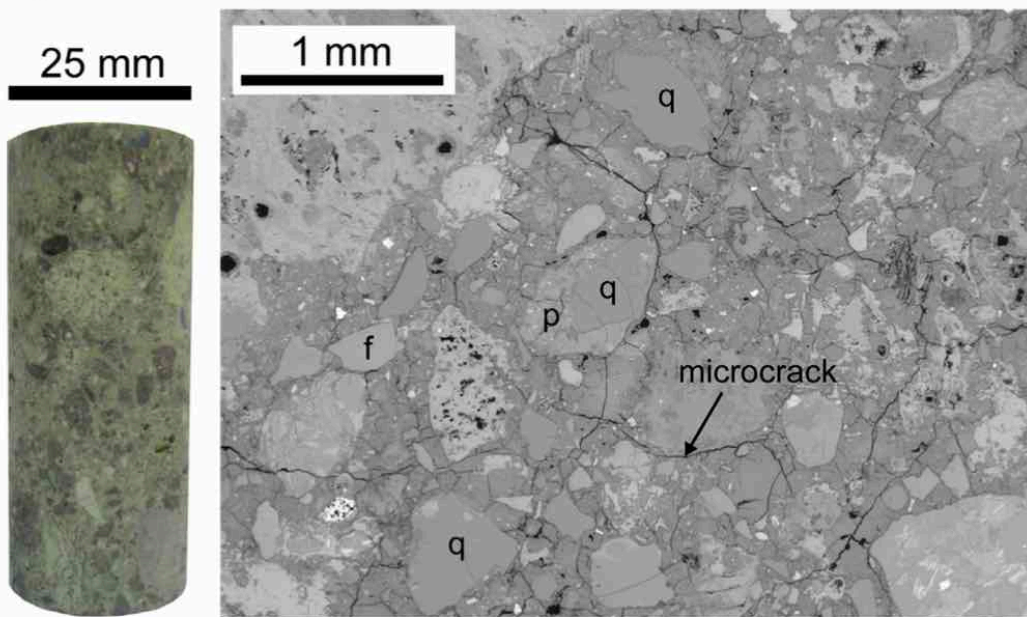
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480 **Fig. 2.** (a) Photograph of the exterior wall of St. George's church (Nördlingen,
481 Germany) showing an example of the original weathered suevite. Olivier Lengliné for
482 scale. (b) Photograph of the exterior wall of St. George's church showing the
483 replacement synthetic suevite and Schönbrunn sandstone. (c) Photograph of the exterior
484 wall of St. George's church showing the replacement suevite from the quarry at
485 Seelbronn.

a) Seelbronn suevite

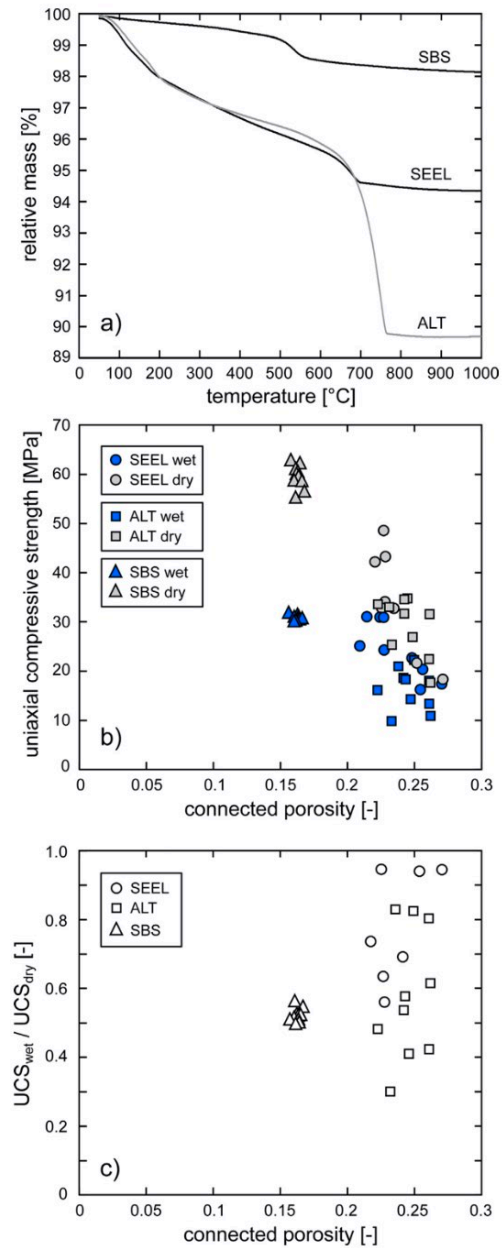


b) Altenbürg suevite



486

487 **Fig. 3.** (a) Photograph of cylindrical sample of Seelbronn suevite alongside a
488 backscattered scanning electron microscope image of Seelbronn suevite. (b)
489 Photograph of cylindrical sample of Altenbürg suevite alongside a backscattered
490 scanning electron microscope image of Altenbürg suevite. f—K-feldspar. p—
491 plagioclase. q—quartz.



492

493 **Fig. 4.** (a) Relative mass as a function of temperature, measured using a Netzsch STA
 494 449 C thermobalance apparatus. (b) Uniaxial compressive strength as a function of
 495 connected porosity for the three rocks tested in this study. (c) The ratio of wet to dry
 496 strength as a function of connected porosity for the three rocks tested in this study.
 497 SBS—Schönbrunn sandstone. ALT—Altenbürg suevite. SEEL—Seelbronn suevite.
 498 Wet—vacuum-saturated in deionised water (see text for details). Dry—dried in a
 499 vacuum oven at 40 °C for at least 48 h. UCS_{wet} —wet uniaxial compressive strength.
 500 UCS_{dry} —dry uniaxial compressive strength.