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KG²B, a collaborative benchmarking exercise for estimating the permeability of the Grimsel granodiorite-Part 2: modelling, microstructures and complementary data

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1
2 **KG²B, a collaborative benchmarking exercise**
3 **for estimating the permeability of the Grimsel granodiorite:**
4 **modeling, microstructures and complementary data**

5
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7
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13
14 **Key Points:**

- 15 • A benchmarking exercise involving 24 laboratories was organized to estimate the
16 permeability of the Grimsel granodiorite
- 17 • The microstructures of the Grimsel granodiorite were analyzed and quantified using
18 BIB-SEM, micro-CT scanning, MICP and NMR techniques
- 19 • Permeability predictions from different models using microstructure data as input
20 parameters are in good agreement with measurements
21

22 **Abstract**

23 A benchmarking exercise involving 24 laboratories was organized for measuring and
24 modeling the permeability of a single low permeability material, the Grimsel granodiorite. To
25 complement the data set of permeability measurements presented in a companion paper, we
26 focus here on (i) quantitative analysis of microstructures and pore size distribution, (ii)
27 permeability modeling and (iii) complementary measurements of permeability anisotropy and
28 poroelastic parameters. BIB-SEM, micro-CT, MICP and NMR methods were used to
29 characterize the microstructures and provided the input parameters for permeability
30 modeling. Several models were used: (i) basic statistical models, (ii) 3D pore network and
31 effective medium models, (iii) percolation model using MICP data and (iv) free-fluid model
32 using NMR data. The models were generally successful in predicting the actual range of
33 measured permeability. Statistical models overestimate the permeability because they do not
34 adequately account for the heterogeneity of the crack network. Pore network and effective
35 medium models provide additional constraints on crack parameters such as aspect ratio,
36 aperture, density and connectivity. MICP and advanced microscopy techniques are very
37 useful tools providing important input data for permeability estimation. Permeability
38 measured ~orthogonal to foliation is lower than ~parallel to foliation. Combining the
39 experimental and modeling results provides a unique and rich data set.

40

41 **1. Introduction**

42 Following a workshop on «The challenge of studying low permeability materials»
43 that was held at Cergy-Pontoise University in December 2014, a benchmark exercise in
44 which several laboratories estimate the permeability of a single material was proposed to the
45 attendees. The selected material was the Grimsel granodiorite (Switzerland) and the
46 benchmark was named the “KG²B” project, from “K for Grimsel Granodiorite Benchmark”
47 (David et al., 2017). Multiple objectives were defined: (i) to compare the results for a given
48 method, (ii) to compare the results between different methods, (iii) to analyze the accuracy of
49 each method, (iv) to study the influence of experimental conditions (especially the nature of
50 pore fluid), (v) to discuss the relevance of indirect methods and models, and finally (vi) to
51 suggest good practice for low permeability measurements. The permeability measurements
52 are presented in the companion paper. Here we will focus on item (v) and present the results
53 of microstructure analyses and permeability modeling.

54 Fluid flow processes in rocks are controlled by the geometrical properties of pore
55 and/or cracks and the topology of the pore/crack network. Linking permeability to
56 microstructural properties has always been a challenge in rock physics. A first step is to
57 acquire high quality data that allow thorough characterization of the pore space, preferably in
58 3D. As we are dealing with a crystalline rock, the focus is on cracks rather than pores. Cracks
59 in rocks can be approximated as planar features with small width or aperture, randomly
60 oriented or not in a 3D medium. Due to their limited resolution, optical microscopy
61 techniques are not well-suited for the study of cracks. SEM studies have been commonly
62 used to analyze cracks on thin-sections at high magnification. Ion beam milling is
63 recommended to avoid biased interpretation of the microcrack morphology and statistics
64 (Wong, 1982). Crack statistics provided by SEM studies can be from 2D analyses, from
65 which 3D parameters (like crack surface per unit volume) can be inferred using stereology
66 (Fredrich & Wong, 1986). Recent advances in ion polishing now allow improved images of
67 pore structures and crack networks to be obtained using BIB-SEM (Klaver et al., 2015), or
68 even 3D structures from FIB-SEM image stacks (Holzer et al., 2004). Wood’s metal injection

69 into the pore space greatly enhance pore and crack detection and analysis on SEM images
70 (Hu et al., 2012; Klaver et al., 2015). High resolution micro-CT techniques have become
71 widely used to investigate the three-dimensional distribution of minerals and pores (Baker et
72 al., 2012; Godel, 2013). With improvement of technology and analytical tools, sub-micron
73 resolution can now be achieved with micro-CT imaging methods, but sometimes even this is
74 insufficient to identify tiny cracks in crystalline rocks. One major advantage of micro-CT is
75 that the technique is non-destructive and can be applied on centimeter scale plugs. Pore or
76 crack size distributions can be obtained by image analysis on SEM images (2D analysis) or
77 micro-CT reconstructed volumes (3D analysis), and also by conducting mercury injection
78 capillary pressure (MICP) tests on small plugs. MICP is commonly used in petrophysical
79 studies to obtain the throat size distribution and capillary breakthrough pressure by injecting
80 mercury under increasing pressure (Hu et al., 2015). The throat size distribution given by
81 MICP does not actually match the pore size distribution of the rock because of constrictions
82 and ink-bottle effects in the pore space (Abell et al., 1999) but provides a first-order
83 approximation that can be used in models. Other methods that provide insight into the pore
84 size distribution include the gas adsorption (or BET) method (Schull, 1948) and NMR
85 techniques (Josh et al., 2012).

86 Permeability models using microstructural data as input parameters have evolved
87 since the pioneering work of Kozeny in the 1920s (Kozeny, 1927). A main challenge of all
88 permeability models is to identify the characteristic length scale controlling permeability.
89 This general statement rises from the permeability having the unit of squared length, but
90 other factors like pore size variability and connectivity are also very important. Many
91 different approaches have been proposed (Guéguen & Palciauskas, 1994). Originally based
92 on the Kozeny-Carman equation (Kozeny, 1927), the equivalent channel model states that the
93 characteristic length scale is the hydraulic radius, defined as the ratio between the pore
94 volume and the pore surface area (Paterson, 1983; Walsh & Brace, 1984). In the equivalent
95 channel model, permeability depends on bulk properties related to the pore space (volume to
96 surface ratio, porosity, tortuosity - an ill-defined parameter related to the increased path
97 length in a “tortuous” pore space) that, with the exception of tortuosity, are measurable at the
98 sample scale. Statistical and effective medium models take advantage of the statistics of pore
99 or crack geometries. For example, Gueguen & Dienes (1989) proposed a statistical model for
100 crystalline rocks in which permeability depends on the mean crack aperture and radius, with
101 cracks modeled as penny-shaped objects, on the average distance between cracks and on the
102 fraction of connected cracks (which can be estimated from percolation theory). Only
103 ensemble averages are estimated with limited input of the crack network topology. In
104 contrast, network topology is taken into account in percolation and network models. For the
105 percolation model proposed by Katz & Thompson (1986) the characteristic length scale is the
106 so-called critical conductance (linked to a critical crack size), defined as the smallest
107 conductance in the sample-spanning sub-network made of conductances larger than the
108 critical conductance. The critical length scale can be obtained from the breakthrough pressure
109 in MICP experiments using Washburn’s equation (Hu et al., 2015). Percolation models are
110 supposed to work best when the pore size distribution is very wide. In heterogeneous porous
111 media, preferential flow paths (with similar properties as the critical percolation subnetwork)
112 are more likely to occur (David, 1993).

113 Pore network modeling has been widely used for permeability prediction (Bauer et al.,
114 2012; Bernabé et al., 2003). In such models fluid flows in pipes or cracks forming the bonds
115 of a 3D (or 2D) lattice with fixed topology (e.g. a cubic lattice). The geometrical properties of
116 the conducting elements follow the pore/crack size statistics obtained by SEM analysis or

117 MICP (David et al., 1990). The flow equations are solved at each node and permeability is
118 directly derived from Darcy's law, so does not depend on statistical averages (De Boever et
119 al., 2012). Pore network modeling also allows the bond occupancy probability to be varied,
120 so that networks with different average coordination number (or connectivity) can be
121 considered for permeability estimation (David, 1993). Several of the permeability models
122 mentioned above were tested by Casteleyn et al. (2011) on series of oolitic limestones from
123 the Paris basin. Since the pore size distribution of these rocks was not very heterogeneous,
124 hence statistical and network models were successful in matching the measured permeability,
125 while the percolation model underestimated the permeability by about one order of
126 magnitude.

127 One of the objectives of the KG²B benchmark was to conduct permeability modeling.
128 Several models were selected by the participants. To achieve successful modeling, as
129 discussed above, information is required about the rock microstructure (such as porosity,
130 pore/crack aperture and length distribution, and connectivity). We will present the results of a
131 thorough microstructural analysis and from NMR and MICP tests, as well complementary
132 data on anisotropy and poroelastic parameters measured on a voluntary basis by some
133 participants.

134

135 **2. The KG²B Project: Summary**

136 In total 30 laboratories from 8 different countries volunteered to participate in KG²B,
137 and we received results from 24 laboratories that form the "KG²B Team". The complete list
138 of participants who sent results is given in Appendix A. A dedicated website [https://labo.u-
139 cergy.fr/~kgggb/](https://labo.u-cergy.fr/~kgggb/) was created with information on the benchmark, including a web page where
140 the progress of the project could be followed on the "KG²B-wheel", which was updated as
141 soon as results were received from any of the participants. It took one year to collect all of the
142 results. In total we collected 45 permeability values, including 39 measured values and 6
143 results from modeling, on which this paper will focus. Statistical, network, percolation and
144 effective medium models were used. We add a seventh modeling result in which a rock
145 sample is treated as an RC (Resistance + Capacitor) low pass filter during pore pressure
146 oscillation tests.

147 The Grimsel granodiorite was obtained from the Swiss Grimsel test site, a 450 meter
148 deep Underground Research Laboratory (URL). The 950 meter long and 3.5 meter diameter
149 tunnels were excavated in 1983 by a full face Tunnel Boring Machine (TBM) in hard rocks,
150 mainly granite and granodiorite, at an altitude of 1730 m in the Central Aar Massif in
151 Switzerland. The TBM excavation method limited perturbation of the host rock, with a quite
152 small Excavation Damage Zone (EDZ) around the tunnel (Egger, 1989). Along the tunnel,
153 major damage zones are located in meter scale shear zones or widely spaced discontinuities
154 caused by regional deformation. Two cores of Grimsel granodiorite, each about one meter
155 long and of diameter 85 mm, were provided by our Swiss colleagues in September 2015.
156 These cores were retrieved at a distance of 4 to 6 meters from the tunnel of the Grimsel test
157 site, far away from the EDZ influence. The cores were cut into small blocks at lengths
158 requested by each participant (between 2 and 10 cm). A grain shape foliation is visible on the
159 cores at an angle of about 20-30° with respect to the core axis. The foliation is related to
160 compositional banding of alternating dark biotite layers and quartz-rich layers (Schild et al.,
161 2001). Natural and induced cracks have been observed in past studies (e.g. Smith et al.,
162 2001). In particular there is a natural interconnected network of cracks producing about 1%

163 porosity in the granitic matrix. Stress release due to drilling and sample preparation outside
164 the URL seems to be responsible for larger micro-crack apertures than those observed
165 directly in situ (Schild et al., 2001). As some laboratories provided permeability
166 measurements in directions other than that required of the participants (i.e. the core axis
167 direction), we will also discuss the permeability anisotropy.

168 The detailed analysis of the permeability measurements is given in the companion
169 paper. Let us recall the most important results. For the whole data set of 39 measurements,
170 the average permeability was $1.47 \cdot 10^{-18} \text{ m}^2$; however 4 outliers were identified and removed,
171 leading to an average permeability of $1.11 \cdot 10^{-18} \text{ m}^2$ and a standard deviation of $0.57 \cdot 10^{-18} \text{ m}^2$.
172 A striking result was the large difference between measurements using gas or liquid as the
173 pore fluids: the permeability to gas was about twice as large as the permeability to liquid
174 ($k_{\text{gas}}=1.28 \cdot 10^{-18} \text{ m}^2$, $k_{\text{liquid}}=0.65 \cdot 10^{-18} \text{ m}^2$). The model predictions presented in this paper will
175 be compared to those values.

176 We will use the same convention as in the companion paper for presenting the data
177 set. Each lab was assigned a number in increasing order with respect to the distance between
178 their sample and the tunnel. Lab#01 worked on the sample closest to the tunnel, and Lab#24
179 on the farthest sample.

180

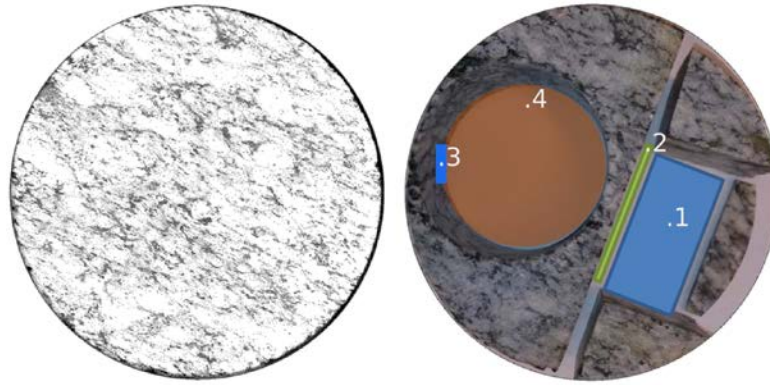
181 **3. Microstructure and porosity analyses**

182 3.1. Quantitative Microstructural Analysis

183 Here we describe efforts to determine the main fluid flow pathways at the centimeter
184 scale, which is the relevant scale for the laboratory experiments. To this purpose, several
185 direct imaging methods were used: automated optical microscopy of thin-sections, and Broad
186 Ion Beam/Scanning Electron Microscopy (BIB-SEM) of intact or Wood's Metal (WM)
187 impregnated samples.

188 *3.1.1 Methods*

189 Two adjacent blue dye impregnated thin-sections of standard size were prepared
190 perpendicular and parallel to the core axis from the original core sample (Figure 1). Thin-
191 sections were automatically scanned with the Virtual Petroscan (ViP) (Schatz et al., 2010)
192 in plane polarized and crossed polarized light (PPL and XPL). Porosity was segmented from
193 the PPL image map (approximately $20,000 * 12,000$ pixels, pixel size of $1.4 \mu\text{m}$ i.e. $2.8 \text{ cm} * 1.68 \text{ cm} \approx 4.7 \text{ cm}^2$) by unsupervised iso-cluster classification and re-grouped into porosity
195 and matrix based on visual inspection followed by a boundary cleaning operation (dilation),
196 all in ArcGIS 10.



197

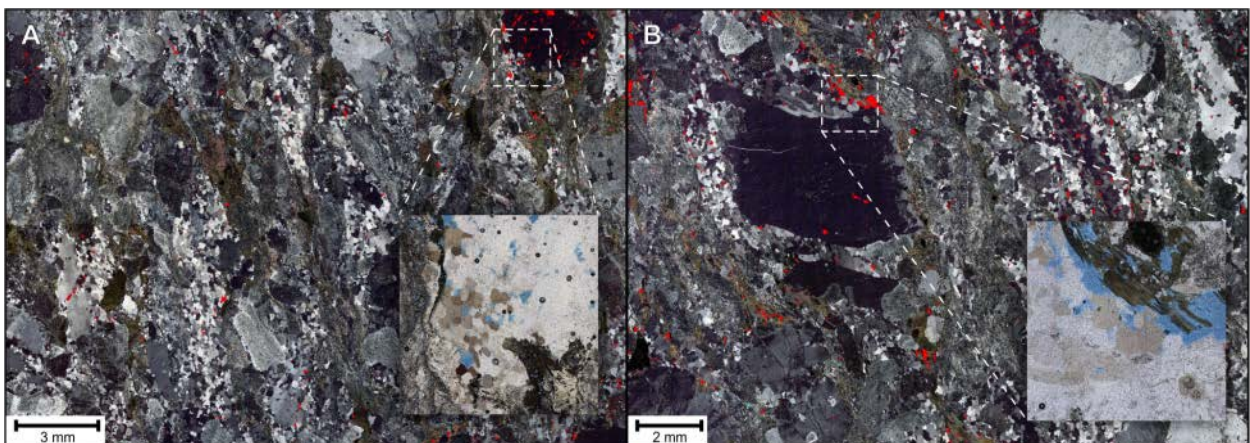
198 **Figure 1.** Grimsel granodiorite core (left) and sampling (right) for thin sections perpendicular (1), and parallel
 199 (2) to the core axis, for BIB-SEM and WM (3), and plug for permeability measurements for Lab#23 (4).

200 From the same core sample, one subsample was prepared by BIB polishing to investigate the
 201 microstructure by SEM. Details on this technique are given by Klaver et al. (2012). Four
 202 areas were mapped at high resolution (10,000 – 20,000 x magnification) for quantitative
 203 analyses of the pore space. Porosity was segmented by a seed-and-grow algorithm (Jiang et
 204 al., 2015) and manually corrected where needed. Pore spaces with circularity below 0.2 and
 205 an axial ratio above 3 were automatically classified as cracks (including grain boundary
 206 cracks). Average crack intensity (expressed in crack number/m) and average crack thickness
 207 were calculated based on each pixel row from every map.

208 Another sub-sample was injected at 500 MPa with Wood’s metal (WM), which is a non-
 209 wetting alloy with wetting properties similar to mercury and which solidifies at room
 210 temperature. This method resembles Mercury Intrusion Porosimetry (Klaver et al., 2015). We
 211 expected insignificant damage to the pores due to the material strength.

212 *3.1.2 Visible porosity and pore size distributions*

213 Over 60,000 pores were segmented from the thin-sections and the largest pores were
 214 approximately 0.3 millimeter in equivalent diameter (Figure 2). The thin-sections show
 215 different visible porosities: 0.71% and 1.55% for the parallel and perpendicular sections,
 216 respectively. This difference most likely occurred because the thin-sections are not wholly
 217 representative at the centimeter scale regarding porosity. Alternatively, this contrast may owe
 218 to highly anisotropic pore shapes with large pore diameters parallel to the section and small
 219 diameters perpendicular to the section.
 220
 221

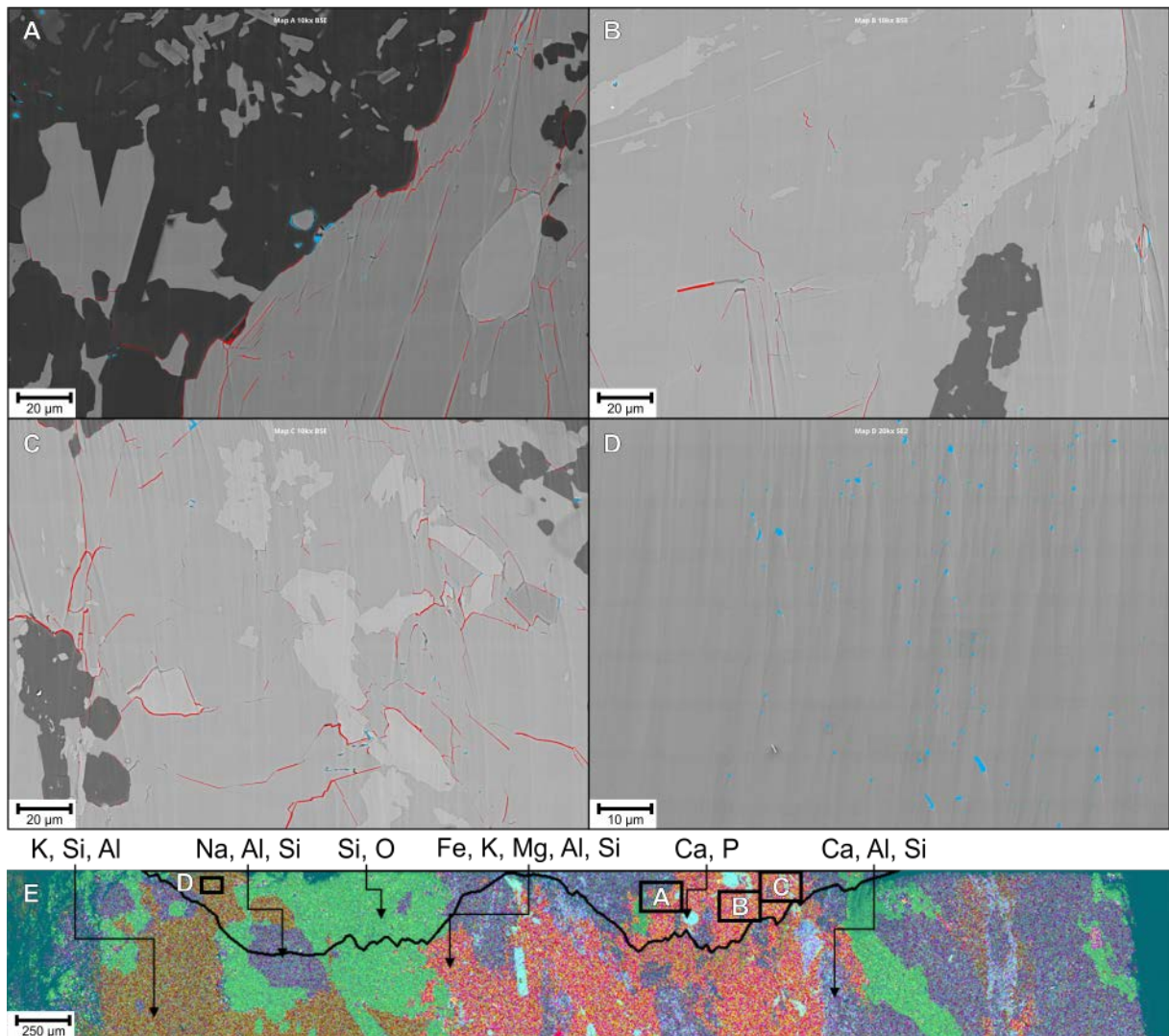


222

223 **Figure 2.** ViP XPL maps overlain by pore segmentation in red of the parallel thin-section (A) and perpendicular
224 thin-section. The insets show the blue dye filled pores in PPL.

225 From SEM, the weighted average porosity in segmented maps perpendicular to the core
226 direction is 0.45% with a porosity of 0.54%, 0.16%, 0.64% and 0.39% in maps A, B, C and
227 D, respectively (Figure 3A-D). However, most of the pore space (average 0.36%) is
228 associated with cracks, indicated in red in the figure. In map D, no cracks were counted, and
229 all pores are interpreted as isolated pores within a single phase consisting mainly of K, Si, Al
230 (Figure 3E) and interpreted as K-feldspar. Other pore space-mineral associations are: 1)
231 cracks at grain boundaries and within biotite (Fe, K, Mg, Al, Si); 2) minor pores and cracks
232 along albite/plagioclase (Na/Ca, Al, Si) grain boundaries; 3) pores and cracks at quartz (Si,
233 O) grain boundaries and fluid inclusions; and, 4) fluid inclusions in apatite (Ca, P).

234

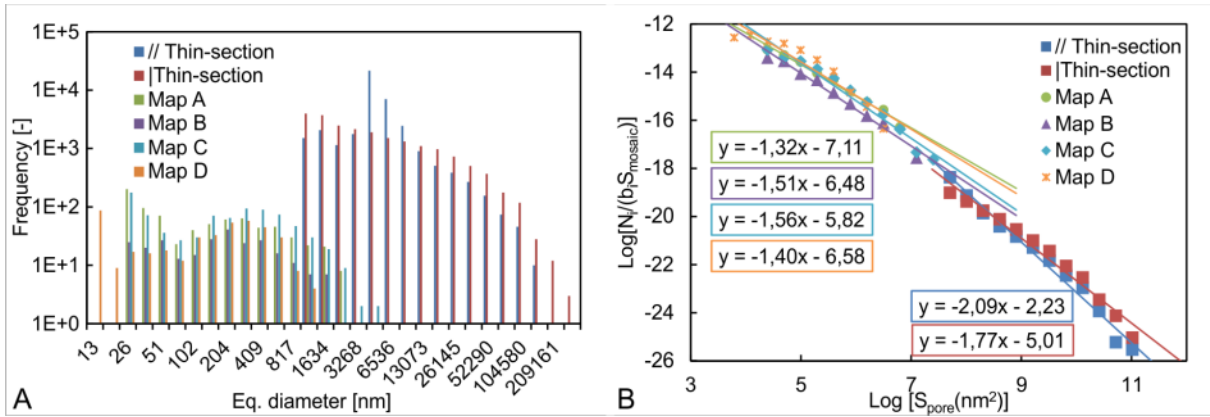


235

236 **Figure 3.** Backscattered Electron (BSE) image maps with pore space segmentation of maps A-D. Interpreted
237 cracks are in red and pores in cyan. The EDS (Energy Dispersive Spectroscopy) overview map shows the
238 locations of the maps with respect to BIB cross-sections and elemental compositions (E).

239 The pore size distributions (PSDs) of the imaged thin-sections show a clear increase in pore
240 frequency with decreasing equivalent diameter to about 6 μm (Figure 4A). The PSDs of the
241 BIB-SEM maps show a clear peak at 200 - 300 nanometer equivalent diameter and another
242 apparent increase below 100 nanometers. These smaller segmentations are below 18 pixels in
243 size. They are interpreted as noise and hence excluded from the analyses in Figure 4B, which

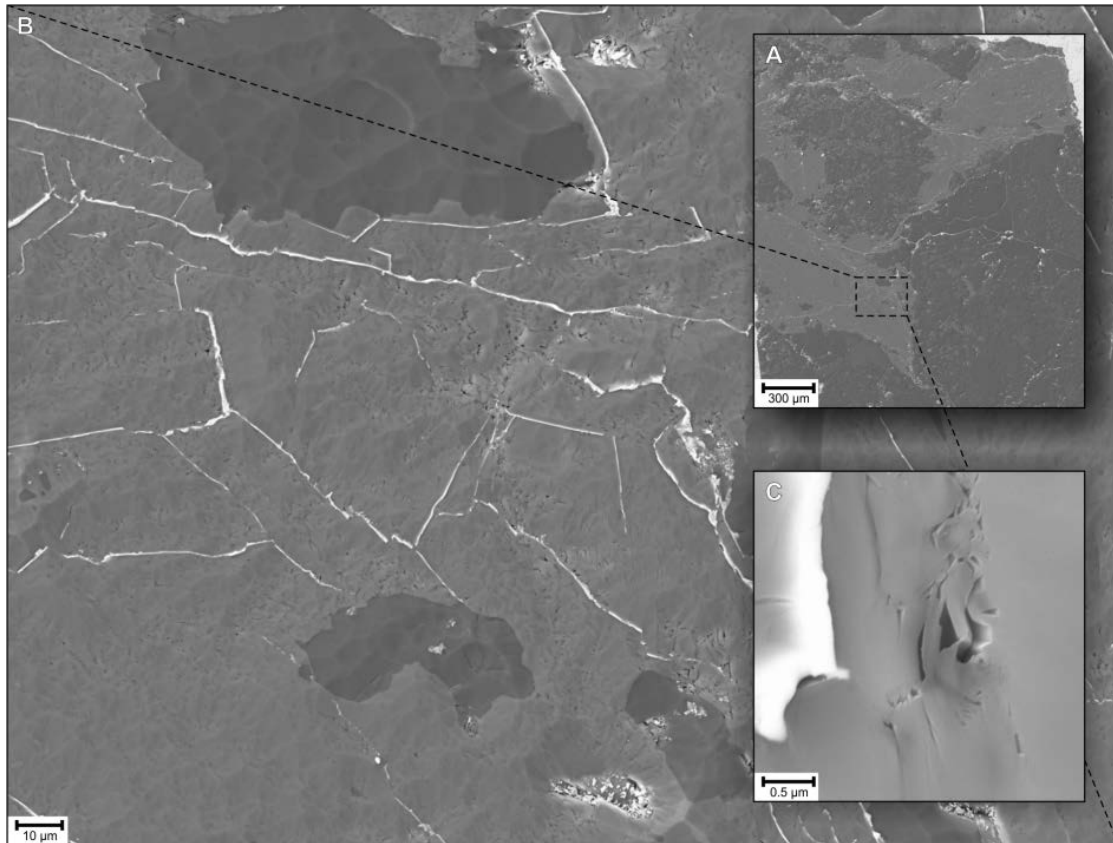
244 shows normalized frequencies (number of pores divided by the imaged area and bin width).
 245 Taking into account both pores and interpreted cracks, only maps B and C show comparable
 246 best fits. The fact that the normalized PSDs do not show uniform best fits indicates that pore
 247 space may have been underestimated due to the large grain sizes and other heterogeneities.
 248 Considering only the interpreted cracks in red (Figure 3A-D), the average crack thickness is
 249 283 nm, within the visible range in Figure 4A. The average crack intensity over maps A-C is
 250 14749 cracks/m.
 251



252 **Figure 4.** A) PSDs of segmented porosity in the thin-sections and BIB-SEM maps. B) Plot showing the PSDs,
 253 normalized over the imaged area for all segmented pores above 18 pixels in size, i.e. 6.5 μm , 144 and 72 nm for
 254 the thin-sections, map A-C and map D respectively.
 255
 256

257 *3.1.3 Pore connectivity*

258 The WM-filled cross-section is shown in Figure 5; the minerals are mostly biotite,
 259 albite, plagioclase and quartz (Figure 5A). Most of the WM is located in the cracks. Most of
 260 the WM-filled cracks seem to be associated with biotite (Figure 5B), and have widths of
 261 approximately 0.2-1 μm (Figure 5C).



262

263 **Figure 5.** (A) Overview BSE image showing the WM intrusion (in white) at the sample scale. (B) Higher
 264 definition image map of the biotite dominated area shows connected crack networks in 2D. (C) WM-filled crack
 265 200 nm in width next to isolated pores.

266

3.1.4 Synthesis of microstructural analysis

267

268 Macroscopic investigation reveals minerals of several centimeters in size, indicating
 269 that microstructural investigations limited to two adjacent thin-sections are most likely not
 270 representative of porosity at the centimeter scale. The variability in porosity at the thin-
 271 section scale is significant (with values of 0.71% and 1.55%). However, the expected order of
 272 magnitude of porosity (about 1%) is attained. A greater number of realizations would be
 273 necessary to achieve representativeness in a statistical sense.

273

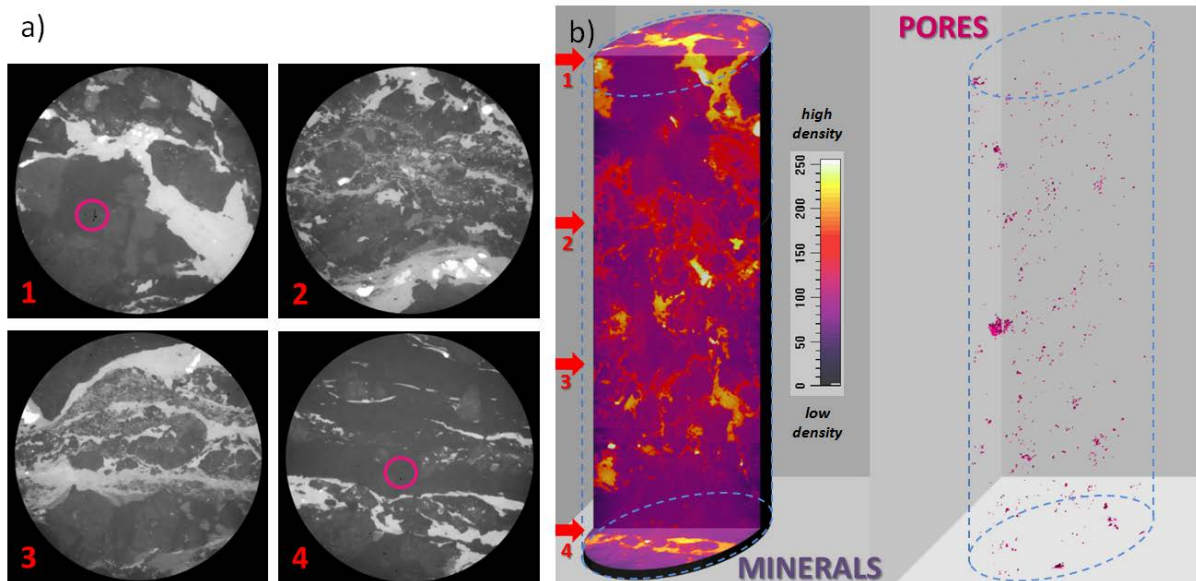
274 In addition ViP- BIB-SEM investigations provided PSDs, enabling comparison with bulk
 275 measurements, and revealed pore-mineral associations which can help with up-scaling
 276 scenarios. Most of the pore space is visible with optical microscopy, indicating that the
 277 relevant pores for storage are in the sub-millimeter to micrometer range. However, the pore
 278 connections are most likely in the submicron range as indicated by the BIB-SEM
 279 investigations, which revealed significant cracks and grain-boundary features in that range.
 280 The WM-BIB-SEM investigations also indicate that crack flow is the most important
 281 transport process. The WM-filled cracks tend to be wider and are connected in 2D, perhaps
 282 opened due to the high pressures (while closing smaller cracks). This hypothesis is the
 283 subject of ongoing research.

283

284 This analysis is complemented by simplified calculations of permeability in Section 4, which
 285 assume that biotite is the main contributor to fluid flow, and that at room conditions the rock
 286 has an average porosity of 0.45%, a crack aperture of 283 nm, and a crack density of 14749
 287 cracks/m. These estimates provide insights into the key factors controlling the transport
 288 properties and flow paths identified by microscopy.

290 3.2. Microstructure study using micro-CT

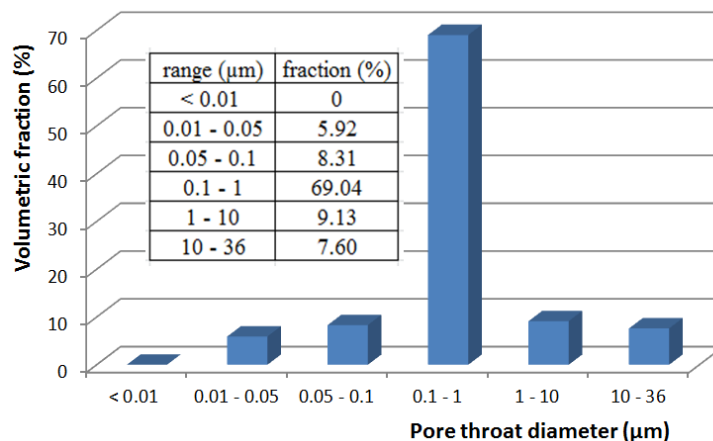
291 A micro-tomography study was conducted at CSIRO Perth on a small sample of
 292 Grimsel granodiorite with 4 mm diameter and 10 mm length. The micro-CT equipment is the
 293 Xradia™ Versa microtomography system (XVRM126). This system is composed of an X-
 294 Ray source, a rotating sample holder and an X-Ray detection system. The source is generated
 295 by the impact of a focused beam on a thin target; the spot size can vary from 1 to 5 μm
 296 depending on the operating conditions. The diverging geometry of the X-Ray results in a
 297 magnification of the object. The X-Ray source used allows application of voltage and power
 298 ranges from 40 to 160 kV and from 4 to 10 W respectively. The X-Ray detector comprises
 299 several lenses mounted on a turret and the detector itself picking up X-Ray images of the
 300 sample. The mounted lens ranges from magnification level 0.4X to 40X covering resolutions
 301 from few tens of μm to 0.7 μm in optimal conditions. The latter resolution can be obtained on
 302 5 mm diameter samples. The images are generated by acquisition of a set of radiographs,
 303 while rotating the sample stepwise through a 360° rotation. For the present study, the voxel
 304 size was 5 μm , enough to identify tiny pores (as shown also in BIB-SEM analysis) but
 305 insufficient to see the cracks, which have thicknesses dominantly in the sub-micron range. In
 306 Figure 6a, four density maps with grey-scale coding are shown on cross-sections at different
 307 heights from top to bottom. The brighter areas correspond to denser minerals. Clearly the
 308 rock appears very heterogeneous from the mineralogical viewpoint. The foliation oriented
 309 from left to right on the images is visible. Magenta circles highlight the presence of tiny,
 310 probably isolated pores, as discussed in the BIB-SEM section. 3D reconstructions of the
 311 sample are shown in Figure 6b. Again heterogeneity is ubiquitous. The reconstructions
 312 confirm that, at this scale, the investigated volume is below the REV (as discussed in the
 313 companion paper). The pore space reconstruction (excluding cracks) shows that the tiny
 314 pores are isolated and should not contribute significantly to macroscopic flow, unless
 315 connected through the crack network. Generally the pores are uniformly distributed in the
 316 rock, although clusters are sometimes observed (Figure 6b). As mentioned in the BIB-SEM
 317 analysis, fluid flow is controlled by a 3D network of cracks that is mostly located at grain
 318 boundaries or within biotite. Indeed such cracks not visible at the micro-CT scale were filled
 319 with Wood's metal (Figure 5) after WM injection.



321 **Figure 6.** Micro-CT scan analysis of a small sample of Grimsel granodiorite (diameter 4mm, length 10 mm). a)
 322 Four sections at different heights from top to bottom; the pink circles highlight some pores (black spots). b)
 323 Left, 3D reconstruction of the matrix density map (8 bits color coding), with red arrows indicating locations of
 324 the four cross-sections; right, 3D map showing isolated or clustered tiny pores. The cracks evidenced by BIB-
 325 SEM analysis could not be resolved by this technique.

326 3.3 Pore Structure Analysis with MICP and NMR

327 Mercury injection capillary pressure (MICP) can be used to measure pore structure
 328 characteristics such as total pore area, bulk density, porosity, pore throat distribution,
 329 permeability and tortuosity (Hu et al., 2015). Liquid mercury, which has a high surface
 330 energy and is non-wetting, is forced into the pore space under increasing capillary pressure.
 331 As mercury pressure increases, smaller pore throats are invaded. Mercury will only invade a
 332 pore throat when a sufficient mercury pressure, inversely proportional to the throat diameter
 333 is applied (Gao & Hu, 2013). This is expressed through the Washburn equation, which
 334 assumes a cylindrical pore shape (Washburn, 1921). For a 1cm long cubic sample a typical
 335 MICP test takes 3-4 hours to complete, with measurable pore-throat size ranging from 3 nm
 336 to 36 μm for low-porosity (<5%) samples. Figure 7 shows the results obtained from MICP on
 337 the Grimsel granodiorite.

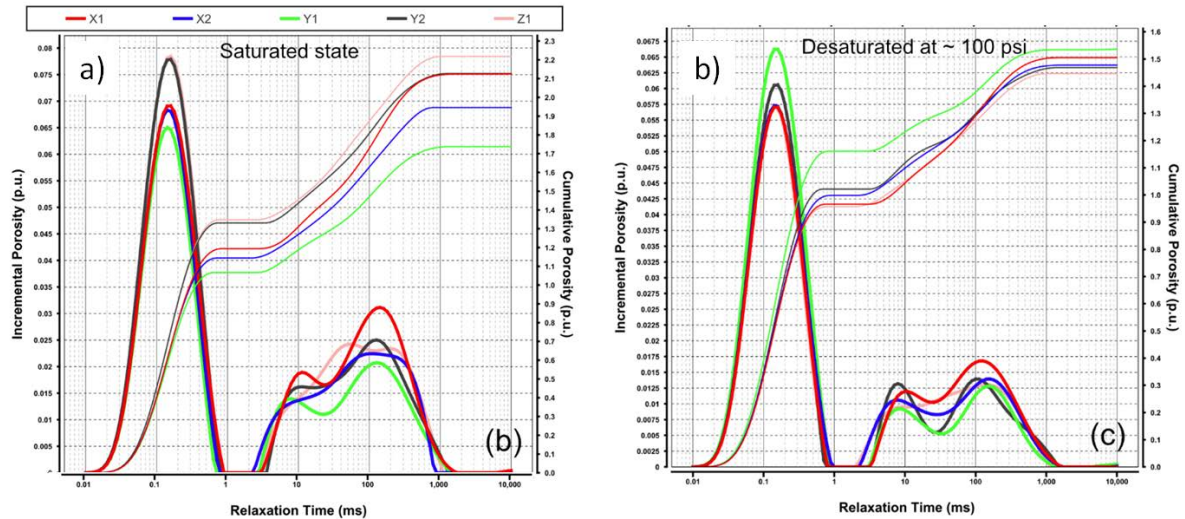


338

339 **Figure 7.** Throat size distribution derived from MICP on the Grimsel granodiorite.

340 The porosity provided by the mercury injection test at the highest capillary pressure is
 341 0.59%, lower but close to the average porosity found by other teams using different
 342 techniques (0.77%). This is probably linked to the smaller size of the MICP plug compared to
 343 the permeability samples. A very strong peak is observed on the histogram, corresponding to
 344 a pore throat radius in the range between 0.1 and 1 μm .

345 In Figure 8 we present the results of NMR spectroscopy conducted on five small
 346 plugs (diameter 25 mm, length 22 mm) saturated with water under vacuum and 13 MPa
 347 hydrostatic pressure, using a 2 MHz GeoSpec2 from Oxford-GIT Ltd. Low-field proton
 348 NMR provides the transverse relaxation time T_2 from which bulk and bound water
 349 distributions can be extracted (Dillinger & Esteban, 2014). For the saturated state (Figure 8a),
 350 the results are very consistent, with one strong peak at $T_2=0.15$ ms and two weakest ones in
 351 the range 10 - 100 ms. Short relaxation times usually correspond to bound water (e.g.
 352 capillary pore sizes and clay bound water) and long relaxation times correspond to free (or
 353 mobile) water; Figure 8 shows that, in the Grimsel granodiorite, most of the water in the pore
 354 space is bound water at 13 MPa hydrostatic pressure.



355

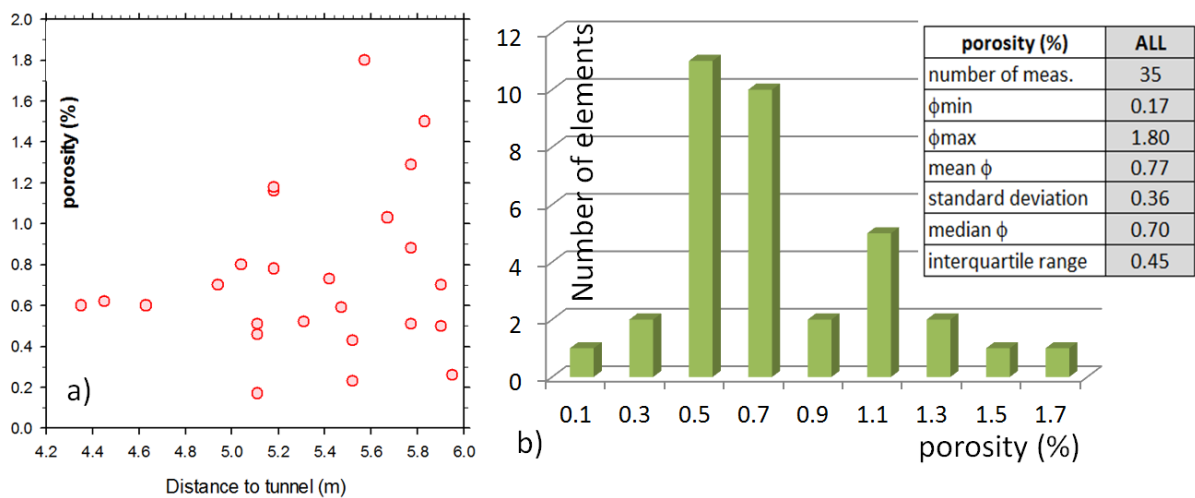
356 **Figure 8:** NMR transverse relaxation time T_2 spectra and associated cumulative porosity in five small core
 357 plugs of Grimsel granodiorite (a) under water saturated conditions, and (b) a desaturated state at ~ 6.9 bars.

358 For these five plugs the NMR porosity ranges from 1.75 to 2.2 % (average 2.03 %) which
 359 agrees with the range found with direct measurements (see next section). The five samples
 360 were also desaturated by centrifuge to achieve an equivalent capillary pressure of ~ 6.9 bars,
 361 and NMR measurements were repeated (Figure 8b). Such experiments allow one to evaluate
 362 the relative amount of mobile water and irreducible water. Note that sample Y1 has a
 363 different behavior than the others.

364

365 3.3. Porosity measured on plugs

366 We collected 35 porosity values using different methods (helium pycnometry, triple
 367 weight method, mercury injection, NMR). As with permeability, no systematic trend was
 368 found when plotting porosity values as a function of the distance to the tunnel (Figure 9a).
 369 However more consistent values seem to occur in the first eighty centimeters. The average
 370 porosity is 0.77% (Figure 9b) with a standard deviation of 0.36%.



371

372 **Figure 9.** a) Porosity vs. distance to the tunnel. b) Statistics of porosity measurements on plugs.

373 These values measured on macroscopic samples are in good agreement with those derived
374 from thin section analyses reported in section 3.

375

376 **4. Permeability Estimation from Models**

377 About 13% of the permeability estimates collected during the benchmarking exercise
378 were obtained from model predictions. Several models have been used and can be classified
379 as statistical, percolation, free-fluid, pore network and effective medium models. In addition,
380 we propose a model based on the analogy with an RC filter circuit to interpret the results
381 from pore pressure oscillation experiments.

382 *4.1 Permeability Estimation from Statistical Models*

383

384 Past research on natural or artificial geo-materials (Scherer et al., 2007; Song et al.,
385 2015) has shown that the order of magnitude of fluid permeability may be assessed with
386 simple statistical models. This requires a number of assumptions, the first being that the fluid
387 does not interact with the solids.

388 The pore network in a crystalline rock can be approximated by a 3D array of
389 orthogonal flat cracks with constant length and aperture $2w$ (w is defined hereafter as the half
390 aperture). The pore space in the Grimsel granodiorite is considered with such model, in which
391 the aperture is replaced by the average crack width obtained from the BIB-SEM analysis. The
392 simplest model derived from Poiseuille's law for flow into straight parallel cracks gives:

393

$$394 k = \phi w^2/3 \quad (1)$$

395

396 In real materials, the pores are non-circular, intersecting and tortuous, so that the equation
397 above is oversimplified (Scherer et al., 2007). The BIB-SEM results in Section 3 yielded an
398 average porosity $\phi=0.45\%$ and average crack aperture $2w=283$ nm or $1 \mu\text{m}$. This provides a
399 permeability prediction of $3 \cdot 10^{-17} \text{ m}^2$ if the main pore width is 283 nm, and $3.7 \cdot 10^{-16} \text{ m}^2$ if the
400 main pore width is $1 \mu\text{m}$. As shown earlier, the order of magnitude of measured permeability
401 for the Grimsel granodiorite is 10^{-18} m^2 . This suggests that the main pore size for transport is
402 sub-micrometric, rather on the order of 283 nm, taking into account that the permeability
403 measurements were done at 5 MPa effective pressure whereas the porosity measurements
404 were done on unstressed rock.

405 Alternatively, permeability can be estimated by a fracture-based relationship for laminar flow
406 (Zimmermann et al., 2005):

$$407 k = 2\lambda_L w^3/3 \quad (2)$$

408 where λ_L is the linear frequency of fractures or cracks. Taking $\lambda_L = 14749 \text{ m}^{-1}$ and again $2w$
409 $= 283$ nm results in a predicted permeability of $2.8 \cdot 10^{-17} \text{ m}^2$. However, considering that most
410 of the cracks relevant for flow are associated with biotite, and assuming a biotite content of
411 40%, the predicted permeability based on crack density is $1.1 \cdot 10^{-17} \text{ m}^2$ (i.e. $11 \cdot 10^{-18} \text{ m}^2$), in
412 agreement with the prediction of the previous model. This value is also larger than the
413 average measured permeability by one order of magnitude, but again corresponds to the
414 unstressed rock.

415 Although this analysis is quite simplistic, it provides useful insights into the location of fluid
416 pathways and relates permeability measurement to microstructure quantification. Further

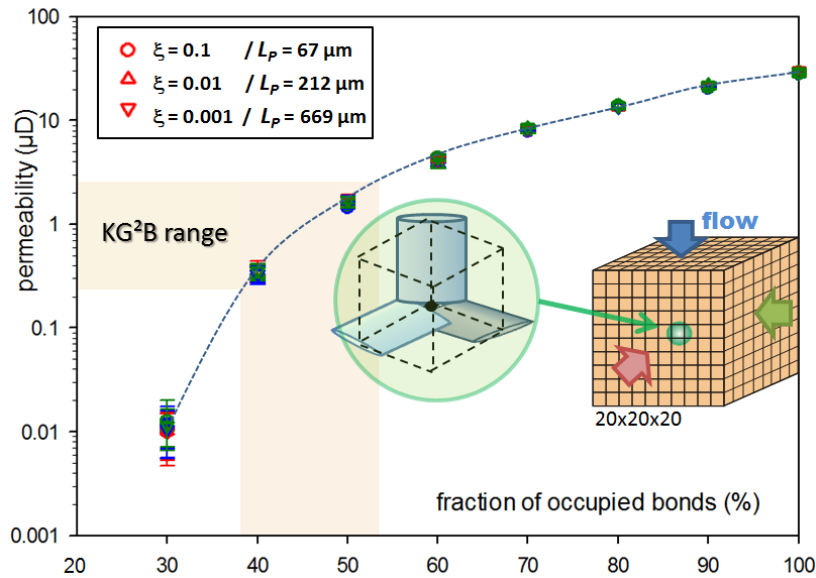
417 analysis could be done by 3D pore quantification and modeling, as done by (Song et al.,
418 2016) for a tight sandstone (with crack-like pores). Such analyses allow us to assess the
419 contributions of different pore (crack) sizes to transport, material anisotropy, and the effect of
420 stress on permeability variations.

421

422 *4.2 Permeability Estimation from Pore Network Modeling*

423 Permeability simulations were conducted using a 3D pore network model (PNM)
424 described in Casteleyn et al. (2011). The input data required for such modeling include (i) an
425 analytical description of the pore (or crack) size distribution, (ii) the average pore (or crack)
426 shape, and (iii) the rock porosity. In the Grimsel granodiorite, fluid flows through a network
427 of cracks with low aspect ratio (Figure 5). In the PNM simulation, fluid flows through a
428 network of pipes with elliptical cross-section. For sake of simplicity all the pipes have the
429 same aspect ratio ξ and constant length L_P (David, 1993). MICP provides an estimate of the
430 crack aperture distribution (equivalent to the throat size diameter in Figure 7) which
431 corresponds to the minor axis $2w$ of the elliptical pipes in the model; the semi-major axis R
432 given by $R=w/\xi$ in the model corresponds to the half-width of the cracks. The local
433 conductance of each bond is given by $\pi w^4/(4L_P\xi(1+\xi^2))$ (David, 1993). The experimental
434 crack aperture distribution (Figure 7) is modelled by a log-normal distribution in the range
435 (0.01 μm , 30 μm) with a peak centered at 0.5 μm . The PNM is a cubic lattice with 20 nodes in
436 each direction (Figure 10); the pipes are located at the branches of the lattice. An algorithm
437 generates as many aperture values as pipes in the network (about 24000), following the log-
438 normal distribution. These aperture values are randomly assigned to the pipes in the network.
439 The constant pipe length is derived from the “network porosity” which must match the rock
440 porosity. For sake of simplicity the network porosity was fixed at 1%, close to the average
441 porosity value measured on plugs. Fluid flow is simulated by imposing a constant pressure
442 gradient across any pair of opposite faces of the network (David et al., 1990) and the
443 permeability is derived from the net flow rate at the outlet face using Darcy’s law. The whole
444 process is repeated 10 times to obtain an average permeability and standard deviation.
445 Several simulations were conducted for three different values of the aspect ratio in the range
446 $\xi=0.001, 0.01$ and 0.1 (Figure 10). The simulations were done for different bond occupancy
447 ratios until permeability fell to zero (the percolation threshold); this can be achieved by
448 randomly removing pipes in the network until a selected value of bond occupancy is
449 achieved.

450 The results of PNM simulations show that (i) permeability decreases when the
451 fraction of pipes in the network decreases, with a sharp fall near the percolation threshold
452 (0.25 for a cubic lattice), (ii) permeability is the same in all three directions within numerical
453 errors, and (iii) permeability is not changed by the pipe aspect ratio. This last result shows
454 that permeability is essentially controlled by the crack aperture distribution which is the same
455 in all simulations. For 100% bond occupancy, the coordination number is equal to 6 and the
456 network permeability is $28 \cdot 10^{-18} \text{ m}^2$. Such a high coordination number (and permeability) is
457 probably much too high for the Grimsel granodiorite.



458

459 **Figure 10.** Results of permeability simulation using a 3D pore network model on a 20x20x20 cubic lattice.
 460 Cracks are represented by pipes with elliptical cross-sections with minor axes derived from MICP data, constant
 461 aspect ratio and constant length. Three aspect ratios were considered: 0.1 (circles), 0.01 (upward triangles) and
 462 0.001 (downward triangles). Colors red, blue and green define the directions in which permeability is calculated.
 463 Error bars correspond to the standard deviation of permeability values for 10 network realizations with the same
 464 statistical properties.

465 The experimental permeability range found in the benchmarking exercise is highlighted in
 466 Figure 10. This range is consistent with a fraction of occupied bonds between 38% and 53%,
 467 thus a mean coordination number probably lower than 3, a reasonable value for a hard rock in
 468 which crack connectivity is expected to be low. The crack network in Figure 5 suggests an
 469 average coordination number close to 3, although it is hard to imagine what the real 3D
 470 coordination number is from 2D images. Given the crack lengths observed in Figure 5 (tens
 471 of micrometers) and the PNM results (Figure 10), our simulations suggest that the crack
 472 aspect ratio should range between 10^{-1} and 10^{-2} . As we tried to match the permeability
 473 measured at 5 MPa effective pressure, the inferred microstructural properties (aspect ratio
 474 and coordination number) correspond to that of the stressed rock.

475

476 *4.3 Permeability Estimation from Effective Medium Modeling*

477 Based on the microstructural data available, the Grimsel granodiorite is modeled as a
 478 homogeneous and isotropic solid, an aggregate of randomly oriented and naturally fused
 479 grains containing randomly oriented and spaced micro-cracks with finite diameter $2R$ and
 480 aperture $2w$. The number of micro-cracks per unit volume is N_V , and their aspect ratio is $\xi =$
 481 w/R . For sake of simplicity, the micro-cracks are modeled as oblate ellipsoids (thin cracks
 482 with $\xi \ll 1$). They can overlap/intersect so as to allow hydraulic connectivity and fluid flow
 483 through the rock at the macroscopic scale. The theoretical porosity of such a medium is given
 484 by Garboczi et al. (1995):

485
$$\phi = 1 - e^{V_C N_V} \quad (3)$$

486 where V_C is the volume of a single ellipsoidal micro-crack,

487
$$V_C = \frac{4}{3}\pi\xi R^3 \quad (4)$$

488 In this context, the crack density $\rho_V = N_V R^3$ is (Sarout, 2012; Walsh, 1965)

489
$$\rho_V = -\frac{3}{4\pi\xi}\log(1 - \phi) \quad (5)$$

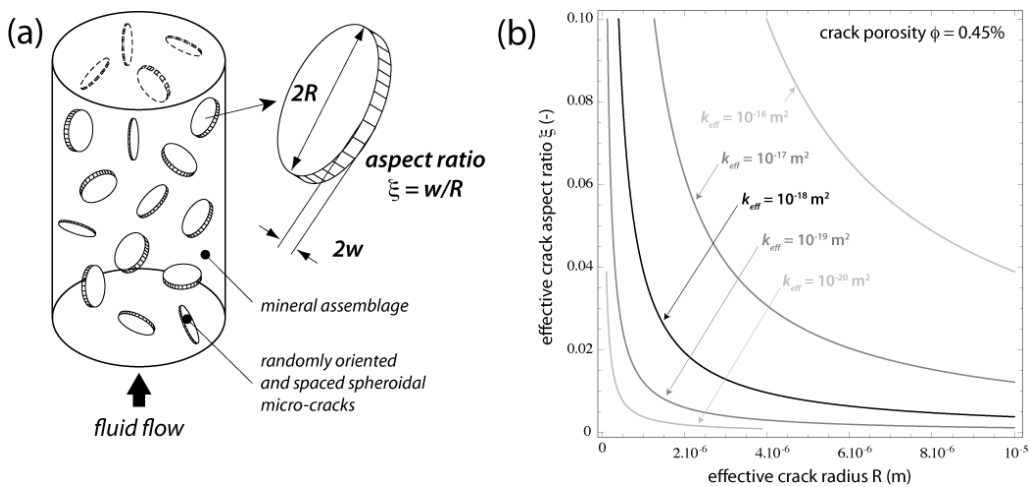
490 Let us assume that the network of micro-cracks in the Grimsel granodiorite is well above the
 491 hydraulic percolation threshold and that this network is the sole source of permeability (no
 492 background porosity). In this case, the permeability of the rock can be modeled using the
 493 concept of hydraulic radius (Gueguen & Dienes, 1989)

494
$$k \sim \alpha \phi m^2 \quad (6)$$

495 where $m = V_C / S_C$ is the hydraulic radius of ellipsoidal micro-cracks defined as their volume-
 496 to-surface ratio; and α is a dimensionless parameter derived from Poiseuille's law, related to
 497 the geometry of the hydraulically conducted network of micro-cracks, of the order of $\alpha \sim 1/3$
 498 for a network of ellipsoidal micro-cracks (Sarout, 2012). The effective permeability of this
 499 cracked medium is explicitly related to its micro-structural parameters by (Sarout, 2012;
 500 Sarout et al., 2017)

501
$$k_{eff}(\phi, \xi, R) = \frac{16}{27} \frac{\phi R^2 \xi^2 (1 - \xi^2)}{2\sqrt{1 - \xi^2} + \xi^2 \log\left(\frac{2 - \xi^2 + 2\sqrt{1 - \xi^2}}{\xi^2}\right)} \quad (7)$$

502 This simple model explicitly relates the effective permeability of the micro-cracked rock to
 503 the crack porosity ϕ , the crack aspect ratio ξ and radius R or, equivalently, to the crack
 504 density ρ_V , ξ , and R (Figure 11). This is because ϕ and ρ are related through equation (5)
 505 once the geometry of the cracks is set in the micro-structural model (oblate ellipsoids with ξ
 506 $\ll 1$).



507

508 **Figure 11.** (a) Microstructural model of the Grimsel granodiorite. (b) Effective permeability predictions as a
 509 function of crack porosity, effective aspect ratio, and crack radius.

510 The experimental and microstructural parameters derived from measurements are the
511 following:

- 512 • Measured average permeability @ $P_{\text{eff}} = 5 \text{ MPa}$: $0.6 \cdot 10^{-18} \text{ m}^2$ (liquid) to $1.3 \cdot 10^{-18} \text{ m}^2$
513 (gas)
- 514 • Permeability extrapolated to $P_{\text{eff}} = 0 \text{ MPa}$ (room conditions): $k_{\text{exp}} = 1 \text{ to } 5 \cdot 10^{-18} \text{ m}^2$
- 515 • Measured porosity @ $P_{\text{eff}} = 0 \text{ MPa}$: $\phi_{\text{exp}} = 0.8\%$ (cracks only)
- 516 • Porosity from microstructure @ $P_{\text{eff}} = 0 \text{ MPa}$: $\phi_{\text{micro}} = 0.45\%$ (cracks only)
- 517 • Crack half-aperture @ $P_{\text{eff}} = 0 \text{ MPa}$: $w_{\text{micro}} = 140 \text{ nm}$
- 518 • Linear crack number density @ $P_{\text{eff}} = 0 \text{ MPa}$: $\lambda_{\text{L-micro}} = 14749 \text{ m}^{-1}$

519 One model parameter can be inferred from these data, the volumetric crack density ρ_V
520 defined in equation (5) which is related to the surface crack number density λ_A through the
521 average of their squared crack radius $\langle R^2 \rangle$ (Hadley, 1976)

$$522 \quad \rho_V = \frac{3}{4\pi} \lambda_A \langle R^2 \rangle \quad (8)$$

523 The linear and surface crack number density are related through (Zimmermann *et al.*, 2005)

$$524 \quad \lambda_A = \frac{\pi \lambda_L}{2 \langle R \rangle} \quad (9)$$

525 Combining equations (8), (9) and (5) yields

$$526 \quad \rho_V = \frac{3}{8} R \lambda_L \text{ and } \phi(\lambda_L, \xi, R) = 1 - e^{-\frac{1}{2}\pi R \xi \lambda_L} = \phi(\lambda_L, w) = 1 - e^{-\frac{1}{2}\pi w \lambda_L} \quad (10)$$

527 so that the permeability in equation (7) can be rewritten as

$$528 \quad k_{\text{eff}}(\lambda_L, \xi, w) = \frac{16}{27} \frac{w^2(1-\xi^2)}{2\sqrt{1-\xi^2} + \xi^2 \log\left(\frac{2-\xi^2+2\sqrt{1-\xi^2}}{\xi^2}\right)} \left(1 - e^{-\frac{1}{2}\pi w \lambda_L}\right) \quad (11)$$

529 The data inversion strategy consists of the following steps:

530 1. Using equation (7), and the measured porosity ϕ_{exp} and permeability k_{exp} , we first
531 define the effective crack radius function $R_{\text{sol}}(\xi)$ satisfying $k_{\text{eff}}(\phi_{\text{exp}}, \xi, R_{\text{sol}}(\xi)) = k_{\text{exp}}$,

$$532 \quad R_{\text{sol}}(\xi) = \frac{3}{4} \left[\frac{3k_{\text{exp}}}{\phi_{\text{exp}} \xi^2 (1-\xi^2)} \left[2\sqrt{1-\xi^2} + \xi^2 \log\left(\frac{2-\xi^2+2\sqrt{1-\xi^2}}{\xi^2}\right) \right]^2 \right]^{1/2} \quad (12)$$

533 2. Noting that by definition $R_{\text{def}}(\xi, w) = w / \xi$, we equate $R_{\text{sol}}(\xi) = R_{\text{def}}(\xi, w_{\text{sol}})$ and
534 determine the effective crack half-aperture w_{sol} so that this equality is satisfied for all aspect
535 ratios ξ .

536 3. Using equation (10), and noting that $\phi(\lambda_{\text{L-sol}}, w_{\text{sol}}) = \phi_{\text{exp}}$, we determine the linear
537 crack number density $\lambda_{\text{L-sol}}$ satisfying this equality.

538 4. Finally, using equation (11), and setting $k_{eff}(\lambda_{L-sol}, w_{sol}/R_{sol}, w_{sol}) = k_{exp}$, we determine
 539 the effective crack radius R_{sol} satisfying this equality.

540 5. Knowing w_{sol} and R_{sol} , we compute the effective aspect ratio of the cracks $\xi_{sol} = w_{sol}$
 541 $/ R_{sol}$.

542 This strategy is implemented considering the permeability values estimated at room
 543 conditions in the range 1 to 5 μD and a porosity of either $\phi = 0.8\%$ (experimentally
 544 measured) or $\phi = 0.45\%$ (determined from 2D microstructure). Table 1 summarizes the
 545 results of the data inversion using these input parameters.

546

run #	ϕ (%)	k (10^{-18} m ²)	w (nm)	λ_L (m ⁻¹)	R (μm)	ξ
1	0.8	1	29	99009	none	none
2	0.8	5	65	44173	none	none
3	0.45	1	39	73622 ($\rho_v \sim 0.032$)	0.92	4.2×10^{-2}
4	0.45	5	87	33003 ($\rho_v \sim 0.025$)	2.6	3.3×10^{-2}

547 **Table 1.** Results of the data inversion from effective medium modeling.

548

549 For the first two scenarios (run #1 and #2) in Table 1 we observe that no value of the
 550 effective crack radius R can satisfy $\phi = 0.8\%$ and $k = 1 \mu\text{D}$, or $\phi = 0.8\%$ and $k = 5 \mu\text{D}$. The
 551 derived aperture w and linear crack number density λ_L do not match the corresponding
 552 parameters estimated from 2D microstructural analysis ($w_{micro} \sim 140 \text{ nm}$ and $\lambda_{L-micro} \sim 14724$
 553 m^{-1}).

554 The two other scenarios (run #3 and #4) yield reasonable results, that is,

- 555 - An effective crack radius exists ($R = 0.92$ to $2.6 \mu\text{m}$) that honors the measured
 556 permeability ($k = k_{exp} = 1$ to $5 \mu\text{D}$) and porosity ($\phi = \phi_{micro} = 0.45\%$)
- 557 - The inverted apertures ($w_{sol} = 39$ to 87 nm) do not match the corresponding parameter
 558 estimated from 2D microstructural analysis ($w_{micro} \sim 140 \text{ nm}$ and $\lambda_{L-micro} \sim 14724 \text{ m}^{-1}$).
 559 However, out of all scenarios, #4 ($\phi = 0.45\%$ and $k = 5 \mu\text{D}$) offers the value of half-
 560 aperture ($w = 87 \text{ nm}$) closest to that determined from 2D microstructural analysis ($w =$
 561 140 nm).
- 562 - The inverted crack number densities ($\lambda_L = 33003$ to 73622 m^{-1}) do not match the
 563 corresponding parameter estimated from 2D microstructural analysis ($\lambda_L \sim 14724 \text{ m}^{-1}$).
 564 However, out of all scenarios, #4 ($\phi = 0.45\%$ and $k = 5 \mu\text{D}$) offers the value of crack
 565 number density ($\lambda_L = 33003 \text{ m}^{-1}$) closest to the value determined from 2D
 566 microstructural analysis ($\lambda_L = 14724 \text{ m}^{-1}$).
- 567 - The inverted crack aspect ratio ($\xi = 3.3$ to 4.2×10^{-2}) reflects a realistic crack geometry
 568 ($\xi \ll 1$).

569 In conclusion, scenario #4 is the most realistic in view of the available experimental and
 570 microstructural data. To generate this scenario, we have used as an input $k = k_{exp} = 5 \text{ mD}$ and

571 $\phi = \phi_{\text{micro}} = 0.45\%$. The model and data inversion strategy outputs are: an effective half-
572 aperture $w \sim 90$ nm, an effective crack radius $R \sim 2.6$ μm , an effective aspect ratio $\xi \sim 3 \times 10^{-2}$
573 and a crack number density $\lambda_L \sim 33003$ m^{-1} (or crack density $\rho_V \sim 0.025$).

574 Although the inverted w , R , ξ , and λ_L are not exactly those determined from the
575 microstructural analysis, they are reasonably close, and most importantly, they yield the
576 expected porosity and permeability. The discrepancies can be explained as follows:

577 - The difference in crack aperture (90 nm versus 140 nm) could be due to (i) the
578 resolution limits of the 2D image; (ii) an undesired inflation of the cracks after
579 Wood's metal injection; and/or (iii) the use of 2D images to determine a 3D
580 parameter.

581 - The difference in crack number density (33003 m^{-1} versus 14724 m^{-1}) could be due to
582 the heterogeneity of the rock and the fact that the images probe only a sub-volume (in
583 fact a 2D surface) of the whole sample on which the porosity/permeability are
584 measured.

585 - The difference between the measured porosity (0.8%), and the porosity determined
586 from 2D microstructures (0.45%) could be due to: (i) the heterogeneity of the rock
587 and the fact that the images probe only a sub-volume (in fact a 2D surface) of the
588 whole sample on which the porosity/permeability are measured, and/or (ii) a
589 resolution limit of the porosity measurement as this type of crack porosity is
590 inherently very small.

591 - The inverted crack radius $R \sim 2.6$ μm does not seem to qualitatively reflect the scale
592 of the cracks highlighted by Wood's metal injection in Figure 5; in the figure, the
593 cracks appear longer than 2.6 μm . However, the effective crack radius is determined
594 from the effective hydraulic permeability of the rock which hosts natural and jagged
595 cracks, perhaps with multiple contact points between asperities (see Sarout et al.
596 (2017)), so that the effective hydraulic radius is smaller than the cracks length
597 visualized in the 2D thin section. Other possible causes of discrepancy listed above
598 could also contribute to the discrepancy in the inverted crack radius. For instance, the
599 injection of Wood's metal could have inflated the crack network so that the cracks
600 appear thicker (larger aperture), and longer (less contacts at asperities).

601

602 4.4 Permeability Estimation from Percolation Model (MICP)

603 MICP results from the Grimsel granodiorite can be used with the Katz and Thompson
604 equation (Katz & Thompson, 1986) as outlined in (Hu et al., 2015). This model is based on
605 percolation theory and states that a critical pore (or crack) size controls permeability. The
606 critical pore size can be determined from the inflection point of the MICP cumulative
607 intrusion curve when mercury starts to percolate into the pore space. According to this model,
608 the permeability k is given by:

$$609 \quad k = \frac{1}{89} (d_{max})^2 \left(\frac{d_{max}}{d_C} \right) \phi S(d_{max}) \quad (13)$$

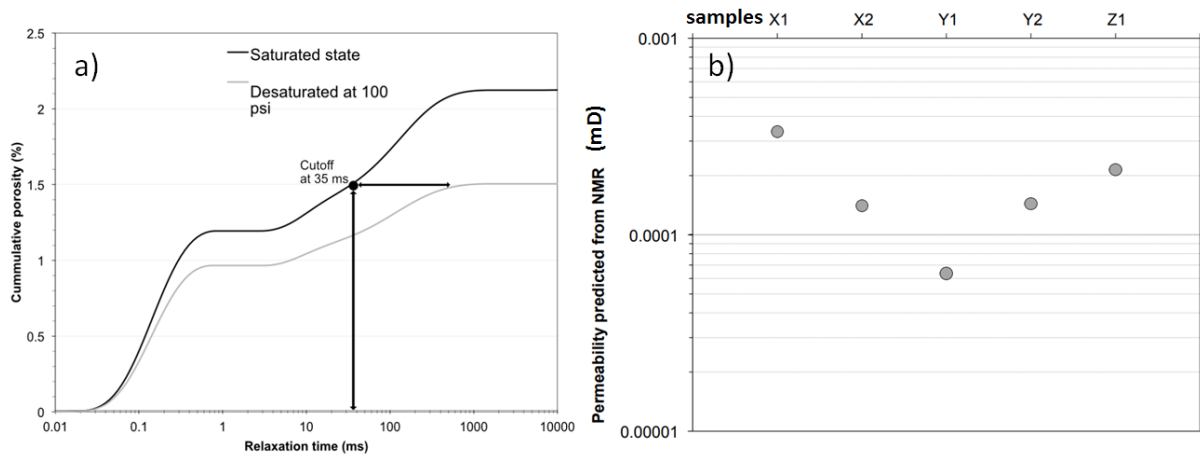
610 where d_{max} is the pore throat diameter at which conductance is maximum, d_C is the critical

611 pore throat diameter at percolation threshold and $S(d_{max})$ is the mercury saturation at a
 612 pressure corresponding to d_{max} (Hu et al., 2015). Using the throat size distribution given in
 613 Figure 7 and the porosity derived from MICP on the same plug, a predicted permeability
 614 value of $1.05 \cdot 10^{-18} \text{ m}^2$ for the unstressed rock is obtained, suggesting that MICP captures the
 615 correct characteristics of the fluid flow pathways at the sample scale.

616

617 4.5 Permeability Estimation from Free-Fluid Model (NMR)

618 NMR analysis is also able to predict the permeability from the T_2 relaxation time
 619 distribution (Josh et al., 2012) shown in Figure 8. In this analysis permeability prediction is
 620 based on the free fluid model by Coates et al. (1991). As the five samples were first measured
 621 saturated then desaturated after centrifuging, one can estimate the Free Fluid Index FFI
 622 (corresponding to the water removed at 6.9 bars equivalent capillary pressure) and the Bound
 623 Volume Index BVI (corresponding to irreducible water). Saturated and desaturated samples
 624 help to define the T_2 cutoff that separate FFI from BVI as shown in the example on sample
 625 X1 (Figure 12a). The five samples record a T_2 cutoff around $30 \pm 10 \text{ ms}$, very close to values
 626 found in the literature for quartz rich rocks (around 33 ms).



627

628 **Figure 12.** a) Example of NMR cumulative porosity of sample X1 under saturated and desaturated conditions to
 629 measure the T_2 cutoff that separates mobile and irreducible water. b) Predicted permeability from NMR in five
 630 small core plugs of Grimsel granodiorite using classical parameters from Coates.

631 As formulated in the Coates model (Coates et al., 1991), the NMR predicted
 632 permeability is given by:

$$633 \quad k = \left(\frac{\phi}{\Gamma}\right)^4 \left(\frac{FFI}{BVI}\right)^2 \quad (14)$$

634 where Γ is a constant related to pore geometry. Using a standard value for Γ according to the
 635 Coates model ($\Gamma=10$ when the permeability unit is mD (10^{-15} m^2) and porosity is in %, the
 636 five tested plugs have a predicted permeability ranging from 0.14 to $0.35 \cdot 10^{-18} \text{ m}^2$ (average
 637 $0.20 \cdot 10^{-18} \text{ m}^2$) except for sample Y1, which has a lower permeability ($0.063 \cdot 10^{-18} \text{ m}^2$)(Figure
 638 12b). These values are lower than the average permeability found in the benchmark (see
 639 companion paper). However they were obtained at 13 MPa confining pressure whereas the
 640 KG^2B effective pressure target was 5 MPa. Taking into account the pressure dependence of
 641 permeability shown in the companion paper, the NMR predicted permeability values are in

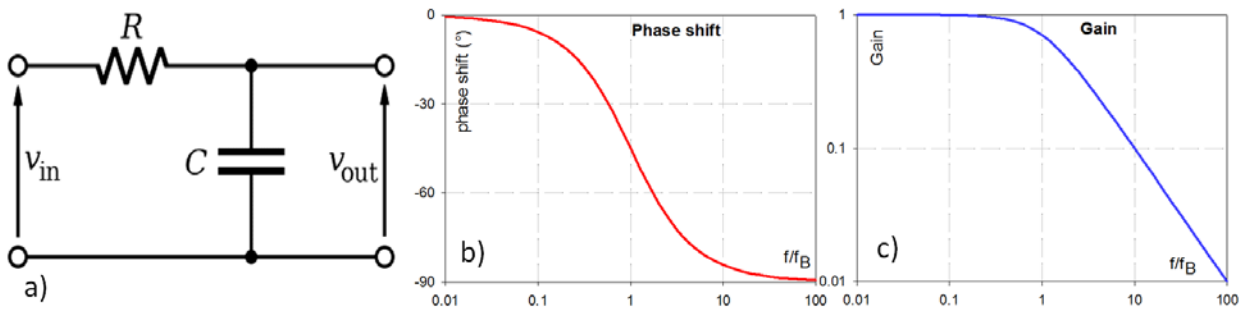
642 good agreement with the measured permeability range.

643

644 4.6 Permeability Estimation from RC Filter Analog

645 Here we report a new way to analyze the data generated by pore fluid pressure
646 oscillation experiments (see companion paper) based on modeling the rock as a RC filter. The
647 approach has been used by Mckernan et al. (2017) and Rutter and Mecklenburgh (2018). In
648 contrast to the four previous models, this model is based on a physical analog rather than
649 microstructural data. Oscillatory flow of fluid through the pores of a rock is analogous to the
650 flow of electricity through a resistor-capacitor network. A first order resistance-capacitance
651 (RC) filter is shown in Figure 13a. This corresponds to a rock sample (the resistive element)
652 of zero storativity (zero porosity), and the downstream reservoir corresponds to the capacitive
653 element. The transfer function or gain $G=V_{out}/V_{in}$ depends on the frequency f because of the
654 time required to charge the capacitor through the resistor. At low frequencies the capacitor is
655 infinitely resistant so a waveform applied as V_{in} passes unimpeded (provided the output does
656 not draw current). Beyond the break frequency f_B the capacitor can conduct so the R and C
657 elements form the arms of a potential divider and the output is progressively attenuated as
658 frequency is increased. This is a low pass filter, because the unattenuated frequencies are low
659 frequencies. The high frequency waveform amplitude attenuation rate (gain) is always 20 dB
660 per decade; it has a slope of -1 on a plot of $\log G$ vs $\log f$. The linear prolongation of the high
661 frequency slope intersects the gain = 1 abscissa at a characteristic break frequency (or corner
662 frequency) $f_B = 1/(2\pi RC)$. The output (across the capacitor) of an RC filter also has a
663 particular response to a step change in input voltage, with v_{out} decaying exponentially with
664 time. This was the basis of the widely-used pulse transient decay method proposed by Brace
665 et al. (1968) for the measurement of permeability of tight rocks.

666



667 **Figure 13.** a) A first order electrical low pass filter analogous to fluid flow through a resistant rock R of zero
668 storage capacity, with a capacitor C analogous to the downstream storage reservoir. Variation of b) phase shift
669 and c) gain A with applied waveform frequency for a low pass electrical filter.

670

671 In addition to progressively attenuating the output waveform, the filter progressively shifts its
672 phase over the frequency range between the two linear segments, from 0° to 90° (Figure 13b).
673 The gain G and phase shift θ can be expressed respectively as:

674

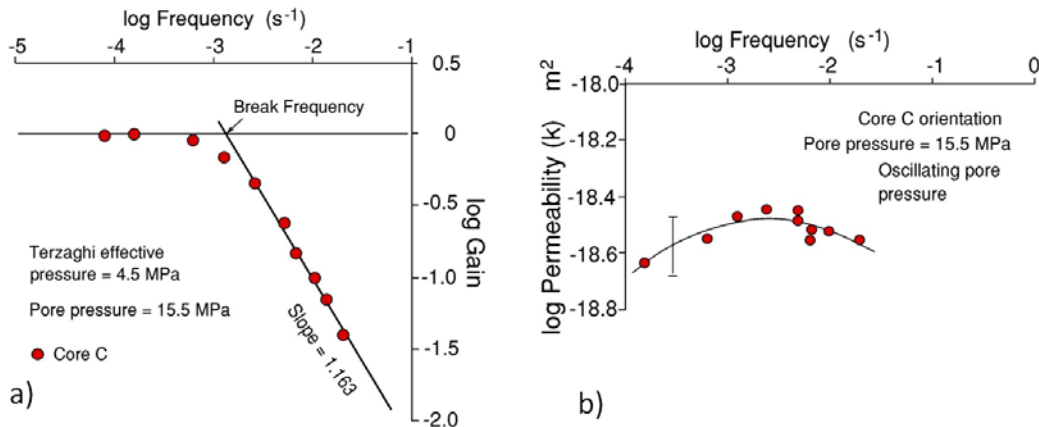
$$675 \quad G = \frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+(f/f_B)^2}} \quad (15)$$

676

$$\theta = -\tan^{-1}\left(\frac{f}{f_B}\right) \quad (16)$$

677 Higher-order low-pass filters can be formed by cascading first order filters to simulate the
 678 behavior of more porous rocks (higher storativity). A rock might be imagined as a series of
 679 such filters, with capacitive components corresponding to pore spaces connected by resistors
 680 that combine to form the total resistance to flow. Each RC element in series can apply an
 681 additional phase shift, but many such phase shifts will result in severe attenuation. Many
 682 possible topologies of R and C combinations can be imagined, with the final capacitor
 683 corresponding to the downstream volume of the permeameter. Analysis of such combinations
 684 is beyond the scope of the present paper. Smaller ratios of rock storativity to downstream
 685 storage translate to smaller phase shifts for a given gain, so that the behavior more closely
 686 resembles that of a first-order filter.

687 This approach was evaluated on a Grimsel granodiorite sample cut at a high angle to the
 688 foliation (called hereafter core C), to investigate how similar its behavior is to that of an RC
 689 filter. Pore fluid pressure oscillation tests were conducted with a pressure cycling period
 690 ranging from 50 to 12800 seconds (i.e. $7.8 \cdot 10^{-5} \text{ s}^{-1} < f < 2 \cdot 10^{-2} \text{ s}^{-1}$). Figure 14a shows a plot of
 691 $\log G$ vs $\log f$ for the driving waveform when total confining pressure is 20.0 MPa and pore
 692 pressure is 15.5 MPa. As expected the behavior is similar to that of an RC filter with $\log f_B =$
 693 -2.869 (i.e. $f_B = 1.35 \cdot 10^{-3} \text{ s}^{-1}$). The slope in the frequency-dependent region is -1.16 , slightly
 694 greater than unity, as might be expected for the small degree of storativity (non-zero porosity)
 695 within the rock specimen.



696

697 **Figure 14.** a) Plot of $\log G$ versus $\log f$ for core C at 4.5 MPa effective pressure and 15.5 MPa pore pressure of
 698 argon gas. This is typical of rock behavior as a first order filter with very small storativity in the rock sample
 699 (slope of -1.16 close to unity). b) Frequency dependence of permeability calculated for the individual data. The
 700 peak in the convex upward curve corresponds to the break frequency. The average of the $\log k$ data lying above
 701 the break frequency is -18.52 .

702 The fluid flow analogs of resistance R and capacitance C are:

703

$$\mathbf{R} = \frac{L\mu}{Ak} \text{ and } \mathbf{C} = \beta_D \quad (17)$$

704 where L and A are the length and cross-sectional area of the sample respectively, and β_D is
 705 the storage of the downstream reservoir (m^3/Pa). Permeability can therefore be calculated
 706 from the break frequency provided that the frequency-dependence of gain is measured at
 707 constant confining pressure and pore pressure conditions:

708

$$k = 2\pi\mu(L/A)\beta_D f_B \quad (17)$$

709 This yields $\log k = -18.33$ (i.e. $k=0.47 \cdot 10^{-18} \text{ m}^2$) for the tested sample. Leaving aside the most
710 extreme values of very small or very large gain, the average of all the individual permeability
711 measurements is $\log k = -18.52 \pm 0.06$ ($k=0.30 \cdot 10^{-18} \text{ m}^2$). The plot of $\log k$ vs $\log f$ (Figure
712 14b) shows slight upward convexity, similar to what was found for a sandstone by Song and
713 Renner, (2007). One of the KG²B labs (Lab#18, see companion paper) measured a
714 permeability of $0.501 \cdot 10^{-18} \text{ m}^2$ on this sample with the standard approach for analyzing pore
715 pressure oscillation tests (Bernabé et al., 2006), and $0.582 \cdot 10^{-18} \text{ m}^2$ using a transient pulse
716 test.

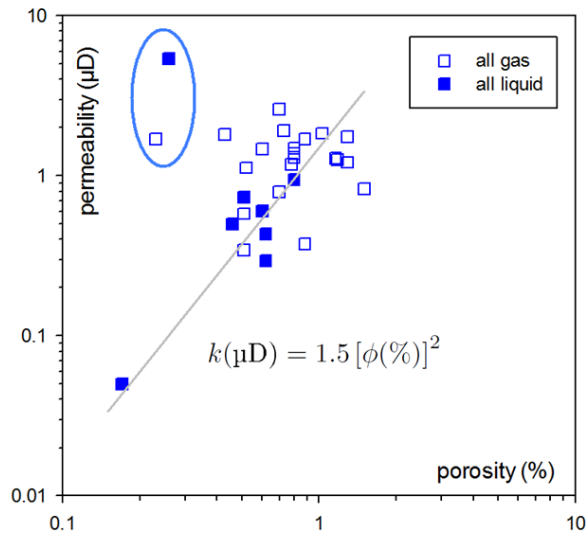
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718 **5. Complementary Outcome of the Benchmarking Exercise**

719 In this section we present additional data produced by the KG²B team in their study of
720 the Grimsel granodiorite core samples. This data set is not as exhaustive as the permeability
721 data set because it was done on a voluntary basis with no specific instructions.

722 5.1. Permeability – Porosity Relationship

723 A log-log plot of permeability vs. porosity (Figure 15) shows a general trend with two
724 outliers and one isolated point aligned with the general cloud consistent with the expected
725 trend of permeability decrease with decreasing porosity. The correlation is not very strong,
726 which is not really surprising as permeability is controlled by the geometrical properties (pore
727 size and shape, topology and connectivity) of the 3D pore or crack network and not simply by
728 the bulk porosity. Nevertheless, a simple power-law can be fitted to the data set (minus two
729 outliers) with an exponent equal to 2 (Figure 15). The sample in the lower left corner was
730 considered as an outlier in the statistical analysis presented in the companion paper: its low
731 permeability can be explained by its porosity being much lower than all the others. A power-
732 law relationship between permeability and porosity has often been invoked (e.g. David et al.,
733 1994 and references therein). Wang et al. (2016) found an exponent between 4 and 5 in their
734 permeability-porosity correlation for two granite gneiss samples. In our KG²B experiments,
735 porosity was measured at room conditions whereas permeability was measured at 5 MPa
736 effective pressure. If both properties were measured under the same pressure conditions, the
737 correlation would probably have been better.



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Figure 15. Correlation between permeability and porosity.

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5.2. Permeability Anisotropy

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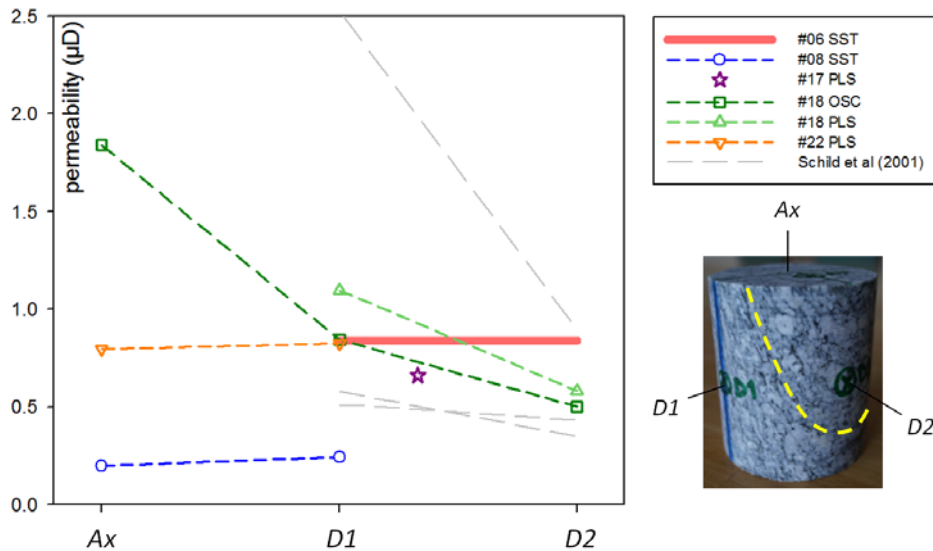
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Three participants (Lab#8, Lab#18 and Lab#22) reported permeability measurements in more than one direction in order to test for permeability anisotropy. These data sets include the one presented in section 4.6. which was obtained by Lab#18 using the oscillating pore pressure method and supplemented with measurements made in two other directions using the transient pulse method. The two other labs used the steady state and the transient pulse methods. All the anisotropy data was obtained using gas as the flowing fluid. The results are compiled in Figure 16, together with those from (Schild et al., 2001). For the KG²B core, an orientation nomenclature was adopted whereby A_x represents the direction parallel to the core axis, $D1$ is the direction perpendicular to A_x and parallel to the foliation; and $D2$ is perpendicular to both A_x and $D1$. Note that $D2$ is nearly perpendicular to the foliation ($\sim 70^\circ$). Schild et al., (2001) investigated permeability parallel and perpendicular to the foliation and for the sake of comparison those directions were associated with directions $D1$ and $D2$, respectively. Overall, anisotropy emerges from the comparison between directions $D1$ and $D2$, where the permeability along the foliation consistently measures higher than the one (quasi-) perpendicular to it (respective anisotropy coefficients of $\sim 50\%$ and $\sim 60\%$ for the OSC and PLS measurements of Lab #18). This result is qualitatively consistent with the data of Schild et al., (2001), albeit over a greater range of anisotropy coefficients. It also compares well with the velocity data of Schild et al., (2001) and the velocity measurements made during our screening of the KG²B plugs ($\sim 30\%$ P-wave anisotropy reported in (David et al., 2017)).



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Figure 16: Permeability measured in direction Ax , along the core axis, $D1$ parallel to the foliation and $D2$ nearly perpendicular to the foliation. The grey lines are data published in Schild et al. (2001).

765 When both $D1$ and $D2$ plugs were tested, the permeability nearly perpendicular to foliation
 766 (along $D2$) was systematically smaller than that in the direction nearly parallel to foliation (along
 767 $D1$ or Ax). Little permeability anisotropy was expected to arise from the measurements made
 768 along Ax and $D1$, as Ax is relatively close to the foliation. This is confirmed by the results of
 769 Lab#08 and Lab#22. The value obtained along Ax by Lab#18 is not consistent with that
 770 picture; it might be attributable to heterogeneity from sample to sample. More specifically,
 771 since permeability is considered as being largely controlled by micro-cracking in the biotite
 772 grain fraction, slight changes in biotite content and grain size from sample to sample could
 773 result in large baseline contrasts. A better assessment could be obtained if the same
 774 representative elementary volume was measured along several directions as opposed to
 775 distinct plugs of various dimensions. Two additional participants (Lab#6, Lab#17) measured
 776 the permeability only in radial directions: both values fall in the range of radial permeability
 777 found by the others. The sample tested by Lab#17 was oriented at about 30° from the
 778 foliation, and the radial permeability measured by Lab#06 is an average one (plotted with an
 779 horizontal line) derived from a radial water flow experiment on a hollow cylinder parallel to
 780 the core axis (Monfared et al., 2011) at 1.75 MPa effective confining pressure, lower than the
 781 KG2B target. Due to the limited number of samples, the anisotropy analysis is far from being
 782 as convincing as the general KG²B data set.

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5.3. Poroelastic Parameters

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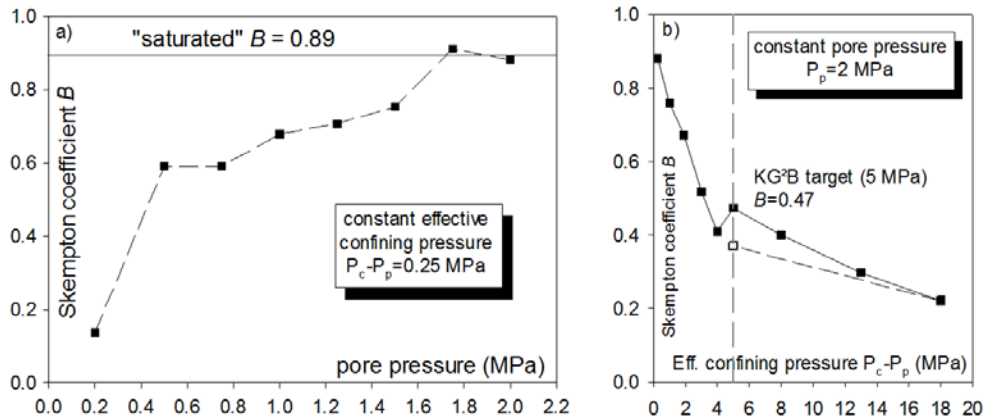
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In situ rock masses include pore, crack, fracture networks which are usually saturated or partially saturated with fluids, often with 2 or more fluid phases such as gas, water, or oil. The degree of saturation, ranging between 0 and 1, is the ratio of volume of pore fluid in the pore space to the pore volume. Controlling saturation during laboratory tests is important for two main reasons: i) to reproduce field conditions; ii) for intrinsic permeability estimates. For the latter purpose, full saturation of specimens with fluid used for measurement is essential (Zinszner & Pellerin, 2007). For measurements using gas, particular attention has to be paid to sample preparation and drying. For permeability measurement using liquids, key issues include expelling trapped gas and checking for full saturation with liquid phase. For measurement with water, flushing of de-aired water into the specimen, followed by a step by step back pressure increase, have been recommended in order to avoid additional gas entry

795 and to force trapped gas into solution (Black and Lee, 1973). This method was successfully
 796 applied to a tight porous rock, the Opalinus clay (Wild et al., 2015) and also in the present
 797 study by Lab#04 on a Grimsel granodiorite sample. Between each back pressure step, the
 798 poroelastic response to hydrostatic confinement was checked in order to assess the degree of
 799 saturation. The isotropic Skempton's coefficient measurements, defined as $B = \Delta P_p / \Delta P_c$, the
 800 ratio of pore pressure change to confinement pressure change, should reach a plateau when
 801 all trapped gas bubbles are dissolved in the solution. For the Grimsel granodiorite initially
 802 filled with water under vacuum, a plateau is reached when the pore pressure exceeds about
 803 1.8 MPa (Figure 17a), and the "saturated" Skempton's coefficient is $B=0.89$ at 0.25 MPa
 804 effective confining pressure.



805

806 **Figure 17.** a) Evolution of the Skempton's coefficient B vs. pore pressure. b) Evolution of the Skempton's
 807 coefficient B vs. effective confining pressure at constant pore pressure (2 MPa).

808 Once the "saturation" pore pressure was reached, the confining pressure was increased at
 809 constant pore pressure ($P_p = 2$ MPa) to the KG²B pressure target ($P_{eff} = 5$ MPa) and beyond.
 810 The increase of effective confining pressure resulted in a sharp drop of the Skempton's
 811 coefficient (Figure 17b) to 0.47 at the target pressure, and even lower at higher pressures.
 812 This behavior is probably linked to the progressive closure of cracks in the rock sample.

813 Another poroelastic parameter was determined by one of the participants (Lab#19), the Biot-
 814 Gassmann effective pressure coefficient α . This coefficient was obtained from several
 815 permeability measurements under different pressure conditions (both P_p and P_c). The
 816 effective pressure law $P_{eff} = P_c - \alpha P_p$ was established for permeability, and it was shown that
 817 the effective pressure coefficient α was equal to 1 (see companion paper).

818

819 6. Discussion

820 To complement the experimental permeability data set presented in the companion
 821 paper, we present additional data from microstructural analyses using BIB-SEM and micro-
 822 CT, as well as permeability predictions from various models. High quality imaging with BIB-
 823 SEM technology allowed us to identify pores and cracks at the micrometer scale and their
 824 relation with the rock mineralogy. Most of the cracks are located within biotite or at grain
 825 boundaries. The Wood's metal injection technique, combined with SEM, provided detailed
 826 and realistic images of the actual crack network, its connectivity (from which an average
 827 coordination number can be estimated) and tortuosity. A statistical analysis provided relevant

828 data on pore size, crack length and aperture, and porosity obtained from more than 60,000
829 elements; the amount and quality of these data provided valuable information for
830 permeability modeling. Micro-CT imaging provided 3D volume rendering of the matrix
831 density as well as a 3D map of pore locations. Two important conclusions could be drawn: (i)
832 at the sample scale, the material appears to be very heterogeneous, with the size of
833 heterogeneities exceeding the sample size and (ii) the pores resolved by micro-CT are
834 isolated, confirming that fluid flow is controlled by a network of submicron cracks. It seems
835 clear that the size of the samples studied (core sample with 4 mm diameter and 10 mm
836 length) is well below the REV, which may explain the larger scatter in measured permeability
837 values for small samples shown in the companion paper.

838 Table 2 summarizes the results of permeability modeling using microstructural data as
839 input parameters. For each model, a short description is provided, and the input parameters
840 are given.

MODEL	DESCRIPTION	INPUT PARAMETERS	PERMEABILITY PREDICTION
Statistical model	3D array of orthogonal intersecting cracks with same length and aperture	porosity, mean crack aperture	$k_{pred} = 30 \cdot 10^{-18} \text{ m}^2$
Statistical model (Zimmermann et al., 2005)	array of parallel cracks with the same aperture	linear density of cracks, mean crack aperture	$k_{pred} = 28 \cdot 10^{-18} \text{ m}^2$
Percolation model (Katz & Thompson, 1986)	based on the estimation of the critical crack aperture at percolation threshold	MICP intrusion volume vs. pressure graph, pore throat and saturation at threshold pressure, porosity	$k_{pred} = 1.1 \cdot 10^{-18} \text{ m}^2$
Free-fluid model (Coates et al., 1991)	based on NMR relaxation time distribution	NMR T_2 spectrum, porosity, free and bound water fractions	$0.13 \cdot 10^{-18} \text{ m}^2 < k_{pred} < 0.33 \cdot 10^{-18} \text{ m}^2$ (@13 MPa)
Pore network model (David, 1993 Casteleyn et al., 2011)	3D cubic network of pipes with elliptical cross-section and constant length	crack aperture distribution from MICP, crack aspect ratio, porosity, fraction of occupied bonds χ	$(\chi=100\%) \quad k_{pred} = 28 \cdot 10^{-18} \text{ m}^2$ $(\chi=53\%) \quad k_{pred} = 2.5 \cdot 10^{-18} \text{ m}^2$ $(\chi=38\%) \quad k_{pred} = 0.25 \cdot 10^{-18} \text{ m}^2$
Effective medium model (Sarout et al., 2017)	3D random distribution of penny-shaped cracks	crack density, porosity, crack aperture, crack aspect ratio	$k_{pred} = 5 \cdot 10^{-18} \text{ m}^2$

841 **Table 2.** Summary of permeability predictions obtained with 6 different models using input parameters based on
842 microstructural data.

- 843
- 844 • Both statistical models yield a permeability value of about $30 \cdot 10^{-18} \text{ m}^2$, significantly
845 larger than the mean outcome for the measured permeability data set ($\sim 1 \cdot 10^{-18} \text{ m}^2$).
846 These models are based on an oversimplified representation of the pore space where
847 heterogeneity is absent, so that analytical solutions for permeability can be calculated.
848 The predicted values are likely higher because the microstructural data were obtained
849 on stress-free samples, whereas permeability measurements were obtained at 5 MPa
effective confining pressure. However, if one takes into account the pressure

850 dependence of permeability shown in the companion paper, extrapolated permeability
851 at zero effective pressure would give a value in the range 2-10 10^{-18} m², still lower
852 than the permeability predicted by both statistical models. This discrepancy suggests
853 that the heterogeneous nature of the rock pore space is poorly accounted for in
854 statistical models.

855 • In contrast, the percolation model proposed by Katz & Thompson (1986) takes
856 advantage of the full mercury volume vs. pressure curve obtained in MICP
857 experiments. This model postulates the existence of a subnetwork spanning the rock
858 sample, consisting of highly conducting cracks with conductance larger than a critical
859 value. Heterogeneity is taken into account, the model prediction of the model ($\sim 1 \cdot 10^{-18}$
860 m²) is in good agreement with the measured permeability despite the fact that the
861 effective pressures do not match. MICP coupled with percolation modeling provides
862 the correct length scale for permeability estimation.

863 • Generally consistent results were obtained for NMR-predicted permeability using the
864 free fluid model. This model is based on NMR detection of the fraction of bound
865 water in the pore space. Although little information is captured regarding pore space
866 geometry, the model was successful in predicting the correct range of permeability at
867 the NMR operating confining pressure (13 MPa), based on the pressure dependence
868 of permeability presented in the companion paper.

869 • The three-dimensional nature of fluid flow in porous rocks is accounted for in both
870 the pore network model and the effective medium model. The difference between
871 these models is the topology of the crack network: cracks are located at bonds in a
872 cubic lattice for the former, and randomly distributed for the latter. For both models,
873 the number of input parameters is larger: porosity, crack aperture and aspect ratio,
874 length of pipes in the PNM and crack density in the effective medium model. Not all
875 of these parameters are well constrained either by MICP or microstructural data.
876 Therefore reasonable assumptions were made to find the best set of parameters to
877 match permeability measurements at 5 MPa effective pressure. Interestingly, both
878 models converge to a similar value of crack aspect ratio ($\sim 10^{-2}$), an apparently
879 reasonable value based on the micrographs in Figures 3 and 5. Another outcome of
880 the pore network model is that a permeability prediction consistent with the measured
881 value requires a coordination number close to three, again in agreement with the
882 micrographs in Figures 3 and 5. However, the models disagree regarding crack length,
883 of order 100 μ m for the PNM, and 1 μ m for the effective medium model. Whereas the
884 former value corresponds more or less to the actual crack length imaged in Figure 5,
885 the latter does not, and one may conclude that the effective medium model is unable
886 to match all our observations. Nevertheless, as discussed in section 4.3, the
887 discrepancy may be explained by the presence of asperities and the jagged nature of
888 observed cracks; in the effective medium model, an actual crack might be viewed as a
889 combination of smaller cracks relevant for fluid flow.

890

891 **7. Conclusion**

892 In the companion paper the complete data set of low-permeability measurements from
893 a benchmarking exercise involving 24 laboratories was analyzed; here we present
894 complementary results focusing on (i) quantitative analysis of microstructures and pore size

895 distributions, (ii) permeability modeling and (iii) measurements of permeability anisotropy
896 and poroelastic parameters. BIB-SEM, micro-CT, MICP and NMR methods were used to
897 characterize microstructures (both in 2D and 3D) and quantify pore size distribution. Wood's
898 metal injection was used to image the crack networks on 2D images. All of these studies
899 provided input parameters for permeability modeling using (i) basic statistical models, (ii) 3D
900 pore network and effective medium models, (iii) a percolation model using MICP data and
901 (iv) a free-fluid model using NMR data. A new method for simpler analysis of pore pressure
902 oscillation tests, modeling the rock as an RC electrical circuit, was also described for the case
903 of small sample storativity. The models were generally successful in predicting the observed
904 range of measured permeability using microstructural, MICP and/or NMR data. Whereas
905 statistical models overestimate the permeability due to lack of information on heterogeneity,
906 percolation, pore network and effective medium models are more relevant and provide
907 additional constraints on crack parameters such as aspect ratio, aperture, density and
908 connectivity. This confirms that MICP and advanced microscopy techniques are potentially
909 able to provide useful input data for permeability estimation. Additional results to
910 complement the measured permeability data set show that (i) the average porosity measured
911 on plugs is 0.77% +/-0.36%, (ii) a weak power-law with exponent 2 relates permeability to
912 porosity, (iii) permeability measured ~orthogonal to foliation is lower than ~parallel to
913 foliation, and (iv) the Skempton's coefficient at 5 MPa effective pressure is about 0.5. A
914 second round of benchmarking is currently under way, with another tight material, the
915 Cobourg Limestone. Additional challenges are expected in this benchmark, project called
916 KCL as the permeability is in the nano-Darcy range (10^{-21} m²).

917

918 **List of symbols**

919 P_c , confining pressure (Pa)
920 P_p , pore pressure (Pa)
921 $P_{eff} = P_c - P_p$, effective pressure (Pa)
922 α , effective pressure coefficient
923 B , Skempton's coefficient
924 k , permeability (m²)
925 k_{exp} , experimental value of permeability (m²)
926 k_{pred} , predicted value of permeability (m²)
927 k_{gas} , permeability measured with gas (m²)
928 k_{liquid} , permeability measured with liquid (m²)
929 k_{eff} , predicted permeability given by the effective medium model (m²)
930 T_2 , NMR transverse relaxation time (s)
931 ϕ , porosity
932 ϕ_{micro} , porosity obtained from BIB-SEM analysis
933 w , average crack half aperture (m)
934 w_{sol} , effective crack half-aperture, solution of the effective medium model (m)
935 λ_L , linear crack density (m⁻¹)
936 λ_A , surface crack density (m⁻²)
937 L_p , length of the pipes in the pore network model (m)
938 χ , fraction of occupied bonds in the pore network model
939 R , average crack radius (m)
940 R_{sol} , effective crack radius, solution of the effective medium model (m)
941 ξ , crack aspect ratio (=w/R)

942 ξ_{sol} , effective crack aspect ratio, solution of the effective medium model
 943 N_V , number of cracks per unit volume (m^{-3})
 944 V_C , volume of a single spheroidal crack (m^3)
 945 $\rho_V = N_V \cdot R^3$, crack density for effective medium model
 946 m , hydraulic radius (m)
 947 α , dimensionless parameter for Poiseuille's law (=1/3 for cracks)
 948 *FFI*, free fluid index
 949 *BVI*, bound volume index
 950 Γ , constant linked to pore geometry in the free-fluid model
 951 R , equivalent resistance in RC circuit
 952 C , equivalent capacitor in RC circuit
 953 $G = V_{out}/V_{in}$, gain
 954 θ , phase shift (rad)
 955 f , frequency (s^{-1})
 956 f_B , break frequency (s^{-1})
 957 L , sample length (m)
 958 A , sample cross-sectional area (m^2)
 959 μ , dynamic viscosity (Pa.s)
 960 β_D , downstream reservoir storage (m^3Pa^{-1})
 961 KG²B, K for Grimsel granodiorite benchmark
 962 BIB-SEM, broad ion beam – scanning electron microscopy
 963 ViP, Virtual Petroscan
 964 PPL/XPL, in-plane / crossed polarized light
 965 EDS, energy dispersive spectroscopy
 966 PSD, pore size distribution
 967 NMR, nuclear magnetic resonance
 968 PNM, pore network modeling
 969 WM, Wood's metal
 970 MICP, mercury injection capillary pressure
 971 REV, representative elementary volume
 972 CT, computerized tomography

973

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 979 Permeable Media”. We thank Yves Bernabé and Steve Ingebritsen for their thorough early
 980 review of both companion papers. All the data presented in this paper can be made available
 981 upon request.

982

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APPENDIX A

1148 ⁽³⁾**The KG²B Team:** the benchmark involved 24 rock physics laboratories around the
 1149 world. The name, e-mail addresses and institution of each participant and co-author are given
 1150 in Table A1.
 1151

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