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Michael Heap, Marlène Villeneuve, Alexandra R.L. Kushnir, Jamie Farquharson, Patrick Baud, et al.. Rock mass strength and elastic modulus of the Buntsandstein: An important lithostratigraphic unit for geothermal exploitation in the Upper Rhine Graben. *Geothermics*, 2019, 77, pp.236 - 256. 10.1016/j.geothermics.2018.10.003 . hal-01937190

HAL Id: hal-01937190

<https://hal.science/hal-01937190>

Submitted on 18 Nov 2020

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1 Rock mass strength and elastic modulus of the Buntsandstein: an
2 important lithostratigraphic unit for geothermal exploitation in the
3 Upper Rhine Graben

4
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16
17 **Abstract**

18 Geothermal exploitation in the Upper Rhine Graben increasingly targets the interface between
19 the granitic basement and the overlying Buntsandstein unit. Results from deformation experiments are
20 combined with structural assessments to provide reservoir-scale wet and dry strength and elastic
21 modulus profiles for the Buntsandstein at Soultz-sous-Forêts (France). Our analysis finds five zones
22 characterised by low strength and elastic modulus. The strength and elastic modulus of “massive” zones
23 are lower when the rock is wet (i.e. water-saturated), highlighting the importance of performing wet
24 deformation experiments for geothermal rock mass assessments. These data and methods can be used
25 to provide assessments of other geothermal sites within the region to assist prospection, stimulation, and
26 optimisation strategies.

27

28 **Keywords:** Buntsandstein; uniaxial compressive strength; triaxial deformation experiments; porosity;
29 clay content; geothermal reservoir

30

31 **Highlights**

32

- 33 • Buntsandstein sandstone is of lower strength when wet.
- 34 • Water-weakening in sandstone is likely due to the presences of clays.
- 35 • Five low strength and stiffness zones exist within the Buntsandstein at Soultz.
- 36 • Wet experiments are important for geothermal rock mass assessments.
- 37 • Method presented can be adopted to provide assessments for other geothermal sites.

38

39 **1 Introduction**

40 An understanding of the strength and elastic modulus of rock within a geothermal reservoir is
41 an important input in models that guide reservoir prospection, stimulation, and optimisation strategies.
42 Laboratory experiments designed to measure these parameters are typically performed on samples with
43 dimensions shorter than the meso- or macrofracture length scale. As a result, laboratory data gathered
44 on nominally intact rock cannot be directly applied to large-scale geotechnical practices. Although
45 upscaling laboratory values to the reservoir- or borehole-scale is non-trivial, widely used empirical
46 geotechnical tools exist to bridge this length scale discrepancy. Two equations from the geotechnical
47 toolbox, which provide estimates for rock mass strength and rock mass elastic modulus, respectively,
48 are the generalised Hoek-Brown failure criterion (Hoek et al., 2002) and the Hoek-Diederichs equation
49 (Hoek and Diederichs, 2006). Both of these approaches take an assessment of the rock mass structure
50 (e.g., fracture density) and the surface condition of the fractures (e.g., smooth/rough, the pervasiveness
51 of weathering or alteration, the nature of the fracture infilling) into account to determine the rock mass
52 strength and elastic modulus, which will be often less than that of the intact material.

53 Geothermal energy exploitation is common in the Upper Rhine Graben, a 350 km-long and 50
54 km-wide Cenozoic rift valley that extends from Frankfurt (Germany) down to Basel (Switzerland), due

55 to the presence of anomalously high thermal gradients (areas of geothermal interest typically have
56 thermal gradients > 80 °C) attributed to hydrothermal circulation within the fractured Palaeozoic granitic
57 basement and the overlying Permian and Triassic sedimentary rocks (e.g., Pribnow and Schellschmidt,
58 2000; Buchmann and Connelly, 2007; Guillou-Frottier et al., 2013; Baillieux et al., 2013; Magnenet et
59 al., 2014; Freymark et al., 2017). A total of 15 geothermal wells have been drilled (to depths between
60 ~ 1000 and ~ 5000 m) in the Upper Rhine Graben since the 1980s (Vidal and Genter, 2018) and notable
61 geothermal sites include Soultz-sous-Forêts (e.g., Kappelmeyer et al., 1991; Baria et al., 1999; Gérard
62 et al., 2006; Figure 1) and Rittershoffen (e.g., Baujard et al., 2017; Glaas et al., 2018; Figure 1) in France,
63 Brühl (e.g., Bauer et al., 2017), Insheim, Trebur, and Bruchsal in Germany, and Riehen in Switzerland.

64 A recent study (Villeneuve et al., 2018) provided rock mass strengths (using the generalised
65 Hoek-Brown failure criterion; Hoek et al., 2002) and elastic moduli (using the Hoek-Diederichs
66 equation; Hoek and Diederichs, 2006) for the fractured Palaeozoic granitic basement from exploration
67 well EPS-1 at the Soultz-sous-Forêts geothermal site (Figure 1) using laboratory experiments on intact
68 material and structural data from core analyses. Our goal here, using the same approach, is to provide
69 estimates of borehole-scale rock mass strength and elastic modulus for the lowermost overlying Permian
70 and Triassic sedimentary rocks sampled from exploration well EPS-1 (located about 1 km southwest of
71 Soultz-sous-Forêts; Figure 1), from a depth of 1008 to 1414 m (i.e. the Buntsandstein lithostratigraphic
72 unit). The reasons for choosing Soultz-sous-Forêts as a case study are twofold. First, the Buntsandstein
73 was continuously cored at exploration well EPS-1 (to a core diameter of 78 mm), providing the samples
74 required for laboratory testing (uniaxial and triaxial compression experiments). Second, there exists a
75 wealth of structural data (fracture density and fracture fill, for example) for the borehole at EPS-1,
76 providing the data required for the assessment of rock mass structure. Since the Buntsandstein is known
77 to be laterally extensive (Aichholzer et al., 2016; Vidal and Genter, 2018), the results of this study can
78 not only be used to help optimise current geothermal sites in the Upper Rhine Graben, but also to help
79 guide and optimise future geothermal sites currently in development, such as those at Illkirch and
80 Vendenheim (both in Alsace, France). One of the principal motivations for this study is that recent (e.g.,
81 Rittershoffen; Baujard et al., 2017; Figure 1) and future geothermal exploitation in the Upper Rhine

82 Graben has and will target the interface between the granitic basement and the overlying Permian and
83 Triassic sedimentary rocks.

84 Providing estimates of rock mass strength and elastic modulus for the Buntsandstein is
85 complicated for two principal reasons. First, the petrophysical variability of the Buntsandstein (e.g.,
86 Vernoux et al., 1995; Aichholzer et al., 2016; Heap et al., 2017) demands that the intact rock properties
87 (strength and elastic modulus) are characterised for materials sampled from a number of different depths.
88 Although the assumption of mechanical homogeneity (i.e. similar intact strength and elastic modulus at
89 different depths) was justified when providing rock mass properties of the porphyritic granite
90 (monzogranite) from EPS-1 from a depth of 1414 to 2200 m (Villeneuve et al., 2018), the mechanical
91 properties of the Buntsandstein vary considerably due to the variability in porosity and microstructural
92 attributes such as pore size and grain size (Vernoux et al., 2005; Haffen et al., 2013; Griffiths et al.,
93 2016; Heap et al., 2017; Kushnir et al., 2018a), parameters known to greatly influence the strength and
94 stiffness of rocks, including sandstone (e.g., Palchik et al., 1999; Chang et al., 2006; Baud et al., 2014).
95 Here, therefore, we perform systematic laboratory measurements on material sampled at regular depth
96 intervals (from 1008 to 1414 m) from the EPS-1 core at the Soultz-sous-Forêts geothermal site. Second,
97 experimental studies have shown that clay plays an important role in the observed weakening of
98 sandstone in the presence of water (e.g., Rutter and Mainprice, 1978; Hawkins and McConnell, 1992;
99 Baud et al., 2000; Demarco et al., 2007). For example, Hawkins and McConnell (1992) found that the
100 uniaxial compressive strength (UCS) of sandstone was reduced by 78% for clay-rich sandstones and by
101 only 8% for siliceous sandstones in the presence of water. The variable, and sometimes high, clay
102 contents of the Buntsandstein sandstones (e.g., Heap et al., 2017) thus calls into question the use of
103 laboratory strength and elastic moduli data determined for dry rocks typically used in geotechnical rock
104 mass assessments. Therefore, we here perform dry and wet laboratory deformation measurements to
105 provide estimations of the dry and wet rock mass strength and elastic modulus for the Buntsandstein
106 unit at the Soultz-sous-Forêts geothermal site.

107

108 **2 Methods and materials**

109 2.1 Intact failure criteria

110 The strength of intact rock, including sandstone, in the brittle regime increases with increasing
111 confining pressure or depth (e.g., Wong et al., 1997; Baud et al., 2000; Bésuelle et al., 2003). The Hoek-
112 Brown failure criterion for intact rock is an empirical failure criterion that provides strength estimates
113 for intact rock at depth using the uniaxial compressive strength, C_o , (i.e., the strength of the rock at
114 ambient pressure) and a constant, m_i :

115

$$116 \quad \sigma'_1 = \sigma'_3 + C_o \left(m_i \frac{\sigma'_3}{C_o} + 1 \right)^{0.5} \quad (1)$$

117

118 where σ'_1 and σ'_3 are the effective maximum and minimum principal stresses, respectively. The unitless
119 constant m_i describes the shape of the failure envelope on a graph of σ'_1 as a function of σ'_3 , and is
120 therefore related to the microstructural and mineralogical attributes of the rock (mineral content, grain
121 size, grain shape, pore size, and pore shape, amongst many others) (Eberhardt, 2012). The most reliable
122 method to determine m_i is to run a series of triaxial deformation experiments on the rock of interest
123 (Hoek and Brown, 1980); however values of m_i are often estimated using charts that offer values for
124 common lithologies (e.g., Hoek and Brown, 1997).

125 In this study, C_o is determined for samples of Buntsandstein sandstone taken from regular depth
126 intervals (every 40 to 50 m) from the continuous core available at the EPS-1 exploration well (Figure
127 1). Values of empirical constant m_i are often taken from tables of “standard” values for common
128 lithologies; the recommended value of m_i for sandstone is 19 (Hoek and Brown, 1997). However, in
129 our study, we chose instead to perform a suite of triaxial experiments on samples from one of the
130 sampled depth intervals in order to better constrain m_i for the Buntsandstein (see Section 2.6). Uniaxial
131 experiments were performed under both dry and wet conditions to provide the dry intact uniaxial
132 strength, C_{o_d} , and the wet intact uniaxial strength, C_{o_w} (see Section 2.5). Similarly, wet and dry triaxial
133 experiments provide estimates for m_i under dry conditions, m_{i_d} , and under wet conditions, m_{i_w} (see
134 Section 2.6). Therefore, Equation (1) can be modified to provide the intact rock strength with depth for
135 dry (Equation 2) and wet rock (Equation 3), respectively:

136

137
$$\sigma'_1 = \sigma'_3 + C_{o_d} \left(m_{i_d} \frac{\sigma'_3}{C_o} + 1 \right)^{0.5} \quad (2)$$

138

139
$$\sigma'_1 = \sigma'_3 + C_{o_w} \left(m_{i_w} \frac{\sigma'_3}{C_o} + 1 \right)^{0.5} \quad (3)$$

140

141 2.2 Rock mass strength failure criteria

142 Rock mass strength can be determined using the generalised Hoek-Brown failure criterion:

143

144
$$\sigma'_1 = \sigma'_3 + C_o \left(m_b \frac{\sigma'_3}{C_o} + s \right)^a \quad (4)$$

145

146 where m_b , s , and a are unitless fitting parameters for a fractured rock mass and are defined as follows

147 (Hoek et al., 2002):

148

149
$$m_b = m_i e^{\left(\frac{GSI-100}{28-14D} \right)} \quad (5)$$

150
$$s = e^{\left(\frac{GSI-100}{9-3D} \right)} \quad (6)$$

151
$$a = \frac{1}{2} + \frac{1}{6} \left(e^{-\frac{GSI}{15}} + e^{-\frac{20}{3}} \right) \quad (7)$$

152

153 where D is a unitless disturbance factor related to blasting damage in large excavations (since well

154 drilling does not use explosives, $D = 0$ in our case study; we provide the full equation here for

155 completeness) and GSI is the Geological Strength Index, a unitless value that describes the rock mass

156 characteristics (Marinos et al., 2005). Values of GSI range from 0 to 100, where high values indicate

157 intact or massive rock masses with fresh surfaces and low values indicate

158 blocky/disintegrated/laminated rock masses with highly weathered surfaces and clay coatings or fillings

159 (Marinos et al., 2005). GSI is typically obtained from rock outcrop exposures, but for this study values

160 of GSI were determined using structural data collected on the EPS-1 core material (see Section 2.7), as

161 described in Villeneuve et al. (2018). Equation (4) can be recast to provide the rock mass strength with
 162 depth for dry (Equation 8) and wet rock (Equation 9), respectively:

163

$$164 \quad \sigma'_1 = \sigma'_3 + C_{o_d} \left(m_{b_d} \frac{\sigma'_3}{C_{o_d}} + s \right)^a \quad (8)$$

165

$$166 \quad \sigma'_1 = \sigma'_3 + C_{o_w} \left(m_{b_w} \frac{\sigma'_3}{C_{o_w}} + s \right)^a \quad (9)$$

167

168 where m_{b_d} and m_{b_w} are given as, respectively:

169

$$170 \quad m_{b_d} = m_{i_d} e^{\left(\frac{GSI-100}{28-14D}\right)} \quad (10)$$

$$171 \quad m_{b_w} = m_{i_w} e^{\left(\frac{GSI-100}{28-14D}\right)} \quad (11)$$

172

173 2.3 Intact and rock mass elastic modulus

174 The elastic modulus of intact rock, E_i , can be determined from the elastic portion of the stress-
 175 strain curve of a rock deforming in compression. The rock mass elastic modulus, E_{rm} , can be determined
 176 using the Hoek-Diederichs equation (Hoek and Diederichs, 2006):

177

$$178 \quad E_{rm} = E_i \left(0.02 + \frac{1 - \frac{D}{2}}{1 + e^{\left(\frac{60+15D-GSI}{11}\right)}} \right) \quad (12)$$

179

180 As for the rock strength equations in Section 2.2, the disturbance factor D is equal to zero for our
 181 application. As mentioned in Section 2.2, values of GSI were determined using structural data collected
 182 on the EPS-1 core material (see Section 2.7). Equation (12) can be modified to provide values for the
 183 elastic modulus of a dry (Equation 13) and wet rock mass (Equation 14), respectively:

184

185
$$E_{rm_d} = E_{i_d} \left(0.02 + \frac{1 - \frac{D}{2}}{1 + e^{((60+15D-GSI)/11)}} \right) \quad (13)$$

186

187
$$E_{rm_w} = E_{i_w} \left(0.02 + \frac{1 - \frac{D}{2}}{1 + e^{((60+15D-GSI)/11)}} \right) \quad (14)$$

188

189 where E_{i_d} and E_{i_w} are the intact elastic moduli of dry and wet rock, respectively.

190

191 2.4 Experimental materials and sample preparation

192 The Buntsandstein lithostratigraphic unit was sampled at regular (~40-50 m) depth intervals
 193 (between 1008 to 1414 m; Figure 1b) from the EPS-1 exploration well from the Soultz-sous-Forêts
 194 geothermal site (Figures 1 and 2). This Permian and Triassic sedimentary unit (described in, for example,
 195 Vernoux et al., 2005; Haffen et al., 2013; Vidal et al., 2015; Aichholzer et al., 2016; Griffiths et al.,
 196 2016; Heap et al., 2017; Kushnir et al., 2018a) directly overlies the fractured Palaeozoic granitic
 197 reservoir (described in, for example, Genter and Traineau, 1996; Genter et al., 1997; Sausse et al., 2006;
 198 Dezayes et al., 2010; Genter et al., 2010). We collected 1 m-long pieces of the 78 mm-diameter core at
 199 each of the sampled depths. In total, twelve depths were sampled (one sandstone from the *Voltzia* unit,
 200 one from the *Couches Intermédiaires* unit, three from the *Karlstal* unit, two from the *Rehberg* unit, two
 201 from the *Trifels* unit, two from the *Annweiler* unit, and one from the *Anté-Annweiler* unit; Figure 1b).
 202 Four or five cylindrical samples, 20, 18.75, or 12 mm in diameter (depending on the strength of the
 203 sandstone), were cored from each of the twelve cores collected and precision-ground to a nominal length
 204 of 40, 37.5, or 24 mm, respectively. These samples were cored so that their axes were parallel to the
 205 EPS-1 borehole (i.e. perpendicular to bedding; Figure 2). We complement these borehole samples with
 206 samples prepared from blocks (all from the Buntsandstein) acquired from local quarries (from Rothbach,
 207 Adamswiller, and Bust, all in France; see Figure 1c for quarry locations). Samples from the quarry
 208 blocks were cored perpendicular to bedding to a diameter of 20 mm and precision-ground to a nominal

209 length of 40 mm. All of the samples were washed using tapwater and then dried in a vacuum oven at 40
210 °C for at least 48 hours.

211 The twelve samples collected from exploration well EPS-1 are feldspathic (>10 wt.% feldspar)
212 or quartz-rich (<10 wt.% feldspar) sandstones that contain variable amounts of pore-filling clay
213 (muscovite/illite–smectite) (from 2 to 13.1 wt.%) (Figure 3; Table 1; Heap et al., 2017). Most of the
214 sandstones are homogeneous at the sample scale, although a few (in particular samples 299, 497, and
215 540) contain obvious bedding-parallel laminations (Figure 2). The average grain diameter of these
216 samples varies from 142 to 424 μm (Figure 3; Table 2; Heap et al., 2017). The microstructural and
217 textural features of these samples are summarised in Table 2, and are described at length in Heap et al.
218 (2017). The three quarry rocks are all feldspathic sandstones (Table 1). The sandstones from Bust and
219 Adamswiller do not contain any obvious laminations/bedding, although the Adamswiller sandstone is
220 known to exhibit a mechanical anisotropy (Baud et al., 2005). Rothbach sandstone, a rock that also
221 shows significant mechanical anisotropy (Louis et al., 2009), however, contains alternating layers that
222 show differences in grain size and porosity (Louis et al., 2005).

223 Before the samples were deformed, their connected porosity was determined using the
224 connected (skeletal) volume measured by a helium pycnometer (Micromeritics AccuPyc II 1340) and
225 the bulk volume calculated using the sample dimensions.

226

227 2.5 Determining C_o (intact uniaxial compressive strength) and E_i (intact elastic modulus)

228 The prepared cylindrical samples were deformed uniaxially at a strain rate of $1.0 \times 10^{-6} \text{ s}^{-1}$ until
229 macroscopic failure. Half of the samples were deformed “dry” (dried at 40 °C in a vacuum-oven for at
230 least 48 hours prior to deformation) and half were deformed “wet” (vacuum-saturated in deionised water
231 and deformed in a water bath) (see Heap et al. (2014) for a schematic of the experimental device). A
232 lubricating wax was applied to the end-faces of the dry samples to avoid problems associated with the
233 friction between the sample and the pistons. We chose to deform the samples at a relatively low strain
234 rate of $1.0 \times 10^{-6} \text{ s}^{-1}$ to ensure drainage in the low-porosity, low-permeability samples deformed under
235 saturated conditions. During deformation, axial displacement and axial load were measured using a
236 linear variable differential transducer (LVDT) and a load cell, respectively. These measurements were

237 converted to axial strain and axial stress using the sample dimensions. C_{o_d} and C_{o_w} were taken as the
238 peak stress obtained in these uniaxial compressive strength tests under dry and wet conditions,
239 respectively. Values of E_{i_d} and E_{i_w} were determined using the slope of the linear elastic portion of the
240 dry and wet uniaxial stress-strain curves, respectively (Ulusay and Hudson, 2007).

241

242 2.6 Determining m_i

243 The unitless parameter m_i describes the shape of the failure envelope in a graph of σ'_1 as a
244 function of σ'_3 (i.e. the principal stress space). We determined m_i using triaxial experiments conducted
245 on dry and wet cylindrical cores (20 mm in diameter and 40 mm in length) prepared from the core
246 sampled from a depth of 1239 m (from the *Rehberg* unit; porosity 0.18). Constant strain rate (1.0×10^{-6}
247 s^{-1}) triaxial experiments were performed at constant effective pressures (defined here as the confining
248 pressure minus the pore fluid pressure) of 2.5, 5, 7.5, 10, and 15 MPa. Samples deformed under dry
249 conditions were therefore deformed at constant confining pressures of 2.5, 5, 7.5, 10, and 15 MPa (pore
250 pressure = 0 MPa). A lubricating wax was applied to the end-faces of the dry samples to avoid problems
251 associated with the friction between the sample and the pistons. Samples deformed under wet conditions
252 were deformed using a constant pore fluid (deionised water) pressure of 10 MPa, and confining pressures
253 of 12.5, 15, 17.5, 20, and 25 MPa. The confining and pore pressures were maintained constant during
254 deformation using a confining and pore fluid pressure intensifier, respectively. During deformation,
255 axial displacement and axial load were measured using an LVDT and a load cell, respectively. These
256 measurements were converted to axial strain and axial stress using the sample dimensions. We
257 determined m_{i_d} and m_{i_w} using the compressive strengths measured for these experiments using the
258 data fitting function (modified cuckoo fit algorithm, basic error summation, and absolute error type) in
259 RocData (Rocscience, 2017).

260

261 2.7 Determining the Geological Strength Index (GSI)

262 The GSI is a unitless value that describes the rock mass characteristics using an assessment of
263 the rock mass structure (e.g., fracture density) and the surface condition of the fractures (e.g.,

264 smooth/rough, the pervasiveness of weathering or alteration, the nature and thickness of the fracture
265 infilling) (Marinos et al., 2005). The logging data from EPS-1 in the Bundsandstein contains the type,
266 location (depth), orientation, infilling type, and infilling thickness of all discontinuities mapped along
267 the core. The locations (depths) were used to derive a fracture frequency. The discontinuity type,
268 infilling type, and infilling thickness were used to assess the joint condition. The rock mass structure
269 and surface condition were assigned broad descriptors, such as “blocky” and “poor”, respectively, which
270 were then used to determine a GSI value using a visual look-up chart (Marinos et al., 2005). Due to the
271 available logging data and core photographs, we consider that our GSI estimates lack the subjectivity
272 often associated with estimates of GSI.

273 The determination of the surface quality is relatively straightforward in this case study because
274 of the high quality of the core logs in the Bundsandstein. Despite not having descriptions of joint
275 roughness, we feel confident that our assessments using discontinuity type, infilling type, and infilling
276 thickness provide a suitable basis for assessing the joint condition. For example, discontinuities
277 identified as faults can be assumed to have smooth to slickensided surfaces, resulting in a condition
278 assessment of fair if they have no infilling, or very poor if they have thick (> 2 mm), clayey infilling.
279 Discontinuities identified as joints can be assumed to have rough to smooth surfaces, resulting in a
280 condition assessment of very good if they have no infilling, or very poor if they have thick (> 2 mm),
281 clayey infilling.

282 The determination of the rock mass structure requires the selection of the scale at which the rock
283 mass assessment is conducted. For example, Villeneuve et al. (2018) assessed the rock mass strength
284 and elastic modulus of the granite underlying the Bundsandstein at the borehole scale. These authors
285 demonstrated that the rock mass is so densely fractured in some intervals that the intact rock parameters
286 are not appropriate. Villeneuve et al. (2018) suggested a range of 7-10 fractures per metre as the cut-off
287 fracture density to decide between using the intact rock failure criterion (Equation 1) and using the rock
288 mass failure criterion (Equation 4). In the present case study we derive the rock mass parameters at the
289 reservoir scale (tens of metres). Based on the recommendations of Schultz (1996), we use a block size
290 to reservoir scale ratio of 5-10 as the cutoff for using rock mass strength and elastic modulus. We use
291 fracture densities of 1 fracture per metre and 2 fractures per metre to differentiate between massive and

292 blocky, and blocky and very blocky, respectively. In accordance with the reasoning detailed in
293 Villeneuve et al. (2018), the cut-off between intact and rock mass failure criteria corresponds to
294 approximately 2 fractures per metre.

295

296 **3 Laboratory testing**

297 3.1 Uniaxial compressive strength experiments

298 Representative uniaxial stress-strain curves for the dry Buntsandstein samples are shown in
299 Figure 4a. These stress-strain curves (Figure 4a) are typical of those for brittle rock in compression (e.g.,
300 Hoek and Bieniawski, 1965; Brace et al., 1966; Scholz, 1968). The maximum axial stress obtained
301 during the experiment is the uniaxial compressive strength, C_o (as labelled for one of the dry curves in
302 Figure 4a). Representative uniaxial stress-strain curves for a dry and wet sample of sample 100 are
303 shown in Figure 4b. These curves show that the uniaxial compressive strength is lower when the sample
304 is wet. In the example shown in Figure 4b, the dry strength, C_{o_d} , was 150.8 MPa and the wet strength,
305 C_{o_w} , was 89.9 MPa. These representative curves also show that the slope of the stress-strain curve in
306 the elastic region (i.e. the elastic modulus) and the axial strain at macroscopic failure are lower when
307 the sample is wet (Figure 4b).

308 Dry (white circles) and wet (blue squares) uniaxial compressive strengths (C_{o_d} and C_{o_w} ,
309 respectively) and elastic moduli (E_{i_d} and E_{i_w} , respectively) are plotted as a function of connected
310 porosity in Figures 5a and 5b, respectively (data available in Table 3). These data show that the strength
311 (Figure 5a) and elastic modulus (Figure 5b) of the Buntsandstein samples studied here both decrease as
312 the connected porosity is increased. For example, the dry strength and dry elastic modulus of the
313 Buntsandstein samples tested herein range from ~50 MPa and ~10 GPa, respectively, at a porosity of
314 ~0.25 up to ~250 MPa and ~40 GPa, respectively, at a porosity of ~0.04 (Figures 5a and 5b). These data
315 also show that the wet strength and wet elastic modulus of the sandstones is systematically lower than
316 the dry strength and elastic modulus across the entire tested porosity range (Figures 5a and 5b).

317 The ratios of wet to dry strength are plotted as a function of connected porosity and clay content
318 in Figures 6a and 6b, respectively. These data show that the ratio of wet to dry strength varies from

319 ~0.55 to ~0.84 for the rocks tested herein (Figure 6). Figure 6a shows that the observed water-weakening
320 does not appear to depend on the connected porosity. However, although there is some scatter in the
321 data, there is a trend of increasing water-weakening as clay content is increased (Figure 6b). Indeed, the
322 sample that contains the most clay (13.1 wt.%; sample 540) has the lowest ratio of wet to dry strength,
323 and the sample containing the least clay (1.8 wt.%; Rothbach sandstone) has the highest ratio of wet to
324 dry strength (Figure 6b). The ratios of wet to dry elastic modulus are plotted as a function of connected
325 porosity and clay content in Figures 7a and 7b, respectively. These data show that the ratio of wet to dry
326 elastic modulus varies from ~0.74 to ~1.00 for the rocks tested herein (Figure 7). The ratio of wet to dry
327 elastic modulus does not appear to depend on either connected porosity (Figure 7a) or clay content
328 (Figure 7b).

329

330 3.2 Triaxial compressive strength experiments

331 The stress-strain curves for the dry and wet triaxial experiments (on samples from sample 347)
332 are shown in Figures 8a and 8b, respectively (experiments unique to this study). The sandstone is brittle
333 over the tested pressure range and failure (marked by a stress drop in the stress-strain data; Figure 8)
334 was manifest as a through-going shear fracture. These data show that the dry (Figure 8a) and wet (Figure
335 8b) strength increases as the effective pressure is increased, in accordance with many experimental
336 studies on sandstones in the brittle field (e.g., Wong et al., 1997; Baud et al., 2000; Bésuelle et al., 2003).
337 For example, the dry strength was increased from ~58 MPa at an effective pressure of 0 MPa to ~141
338 MPa at an effective pressure of 15 MPa (Figure 8a) (data available in Table 4). Our triaxial experiments
339 also show that sample 347 is weaker when wet over the entire tested range of effective pressure (i.e. up
340 to 15 MPa) (Figure 8).

341 The triaxial data plotted in principal stress space (σ_1 as a function of σ_3 ; Figure 9) show that
342 the failure envelope for the wet samples (blue symbols in Figure 9) is lower than the failure envelope
343 for the dry samples (white symbols in Figure 9). The fits to these data were provided by the Modified
344 Cuckoo data fitting algorithm using basic (vertical) error summation, and relative (divided by the y-
345 value of the curve fit) error type) in RocData (Rocscience, 2017). These fits provide values of 19
346 (relative residuals 0.008) and 23 (relative residuals 0.012) for m_{i_d} and m_{i_w} , respectively. We note that

347 the value for dry sandstone is within the range of m_i values typically associated with sandstone (17 ± 4 ,
348 as given in Hoek (2007)), whereas the value for wet sandstone is slightly higher than this range.

349

350 3.3 Geological Strength Index (GSI)

351 The rock mass descriptions, based on fracture frequency, infilling type, and infilling thickness
352 are summarised in Table 5, along with their associated rock mass descriptions at the reservoir scale.
353 Figure 10 shows how the look-up chart from Marinos et al. (2005) was used to assess the GSI for two
354 example intervals. For the depth interval 1365-1381 m the fracture density is 2.1 fractures per metre,
355 and is therefore assessed as a “very blocky” (see Figure 10) rock mass structure. The fractures are infilled
356 with barite and minor calcite (both hard minerals that tend to seal fractures) with an infilling thickness
357 averaging 2 mm. The surface condition of the fractures is therefore assessed as “good” (see Figure 10)
358 because barite and calcite are precipitated mineral infillings and will therefore contribute cohesive and
359 frictional strength to the fracture. The combination of the two assessments results in a GSI range of 45-
360 60. Since our analysis requires a single value of GSI, we use GSI = 55 for this interval (1365-1381 m)
361 (Table 5). Similarly, the depth interval 1012-1020 m has been assessed a “very blocky” (see Figure 10)
362 structure. Because of the presence of four faults within an 8 m thick interval, and an infilling thickness
363 averaging 9 mm, the surface condition is assessed as “poor” (see Figure 10). The combination results in
364 a range of GSI of 25-40. Again, since our analysis requires a single value of GSI, we use GSI = 35 for
365 this interval (1012-1020 m) (Table 5).

366 The majority of the rock mass in the Bundsandstein has a GSI of 100 (Table 5) because of its
367 low fracture density (< 2 fractures per metre), with the resulting assessment of “massive” for the rock
368 structure and the use of the intact Hoek-Brown failure criterion (Equation 1) to determine rock strength
369 over these intervals. The intervals with GSI less than 100, of which there are five, are associated with
370 highly fractured zones (e.g., the interval between depths 1151 and 1156 m has a fracture density of 2
371 discontinuities per metre) (Table 5). The five zones that are characterised by low values of GSI are
372 located at depths of ~ 1012 -1020, ~ 1151 -1156, ~ 1205 -1216, ~ 1347 -1350, and ~ 1365 -1381 m (Table 5).
373 The zones with the lowest GSI (GSI = 35) are associated with highly fractured zones that contain
374 fractures with a very thick average infilling (e.g., the interval between depths 1205 and 1216 m has an

375 average infilling thickness of 11 mm; Table 5). The three zones with the lowest GSI (Table 5) were
376 previously identified as the three main fractured zones within the EPS-1 core (Vernoux et al., 2005).

377

378 **4 Reservoir-scale strength and elastic modulus for the Buntsandstein**

379 The dry and wet intact and rock mass strength and elastic modulus, calculated using the reservoir
380 scale GSI and Equations 1, 2, 3, 8, and 9 (for the strength) and Equations 13 and 14 (for the elastic
381 modulus) are given in Table 5. The fracture density with depth (Figure 11a) is plotted alongside the dry
382 and wet strength and elastic modulus in Figures 11b and 11c, respectively. Figures 11b and 11c clearly
383 show the five zones for which the rock mass strength and rock mass elastic modulus is applicable (at
384 depths of ~1012-1020, ~1151-1156, ~1205-1216, ~1347-1350, and ~1365-1381 m; indicated by the
385 black arrows in Figure 11), as opposed to those where the intact values of either property are appropriate.
386 These zones are characterised by low values of strength (Figure 11b) and elastic modulus (Figure 11c).
387 Apart from these five zones, the strength and elastic modulus of the rock mass is given by the intact
388 strength and the intact elastic modulus (GSI = 100; Table 5). Excluding the rock at the interface between
389 the granite and the sedimentary rocks (the *Anté-Annweiler*), which has relatively high values of strength
390 and elastic modulus, the overall strength (Figure 11b) and elastic modulus (Figure 11c) of the
391 Buntsandstein appears to decrease with depth; this is especially true for the elastic modulus (Figure 11c).

392 We also note that, in the five zones where the strength and elastic modulus are described by the
393 rock mass strength and elastic modulus, respectively, there is essentially no difference between the dry
394 and wet values (Figures 11b and 11c). In these zones, the strength and elastic modulus of the rock mass
395 very much depends on the fractures present within the rock mass, rather than the condition (wet or dry)
396 of the rock mass. However, in the depths characterised by the intact strength and elastic modulus, a large
397 difference can be observed between the wet and dry values (Figures 11b and 11c).

398

399 **5 Discussion**

400 **5.1 Water-weakening in sandstones**

401 Water-weakening in rocks can be the result of both mechanical and chemical processes.
402 Mechanically, pressurised pore fluids typically weaken and embrittle rocks (e.g. Paterson and Wong,

403 2005). Chemically, rock can be weakened by subcritical crack growth processes (e.g., Atkinson, 1984)
404 and the reduction of surface free energy (e.g., Parks, 1984). The mechanical effect can be expressed in
405 terms of the effective pressure law, where the effective pressure equals the confining pressure minus the
406 pore fluid pressure multiplied by a poroelastic constant. The study of Baud et al. (2015) shows that this
407 poroelastic constant is very close to unity for porous sandstone. As a result, we do not consider herein
408 the mechanical influence of pore fluids on the strength of our sandstone samples.

409 Our deformation experiments have shown that sandstone is weaker in the presence of water
410 (Figures 4, 5, 6, 7, and 8), in accordance with many published studies (e.g., Rutter and Mainprice, 1978;
411 Bell, 1978; Hadizadeh and Law, 1991; Dyke and Dobereiner, 1991; Hawkins and McConnell, 1992;
412 Kasim and Shakoor, 1996; Zang et al., 1996; Bell and Culshaw, 1998; Baud et al., 2000; Cuss et al.,
413 2003; Lin et al., 2005; Vásárhelyi and Ván, 2006; Demarco et al., 2007; Shakoor and Barefield, 2009;
414 Nespereia et al., 2010; Siedel, 2010; Wasantha and Ranjith, 2014). A handful of these studies highlight
415 that the observed water-weakening in sandstones is related to their clay content. For example, Hawkins
416 and McConnell (1992) found that the uniaxial compressive strength (UCS) of sandstone was reduced
417 by 78% for clay-rich sandstones and by only 8% for siliceous sandstones in the presence of water.
418 Although our data suggest that the water-weakening in sandstone does not depend on connected porosity
419 (Figure 6a), they do highlight that water-weakening may increase as clay content is increased (Figure
420 6b). To better understand the role of connected porosity and clay content on water-weakening in
421 sandstone, we plot ratios of wet to dry strength from numerous studies (data available in Table 6)
422 alongside our new data (Table 3) as a function of porosity and clay content in Figures 12a and 12b,
423 respectively. Figure 12a shows that there is no discernible trend between water-weakening in sandstone
424 and porosity. However, Figure 12b shows that, although there is some scatter in the data, water-
425 weakening increases as clay content is increased. Indeed, the sample containing the highest clay content
426 (~70 %) has the lowest ratio of wet to dry strength (Figure 12b).

427 To explore the reason for the reduction in strength in the presence of water we use the
428 micromechanical model of Sammis and Ashby (1986). This model, based on the classic work of
429 Griffiths, has been previously used to describe the brittle failure of porous sandstones (e.g., Baud et al.,
430 2014). The micromechanical model of Sammis and Ashby (1986) is an inclusion model comprising a

431 two-dimensional elastic medium populated by circular holes of uniform radius, r . As the stress on the
432 medium increases, cracks nucleate and propagate from the circular holes (parallel to the direction of the
433 applied stress) when the stress intensity at the tip of a small crack on the circular surface reaches a
434 critical value (K_{IC} , the fracture toughness). The cracks interact once they are long enough, thus
435 increasing the local tensile stress intensity. Eventually, the cracks coalesce and conspire to induce the
436 macroscopic failure of the elastic medium. In the case of uniaxial compression, Zhu et al. (2010) provide
437 an analytical approximation of Sammis and Ashby's (1986) model to estimate UCS as a function of
438 porosity, ϕ :

439

$$440 \quad C_0 = \frac{1.325}{\phi^{0.414}} \frac{K_{IC}}{\sqrt{\pi r}} \quad (15)$$

441

442 Assuming that Equation (15) can capture the behaviour of the sandstones of Table 6, there are three
443 variables that influence uniaxial compressive strength: the porosity, ϕ , the fracture toughness, K_{IC} , and
444 the pore radius, r . If we assume that the porosity and pore radius are the same for a given sandstone
445 then, according to Equation (15), the observed water-weakening (Figure 12) must be due to a decrease
446 in K_{IC} . Figure 13 shows strength as a function of porosity using Equation (15) for a fixed pore radius
447 (125 μm) and different values of K_{IC} ($K_{IC} = 0.1, 0.3, 0.5,$ and $0.8 \text{ MPa m}^{-1/2}$) alongside the dry (white
448 circles) and wet (blue squares) data for the compiled sandstones. These modelled curves aptly
449 demonstrate that decreasing the K_{IC} at a given porosity and pore size lowers the strength (Figure 13).
450 The reduction in uniaxial compressive strength observed in wet rocks has been attributed to a reduction
451 in fracture surface free energy due to the adsorption of water on the fracture surface (e.g., Parks, 1984;
452 Baud et al., 2000). We conclude here, in line with the conclusions of Baud et al. (2000), that a lower
453 fracture surface free energy in the presence of water reduces K_{IC} and therefore strength. Additionally,
454 we highlight that water adsorption on clay minerals is extremely efficient due to their large surface areas.
455 To emphasise, the specific surface areas of samples 157 (clay content = 2 wt.%) and 540 (clay content
456 = 13.1 wt.%) are 204 and 6170 m^2/kg , respectively (Heap et al., 2017; Tables 1 and 2). Therefore, a
457 higher clay content should ensure that more water is adsorbed on the surface of the fracture, perhaps

458 explaining the correlation between clay content and water-weakening (Figure 12b). The scatter in the
459 data of Figure 12b suggests that clay content does not govern water-weakening in sandstones alone. One
460 factor likely to play a key role is whether the clays are pore-coating or pore-filling, or whether the clays
461 are present within the rock matrix. For water adsorption on clay minerals to influence the fracture surface
462 free energy, the clays must be present within the material through which the fracture propagates (i.e. the
463 matrix). By contrast, clay present within pores may not exert a significant influence on the water-
464 weakening process.

465 We further highlight that the micromechanics of low-porosity rocks is often described using the
466 wing-crack model of Ashby and Sammis (1990), although we note that no or few microcracks were
467 found in the intact microstructure of the studied materials (Figure 3). If the wing-crack model was
468 considered appropriate for the low-porosity materials studied herein, then there is an additional
469 micromechanical parameter—the coefficient of friction—could also be influenced by the presence of
470 water.

471

472 5.2 Implications for geothermal energy exploitation

473 We have provided estimates of the rock mass strength (Figure 11b) and elastic modulus (Figure
474 11c) for the Bundsandstein sedimentary sequence (from the Soultz-sous-Forêts geothermal site) that
475 directly overlies the fractured granitic basement used throughout the Upper Rhine Graben as a
476 geothermal resource. One of the main motivations for this study is that recent (e.g., Rittershoffen;
477 Baujard et al., 2017) and future geothermal exploitation in the Upper Rhine Graben has and will target
478 rock at or close to this interface. Since the Bundsandstein is known to be a laterally extensive unit (e.g.
479 Aichholzer et al., 2016; Vidal and Genter, 2018), these new reservoir-scale strength and elastic modulus
480 estimates could assist prospection, stimulation, and optimisation strategies (for instance, the
481 Bundsandstein was stimulated at the Rittershoffen site in 2013; Vidal et al., 2016; Baujard et al., 2017)
482 at geothermal sites within the Upper Rhine Graben. We can combine our strength and elastic modulus
483 estimates for the Bundsandstein with those for the granite reservoir provided in Villeneuve et al. (2018)
484 to give strength (Figure 14b) and elastic modulus (Figure 15b) estimates for the EPS-1 borehole from a
485 depth of ~1000 to ~2200 m. These data highlight, for example, that the rock mass strength of the granitic

486 reservoir can be lower than that for the Buntsandstein, due to the high fracture density of the granite
487 (Figure 14).

488 However, since the rock mass strength and elastic modulus estimations (Figures 11b, 11c, 14b,
489 and 15b) are very much dependent on the fracture density (and their surface condition), the estimations
490 provided herein may not be directly applicable to the Buntsandstein sedimentary sequence found at other
491 geothermal sites, which will likely be characterised by different fracture densities and intersect regional
492 scale faults at different depths. For example, the Buntsandstein is much deeper at the Rittershoffen site
493 (from ~1800 to ~2200 m; Aichholzer et al., 2016) than at Soultz-sous-Forêts and major fracture zones
494 are found at depths of ~1975, ~1986, and ~2140 m (Vidal et al., 2017). Further, the extent of fracture
495 infilling will also be spatially variable. For instance, Vidal et al. (2015) note that the extent of the fracture
496 sealing can differ in the same fractured zone at different wells (e.g., GPK-2, GPK-3, and GPK-4, which
497 are separated by no more than 1.5 km) at Soultz-sous-Forêts. We further note that the sedimentary units
498 overlying the granitic reservoir can be appreciably different from those at the Soultz-sous-Forêts site at
499 a distance of several tens of kilometres (Kushnir et al., 2018b). However, we highlight that our
500 laboratory data can be re-used to provide upscaled strength and elastic modulus profiles for other sites,
501 using the methods outlined herein, as long as site-specific rock mass descriptions are performed. We
502 highlight that direct core data will provide a more complete characterisation of the fracture network than
503 borehole imaging tools (Genter et al., 1997). A recent study by Bauer et al. (2017) also highlights that,
504 when core materials are not available, care should be taken when selecting outcrop analogues for
505 geothermal reservoir rock.

506 Our laboratory data have shown that the Buntsandstein sandstones are weaker when wet (Figure
507 5). In zones characterised by the intact rock strength and elastic modulus (i.e. all zones except the five
508 highly fractured zones) (Figures 11b and 11c), the reservoir-scale strength and the elastic modulus are
509 lower when the rock is wet. Differences between the dry and wet strength and elastic modulus within
510 the five fractured zones are small: the strength and elastic modulus in these zones is primarily dictated
511 by the rock mass structure (fractures) (Figures 11b and 11c). Since the pore space of rocks within a
512 geothermal reservoir will be saturated with liquid water/brine in-situ, our measurements and analysis
513 therefore highlight the importance of performing wet deformation experiments to provide upscaled

514 strength and elastic modulus assessments for geothermal applications. Indeed, not only are the wet and
515 dry strengths and elastic moduli different (Figure 5), but we also measured a difference between the dry
516 and wet m_i term (Figure 9). We recommend that future studies that adopt this technique also perform
517 wet deformation experiments, particularly because water-weakening has been reported in a wide range
518 of rock types (e.g., sandstone: Hawkins and McConnell, 1992, tuff: Zhu et al., 2011; Heap et al., 2018,
519 basalt: Zhu et al., 2016, carbonates: Baud et al., 2016).

520 Although we performed wet deformation measurements to provide more accurate strength and
521 elastic modulus assessments, we highlight that our experiments were performed at room temperature
522 and used deionised water. First, the temperature of the Buntsandstein rocks at Soultz-sous-Forêts, for
523 example, is between 120 and 140 °C (e.g., Genter et al., 2010). The intact strength and stiffness of
524 sandstone measured in the laboratory may be different at high-temperature, although there is a paucity
525 of data. For example, Ranjith et al. (2012) found that the uniaxial compressive strength and stiffness of
526 Hawkesbury sandstone (containing 20% clay) increased from 36.5 to 42.5 MPa and from 2.8 to 3.3 GPa,
527 respectively, as the testing temperature was increased from 25 to 200 °C. Rao et al. (2007) also observed
528 an increase in uniaxial compressive strength and stiffness for sandstone as temperature was increased
529 from 25 to 150 °C. Therefore, based on these few data, it would appear that the rock mass strength and
530 elastic modulus assessments provided herein (measured at room temperature) may underestimate the
531 strength and elastic modulus of the rock in-situ. However, firm conclusions cannot be drawn without
532 further experimental investigations. For example, Heap et al. (2009a) showed that the compressive
533 strength of three sandstones under triaxial testing conditions (an effective pressure of 30 MPa) was
534 slightly lower at 75 °C than at room temperature. At present it is unclear as to the influence of, for
535 example, mineral content, porosity, and grain size on the compressive strength of sandstone at high-
536 temperature. Second, the rocks within the reservoir are saturated with hydrothermal brines with a pH
537 between 5.2 and 5.5 (e.g., Scheiber et al., 2002). A lower pH should reduce the fracture surface free
538 energy (e.g., Parks, 1984) and therefore reduce intact strength. Indeed, Singh et al. (1999) measured a
539 reduction in uniaxial compressive strength in sandstone from ~65 to ~40 MPa as the pH was reduced
540 from 7 to 2. The uniaxial compressive strength of sandstone samples was also found to decrease with
541 increasing salinity (Shukla et al., 2013; Rathanweera et al., 2014). However, recent triaxial experiments

542 showed that the triaxial compressive strength of sandstone increased with increasing NaCl concentration
543 (Huang et al., 2018). It is therefore difficult to draw firm conclusions as to the influence of the pore fluid
544 composition and pH on the strength and stiffness of sandstone without further laboratory testing.

545 We highlight that the reservoir-scale strength and elastic modulus estimates provided here are
546 representative of the short-term strength. These rock properties, and empirical term m_i , were all
547 determined at a laboratory strain rate of $1 \times 10^{-6} \text{ s}^{-1}$. Although this strain rate is an order of magnitude
548 lower than typically used in laboratory testing, we highlight that the strength of rock, including
549 sandstone, decreases as strain rate is decreased due to time-dependent subcritical crack growth processes
550 (Atkinson, 1984; Brantut et al., 2013). There are many experimental studies on time-dependent
551 deformation in sandstone (e.g., Ngwenya et al., 2001; Baud and Meredith, 1997; Heap et al., 2009a;
552 2009b; Yang and Jiang, 2010; Brantut et al., 2014; Tang et al., 2018). For example, Heap et al. (2009b)
553 showed that sandstone fails at 80% of its short-term failure stress in about 60 hours. Further, and
554 pertinent to the geothermal reservoir case study, the deformation rate during a brittle creep test can
555 increase by up to three orders of magnitude as the temperature is increased from 20 to 75 °C (Heap et
556 al., 2009a). Based on the data provided in these studies, the long-term strength of the Buntsandstein
557 sedimentary sequence may be lower than the short-term strength estimates provided herein.

558

559 **5 Concluding remarks**

560 Recent geothermal exploitation in the Upper Rhine Graben has targeted the interface between
561 the fractured granitic basement and the overlying Permian and Triassic sedimentary rocks (the
562 Buntsandstein), and geothermal projects being developed in the region will continue to do so. Our study
563 provides wet and dry strength and elastic modulus estimates for the Buntsandstein sedimentary sequence
564 (from 1008 to 1414 m) at the Soultz-sous-Forêts geothermal site in France. To provide such estimates
565 we performed 64 uniaxial (32 dry and 32 wet) and 10 triaxial deformation experiments (5 dry and 5
566 wet). These data were coupled with Geological Strength Index (GSI) assessments to provide down-well
567 wet and dry strength and elastic modulus profiles using the Hoek-Brown failure criterion and the Hoek-
568 Diederichs equation, respectively. Our analysis finds five zones characterised by low values of GSI
569 (zones with high fracture densities and infilling thicknesses) that have low values of rock mass strength

570 and elastic modulus. The zones with low fracture densities (i.e. a “massive” rock structure) are
571 characterised by the intact rock properties (i.e. a GSI value of 100) and therefore have higher values of
572 strength and elastic modulus. Additionally, we find that the strength and elastic modulus of these
573 massive zones are lower when the rock is wet, highlighting the importance of performing wet
574 deformation experiments for rock mass assessments of rock that is typically saturated with a liquid
575 phase, such as in a geothermal reservoir. We combine these new data with those for the underlying
576 fractured granite reservoir to produce down-well strength and elastic modulus profiles from a depth of
577 ~1000 to ~2200 m for the Soultz-sous-Forêts geothermal site. Although this type of analysis is somewhat
578 site specific, the methods used and data provided herein can be easily adapted to provide strength and
579 elastic modulus estimates for other geothermal sites within the Upper Rhine Graben to assist reservoir
580 prospection, stimulation, and optimisation strategies.

581

582 **Acknowledgements**

583 This study was funded by LABEX grant ANR-11-LABX-0050_G-EAU-THERMIE-
584 PROFONDE (this research therefore benefited from state funding managed by the Agence National de
585 la Recherche (ANR) as part of the “Investissements d'avenir” program) and ANR grant CANTARE
586 (ANR-15-CE06-0014-01). We are extremely grateful to Albert Genter, who provided the fracture data
587 from EPS-1 (we therefore also acknowledge the Bureau de Recherches Géologiques et Minières
588 (BRGM)). We also wish to thank Chrystal Dezayes, Bertrand Renaudié, Coralie Aichholzer, and
589 Philippe Düringer. The comments of two anonymous reviewers helped clarify certain aspects of this
590 manuscript.

591

592 **Author contributions**

593 M.J. Heap led the project and co-wrote the manuscript with M. Villeneuve. P. Baud, M.J. Heap,
594 and A.R.L. Kushnir chose and collected the samples from the Merkwiller core repository. M.J. Heap
595 and A.R.L. Kushnir measured the porosity of the experimental samples. M.J. Heap performed all the
596 uniaxial compressive strength tests. M.J. Heap, A.R.L. Kushnir, and J.I. Farquharson performed the

597 triaxial compressive strength tests. M. Villeneuve performed the geotechnical analyses. All authors had
598 a hand in the preparation of the manuscript and the interpretation of the data.

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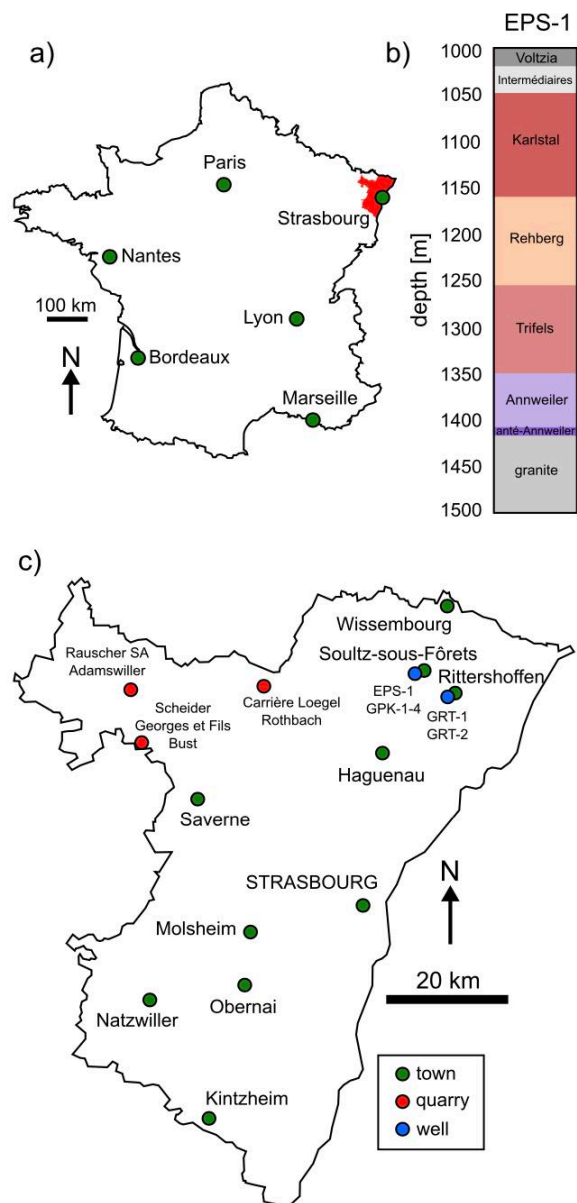
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825 **Figure 1.** (a) Map of France showing the location of the Bas-Rhin (Lower Rhine) department of Alsace

826 (in red). (b) Stratigraphic column showing the units within the Buntsandstein from exploration well

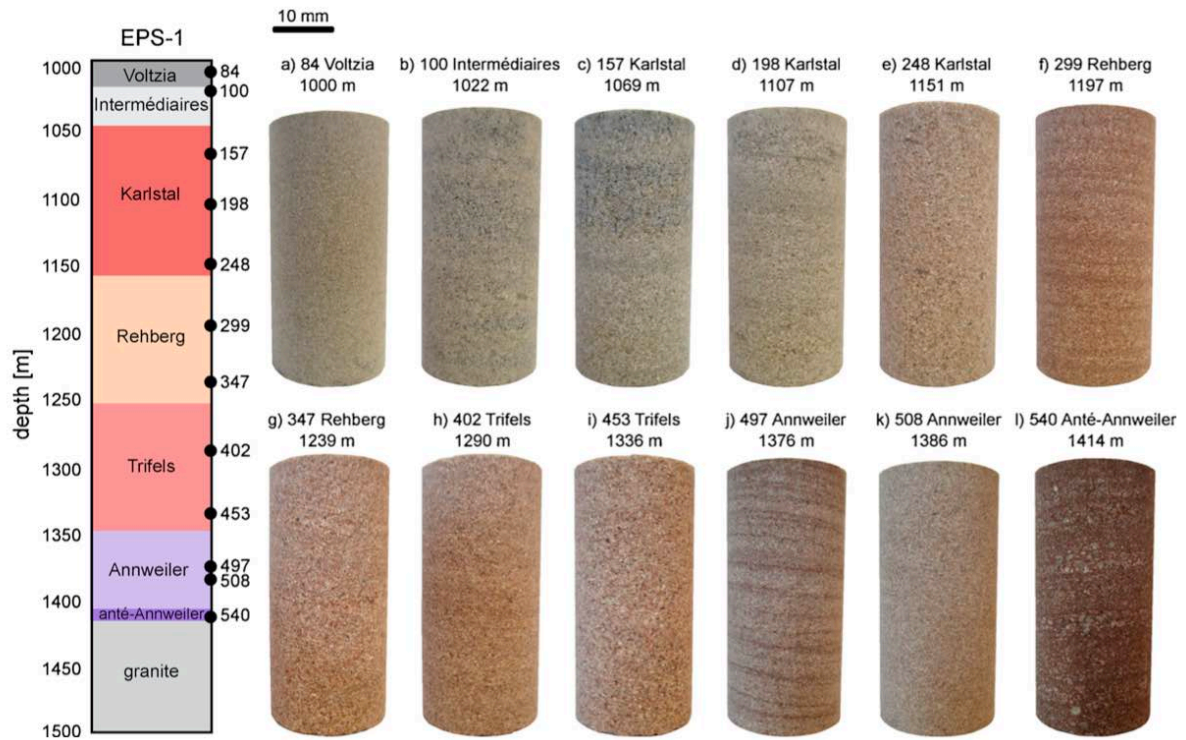
827 EPS-1 at Soultz-sous-Forêts (Alsace, France). The granite basement is encountered at a depth of 1417

828 m. Depths are measured depths. (c) Map of the Bas-Rhin (Lower Rhine) department of Alsace (shown

829 in red in panel (a)) showing the location of the major cities/towns (green circles), the geothermal sites

830 of Soultz-sous-Forêts and Rittershoffen (green circles), the wells EPS-1, GPK-1-4, and GRT-1-2 (blue

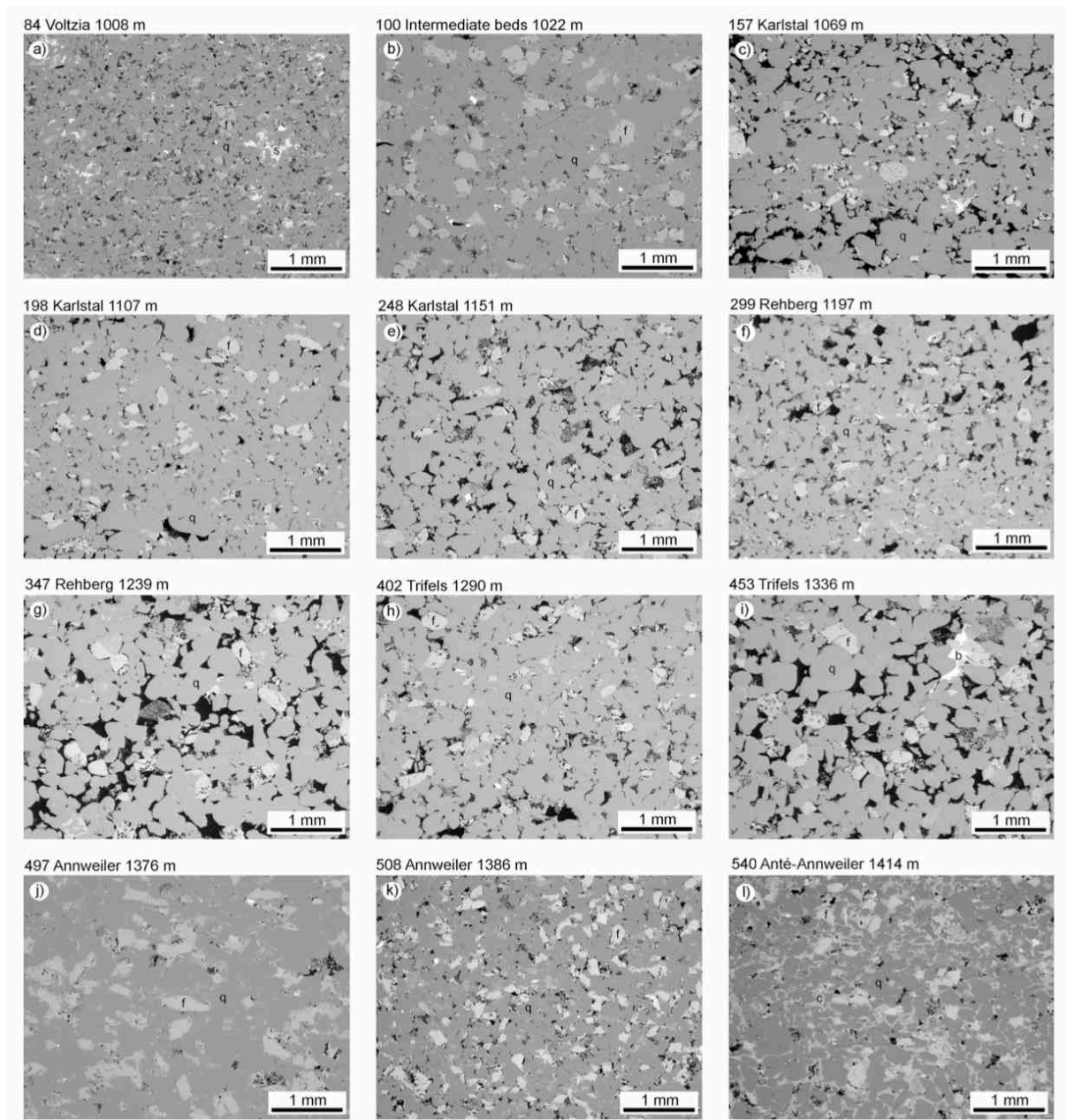
831 circles), and the locations and names of the quarries (red circles).



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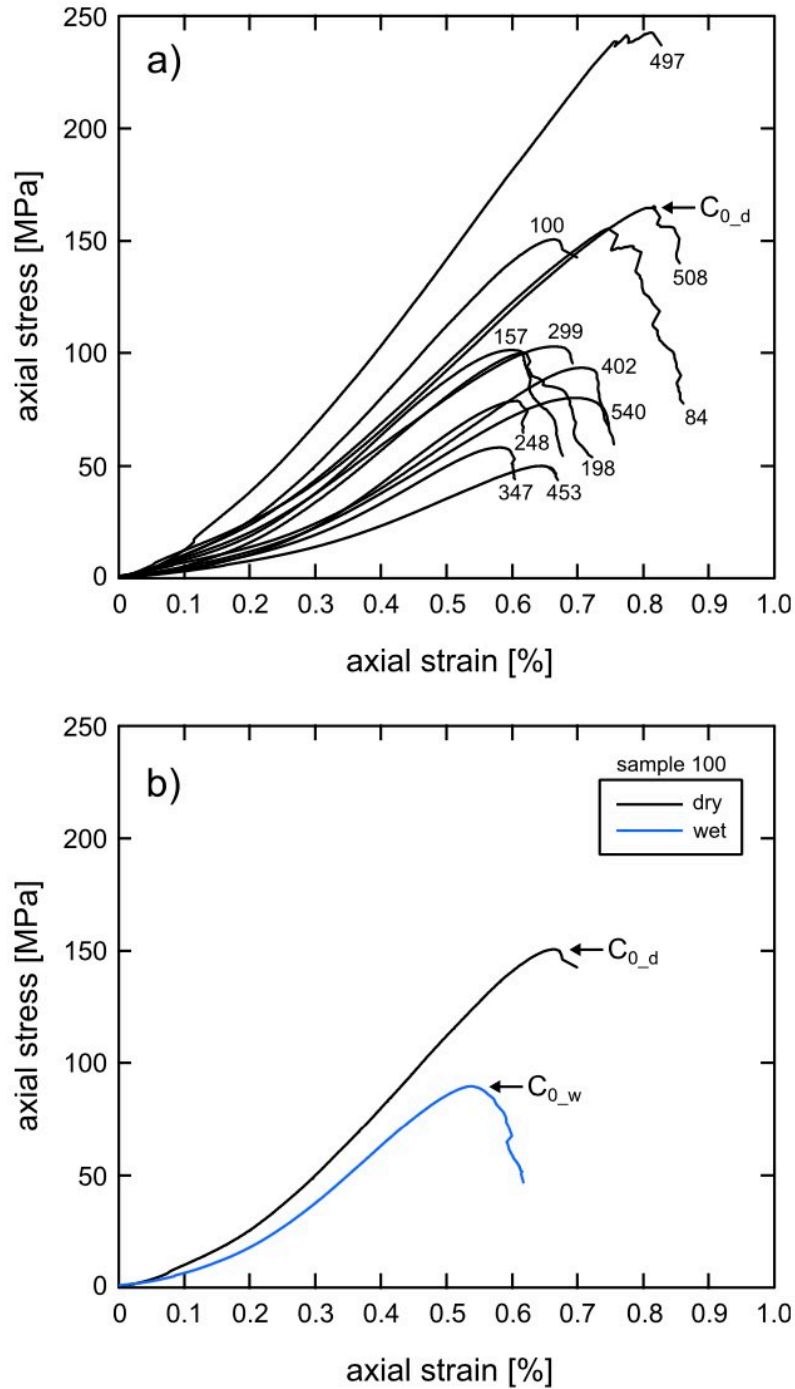
833 **Figure 2.** Photographs of each of the twelve sandstones (20 mm diameter core samples nominally 40
 834 mm in length) sampled from exploration well EPS-1 at Soultz-sous-Forêts. The box number, lithological
 835 unit, and depth are given above each sample. A stratigraphic column showing the units within the
 836 Buntsandstein from exploration well EPS-1 at Soultz-sous-Forêts (Alsace, France) is shown on the left
 837 hand side. The locations for each of the sampled depths are indicated on the stratigraphic column.

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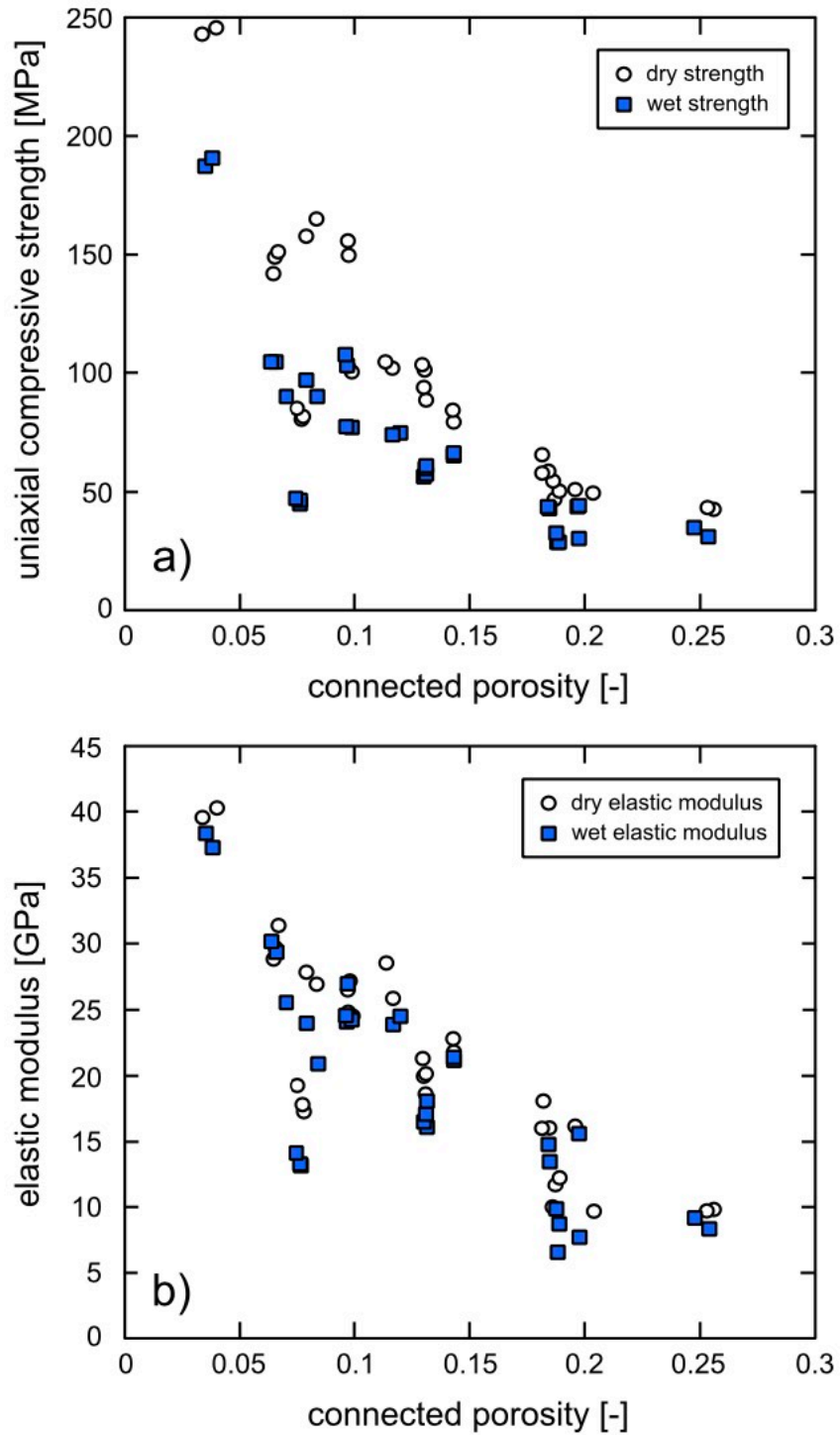
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840 **Figure 3.** Backscattered scanning electron microscope (BSE) images for each of the twelve sandstones
 841 sampled from exploration well EPS-1 at Soultz-sous-Forêts. The box number, lithological unit, and
 842 depth are given above each image. q – quartz; f – feldspar; s – siderite; b – barite; c – clay.



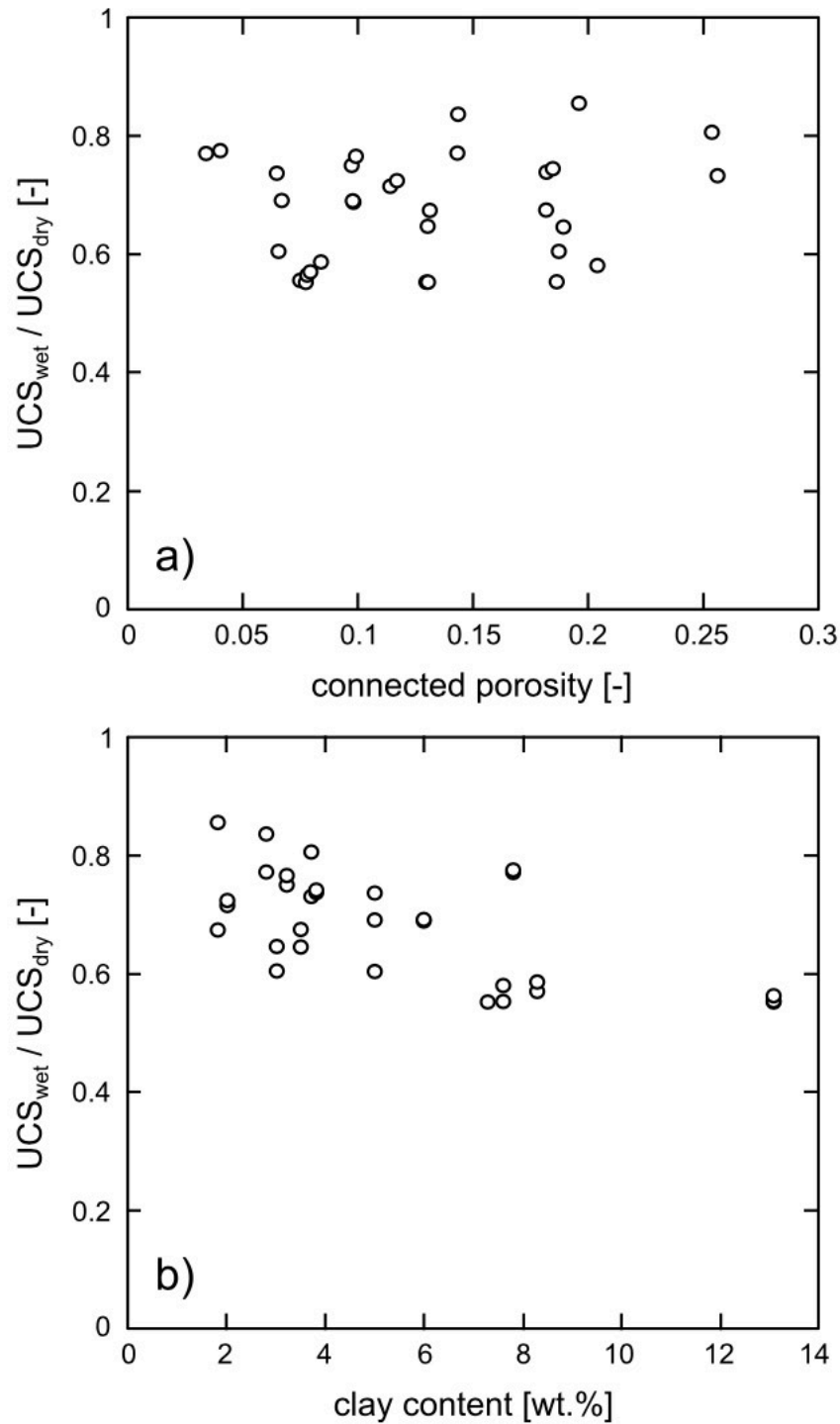
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844 **Figure 4.** (a) Representative dry uniaxial stress-strain curves for each of the twelve sandstones sampled
 845 from exploration well EPS-1 at Soultz-sous-Forêts. Number next to each curve indicates the box number
 846 (see Table 3). The dry uniaxial compressive strength, $C_{0,d}$, is labelled for one of the curves. (b)
 847 Representative dry (black curve) and wet (blue curve) uniaxial stress-strain curves for samples taken
 848 from box number 100 (see Table 3). The dry uniaxial compressive strength, $C_{0,d}$, and the wet uniaxial
 849 compressive strength, $C_{0,w}$, are labelled on the corresponding curves.



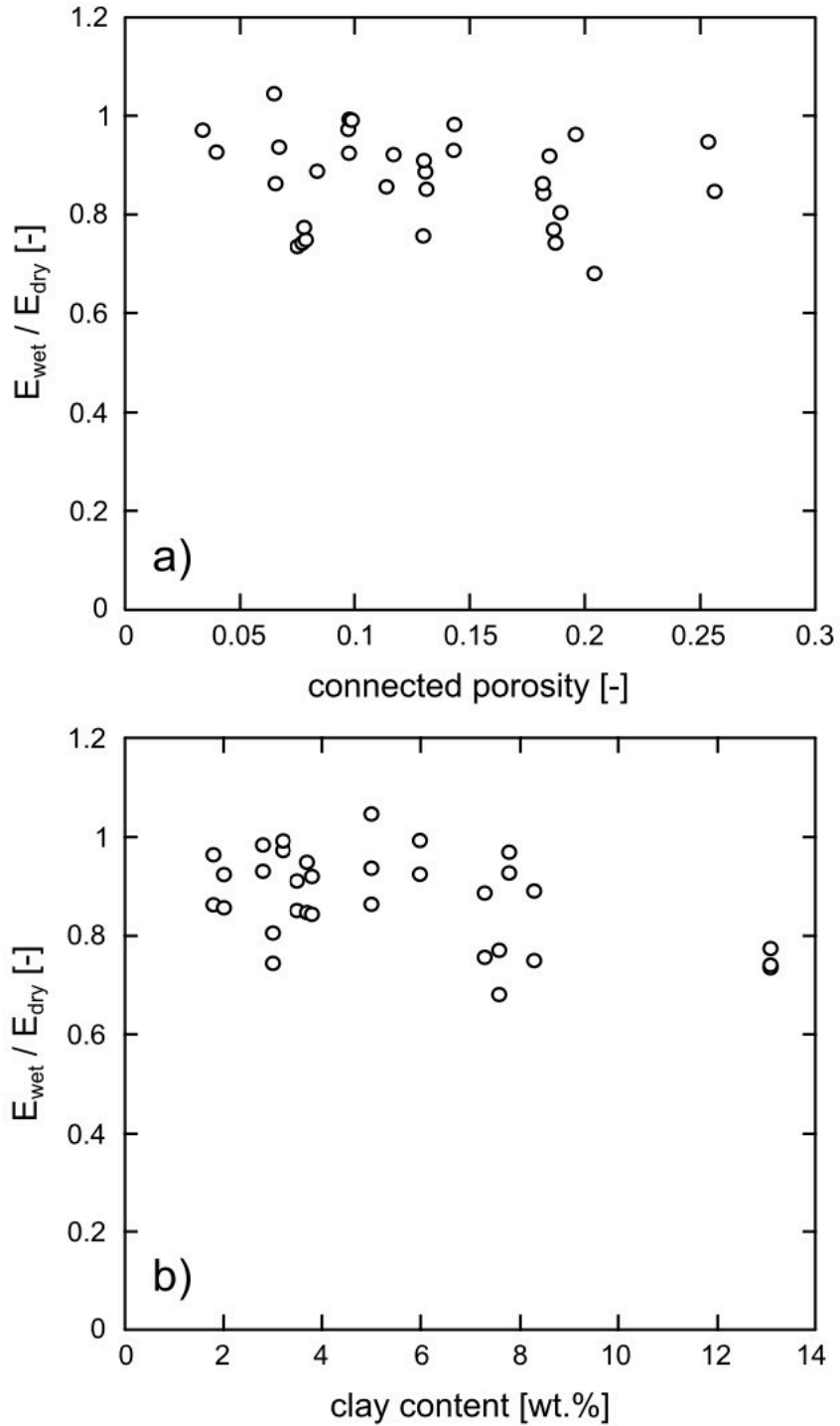
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851 **Figure 5.** (a) Dry (white circles) and wet (blue squares) uniaxial compressive strength for the twelve
 852 sandstones sampled from exploration well EPS-1 at Soultz-sous-Forêts and the three quarry rocks as a
 853 function of connected porosity. (b) Dry (white circles) and wet (blue squares) elastic modulus for the
 854 twelve sandstones sampled from exploration well EPS-1 at Soultz-sous-Forêts and the three quarry rocks
 855 as a function of connected porosity.



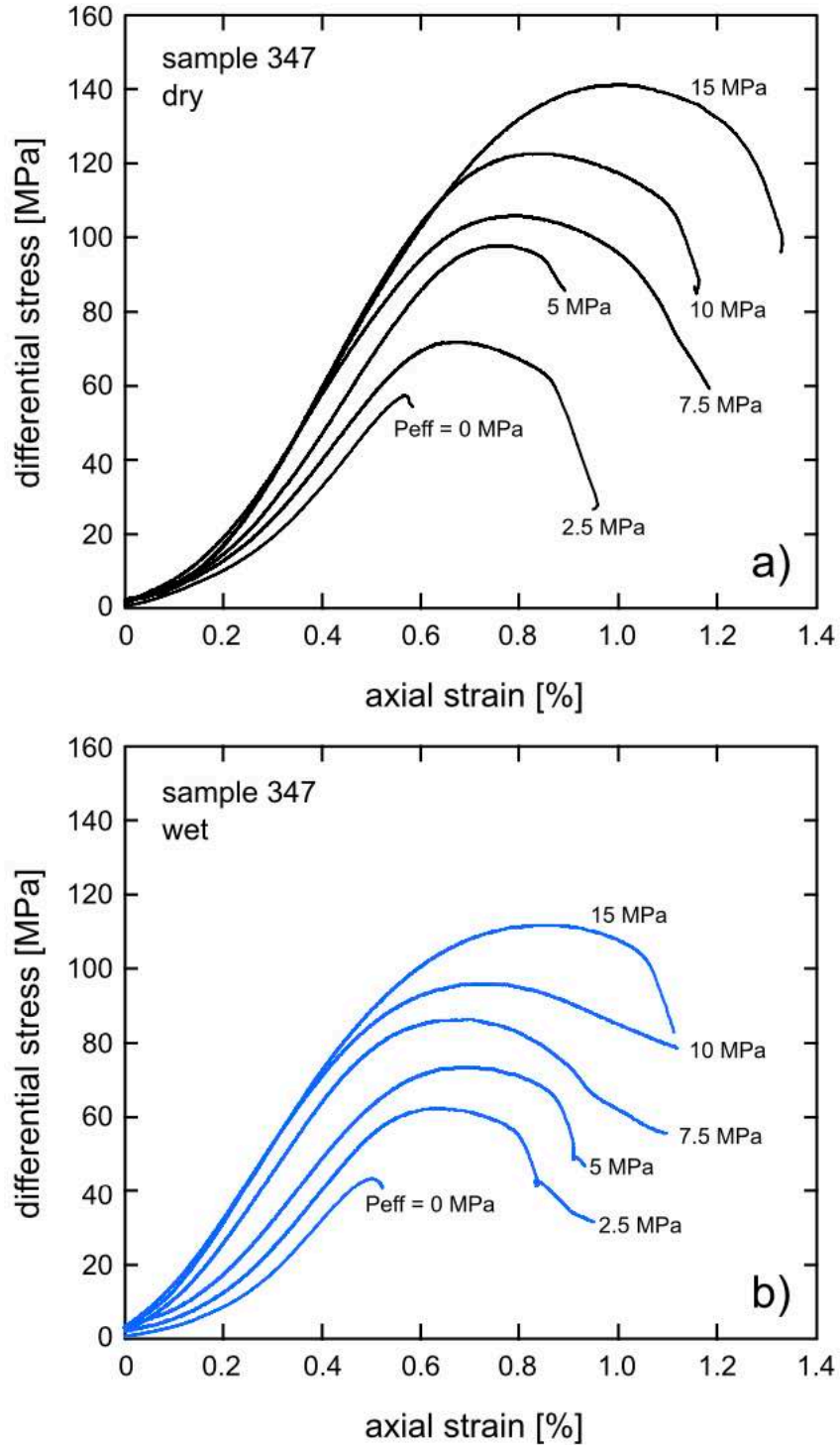
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857 **Figure 6.** (a) The ratio of wet to dry uniaxial compressive strength for the twelve sandstones sampled
 858 from exploration well EPS-1 at Soultz-sous-Forêts and the three quarry rocks as a function of connected
 859 porosity. (b) The ratio of wet to dry uniaxial compressive strength for the twelve sandstones sampled
 860 from exploration well EPS-1 at Soultz-sous-Forêts and the three quarry rocks as a function of clay
 861 content (clay content is the wt.% of muscovite/illite-smectite; Table 1).



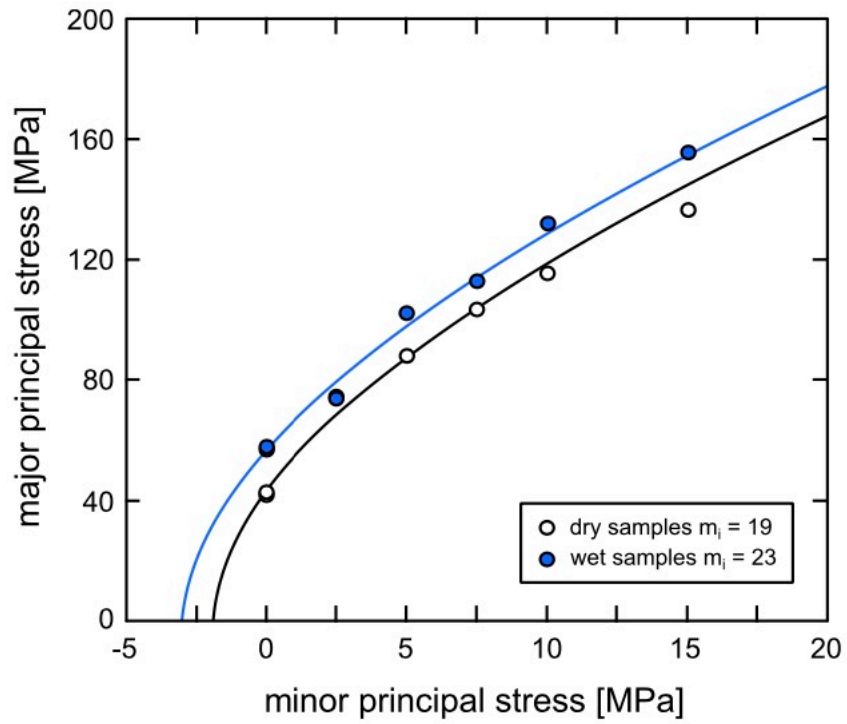
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863 **Figure 7.** (a) The ratio of wet to dry elastic modulus for the twelve sandstones sampled from exploration
 864 well EPS-1 at Soultz-sous-Forêts and the three quarry rocks as a function of connected porosity. (b) The
 865 ratio of wet to dry elastic modulus for the twelve sandstones sampled from exploration well EPS-1 at
 866 Soultz-sous-Forêts and the three quarry rocks as a function of clay content (clay content is the wt.% of
 867 muscovite/illite-smectite; Table 1).



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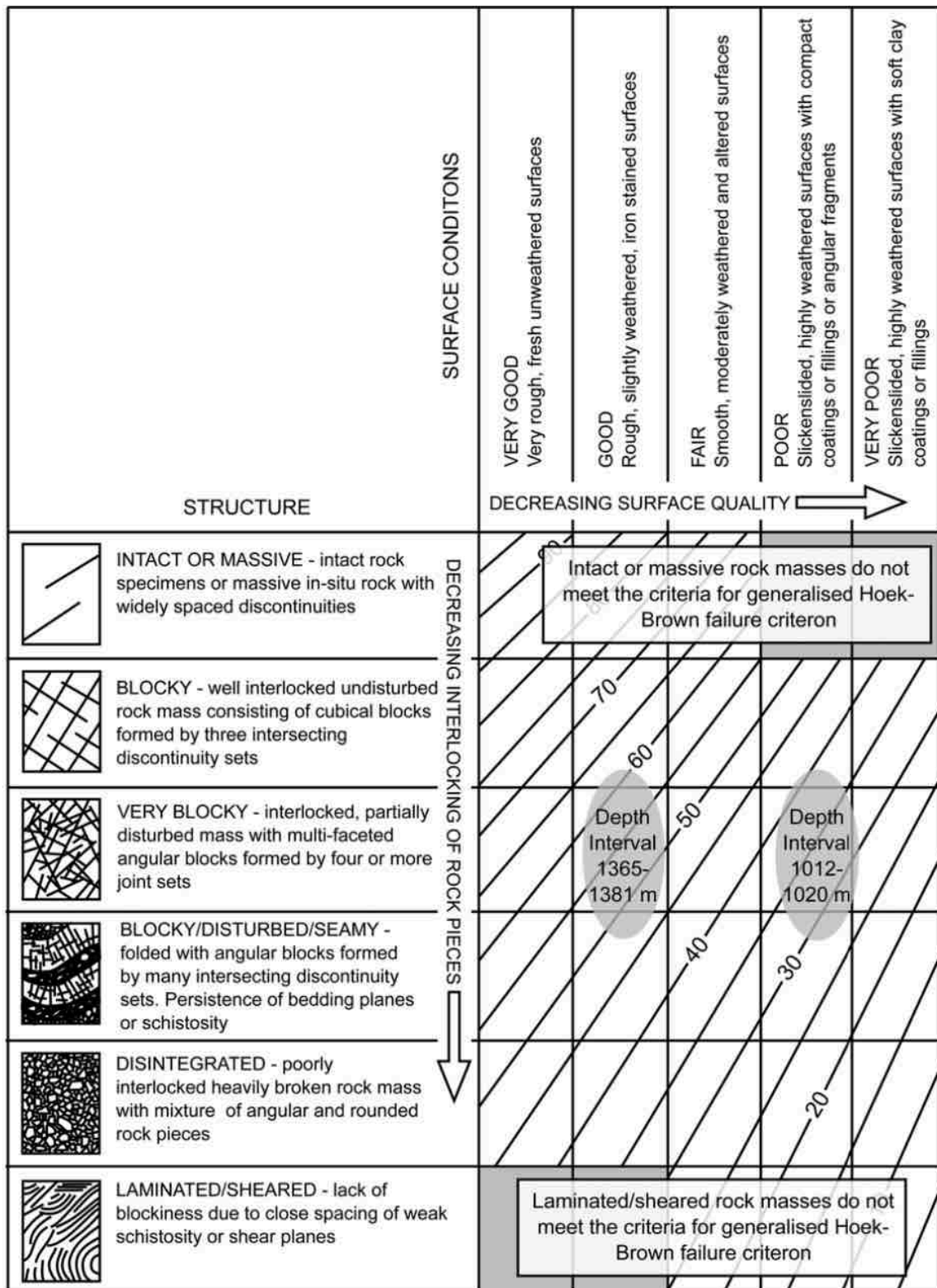
869 **Figure 8.** (a) Dry triaxial stress-strain curves for samples taken from box number 347 (from the *Rehberg*
 870 unit; depth = 1239 m) deformed at different effective pressures (the effective pressure, P_{eff} , is indicated
 871 next to the curves). (b) Wet triaxial stress-strain curves for samples taken from box number 347 (from
 872 the *Rehberg* unit; depth = 1239 m) deformed at different effective pressures (the effective pressure,
 873 P_{eff} , is indicated next to the curves).



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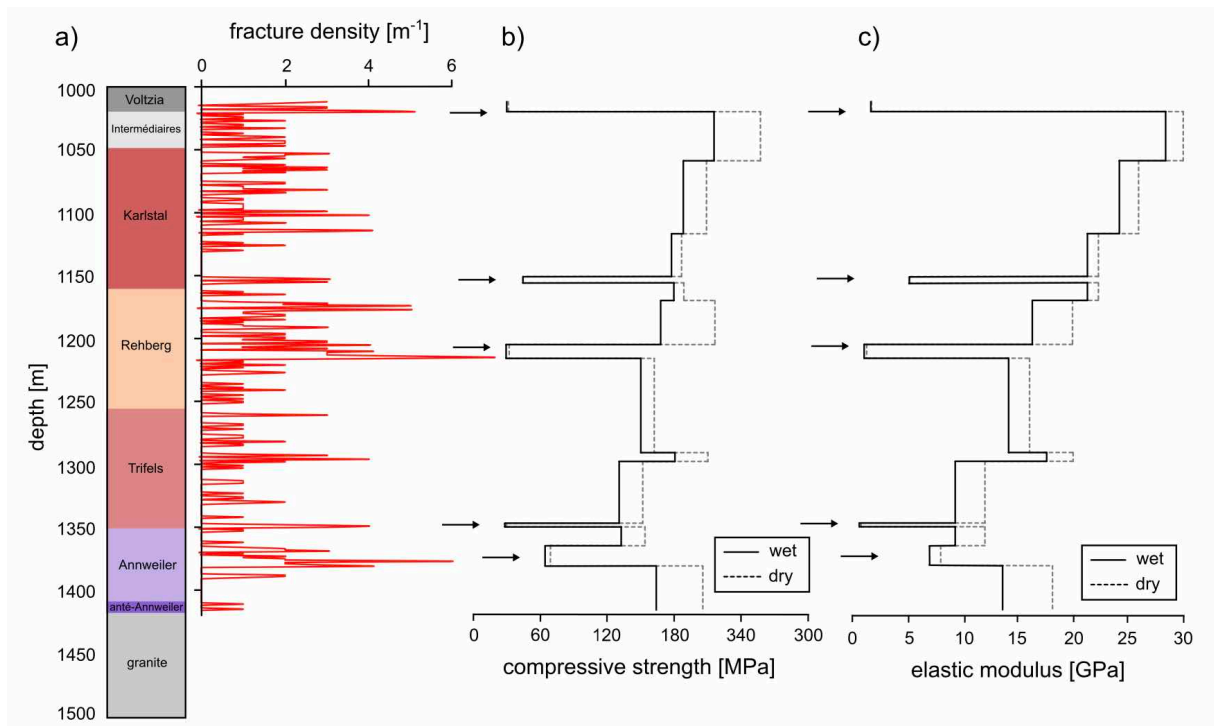
875 **Figure 9.** Triaxial data for wet and dry *Rehberg* unit (depth = 1239 m) plotted in principal stress space
 876 with the intact Hoek-Brown failure criterion fits using Equation 2 (for the dry data) and Equation 3 (for
 877 the wet data). The best-fit m_i values for the dry and wet samples are given on the figure.

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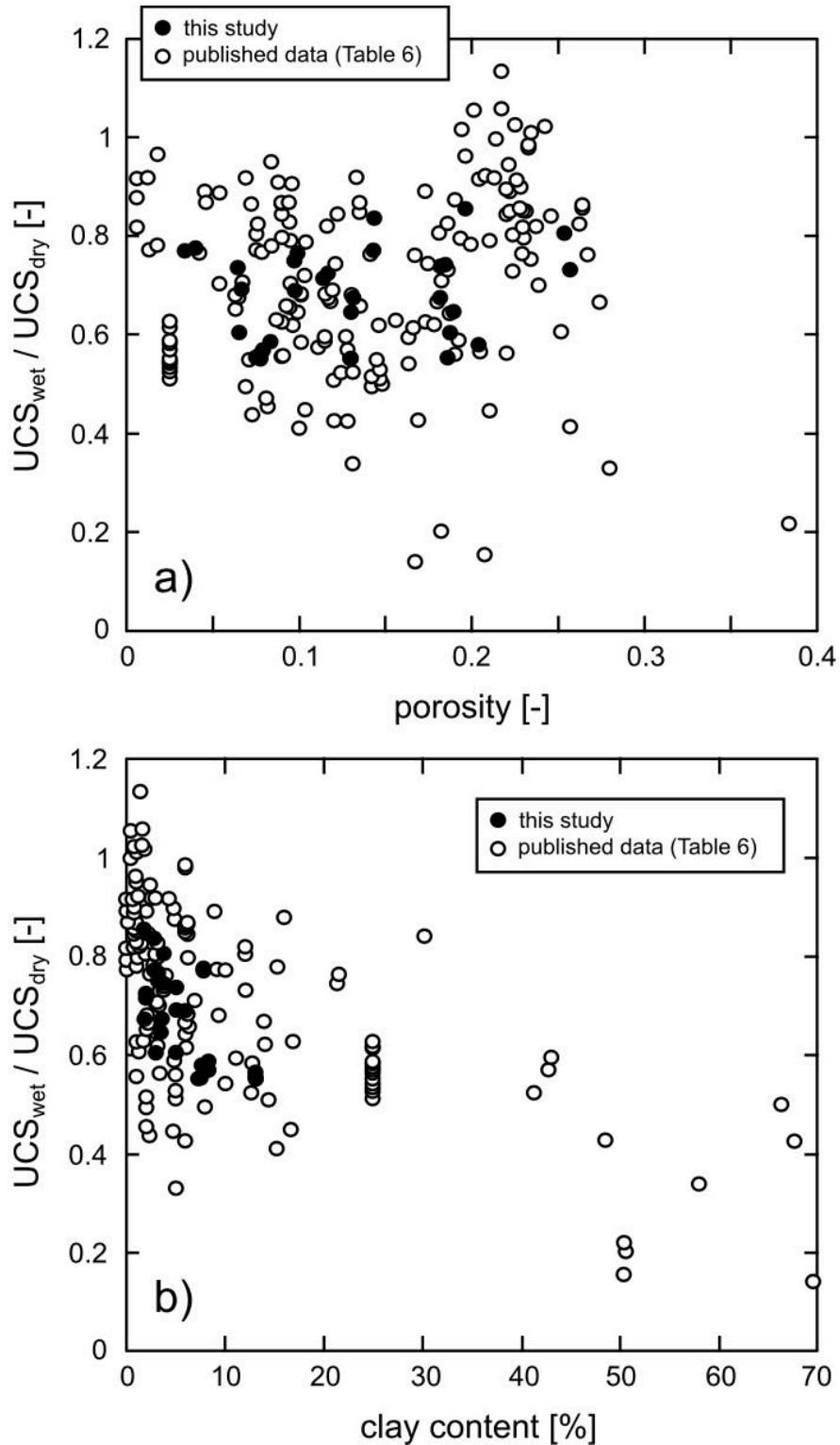
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880 **Figure 10.** Geological Strength Index (GSI) lookup chart (modified from Marinos et al., 2005) showing
 881 the assessed GSI values for two rock mass intervals (see text for details). See Table 5 for rock mass
 882 descriptions based on core logging. Note that the highest and lowest category should not be used for the
 883 generalised Hoek-Brown failure criterion (as indicated on the figure).



884

885 **Figure 11.** (a) Stratigraphic column showing the units within the Buntsandstein from exploration well
 886 EPS-1 at Soultz-sous-Forêts next to the fracture density data for the core. (b) Wet (black line) and dry
 887 (grey dashed line) rock mass compressive strength for the Buntsandstein over the depth interval 1012-
 888 1416 m. (c) Wet (black line) and dry (grey dashed line) rock mass elastic modulus for the Buntsandstein
 889 over the depth interval 1012-1416 m. The black arrows indicate the five fractured zones.



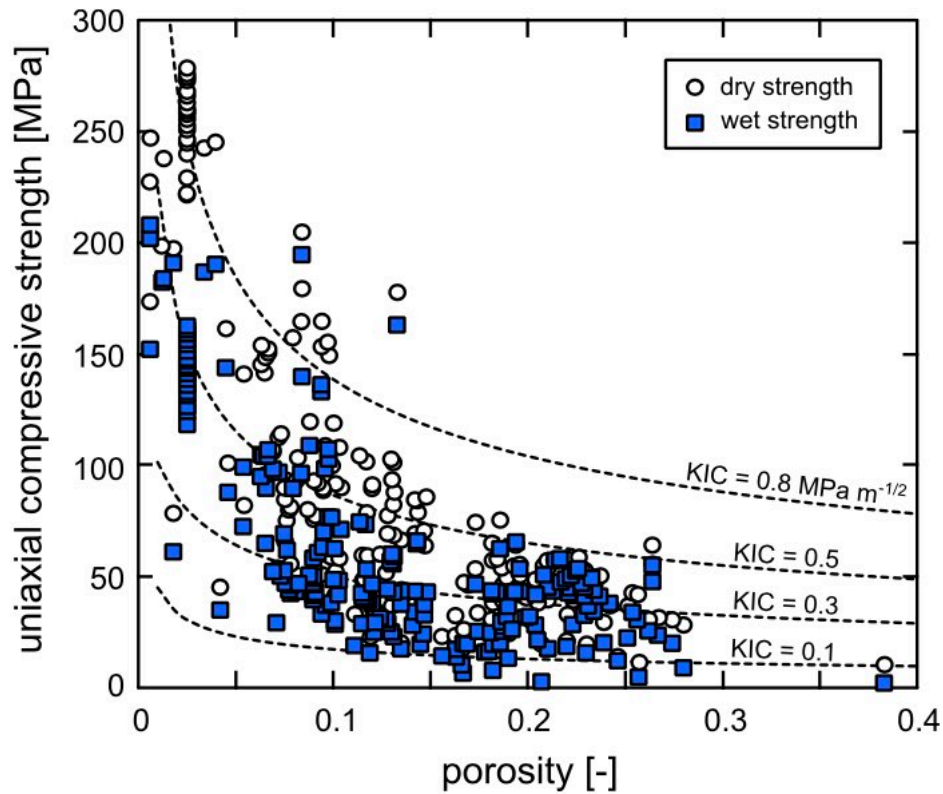
890

891 **Figure 12.** (a) The ratio of wet to dry uniaxial compressive strength for the data unique to this study

892 (Table 3) and data from published studies (Table 6) as a function of connected porosity. (a) The ratio of

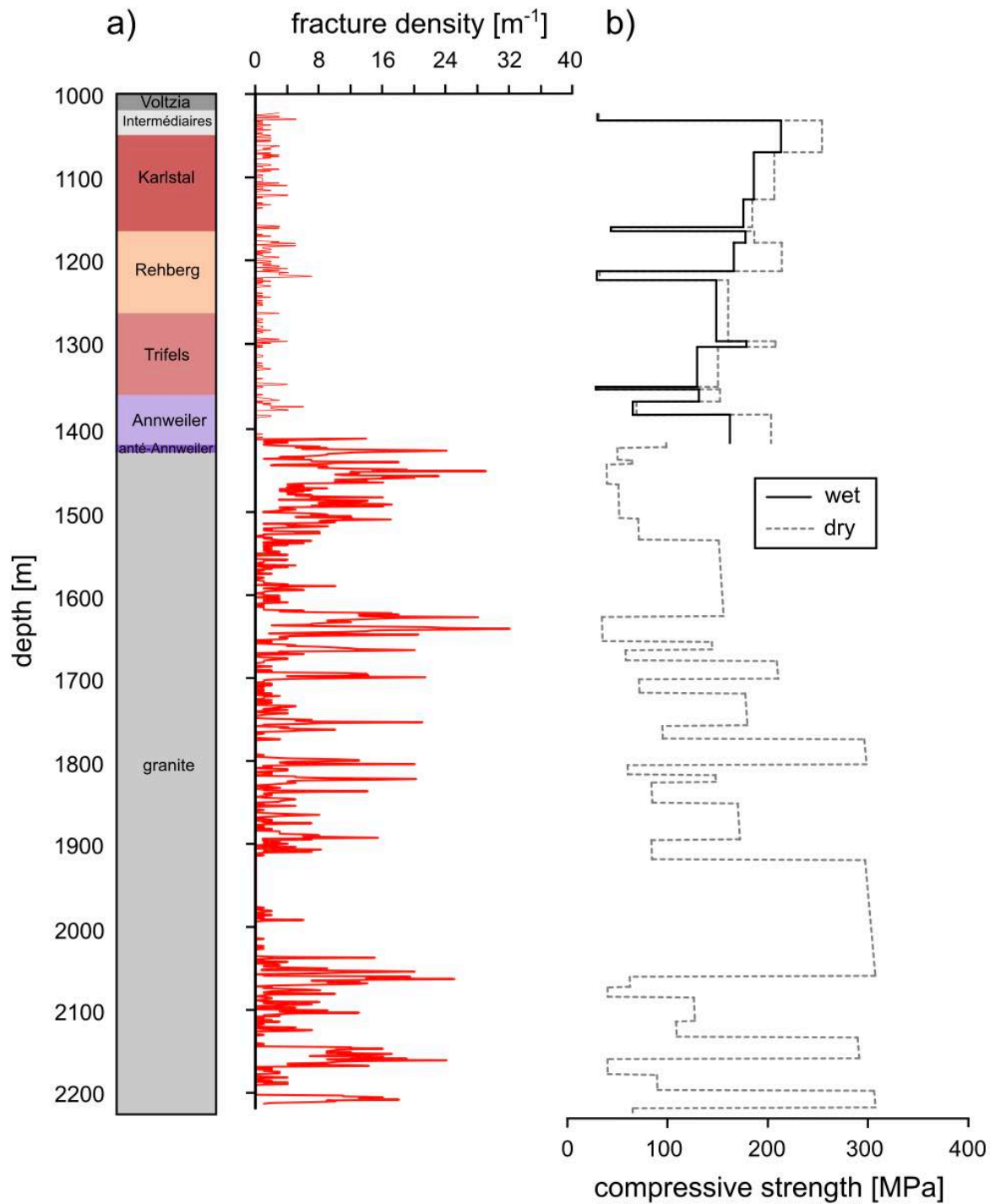
893 wet to dry uniaxial compressive strength for the data unique to this study (Table 3) and data from

894 published studies (Table 6) as a function of clay content.



895

896 **Figure 13.** Dry (white circles) and wet (blue squares) uniaxial compressive strength data (data unique
 897 to this study (Table 3) and published data (Table 6)) as a function of porosity. Modelled curves, using
 898 Equation (15), show curves of uniaxial compressive strength as a function of porosity for a fixed pore
 899 radius (125 μm) and different values of K_{IC} ($K_{IC} = 0.1, 0.3, 0.5,$ and $0.8 \text{ MPa m}^{-1/2}$) (see text for details).



900

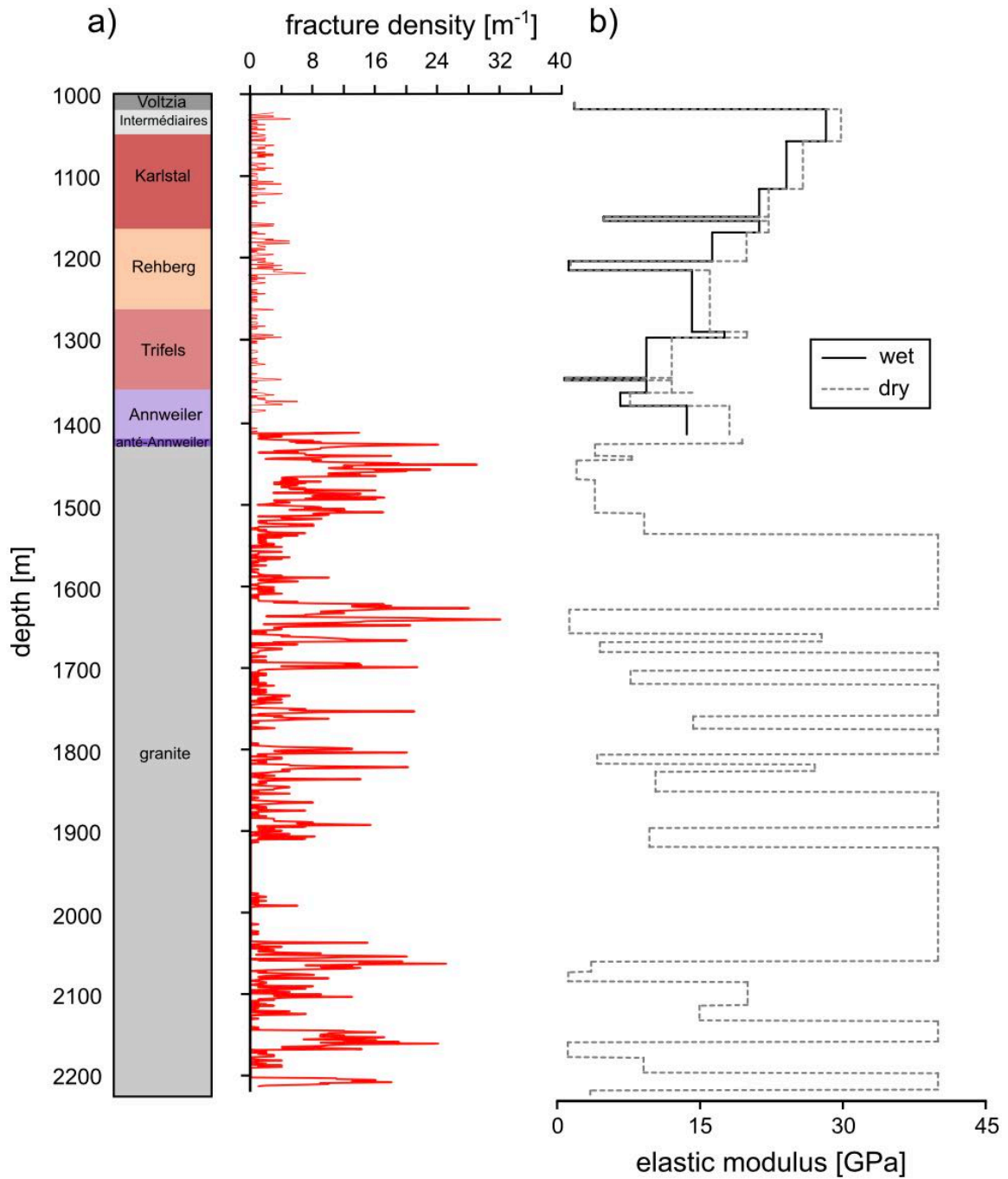
901 **Figure 14.** (a) Stratigraphic column of exploration well EPS-1 at Soultz-sous-Forêts (from 1012 to 2200

902 m) next to the fracture density data for the core. (b) Wet (black line) and dry (grey dashed line) rock

903 mass compressive strength. Note that dry and wet values are given for the Bundsandstein (interval 1012-

904 1416 m) only.

905



906

907 **Figure 15.** (a) Stratigraphic column of exploration well EPS-1 at Soultz-sous-Forêts (from 1012 to 2200
 908 m) next to the fracture density data for the core. (b) Wet (black line) and dry (grey dashed line) rock
 909 mass elastic modulus. Note that dry and wet values are given for the Bundsandstein (interval 1012-1416
 910 m) only.

911

912 **Table 1.** X-ray powder diffraction (XRPD) analysis showing quantitative bulk mineralogical
 913 composition for the twelve sandstones sampled from exploration well EPS-1 at the Soultz-sous-Forêts
 914 geothermal site and the three quarry rocks. Values in wt.%. Data from Heap et al. (2017).

915

Box number	Depth (m)	Unit	Quartz	Orthoclase	Microcline	Muscovite Illite- smectite	Dolomite	Siderite	Hematite	Kaolinite	Chlorite
84	1008	Voltzia	74.5 ± 1.6	3.7 ± 1.9	9.3 ± 0.8	6.0 ± 2.9	4.7 ± 0.1	1.9 ± 0.2	-	-	-
100	1022	Intermédiaires	78.9 ± 1.7	5.6 ± 0.0	9.7 ± 0.5	5.0 ± 2.5	1.0 ± 0.3	-	-	-	-
157	1069	Karlstal	89.2 ± 0.4	4.6 ± 1.1	4.0 ± 1.7	2.0 ± 0.8	0.2 ± 0.1	-	-	-	-
198	1107	Karlstal	89.0 ± 1.1	3.2 ± 0.2	4.6 ± 0.0	3.2 ± 1.3	-	-	-	-	-
248	1151	Karlstal	90.7 ± 1.2	1.9 ± 0.1	4.5 ± 0.2	2.8 ± 1.3	-	-	0.2 ± 0.1	-	-
299	1197	Rehberg	83.4 ± 2.6	1.7 ± 0.2	7.4 ± 0.5	7.3 ± 3.2	-	-	0.5 ± 0.1	-	-
347	1239	Rehberg	87.8 ± 1.3	2.4 ± 0.0	5.9 ± 0.1	3.8 ± 1.5	-	-	0.3 ± 0.0	-	-
402	1290	Trifels	86.7 ± 1.6	3.0 ± 0.8	6.6 ± 0.3	3.5 ± 2.1	-	-	0.3 ± 0.0	-	-
453	1336	Trifels	82.3 ± 1.7	4.3 ± 0.6	9.4 ± 0.4	3.0 ± 1.8	0.8 ± 0.0	-	0.3 ± 0.1	-	-
497	1376	Annweiler	73.3 ± 3.0	4.8 ± 0.4	11.1 ± 0.6	7.8 ± 3.9	2.1 ± 0.0	-	0.9 ± 0.1	-	-
508	1386	Annweiler	70.6 ± 2.8	6.9 ± 1.1	13.8 ± 0.5	8.3 ± 4.5	-	-	0.5 ± 0.1	-	-
540	1414	Anté- Annweiler	66.4 ± 4.0	4.4 ± 0.9	10.7 ± 0.7	13.1 ± 6.0	4.2 ± 0.5	-	1.4 ± 0.1	-	-
Rothbach	Quarry	Karlstal	82.8 ± 0.5	7.8 ± 0.2	7.1 ± 0.2	1.8 ± 0.5	-	-	0.4 ± 0.2	-	-
Adamswiller	Quarry	Voltzia	71.8 ± 0.6	10.4 ± 0.2	11.8 ± 0.5	3.7 ± 1.0	-	-	0.7 ± 0.2	-	1.7 ± 0.2
Bust	Quarry	Voltzia	67.4 ± 1.0	10.4 ± 0.2	13.5 ± 0.5	4.0 ± 1.0	0.5 ± 0.1	-	0.5 ± 0.1	3.6 ± 0.5	-

916

917

918 **Table 2.** Average connected porosity, average grain diameter, specific surface area, average dry and wet
919 P-wave velocity, and average permeability for each of the twelve sandstones sampled from exploration
920 well EPS-1 at the Soultz-sous-Forêts geothermal site and the three quarry rocks. Physical property data
921 taken from Heap et al. (2017). Elastic wave velocities were measured at room pressure and
922 permeabilities were measured under a confining pressure of 1 MPa. Grain size data for Rothbach and
923 Adamswiller sandstone from Louis et al. (2005; 2009) and David et al. (1994), respectively.

924

Box number	Depth (m)	Unit	Average connected porosity	Average grain diameter (μm)	Specific surface area (m^2/kg)	Average dry P-wave velocity (km/s)	Average wet P-wave velocity (km/s)	Average permeability (m^2)
84	1008	Voltzia	0.096	142	1442	3.7	4.4	2.82×10^{-18}
100	1022	Intermédiaires	0.065	306	665	3.6	4.6	6.45×10^{-18}
157	1069	Karlstal	0.117	424	204	3.4	4.3	1.33×10^{-16}
198	1107	Karlstal	0.097	192	1485	3.2	4.4	7.95×10^{-17}
248	1151	Karlstal	0.144	294	1175	3.1	4.1	5.24×10^{-15}
299	1197	Rehberg	0.130	332	1888	3.4	4.1	1.15×10^{-17}
347	1239	Rehberg	0.185	367	1098	2.9	3.8	4.66×10^{-15}
402	1290	Trifels	0.131	259	1349	3.1	4.1	2.37×10^{-16}
453	1336	Trifels	0.189	361	1174	2.7	3.7	9.06×10^{-15}
497	1376	Annweiler	0.034	291	2024	4.1	5.1	2.08×10^{-18}
508	1386	Annweiler	0.082	199	2777	3.4	4.4	2.12×10^{-18}
540	1414	Anté-Annweiler	0.075	379	6170	2.9	4.2	7.89×10^{-18}
Rothbach	Quarry	Karlstal	0.191	100-150 (low-porosity layers) 200-250 (high-porosity layers)	-	3.4	3.9	6.94×10^{-14}
Adamswiller	Quarry	Voltzia	0.253	120	-	2.3	3.0	3.54×10^{-13}
Bust	Quarry	Voltzia	0.192	-	-	2.8	3.2	4.82×10^{-14}

925

926 **Table 3.** Summary of the dry and wet uniaxial compressive strength experiments performed on the
 927 twelve sandstones sampled from exploration well EPS-1 at the Soultz-sous-Forêts geothermal site and
 928 the three quarry rocks. Also included are the connected porosity, average grain diameter, and clay
 929 content (average grain diameter and clay content taken from Heap et al., 2017).

930

Box number	Depth (m)	Unit	Connected porosity	Average grain diameter (μm)	Clay content (wt.%)	Dry UCS ($C_{o,d}$) (MPa)	Wet UCS ($C_{o,w}$) (MPa)	Elastic modulus (GPa)
84	1008	Voltzia	0.098	142	6.0	149.3	-	27.2
84	1008	Voltzia	0.097	142	6.0	155.4	-	26.6
84	1008	Voltzia	0.096	142	6.0	-	107.4	24.6
84	1008	Voltzia	0.097	142	6.0	-	102.8	27.0
100	1022	Intermédiaires	0.067	306	5.0	150.7	-	31.4
100	1022	Intermédiaires	0.065	306	5.0	148.5	-	29.7
100	1022	Intermédiaires	0.065	306	5.0	141.7	-	28.9
100	1022	Intermédiaires	0.070	306	5.0	-	89.9	25.6
100	1022	Intermédiaires	0.066	306	5.0	-	104.2	29.4
100	1022	Intermédiaires	0.064	306	5.0	-	104.4	30.2
157	1069	Karlstal	0.117	424	2.0	101.6	-	25.9
157	1069	Karlstal	0.114	424	2.0	104.3	-	28.6
157	1069	Karlstal	0.117	424	2.0	-	73.6	23.9
157	1069	Karlstal	0.120	424	2.0	-	74.6	24.5
198	1107	Karlstal	0.099	192	3.2	100.2	-	24.5
198	1107	Karlstal	0.097	192	3.2	102.6	-	24.8
198	1107	Karlstal	0.097	192	3.2	-	76.8	24.3
198	1107	Karlstal	0.099	192	3.2	-	77.0	24.1
248	1151	Karlstal	0.143	294	2.8	79.0	-	21.8
248	1151	Karlstal	0.143	294	2.8	84.1	-	22.8

248	1151	Karlstal	0.143	294	2.8	-	66.1	21.4
248	1151	Karlstal	0.143	294	2.8	-	64.9	21.2
299	1197	Rehberg	0.130	332	7.3	103.1	-	21.3
299	1197	Rehberg	0.131	332	7.3	101.1	-	18.6
299	1197	Rehberg	0.130	332	7.3	-	55.9	16.5
299	1197	Rehberg	0.131	332	7.3	-	57.0	16.1
347	1239	Rehberg	0.185	367	3.8	58.2	-	16.1
347	1239	Rehberg	0.182	367	3.8	57.4	-	16.0
347	1239	Rehberg	0.184	367	3.8	-	43.3	14.8
347	1239	Rehberg	0.185	367	3.8	-	42.4	13.5
402	1290	Trifels	0.130	259	3.5	93.6	-	19.9
402	1290	Trifels	0.131	259	3.5	88.2	-	20.1
402	1290	Trifels	0.131	259	3.5	-	59.5	17.1
402	1290	Trifels	0.131	259	3.5	-	60.5	18.1
453	1336	Trifels	0.189	361	3.0	50.0	-	12.3
453	1336	Trifels	0.187	361	3.0	46.6	-	11.7
453	1336	Trifels	0.188	361	3.0	-	32.3	9.9
453	1336	Trifels	0.189	361	3.0	-	28.2	8.7
497	1376	Annweiler	0.034	291	7.8	242.7	-	39.6
497	1376	Annweiler	0.040	291	7.8	245.2	-	40.3
497	1376	Annweiler	0.038	291	7.8	-	190.4	37.3
497	1376	Annweiler	0.035	291	7.8	-	187.1	38.4
508	1386	Annweiler	0.084	199	8.3	164.7	-	27.0
508	1386	Annweiler	0.079	199	8.3	157.3	-	27.9
508	1386	Annweiler	0.079	199	8.3	-	96.7	24.0
508	1386	Annweiler	0.084	199	8.3	-	89.7	20.9
540	1414	Anté-Annweiler	0.077	379	13.1	80.3	-	17.8
540	1414	Anté-Annweiler	0.075	379	13.1	84.7	-	19.3

540	1414	Anté-Annweiler	0.078	379	13.1	81.3	-	17.3
540	1414	Anté-Annweiler	0.077	379	13.1	-	44.4	13.2
540	1414	Anté-Annweiler	0.075	379	13.1	-	47.0	14.2
540	1414	Anté-Annweiler	0.076	379	13.1	-	45.9	13.4
Bust	Quarry	Voltzia	0.204	-	4.0	49.1	-	9.7
Bust	Quarry	Voltzia	0.186	-	4.0	54.0	-	10.0
Bust	Quarry	Voltzia	0.198	-	4.0	-	29.9	7.7
Bust	Quarry	Voltzia	0.188	-	4.0	-	28.5	6.6
Adamswiller	Quarry	Voltzia	0.253	120	3.7	42.8	-	9.7
Adamswiller	Quarry	Voltzia	0.256	120	3.7	42.1	-	9.8
Adamswiller	Quarry	Voltzia	0.254	120	3.7	-	30.8	8.3
Adamswiller	Quarry	Voltzia	0.248	120	3.7	-	34.5	9.2
Rothbach	Quarry	Karlstal	0.196	100-250	1.8	50.5	-	16.2
Rothbach	Quarry	Karlstal	0.182	100-250	1.8	65.1	-	18.1
Rothbach	Quarry	Karlstal	0.197	100-250	1.8	-	43.2	15.6
Rothbach	Quarry	Karlstal	0.198	100-250	1.8	-	43.9	15.6

931

932

933 **Table 4.** Summary of the dry and wet triaxial compressive strength experiments performed on samples
934 taken from box number 347 (from the *Rehberg* unit).

935

Sample	Connected porosity	Condition	Confining pressure (MPa)	Pore fluid pressure (MPa)	Effective pressure (MPa)	Peak differential stress (MPa)
347_12	0.181	Dry	2.5	0	2.5	71.8
347_8	0.179	Dry	5	0	5	97.7
347_13	0.177	Dry	7.5	0	7.5	105.8
347_9	0.178	Dry	10	0	10	122.5
347_11	0.181	Dry	15	0	15	141.1
347_23	0.179	Wet	12.5	10	2.5	62.3
347_14	0.180	Wet	15	10	5	73.4
347_17	0.177	Wet	17.5	10	7.5	86.3
347_16	0.177	Wet	20	10	10	95.9
347_18	0.179	Wet	25	10	15	111.8

936

937 **Table 5.** Summary of rock mass descriptions for Geological Strength Index (GSI) assessment, and the
938 resulting intact and rock mass strength and elastic modulus for the wet and dry sandstone units. Wet and
939 dry intact C_o and E_i are given as averages for the rock type associated with the rock mass interval. S_{hmin}
940 = minimum horizontal stress; UCS = uniaxial compressive strength; E_i = intact elastic modulus; E_{rm} =
941 rock mass elastic modulus.
942
943 See Excel spreadsheet for Table 5.

944 **Table 6.** Published wet and dry uniaxial compressive strength data for sandstones. Rate in brackets for
945 the Pennant sandstone experiments (Hadizadeh and Law, 1991) is the experimental strain rate. H & L =
946 Hadizadeh and Law; H & M = Hawkins and McConnell; para = parallel to bedding; perp = perpendicular
947 to bedding.
948

Sandstone	Porosity	Clay content (%)	Dry UCS (MPa)	Wet UCS (MPa)	UCSwet / UCSdry	Reference
Fell sandstone	0.111	-	33.2	19.1	0.58	Bell (1978)
Fell sandstone	0.127	-	51.9	31.0	0.60	Bell (1978)
Fell sandstone	0.115	-	73.7	43.3	0.59	Bell (1978)
Fell sandstone	0.117	-	79.1	53.5	0.68	Bell (1978)
Fell sandstone	0.205	-	38.1	21.6	0.57	Bell (1978)
Fell sandstone	0.096	-	108.9	98.6	0.91	Bell (1978)
Fell sandstone	0.095	-	88.7	70.2	0.79	Bell (1978)
Fell sandstone	0.104	-	90.2	71.2	0.79	Bell (1978)
Fell sandstone	0.095	-	89.9	63.4	0.71	Bell (1978)
Fell sandstone	0.094	-	51.1	33.5	0.66	Bell (1978)
Fell sandstone	0.099	-	59.0	38.2	0.65	Bell (1978)
Fell sandstone	0.101	-	91.7	62.7	0.68	Bell (1978)
Fell sandstone	0.092	-	92.4	60.9	0.66	Bell (1978)
Fell sandstone	0.072	-	112.4	97.2	0.87	Bell (1978)
Fell sandstone	0.071	-	53.9	29.6	0.55	Bell (1978)
Fell sandstone	0.076	-	75.2	62.0	0.82	Bell (1978)
Fell sandstone	0.096	-	60.2	37.3	0.62	Bell (1978)
Fell sandstone	0.101	-	52.3	30.6	0.59	Bell (1978)
Fell sandstone	0.091	-	77.2	43.1	0.56	Bell (1978)
Fell sandstone	0.078	-	55.7	42.7	0.77	Bell (1978)
Fell sandstone	0.081	-	93.1	43.9	0.47	Bell (1978)
Fell sandstone	0.069	-	107.2	98.4	0.92	Bell (1978)
Fell sandstone	0.065	-	95.8	64.9	0.68	Bell (1978)
Fell sandstone	0.087	-	80.5	50.8	0.63	Bell (1978)
Pennant sandstone ($10^{-2.0} \text{ s}^{-1}$)	0.025	25	257.3	143.5	0.56	H & L (1991)
Pennant sandstone ($10^{-2.0} \text{ s}^{-1}$)	0.025	25	263.7	151.9	0.58	H & L (1991)
Pennant sandstone ($10^{-2.2} \text{ s}^{-1}$)	0.025	25	268.3	141.3	0.53	H & L (1991)
Pennant sandstone ($10^{-2.2} \text{ s}^{-1}$)	0.025	25	259.0	136.2	0.53	H & L (1991)
Pennant sandstone ($10^{-2.4} \text{ s}^{-1}$)	0.025	25	263.1	162.4	0.62	H & L (1991)
Pennant sandstone ($10^{-2.4} \text{ s}^{-1}$)	0.025	25	247.1	151.8	0.62	H & L (1991)
Pennant sandstone ($10^{-2.4} \text{ s}^{-1}$)	0.025	25	272.9	157.3	0.58	H & L (1991)
Pennant sandstone ($10^{-2.6} \text{ s}^{-1}$)	0.025	25	267.7	154.7	0.58	H & L (1991)
Pennant sandstone ($10^{-2.6} \text{ s}^{-1}$)	0.025	25	274.1	161.0	0.59	H & L (1991)
Pennant sandstone ($10^{-2.9} \text{ s}^{-1}$)	0.025	25	275.7	156.4	0.57	H & L (1991)

Pennant sandstone ($10^{-3.3} \text{ s}^{-1}$)	0.025	25	278.5	162.6	0.58	H & L (1991)
Pennant sandstone ($10^{-3.4} \text{ s}^{-1}$)	0.025	25	262.8	154.5	0.59	H & L (1991)
Pennant sandstone ($10^{-3.5} \text{ s}^{-1}$)	0.025	25	253.5	159.1	0.63	H & L (1991)
Pennant sandstone ($10^{-3.6} \text{ s}^{-1}$)	0.025	25	267.9	151.5	0.57	H & L (1991)
Pennant sandstone ($10^{-4.0} \text{ s}^{-1}$)	0.025	25	257.2	148.0	0.58	H & L (1991)
Pennant sandstone ($10^{-4.1} \text{ s}^{-1}$)	0.025	25	258.8	145.4	0.56	H & L (1991)
Pennant sandstone ($10^{-4.5} \text{ s}^{-1}$)	0.025	25	246.5	143.6	0.58	H & L (1991)
Pennant sandstone ($10^{-4.6} \text{ s}^{-1}$)	0.025	25	254.5	144.8	0.57	H & L (1991)
Pennant sandstone ($10^{-4.8} \text{ s}^{-1}$)	0.025	25	265.9	146.9	0.55	H & L (1991)
Pennant sandstone ($10^{-4.8} \text{ s}^{-1}$)	0.025	25	255.3	138.9	0.54	H & L (1991)
Pennant sandstone ($10^{-4.8} \text{ s}^{-1}$)	0.025	25	244.7	138.8	0.57	H & L (1991)
Pennant sandstone ($10^{-5.4} \text{ s}^{-1}$)	0.025	25	250.9	136.1	0.54	H & L (1991)
Pennant sandstone ($10^{-5.5} \text{ s}^{-1}$)	0.025	25	252.5	132.7	0.53	H & L (1991)
Pennant sandstone ($10^{-5.5} \text{ s}^{-1}$)	0.025	25	260.2	133.2	0.51	H & L (1991)
Pennant sandstone ($10^{-6.2} \text{ s}^{-1}$)	0.025	25	240.1	131.3	0.55	H & L (1991)
Pennant sandstone ($10^{-6.8} \text{ s}^{-1}$)	0.025	25	229.3	124.3	0.54	H & L (1991)
Pennant sandstone ($10^{-6.8} \text{ s}^{-1}$)	0.025	25	221.7	118.4	0.53	H & L (1991)
Pennant sandstone ($10^{-7.9} \text{ s}^{-1}$)	0.025	25	222.2	126.5	0.57	H & L (1991)
Applecross	0.054	3.0	141.3	99.3	0.70	H & M (1992)
Donegal Quartzite	0.013	0.0	237.9	184.0	0.77	H & M (1992)
Basal Quartzite	0.006	0.0	247.0	202.1	0.82	H & M (1992)
Brownstones	0.067	3.1	152.0	107.4	0.71	H & M (1992)
Pilton (type A)	0.006	16.0	173.3	152.2	0.88	H & M (1992)
Pilton (type B)	0.006	4.3	227.3	208.4	0.92	H & M (1992)
Upper Cromhall	0.045	0.0	161.4	143.9	0.89	H & M (1992)
Millstone Grit A	0.118	13.9	59.3	39.6	0.67	H & M (1992)
Millstone Grit B	0.116	12.0	49.0	40.2	0.82	H & M (1992)
Millstone Grit C	-	12.7	123.4	72.1	0.58	H & M (1992)
Millstone Grit D	-	9.2	127.5	98.6	0.77	H & M (1992)
Holcomb Brook Grit A	0.1	15.2	119.1	49.0	0.41	H & M (1992)
Holcomb Brook Grit B	0.103	16.7	108.1	48.6	0.45	H & M (1992)
Siliceous Sandstone	0.012	3.0	198.4	182.2	0.92	H & M (1992)
Elland Flags	0.124	12.6	59.9	31.4	0.52	H & M (1992)
Thornhill Rock A	0.12	5.9	89.9	38.4	0.43	H & M (1992)
Thornhill Rock B	0.12	14.4	91.8	46.7	0.51	H & M (1992)
Middle Coal Measures	0.13	9.4	37.1	25.3	0.68	H & M (1992)

Crackington Formation	-	15.3	298.2	232.3	0.78	H & M (1992)
Pennant A	0.073	2.3	114.2	50.0	0.44	H & M (1992)
Pennant B	0.069	7.9	106.2	52.6	0.50	H & M (1992)
Pennant C	0.082	2.0	103.4	47.0	0.46	H & M (1992)
Annan Sandstone	0.135	6.3	66.3	43.6	0.66	H & M (1992)
Penrith A	0.075	1.9	66.0	53.1	0.81	H & M (1992)
Penrith B	0.122	2.2	34.8	29.4	0.85	H & M (1992)
Penrith C	0.054	0.7	82.0	72.8	0.89	H & M (1992)
Penrith D	0.046	0.1	101.2	87.9	0.87	H & M (1992)
Penrith E	0.115	6.2	59.7	40.8	0.68	H & M (1992)
Redcliffe	-	3.2	36.1	22.4	0.62	H & M (1992)
Midford Sands	0.156	1.7	23.2	14.6	0.63	H & M (1992)
Ardingly Sandstone A	0.19	4.9	42.2	36.9	0.87	H & M (1992)
Ardingly Sandstone B	0.173	8.9	53.4	47.6	0.89	H & M (1992)
Ashdown Sandstone	0.201	0.4	30.6	32.3	1.06	H & M (1992)
Greensand A	0.383	50.5	10.5	2.3	0.22	H & M (1992)
Greensand A Dogger	0.173	16.9	74.5	46.7	0.63	H & M (1992)
Chatsworth Grit	0.146	-	39.2	24.3	0.62	Bell (1995)
Sherwood Sandstone	0.257	-	11.6	4.8	0.41	Bell (1995)
Keuper Waterstone	0.101	-	42.0	28.6	0.68	Bell (1995)
Bronllwyn Grit	0.018	-	197.5	190.7	0.97	Bell (1995)
Sneinton Formation sandstone	0.163	11.0	23.7	14.1	0.60	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.178	14.0	26.1	16.2	0.62	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.18	6.0	25.2	16.8	0.67	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.182	7.0	27.6	19.6	0.71	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.167	4.0	26.4	20.1	0.76	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.163	10.0	32.5	17.6	0.54	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.19	5.0	24.4	13.7	0.56	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.186	12.0	28.0	20.5	0.73	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.166	6.0	17.4	10.7	0.62	Bell and Culshaw (1998)
Sneinton Formation sandstone	0.187	6.0	39.8	25.6	0.64	Bell and Culshaw (1998)

Sneinton Formation sandstone	0.181	12.0	30.9	24.9	0.81	Bell and Culshaw (1998)
Penrith sandstone	0.28	5.0	28.4	9.37	0.33	Cuss et al. (2003)
Darley Dale sandstone	0.135	6.0	44.4	37.7	0.85	Cuss et al. (2003)
Tennessee (Crab Orchard) sandstone	0.075	10.0	89.9	69.4	0.77	Cuss et al. (2003)
Tertiary sandstone (Taiwan) (WGS1)	0.174	21.3	34.1	25.4	0.75	Lin et al. (2005)
Tertiary sandstone (Taiwan) (WGS2)	0.167	69.6	47.5	6.7	0.14	Lin et al. (2005)
Tertiary sandstone (Taiwan) (MS1)	0.115	43.1	48.5	28.9	0.60	Lin et al. (2005)
Tertiary sandstone (Taiwan) (MS2)	0.141	21.5	37.1	28.3	0.76	Lin et al. (2005)
Tertiary sandstone (Taiwan) (MS3)	0.131	41.3	82.7	43.3	0.52	Lin et al. (2005)
Tertiary sandstone (Taiwan) (TL1)	0.131	58.1	68.7	23.2	0.34	Lin et al. (2005)
Tertiary sandstone (Taiwan) (TL2)	0.128	42.7	77.5	44.2	0.57	Lin et al. (2005)
Tertiary sandstone (Taiwan) (ST)	0.182	50.6	38.4	7.8	0.20	Lin et al. (2005)
Tertiary sandstone (Taiwan) (NK)	0.148	66.4	86.0	43.2	0.50	Lin et al. (2005)
Tertiary sandstone (Taiwan) (TK)	0.128	67.7	69.0	29.4	0.43	Lin et al. (2005)
Tertiary sandstone (Taiwan) (SFG1)	0.246	30.2	14.5	12.2	0.84	Lin et al. (2005)
Tertiary sandstone (Taiwan) (SFG2)	0.169	48.6	46.4	19.9	0.43	Lin et al. (2005)
Tertiary sandstone (Taiwan) (CL)	0.207	50.4	19.9	3.1	0.16	Lin et al. (2005)
Balatonrendes sandstone (Hungary)	0.042	-	45.7	35.0	0.77	Vásárhelyi and Ván (2006)
Cserkút sandstone (Hungary)	0.018	-	78.6	61.4	0.78	Vásárhelyi and Ván (2006)
Pilisborosjenő sandstone (Hungary)	0.135	-	20.4	17.7	0.87	Vásárhelyi and Ván (2006)
Vác sandstone (Hungary)	0.121	-	33.8	25.2	0.75	Vásárhelyi and Ván (2006)
Bad Bentheim (perp)	0.233	6	50.4	49.4	0.98	Demarco et al. (2007)
Bad Bentheim (para)	0.233	6	50.2	49.5	0.99	Demarco et al. (2007)
Bebertal (perp)	0.09	1	92.8	58.2	0.63	Demarco et al. (2007)
Bebertal (para)	0.09	1	75.8	42.2	0.56	Demarco et al. (2007)
Obernkirchen (perp)	0.264	6	64.4	55.2	0.86	Demarco et al. (2007)
Obernkirchen (para)	0.264	6	55.6	48.0	0.86	Demarco et al. (2007)

Sander (perp)	0.147	5	70.7	37.5	0.53	Demarco et al. (2007)
Sander (para)	0.147	5	64.0	32.7	0.51	Demarco et al. (2007)
Schleeriether (perp)	0.142	2	84.4	43.5	0.52	Demarco et al. (2007)
Schleeriether (para)	0.142	2	69.3	34.3	0.50	Demarco et al. (2007)
Tambach (perp)	0.084	1	204.6	194.6	0.95	Demarco et al. (2007)
Tambach (para)	0.084	1	179.4	140.0	0.78	Demarco et al. (2007)
Weser grau (perp)	0.094	1	164.8	136.5	0.83	Demarco et al. (2007)
Weser grau (para)	0.094	1	153.4	133.2	0.87	Demarco et al. (2007)
Weser rot (perp)	0.063	2	145.5	94.9	0.65	Demarco et al. (2007)
Weser rot (para)	0.063	2	154.0	104.8	0.68	Demarco et al. (2007)
Los Alambres sandstone (Salamanca, Spain)	0.145	-	36.0	19.7	0.55	Nespereira et al. (2010)
Matagrillos sandstone (Salamanca, Spain)	0.119	-	23.0	15.8	0.69	Nespereira et al. (2010)
Arapiles A-1-1 sandstone (Salamanca, Spain)	0.103	-	58.1	42.1	0.72	Nespereira et al. (2010)
Arapiles A-2-1 sandstone (Salamanca, Spain)	0.133	-	177.6	162.9	0.92	Nespereira et al. (2010)
Arapiles A-2-2 sandstone (Salamanca, Spain)	0.088	-	119.4	109.1	0.91	Nespereira et al. (2010)
Cotta-type Elbe sandstone (LG XI)	0.199	2.7	40.5	31.7	0.78	Siedel (2010)
Cotta-type Elbe sandstone (LG 12)	0.239	3.3	29.4	20.6	0.70	Siedel (2010)
Cotta-type Elbe sandstone (LG 14)	0.274	2.1	30.5	20.3	0.67	Siedel (2010)
Cotta-type Elbe sandstone (LG 15)	0.267	2.4	31.6	24.1	0.76	Siedel (2010)
Cotta-type Elbe sandstone (LG 16)	0.22	3.3	33.2	18.7	0.56	Siedel (2010)
Cotta-type Elbe sandstone (LG XVII)	0.21	4.7	39.7	17.7	0.45	Siedel (2010)
Cotta-type Elbe sandstone (Neu 21)	0.22	4.8	21.1	18.9	0.90	Siedel (2010)
Cotta-type Elbe sandstone (Neu 22)	0.23	3.1	19.8	15.8	0.80	Siedel (2010)
Cotta-type Elbe sandstone (Neu Co)	0.192	4.8	45.0	26.5	0.59	Siedel (2010)
Cotta-type Elbe sandstone (UK 12/1)	0.224	2.9	51.8	41.6	0.80	Siedel (2010)

Cotta-type Elbe sandstone (UK 12/2)	0.223	3.4	39.2	28.6	0.73	Siedel (2010)
Cotta-type Elbe sandstone (OK 13/1)	0.229	3.0	43.0	32.9	0.77	Siedel (2010)
Cotta-type Elbe sandstone (Pow 15/1)	0.221	2.4	45.6	43.1	0.95	Siedel (2010)
Cotta-type Elbe sandstone (Hor 16/1)	0.213	2.5	47.8	43.9	0.92	Siedel (2010)
Cotta-type Elbe sandstone (RD A)	0.262	3.1	31.0	25.6	0.83	Siedel (2010)
Cotta-type Elbe sandstone (RD B)	0.234	3.1	46.2	34.8	0.75	Siedel (2010)
Cotta-type Elbe sandstone (RD C)	0.222	2.0	56.9	50.7	0.89	Siedel (2010)
Posta-type Elbe sandstone (ML 1)	0.194	1.8	64.6	65.7	1.02	Siedel (2010)
Posta-type Elbe sandstone (ML 2)	0.217	1.3	51.3	58.2	1.14	Siedel (2010)
Posta-type Elbe sandstone (ML 3)	0.225	1.6	51.4	52.7	1.03	Siedel (2010)
Posta-type Elbe sandstone (Her H)	0.21	0.0	57.6	45.6	0.79	Siedel (2010)
Posta-type Elbe sandstone (Her II)	0.208	1.2	55.1	50.8	0.92	Siedel (2010)
Posta-type Elbe sandstone (Her III)	0.222	1.5	53.2	45.2	0.85	Siedel (2010)
Posta-type Elbe sandstone (Her IV)	0.193	1.1	54.8	43.6	0.80	Siedel (2010)
Posta-type Elbe sandstone (Her V)	0.217	1.5	45.0	47.6	1.06	Siedel (2010)
Posta-type Elbe sandstone (Zei 6/1)	0.22	0.8	58.2	49.2	0.85	Siedel (2010)
Posta-type Elbe sandstone (Zei 6/2)	0.226	0.0	58.8	53.8	0.92	Siedel (2010)
Posta-type Elbe sandstone (Zei 6/3)	0.228	0.9	53.1	45.5	0.86	Siedel (2010)
Posta-type Elbe sandstone (Zei 6/4)	0.228	0.8	53.8	48.4	0.90	Siedel (2010)
Posta-type Elbe sandstone (OV 7/1)	0.234	1.0	43.5	44.0	1.01	Siedel (2010)
Posta-type Elbe sandstone (OV 7/2)	0.186	1.5	75.9	62.7	0.83	Siedel (2010)
Posta-type Elbe sandstone (Mo 8/1)	0.204	0.6	46.1	42.2	0.92	Siedel (2010)
Posta-type Elbe sandstone (Mo 8/2)	0.196	0.9	55.6	53.5	0.96	Siedel (2010)
Posta-type Elbe sandstone (Sch 9/1)	0.242	0.8	37.1	37.9	1.02	Siedel (2010)
Posta-type Elbe sandstone (Sch 9/2)	0.231	1.0	43.8	37.3	0.85	Siedel (2010)
Posta-type Elbe sandstone (OK 13/2)	0.229	1.6	53.2	45.4	0.85	Siedel (2010)

Posta-type Elbe sandstone (WB 14/1)	0.229	0.7	50.3	41.2	0.82	Siedel (2010)
Posta-type Elbe sandstone (WB 14/2)	0.237	1.3	50.5	41.4	0.82	Siedel (2010)
Posta-type Elbe sandstone (Pow 15/2)	0.251	1.2	36.9	22.4	0.61	Siedel (2010)
Posta-type Elbe sandstone (Gri 17/1)	0.214	0.4	57.8	57.6	1.00	Siedel (2010)
Grampians sandstone (10° angle)	0.09	6.2	59.7	50.4	0.84	Wasantha et al. (2014)
Grampians sandstone (20° angle)	0.09	6.2	58.8	47.0	0.80	Wasantha et al. (2014)
Grampians sandstone (35° angle)	0.09	6.2	53.7	46.5	0.87	Wasantha et al. (2014)
Grampians sandstone (55° angle)	0.09	6.2	45.9	39.8	0.87	Wasantha et al. (2014)
Grampians sandstone (83° angle)	0.09	6.2	57.4	49.7	0.87	Wasantha et al. (2014)