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DB Experiment - Comparative study of methods to estimate hydraulic parameters in the hydraulically undisturbed Opalinus Clay --Manuscript Draft--

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Abstract:	The Deep Borehole (DB) experiment gave the opportunity to acquire hydraulic parameters in a hydraulically undisturbed zone of the Opalinus Clay at the Mont Terri underground laboratory (Switzerland). Three methods were used to estimate hydraulic conductivity and specific storage values of the Opalinus Clay formation and its bounding formations through the 248 m deep borehole BDB-1: application of a Poiseuille-type law involving petrophysical measurements, spectral analysis of pressure time series and in situ hydraulic tests. The hydraulic conductivity range in the OPA given by the first method is $4 \cdot 10^{-14}$ to $7 \cdot 10^{-13} \text{ m} \cdot \text{s}^{-1}$ with low vertical variability whereas in situ hydraulic tests suggest higher values up to $7 \cdot 10^{-12} \text{ m} \cdot \text{s}^{-1}$. Core analysis provides economical estimates of the homogeneous matrix hydraulic properties but do not account for heterogeneities at larger scale such as tectonic conductive features. Specific storage values obtained by spectral analysis are consistent and in the order of 10^{-6} to 10^{-1} , while formulations using phase shift and gain between pore pressure signals were found to be inappropriate to evaluate hydraulic conductivity in the Opalinus Clay. The values obtained are globally in good agreement with the ones obtained previously at the rock laboratory.
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1 **DB Experiment - Comparative study of methods to estimate hydraulic parameters in the**
2 **hydraulically undisturbed Opalinus Clay**

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22 **Running title:** Hydraulic parameters determination in the Opalinus Clay at the Mont Terri

23 rock laboratory

24 **Keywords:** Mont Terri rock laboratory, argillaceous formation, Opalinus Clay, hydraulic well

25 tests, Poiseuille-type law, harmonic tidal analysis

26

27 **Abstract**

28 The Deep Borehole (DB) experiment gave the opportunity to acquire hydraulic parameters in
29 a hydraulically undisturbed zone of the Opalinus Clay at the Mont Terri underground
30 laboratory (Switzerland). Three methods were used to estimate hydraulic conductivity and
31 specific storage values of the Opalinus Clay formation and its bounding formations through
32 the 248 m deep borehole BDB-1: application of a Poiseuille-type law involving petrophysical
33 measurements, spectral analysis of pressure time series and in situ hydraulic tests. The
34 hydraulic conductivity range in the OPA given by the first method is $4 \cdot 10^{-14}$ to $7 \cdot 10^{-13}$ $\text{m} \cdot \text{s}^{-1}$
35 with low vertical variability whereas in situ hydraulic tests suggest higher values up to $7 \cdot 10^{-12}$
36 $\text{m} \cdot \text{s}^{-1}$. Core analysis provides economical estimates of the homogeneous matrix hydraulic
37 properties but do not account for heterogeneities at larger scale such as tectonic conductive
38 features. Specific storage values obtained by spectral analysis are consistent and in the order
39 of 10^{-6} m^{-1} , while formulations using phase shift and gain between pore pressure signals were
40 found to be inappropriate to evaluate hydraulic conductivity in the Opalinus Clay. The values
41 obtained are globally in good agreement with the ones obtained previously at the rock
42 laboratory.

43 **1 Introduction**

44 Based on favourable confining properties, such as low permeability, strong retention and self-
45 sealing capacities, clay formations are the preferred host rock option for a deep geological
46 repository of long-lived, intermediate and high level radioactive waste in several countries
47 including France, Belgium and Switzerland. In the latter country, the Opalinus Clay (OPA)
48 has been selected as a potential host rock for a disposal facility (Nagra, 2002) and has been
49 studied at the Mont Terri Underground Rock Laboratory since 1996. The laboratory is located
50 at a depth of ca. 280 m, in the security gallery of the A16 Transjurane motorway, which
51 crosses the Jura Mountains in north-western Switzerland.

52 The accurate hydraulic characterisation of low permeability formations is of utmost
53 importance to ensure the safety of a geological repository. Hydraulic properties can be
54 estimated by various laboratory and field experiments (Van der Kamp, 2001; Yu et al., 2013),
55 including empirical methods based on the rock matrix properties (Chapuis and Aubertin,
56 2003), falling head or constant head permeameter tests in laboratory (Boulin et al., 2012), and
57 in situ field tests that rely on measurement of pore pressure or water level changes due to tidal
58 natural loading (Bredehoeft, 1967; Merritt, 2004; Jiang et al., 2013) or artificial application of
59 an hydraulic pressure different from the static formation pressure (Neuzil, 1982; Butler, 1998;
60 Mejías et al., 2009). As these methods are carried out from sub-millimetre to hectometre
61 investigation scales, scale dependency can affect the results (Keller et al., 1989; Neuzil, 1994).

62 This paper compares three different techniques to estimate hydraulic properties of the
63 Opalinus Clay: application of a Poiseuille-type law involving petrophysical measurements, in
64 situ packer tests and spectral analysis of pore pressure time series.

65 **2 Geological setting**

66 The Opalinus Clay at the Mont Terri site is a moderately overconsolidated claystone
67 Aalenian-Toarcian aged stratigraphically, overlain by 800 m of Middle to Late Jurassic
68 limestones, marls and shales, and underlain by 400 m of Early Jurassic to Triassic marls and
69 limestones, dolomites and anhydrites (Fig. 1). The true lithological thickness of the clayey
70 formation is 130 m and its apparent thickness in the area reaches 160 m due to thrusting and
71 faulting. A period of marine regression occurred between 100 and 25 Ma, leading to a
72 subaerially exposure of the top of the Malm limestone. Starting about 40 Ma, the rifting of the
73 Rhine Graben affected Northern Switzerland, resulting in considerable uplift of the area in the
74 mid-Tertiary and followed by down-warping and burial under late Tertiary sediments. The
75 Opalinus Clay reached a burial depth of 1000 m and 1700 m respectively during these two
76 phases of subsidence. Late Alpine folding during the late Miocene to Pliocene (about 10 to 2
77 Ma) formed the Folded Jura. Erosion exposed the core of the Mont Terri anticline towards 2.5
78 Ma, and allowed fresh water infiltration to the Middle Jurassic limestones. Similarly,
79 infiltration to the Early Jurassic limestones would have started in the Quaternary, around 350
80 thousand years ago (Pearson et al., 2003).

81 Three main facies were identified within the Opalinus Clay (Blaesi et al., 1991): a shaly facies
82 in the lower part of the sequence, a thin carbonate-rich sandy facies in the middle part of the
83 formation, and a sandy facies interstratified with shaly facies in the upper sequence. The shaly
84 facies mineral composition includes 27-78 % of clay minerals (illite, chlorite, kaolinite and
85 illite-smectite mixed layers), 4-29 % of carbonates, 10-32 % of quartz, and accessory
86 feldspars, pyrite and organic matter (Bossart and Thury, 2008).

87 Several minor tectonic faults and a larger fault zone called “Main Fault” can be observed in
88 the Opalinus Clay (Nussbaum et al., 2001). Nagra’s investigations in deep boreholes at
89 Riniken, Weiach, Schafisheim and Benken revealed that the tectonically disturbed zones are

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90 hydraulically similar to the undeformed matrix (Johns et al., 1994; Gautschi, 2001a). Based
91 on permeameter tests and in situ packer tests, hydraulic conductivity values in tectonically
92 disturbed zones are in the range of $2 \cdot 10^{-14}$ to $2 \cdot 10^{-12}$ m s⁻¹, and specific storage ranges from
93 $2 \cdot 10^{-7}$ to $1.7 \cdot 10^{-4}$ m⁻¹ (Marschall et al., 2005).

94 **3 BDB-1 Deep Borehole**

95 The Deep Borehole experiment (DB) aims at evaluating the hydrogeological properties and
96 processes of undisturbed Opalinus Clay at the Mont Terri Underground Rock Laboratory. For
97 the first time in this laboratory, a 247.5 m long 45° downward inclined borehole has been
98 drilled through the Opalinus Clay and the bounding formations. The stratigraphic sequence
99 crossed by the borehole is presented in Figure 2a and is described in detail in Jaeggi et al
(2017, this issue). The borehole was entirely cored for stratigraphic, petrophysic,
100 mineralogical and geochemical studies. The OPA section was drilled with air as drilling fluid.
101 Drilling was immediately followed by the installation of a multipacker system (Fierz and
102 Rösli, 2014) consisting in five double packer measuring intervals and an interval port within
103 the Opalinus Clay, a single packer in the Staffelegg formation at the bottom of the borehole,
104 and a further double packer interval isolating the lowermost zone of the Passwang Formation
105 (Fig. 2b and c). Intervals were equipped with sensors that enable long term monitoring of
106 pressure and temperature (Table 1). Pressure sensors are located at the surface and connected
107 by stainless steel lines to the interval fluids, whereas temperature sensors are located
108 downhole inside the intervals.

110 4 Techniques for hydraulic parameters evaluation

111 4.1 Petrophysical model

112 Assuming a plane-parallel geometry, the intrinsic permeability can be computed across an
113 argillaceous formation using a semi-empirical Poiseuille-type law (Kostek et al. 1992; Pape et
114 al., 1999; Tremosa, 2010):

$$k = \frac{b^2}{3F} \quad (1)$$

115 where k is the intrinsic permeability [m^2], b is the half-pore size [m] and F is the formation
116 factor [-], which accounts for the tortuosity of the porous media and can be determined using
117 the Archie's law (Archie, 1952):

$$F = \omega^{-m} \quad (2)$$

118 where ω is the porosity [-] and m is the cementation factor. The formation factor can also be
119 related to diffusion parameters (Boving and Grathwohl, 2001; Van Loon and Mibus, 2015):

$$F = \frac{D_w}{D_e} \quad (3)$$

120 where D_w is the diffusion coefficient in pure water [$\text{m}^2 \text{s}^{-1}$] and D_e is the effective diffusion
121 coefficient [$\text{m}^2 \text{s}^{-1}$].

122 The half-pore size can be computed from petrophysical parameters according to the following
123 relation based on a mass balance equation (Neuzil, 2000; Altinier, 2006):

$$b = \frac{\omega}{(1 - \omega)\rho_s A_s} \quad (4)$$

124 where b is the half-pore size [m], ω is the porosity [-], ρ_s is the grain density [g m^{-3}] and A_s is
125 the specific surface area [$\text{m}^2 \text{g}^{-1}$].

126 Intrinsic permeability and hydraulic conductivity are linked according to:

$$K = \frac{k\rho_f g}{\mu_f} \quad (5)$$

where K is the hydraulic conductivity [$\text{m}\cdot\text{s}^{-1}$], ρ_f is the fluid density [kg m^{-3}], g is the gravity acceleration [m s^{-2}] and μ_f is the fluid dynamic viscosity [Pa s].

Fluid dynamic viscosity was estimated according to Mercer et al. (1975):

$$\mu_f = (5.38 + 3.8A - 0.26A^2) \cdot 10^{-3} \quad (6)$$

with

$$A = \frac{T - 150}{100} \quad (7)$$

where μ_f is the fluid dynamic viscosity [Pa s] and T is the temperature [$^{\circ}\text{C}$].

The Unesco equation of state (Unesco, 1981) was used to determine the fluid density as a function of salinity, temperature and pressure.

Determination of petrophysical parameters were performed in laboratory on representative element volume samples taken from the central part of BDB-1 drillcores. Porosity and water contents were determined by weighing before and after oven-drying at 105°C until mass stabilisation. Density and degree of saturation were calculated based on Archimede's principle after sample immersion into kerdane following the experimental protocol first proposed by Monnier et al. (1973) and later adapted by Matray et al. (2007) for argillite samples. Grain density was evaluated using a helium pycnometer (Micromeritics® AccuPyc II 1340) on oven-dried samples and also recalculated from results of X-Ray diffraction measurements on bulk samples.

4.2 In situ hydraulic testing experiments

Hydraulic in situ testing in boreholes, also referred as well testing, is the most common method used in groundwater and oil industries to acquire the hydraulic properties of geological formations. Pulse withdrawal tests and constant rate withdrawal tests were

146 conducted in BDB-1 borehole, from March 11th to November 16th 2015. During a withdrawal
147 pulse test, pressure is lowered abruptly by opening and closing the downhole shut-in valve
148 (Bredehoeft and Papadopoulos, 1980; Neuzil, 1982). These tests are preferred as initial phase
149 because they give an immediate measurement of the system compressibility and generally
150 require shorter time frame than pumping tests. Given its quick hydraulic response, performing
151 more pulse tests on interval 1 (Staffelegg Formation, Fig. 2b) was possible, whereas two pulse
152 tests were carried out on each of the other intervals.

153 Constant rate withdrawal test parameters such as flow rate and flow duration must be chosen
154 with caution. In low permeability media, high flow rates can lead to desaturation of the
155 measuring intervals and extreme drops in pressure. Therefore, a flowmeter able to sustain a
156 very low pumping rate of 0.3 g h⁻¹ for several days (Bronkhorst[®] μ -flow L01) was used to test
157 intervals 2 to 7 (Fig. 2b), for which the hydraulic responses to pulse testing were the slowest.
158 Interval 1 was tested with a higher flow rate of 5 ml min⁻¹ using a Bronkhorst[®] Liqui-Flow
159 L10. Experimental setups for both kind of tests and associated hydraulic responses are
160 respectively reported in Figure 3 and 4. Flowmeter failed during the testing of intervals 2 and
161 6 and approximatively two months of pressure recovery were required before performing a
162 second test on these test chambers.

163 Hydraulic test data were analysed using the well-test interpretation program nSIGHTS, which
164 was developed by INTERA for Sandia National Laboratories. The code is based on Barker's
165 equation (1988), which describes flow in an n-dimensional space, and does not restrict to
166 integer dimensions. Uncertainties associated with the fitting parameters are evaluated by
167 performing random perturbation analyses. Plausibility ranges for various parameters were
168 defined prior to the parameter optimisation procedure (Table 2). During the inverse parameter
169 estimation, nSIGHTS provides best-fit results within these pre-defined ranges. Uncertainties

170 associated with the fitting parameters are evaluated by performing random perturbation
171 analyses (not detailed in this paper).

172 4.3 Tidal analysis on pore pressure time series

173 Rotational and gravitational forces exerted by the sun and the moon on the Earth induce
174 latitudinal and longitudinal strains within the solid matrix and cause deformations with two
175 dominant periods: diurnal and semi-diurnal. The tidal gravitational potential can be resolved
176 into a finite set of tidal components described as harmonics, which are sinusoidal functions of
177 given amplitude and frequency (Doodson and Warburg, 1941; Cutillo and Bredehoeft, 2011).
178 Five main components account for about 95% of the tidal potential: the M_2 and N_2
179 semidiurnal lunar tides, the S_2 semidiurnal solar tide, the O_1 diurnal lunar tide, and the K_1
180 diurnal lunar-solar tide.

181 Seasonal or climatic variations, anthropogenic activities and tidal forces induce hydraulic
182 pressure changes in geological formations. The amplitude of the pressure response depends
183 on the poroelastic response of the aquifer matrix. Pressure signal can therefore be analysed to
184 determine hydrogeological properties, such as specific storage, effective porosity and
185 hydraulic conductivity. The models used in this work are based on Terzaghi's (1936) effective
186 stress concept, which assumes a constant total stress distributed between grains and fluid
187 effective stress. Bredehoeft (1967) related tidal strain to specific storage:

$$S_s = \frac{|\Delta\varepsilon|}{|\Delta h|} \quad (8)$$

188 where S_s is the specific storage [m^{-1}], $|\Delta\varepsilon|$ is the amplitude of volumetric strain fluctuation
189 fixed at $2 \cdot 10^{-8}$ for the M_2 tide (Melchior, 1978), and $|\Delta h|$ is the amplitude of relative pressure
190 head fluctuations [m].

191 Jacob's (1940) formula was used to compute the porosity:

$$\omega = \frac{E_W S_s B}{\rho_f g} \quad (9)$$

where ω correspond to the porosity [-], E_W is the stiffness modulus of water, equal to 2.05 GPa, S_s is the specific storage [m^{-1}], B is the barometric efficiency [-], which reflects the elastic response of the system, ρ_f is the fluid density, and g is the gravity acceleration equal to 9.81 $m s^{-2}$.

Hydraulic conductivity was estimated with formulations using the M_2 harmonic amplitude and phase shift (Boldt-Leppin and Hendry, 2003; Timms and Acworth, 2005), measured at two depths, z_1 and z_2 [m] :

$$K_v^{Amp}(f_{M_2}) = S_s(f_{M_2}) \frac{\pi(z_1 - z_2)^2}{(f_{M_2})^{-1}} \left[\ln \left(\frac{A_{z_1}(f_{M_2})}{A_{z_2}(f_{M_2})} \right) \right]^{-2} \quad (10)$$

$$K_v^{\Delta\varphi}(f_{M_2}) = S_s(f_{M_2}) \frac{\pi}{(f_{M_2})^{-1}} \left[\frac{(z_1 - z_2)}{\Delta\varphi(f_{M_2})} \right]^2 \quad (11)$$

where K_v^{Amp} is the ‘‘amplitude effective hydraulic conductivity’’, A_{z_1} and A_{z_2} [kPa], are the M_2 earth tide amplitude associated to the sensors, S_s [m^{-1}] is the arithmetic mean of the effective specific storage coefficients obtained individually for the two sensors, f_{M_2} [s^{-1}] is the frequency of the M_2 earth tide equal to $2.236 \cdot 10^{-5}$ Hz, $K_v^{\Delta\varphi}$ [$m s^{-1}$] is the ‘‘phase effective hydraulic conductivity’’, and $\Delta\varphi$ [rad] is the spectral phase shift between the sensors.

Spectral analysis of BDB-1 borehole pressure dataset was performed using the Multi-Statistical Analysis Tool (MuSTAT), jointly developed by the Institut de Radioprotection et de Sûreté Nucléaire and the Institut National Polytechnique de Toulouse (Fatmi et al., 2008; Ababou et al, 2012; Bailly et al., 2014). Consisting in a Python code associated with toolboxes programmed in Matlab, the package provides automatic features: a) preprocessing of time series, that enables the detection of time gaps and spurious values, as well as data

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210 reconstruction by autoregressive first order process; b) processing of a single time series; c)
211 cross-analysis of two time series.

212 **5 Results at various scales of investigation**

213 5.1 Sub-millimeter to centimeter scale

214 *5.1.1 Petrophysical parameters*

215 The petrophysical parameters necessary for the computation of intrinsic permeability are
216 presented in Figure 5 as a function of distance along BDB-1 borehole.

217 The water accessible porosity is 13.0 % in the Opalinus Clay, with a lower porosity of 12.0 %
218 in the sandy facies compared to the shaly facies, which exhibit a mean porosity of 13.5 %.

219 These values are lower than the mean value of 18 % suggested by previous studies performed
220 at the Mont Terri tunnel level. The Passwang Formation presents slightly lower porosity
221 values ranging between 8.1 % and 14.6 % with a mean value of 12.2 %. The Hauptrogenstein
222 is characterized by the lowest porosity with a mean value of 3.9 %.

223 Grain densities obtained by helium pycnometry have a mean value of 2.74 g cm⁻³ in the
224 Opalinus Clay overlying formations and of 2.72 g cm⁻³ in the argillaceous layer. The lowest
225 grain densities are found in the bituminous Rietheim Member of the Staffelegg Formation
226 (see Fig. 1a), ranging between 2.3 and 2.4 g cm⁻³. These low values are probably linked to the
227 presence of organic matter.

228 The Passwang formation, which directly overlays the Opalinus Clay, does not reveal clear
229 petrophysical discrepancies with the clay formation except for the specific surface area. This
230 parameter has an average value of 13 m² g⁻¹ in the carbonated section of the borehole and
231 shows significant fluctuations linked to the marly composition of the Passwang formation. A
232 higher mean value of 29 m² g⁻¹ characterises the Opalinus Clay.

233 The Opalinus clay is also characterised by a low pore size. Analyses of nitrogen adsorption
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2 234 and desorption isotherms show that 70 % to 93 % of the connected porous network is
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5 235 constituted of mesopores (pore diameter between 2 and 50 nm), with a mean size of 13 nm.
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7 236 Calculation of the half-pore size from petrophysical parameters, following equation (4), gives
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12 238 Ranging between 1.3 and 5.4 (Horseman et al, 1996), the cementation factor was estimated to
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15 239 be close to 2 for compacted and deeply buried sediments (Ullman and Aller, 1982; Tremosa,
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17 240 2010). Van Loon et al (2003b) related the effective diffusion coefficient of tritium measured
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20 241 in the Opalinus Clay to its porosity using a cementation factor of 2.5.
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23 242 *5.1.2 Intrinsic permeability and hydraulic conductivity*

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26 243 The intrinsic permeability profiles (Fig. 6a) show a low vertical variability through the
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28 244 Opalinus Clay, where it ranges between $5.79 \cdot 10^{-21}$ and $6.14 \cdot 10^{-20}$ m² if a cementation factor
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31 245 varying between 2 and 2.5 is taken. For a cementation factor of 2.5, the mean intrinsic
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33 246 permeability is $7.7 \cdot 10^{-21}$ m² for the Opalinus Clay shaly facies and $7.9 \cdot 10^{-21}$ m² for its sandy
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36 247 facies. These values are in good agreement with the range of $1 \cdot 10^{-21}$ and $6 \cdot 10^{-20}$ m² obtained
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38 248 by gas injection experiments performed at the Mont Terri laboratory (Marschall et al., 2005).
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41 249 Based on the same cementation factor, difference can be seen in the carbonate-rich sandy
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43 250 facies, where values are about three times higher than in the shaly and the sandy facies. With
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45 251 a higher exponent $m = 3$, the resulting intrinsic permeability has a mean value of $7.6 \cdot 10^{-21}$ m²
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48 252 and no clear distinction arises between the different facies. The intrinsic permeability values
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51 253 computed in the Passwang formation and the Staffelegg formation are much more
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53 254 heterogeneous and vary between $1.5 \cdot 10^{-21}$ and $5.8 \cdot 10^{-20}$ m².

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56 255 The corresponding hydraulic conductivity profiles are presented (Fig. 6b) and show similar
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58 256 trends compared with the intrinsic permeability profiles. The hydraulic conductivity obtained
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257 for the Opalinus clay ranges between $5.8 \cdot 10^{-14}$ and $5.8 \cdot 10^{-13}$ m s⁻¹ for a cementation factor
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 2 258 varying between 2 and 2.5. For a cementation factor of 2.5, the formation is characterised by a
 3
 4 259 mean hydraulic conductivity of $8.3 \cdot 10^{-14}$ m s⁻¹. No clear discrepancy between the shaly facies
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 7 260 and the sandy facies is revealed, with respective mean values of $7.3 \cdot 10^{-14}$ and $6.9 \cdot 10^{-14}$ m s⁻¹.
 8
 9 261 These values are consistent with the range of $2 \cdot 10^{-14}$ to $1 \cdot 10^{-12}$ m s⁻¹ reported in previous
 10
 11 262 studies (Bossart and Thury, 2008). The Passwang formation and the Staffelegg formation
 12
 13 263 present a various range of hydraulic conductivities between $1.6 \cdot 10^{-14}$ and $6.1 \cdot 10^{-13}$ m s⁻¹.
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17 264 5.2 Decimeter to meter scale: in situ hydraulic tests results

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 20 265 Pore pressure should be fully recovered from artificial disturbance induced by the installation
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 22 266 procedure (e.g. drilling, logging, equipment installation) before starting a hydraulic
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 25 267 test. Steady state was considered to be reached when the tidal components were detected on all
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 27 268 pore pressure time series acquired in BDB-1 borehole, which indicate that the system is fully
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 30 269 pressurised and saturated (see section 5.3.1).
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33 270 The observed compressibility of the test zone (C_{tz}) was deduced from pulse tests and
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 35 271 computed according to:
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$$39 \quad C_{tz} = \frac{1}{V_{tz}} \frac{dV}{dP} \quad (12)$$

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 43 272 where V_{tz} [m³] is the shut-in volume, dV [m³] is the withdrawn volume and dP [Pa] is the pressure
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 45 273 variation. Test zone compressibility in BDB-1 borehole varies $9.1 \cdot 10^{-10}$ Pa⁻¹ and $2.4 \cdot 10^{-9}$ Pa⁻¹ (Fig. 7),
 46
 47 274 approximately up to a factor of 5 larger than water compressibility, which is equal to $4.8 \cdot 10^{-10}$ Pa⁻¹ at
 48
 49
 50 275 10 °C (Kell, 1975). The discrepancy can be attributed to the mechanical compliance of the equipment.
 51
 52 276 Semi-logarithmic plots presented in Figure 8 give a qualitative comparison of the hydraulic behaviours
 53
 54 277 characterising the different tested intervals. Degree of pore pressure dissipation (U) and normalised
 55
 56 278 drawdown pressure (U_{norm}) are respectively defined by the following equations:
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$$U = \frac{U_t - U_0}{U_{min} - U_0} \quad (13)$$

$$U_{norm} = \frac{U_t - U_{min}}{U_0 - U_{min}} \quad (14)$$

where U_t [kPa] is the pore pressure at time t , U_0 [kPa] is the hydrostatic pore pressure in situ and U_{min} [kPa] is the pore pressure reached after pulse application or at the end of the pumping phase.

Discrepancies in the degree of dissipation can be observed between tests performed on a same interval (Fig. 8a). Constant rate withdrawal tests were carried out using the same flow rate of 0.3 g h⁻¹ for different durations. To compare the evolution of pore pressures in the measuring intervals during pumping phase, P_{min} was taken to correspond to the shortest pumping duration in the calculation of U_{norm} . If specific storage is assumed homogeneous through the Opalinus Clay, the order from left to right on Figure 8b gives an indication of decreasing permeability.

The application of a composite model, which takes into account a damaged skin zone, was required for most of the test numerical interpretations. Taking as an example the first pulse test carried out on BDB-1 Interval 2, Figure 9 shows a comparison of the residuals (measured value minus simulated value) to that of a normal distribution, using a homogeneous model and a composite one. The homogeneous model appears to be unsatisfactory because the residuals are not normally distributed, which indicates the presence of a systematic error.

Pulse tests and constant rate pumping tests results are respectively compiled in Table 3. Pulse testing revealed the highest hydraulic conductivity values in the Staffelegg Formation (Interval 1, see Fig. 2b) with best fit values ranging from $2.1 \cdot 10^{-10}$ to $5.9 \cdot 10^{-10}$ m s⁻¹. Located in the basal shaly facies of Opalinus clay (Interval 2), the bottom part of the main fault zone is characterised by conductivity values from $3.1 \cdot 10^{-12}$ to $7.3 \cdot 10^{-12}$ m s⁻¹ and do not differ from the upper shaly facies represented by Interval 4 (Fig. 10) and 5, whose best estimates are up to

300 $4.2 \cdot 10^{-12} \text{ m s}^{-1}$. The lowest values are found in the sandy facies (Interval 6, best fit values up
301 to $2.7 \cdot 10^{-13} \text{ m s}^{-1}$), and the carbonate-rich sandy facies (Interval 3, best fit values up to $5.1 \cdot 10^{-13}$
302 m s^{-1}). The basal part of the Passwang formation, represented by Interval 7, shows similar
303 hydraulic conductivity values to Opalinus clay ($5.8 \cdot 10^{-13}$ to $1.4 \cdot 10^{-12} \text{ m s}^{-1}$).

304 The analyses results of the constant flowrate withdrawal tests are quite consistent with those
305 obtained from pulse tests. Indeed, a similar trend can be observed with slightly higher
306 permeability values in the shaly facies than in the sandy facies of Opalinus Clay.

307 Specific storage and flow dimension estimates are highly variable. One issue with single well
308 hydraulic testing is that the volume of tested rock is limited to the immediate vicinity of the
309 well.

310 5.3 Hectometer scale: tidal analysis

311 *5.3.1 Tidal identification in BDB-1 pore pressure series*

312 Detection of tidal components was performed on the pore pressure time series monitored by
313 the sensors placed in BDB-1 borehole, with an acquisition time step set at 15 minutes. The
314 four largest amplitude tidal components, O_1 , K_1 , S_2 and M_2 appear on all processed signals at
315 the exact expected frequencies for time series between September 1st 2014 and March 10th
316 2015 (Fig. 11).

317 The form ratio is defined as the sum of the two main diurnal component amplitudes, K_1 and
318 O_1 , divided by the sum of the two main semi-diurnal component amplitudes, M_2 and S_2
319 (Wiegel, 1964). Tidal deformation through the Opalinus Clay at Mont Terri is characterized
320 by a form ratio varying between 0.84 and 1.35, which indicates a mixed, mainly semi-diurnal
321 tide (Table 4). The maximum value is found in the interval located in the Passwang formation,
322 for which the diurnal components have slightly higher amplitudes than the semi-diurnal ones.
323 Except for this interval, the M_2 tide presents the highest amplitude among the four major tides.

324 *5.3.1 Hydraulic parameters computation*

1
2 325 The results of specific storage coefficient computation are given in Table 5. Specific storage
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4
5 326 values are ranging between $1.08 \cdot 10^{-6}$ and $1.56 \cdot 10^{-6} \text{ m}^{-1}$ in the Opalinus Clay and are higher for
6
7 327 the adjacent formations ($2.35 \cdot 10^{-6} \text{ m}^{-1}$ for the Lower Dogger limestone and $3.08 \cdot 10^{-6} \text{ m}^{-1}$ for
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9
10 328 the Staffelegg Formation). These estimates are consistent with the range given in the literature,
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12 329 deduced from in situ packer tests and permeameter tests for the Opalinus Clay shaly facies:
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14
15 330 between $1 \cdot 10^{-7}$ and $1 \cdot 10^{-4} \text{ m}^{-1}$, with a best estimate at $2 \cdot 10^{-6} \text{ m}^{-1}$ (Bossart and Thury, 2008).
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18 331 Effective dynamic porosity values obtained using the M_2 tide (Table 6) are globally in well
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20 332 agreement with those obtained from petrophysical measurements. Indeed, coherent values
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22 333 between 8% and 24% are obtained by cross-analyses of measuring intervals located in the
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24
25 334 Opalinus Clay. Statistical analysis carried out in previous studies on Mont Terri samples
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27 335 (Fatmi, 2009, Bailly and Matray, 2015) revealed very low range values between 1% and 4%
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29
30 336 at the tunnel level. These unexplained low values could be related to the hydraulically
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32 337 disturbed state of the studied area and desaturation phenomena.
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35 338 Hydraulic conductivity values obtained in the saturated part of the claystone by cross-analysis
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38 339 (Table 6) are much higher than those obtained by other techniques. Indeed, high
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40 340 conductivities ranging between $5.7 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$ and $1.4 \cdot 10^{-7} \text{ m} \cdot \text{s}^{-1}$ are found in the Opalinus
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42
43 341 Clay. These values are 6 to 8 orders of magnitude higher than the range expected from
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45 342 literature data, suggesting that the method is not appropriate for this formation. Discrepancies
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48 343 up to three orders of magnitude between laboratory hydraulic conductivity results and tidal
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50 344 analysis results were also reported by Boldt-Leppin et al. (2003) who studied the King site
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52 345 claystone formation (Canada). These discrepancies were explained by scale factor effects and
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55 346 the presence of fractured area.
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58 347 Bailly and Matray (2015) performed statistical analysis on pore pressure time series acquired
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60 348 in the BCD-3 borehole located at the Mont Terri tunnel level. They obtained hydraulic
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1 349 conductivities ranging between $1.9 \cdot 10^{-10}$ and $7.5 \cdot 10^{-11}$ m·s⁻¹ in the unsaturated part of the
2 350 Opalinus clay by applying the same method on the S₁ solar diurnal tide. The M₂ tide was not
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4 351 found in the studied pore pressure time series due to suction conditions associated to the rock
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7 352 laboratory level. The study also suggested that the structures observed in this borehole were
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10 353 hydraulically conductive, meaning that the Opalinus clay true permeability should be even
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12 354 lower than the range given by tidal analysis.

15 355 **6 Discussion**

18 356 6.1 Comparability of laboratory tests and in situ tests results

21 357 Reliable estimates of permeability and specific storage that describe the bulk hydraulic
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23 358 behaviour are needed for the evaluation of contaminant leakage in geological formations.
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26 359 Linking the results of laboratory tests to bulk characteristics at the regional scale is not
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28 360 straightforward and the meaning of measured values has to be interpreted. Sedimentary rocks
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31 361 are generally associated with anisotropic properties such as permeability, diffusion coefficient
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33 362 and mechanical features. In the Opalinus Clay, which is a overconsolidated clay, a moderate
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36 363 permeability anisotropy ratio of 5.5 was estimated based on laboratory permeameter tests
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38 364 (Múnoz et al., 2003, Croisé et al., 2004, Fernández-García et al., 2007).

41 365 The petrophysical model is based on a conceptual parallel plane geometry which would be
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43 366 associated to a flow orientation parallel to bedding planes. Since BDB-1 borehole was drilled
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46 367 perpendicular to bedding plane, the main solicited direction for fluid flow during hydraulic
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48 368 testing is also parallel to stratification. For its part, tidal analysis is mainly based on
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51 369 gravitational forces that propagate radially from the center of the Earth and should result,
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53 370 given the setting of the Mont Terri anticline, in composite values of parallel and perpendicular
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56 371 to bedding permeabilities.

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372 Although the petrophysical model may be unsuited to carbonated formations, calculation was
373 also performed on the Passwang formation and the Staffelegg formation, which shows similar
374 petrophysical parameters. Another questionable point is the use of a constant value for the
375 Archie's exponent since this parameter depends on the nature of the porous medium.
376 Consequently, adapted values should be taken according to the evolution of rock facies along
377 the stratigraphic sequence.

378 Fitting the cementation factor by comparing petrophysical results and estimates from
379 hydraulic tests can be debatable. Indeed, the volume of solicited rock is higher in the latter
380 case and takes greater account of formation heterogeneities and local open fractures. This
381 point is clearly illustrated by the discrepancies observed for the Staffelegg formation, in
382 which many fractures were evidenced by drillcore mapping. Indeed, petrophysical
383 measurements on centimetre-scale samples do not take into account these hydraulically
384 conductive structures and underestimate the values of bulk properties.

385 Archie's law is rigorously an empirical relationship that links the electrical resistivity of
386 saturated clay-free rocks and their porosity. However, an analogy can be made between the
387 electrical potential and the concentration gradient. It has been shown that effective diffusion
388 coefficient could be predicted by this relationship in a variety of clay and shales with a
389 cementation factor ranging between 2 and 3 (Boving and Grathwohl, 2001; Van Loon et al.,
390 2003b; Mazurek et al., 2009). Best fit values of hydraulic conductivity obtained from
391 hydraulic testing are generally higher than those computed with the petrophysical law (Fig.
392 12a). Hydraulic conductivities higher than 10^{-12} m s⁻¹ found in the Opalinus Clay shaly facies
393 would be associated to illogical values of cementation factor inferior to 1.3, which was given
394 for clean unconsolidated sand packs by Archie (1942).

395 Whether it be for pulse or constant withdrawal tests, the numerical interpretation of hydraulic
396 tests suggests rather wide and unrealistic ranges of uncertainties for hydraulic conductivity

397 and specific storage. Covering several orders of magnitude and not tightly around the best
398 estimates (Table 3), these uncertainties are probably linked to the large number of fitted
399 parameters. Tidal analysis may be more representative than single well hydraulic testing for
400 specific storage estimation (Fig. 12b), since the tidal deformation is applied to the entire
401 rockmass.

6.2 Consistency with previous results

403 Numerous in situ and laboratory investigations have been carried out at the Mont Terri rock
404 laboratory to characterize the hydraulic properties of the Opalinus Clay. Laboratory
405 permeameter tests revealed conductivity values ranging from 6 to $12 \cdot 10^{-14} \text{ m s}^{-1}$ with high
406 associated storage coefficient of $4.8 \cdot 10^{-4} \text{ m}^{-1}$ (Croisé et al., 2004). Figure 13 shows a
407 compilation of permeability results obtained from packer tests (pulse, constant head and
408 constant rate) performed previously at the Mont Terri site (AF Consult, 2012), along with data
409 collected in BDB-1 borehole. Tests were mainly performed in boreholes oblique or normal to
410 bedding drilled in area unaffected by the excavation damaged zone of the tunnel. Previous
411 permeability values measured at the rock laboratory level range from $1.5 \cdot 10^{-14}$ to $1.1 \cdot 10^{-9} \text{ m s}^{-1}$
412 with 55% of the values in the order of $10^{-13} \text{ m s}^{-1}$. The best fit values obtained from BDB-1
413 hydraulic testing fall virtually in the expected range with higher values in the order of 10^{-12} m
414 s^{-1} characterising the Opalinus Clay shaly facies.

415 Specific storage coefficients obtained by tidal analysis are rather homogeneous within the
416 Opalinus Clay with values in the order of 10^{-6} m^{-1} , which are comparable to the range of $2 \cdot 10^{-6}$
417 to $5 \cdot 10^{-6} \text{ m}^{-1}$ found by Bailly and Matray (2015).

418 No significant correlation between the hydraulic conductivity and the different lithological
419 facies was highlighted by Croisé et al (2004), Nussbaum and Bossart (2004) and AF Consult
420 (2012) due to a lack of data from the sandy facies. Although best fit values obtained from

421 BDB-1 borehole indicate higher values in the shaly facies, uncertainty ranges make it difficult
1
2 422 to conclude on a possible contrast. Sandstone lenses embedded in clay rich strata could affect
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4 423 the hydraulic behaviour of the unit not necessarily against its barrier function. Indeed,
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7 424 Opalinus Clay sandy layers are better cemented and display lower porosities (Fig. 5a).
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10 425 Microscopic observations in the sandy facies revealed precipitation of authigenic quartz,
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12 426 carbonates and kaolinite (Peters et al., 2011). On the other hand, porosity values measured in
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14 427 BDB-1 borehole are globally lower than those obtained at the rock laboratory tunnel level and
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17 428 may reflect the deconfinement and relaxation of stresses occurring at the latter location.
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20 429 The Main fault that intersects the laboratory does not impact the barrier function of the
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22 430 Opalinus Clay. Indeed, the sealing of fault planes by calcite shear fibres and clay minerals
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25 431 induce small effect of tectonic deformation on the hydraulic properties of the Opalinus Clay
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27 432 (Nussbaum et al., 2011). This observation is supported by the consistency between the
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30 433 hydraulic tests performed in the intact shaly facies and those carried out in the interval
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32 434 crossing the fault zone. Similarly, no contrast can be identified on the different profiles
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35 435 obtained with the petrophysical model.
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37 38 436 **7 Conclusions**

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41 437 The Deep Borehole experiment enabled the acquisition of data in a fresh borehole penetrating
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43 438 the entire hydraulically undisturbed Opalinus Clay at Mont Terri. Therefore, the presented
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46 439 results are unique, because other hydraulic data at Mont Terri are or might be influenced by
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48 440 tunneling and experimental activities. Three methods with different investigation volumes
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51 441 were carried out and compared.
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53 442 A model that links intrinsic permeability to petrophysical parameters gives values in the order
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56 443 of 10^{-20} m², corresponding to hydraulic conductivities in the order of 10^{-13} m·s⁻¹. Tidal
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58 444 analysis revealed itself not to be an appropriate method to compute hydraulic conductivity in
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445 our study, giving values overestimated of several orders of magnitudes. However, this
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2 446 approach gives reasonable values for specific storage and effective porosity. As a third
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4 447 method, in situ hydraulic testing was performed using the multipacker system installed in
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7 448 BDB-1 borehole. Hydraulic conductivity values obtained by numerical inversion from pulse
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10 449 tests are consistent with those deduced from constant rate withdrawal tests, and suggest a
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12 450 vertical variability across the formation possibly due to local variations of the matrix structure,
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14 451 composition and cementation, or the presence of fractures. In conclusion, the hydraulic
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17 452 conductivity values of the DB Experiment agree well with previous hydraulic testing results
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19 453 performed in the hydraulically disturbed Opalinus Clay around the Mont Terri Underground
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22 454 Rock Laboratory. Therefore, future hydraulic testing in the laboratory outside the excavated
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24 455 damaged zone can be rated as comparable to undisturbed conditions. However, our results
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26
27 456 clearly show higher values (in the order of 10^{-12} m s⁻¹) for the Opalinus Clay shaly facies than
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29 457 its sandy facies (in the order of 10^{-13} m s⁻¹), which is consistent with microscopic observations
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32 458 (Peter et al., 2011). Further laboratory experiments using Hassler cells will be performed to
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34 459 characterise the Opalinus Clay permeability anisotropy.

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37 460 Petrophysical analysis of drillcores and time-series analyses are complementary to hydraulic
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39 461 testing and can provide economical estimates of hydraulic parameters. These techniques
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42 462 involve different volumes of investigation. Core analysis, as well as laboratory permeameter
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44 463 tests, give the homogeneous matrix hydraulic properties but do not account for larger scale
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47 464 heterogeneities such as sedimentary and tectonic features. Moreover, analyses on core
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49 465 samples might be influenced by deconfining and alteration of the core material, thus resulting
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52 466 in biased values. Therefore, hydraulic testing in a fresh borehole is the recommended method
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54 467 for determination of hydraulic conductivity in overconsolidated clays. However, the pressure
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57 468 perturbations induced by drilling activities have to be taken into account for design and
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59 469 analyses of hydraulic testing. The dissipation of drilling and installation of instrumentation
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1 470 induced pressure perturbations can be identified by the tidal components in the pore pressure
2 471 time series. Our study showed that drilling the BDB-1 borehole with air as drilling fluid and a
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4 472 saturation with artificial porewater was an appropriate choice for our application, because: i)
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7 473 no mud-cake was created, ii) no artificial osmotic effects and borehole convergence were
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9 474 observed so far, iii) future water sampling can be carried out since there was no contamination
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11 475 with drilling mud, and iv) we reached fully undisturbed formation pressures after several
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13 476 months. The latter was possible to do so in an underground laboratory experiment, due no
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15 477 time and financial constraints, which are limiting factors on drill site for exploration boreholes.
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17 478 Therefore, in clay formations, particular care should be taken in the choice of drilling method
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19 479 and drilling fluid as well as borehole instrumentation materials, in order to obtain accurate
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22 480 hydraulic parameters.
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1 **Figure captions**

2 **Fig. 1:** Geological cross-section of the Mont Terri anticline (adapted from Nussbaum et al,
3 2017, this volume). Location of the rock laboratory is indicated by a white line. The BDB-1
4 deep borehole, represented by a thick black line, crosses the lower part of the Dogger aquifer,
5 the entire Opalinus Clay formation and the upper part of the Liassic marls.

6 **Fig. 2:** a) Stratigraphic sequence along the BDB-1 borehole; b) BDB-1 borehole layout; c)
7 Double packer elements.

8 **Fig. 3:** Experimental set up for: a) pulse withdrawal tests; b) constant rate pumping tests
9 performed on BDB-1 borehole (©Solexperts).

10 **Fig. 4:** Records of pore pressure responses in the seven intervals of BDB-1 borehole to: a)
11 pulse tests; b) constant rate withdrawal tests.

12 **Fig. 5:** Petrophysical parameters acquired along BDB-1 borehole: a) Water accessible
13 porosity acquired by oven-drying at 105°C; b) Specific surface area obtained by BJH and
14 BET methods; c) Grain density estimated by helium pycnometry on oven dried samples.

15 **Fig. 6:** a) Intrinsic permeability profile and b) hydraulic conductivity profile computed across
16 the Opalinus Clay and the Passwang formation for cementation factor of 2, 2.3 and 2.5.

17 **Fig. 7:** System compressibility computed from pulse testing in BDB-1 borehole. Dashed line
18 represents the water compressibility at 10°C. The outlier in the lower part of the borehole is
19 due to a very low withdrawn volume.

20 **Fig. 8:** Comparison of the different tests performed on BDB-1 borehole: a) degree of
21 dissipation associated to the recovery phases of pulse withdrawal tests; b) normalised
22 pressure drawdown during constant rate withdrawal tests and c) degree of dissipation
23 following the end of the withdrawal phase.

24 **Fig. 9:** Example of residual plots for the optimization of Interval 2 (OPA shaly facies) pulse
25 sequence fit to the Cartesian pressure response using a) an homogeneous model and b) a
26 composite model with skin.

27 **Fig. 10:** a) Simulation of a pulse test performed on BDB-1 Interval 5 located in the upper
28 shaly facies of Opalinus Clay and b) associated Ramey A plot with best fit parameters.
29 Results of 200 perturbation analyses and their confidence regions (c and d).

30 **Fig. 11:** Estimated RMS spectrum of pore pressure time series measured in BDB-1 borehole
31 between 01/09/2014 and 10/03/2015. The following tides are observable: principal lunar
32 semidiurnal tide M_2 ($2.236 \cdot 10^{-5}$ Hz) and solar semidiurnal tide S_2 ($2.315 \cdot 10^{-5}$ Hz), lunar
33 diurnal tides K_1 ($1.161 \cdot 10^{-5}$ Hz) and O_1 ($1.076 \cdot 10^{-5}$ Hz), and the solar diurnal components S_1
34 ($1.157 \cdot 10^{-5}$ Hz) and P_1 ($1.154 \cdot 10^{-5}$ Hz).

35 **Fig. 12:** Comparison of results obtained by petrophysical analysis, in situ hydraulic testing
36 and tidal spectral analysis performed on BDB-1 borehole: a) hydraulic conductivity; b)
37 specific storage

38 **Fig. 13:** Compilation of results from field permeability tests performed on the Opalinus Clay
39 at the Mont Terri underground laboratory outside the excavated damaged zone (modified
40 from AF Consult, 2012).

1 **Table captions**

2 **Table 1:** Specifications of the pressure and temperature sensors installed in BDB-1 borehole.

3 **Table 2:** Plausibility ranges set in nSIGHTS for fitted parameters. K stands for hydraulic
4 conductivity and Ss for specific storage. Skin zone conductivity ranges were set one order of
5 magnitude higher compared to intact rock.

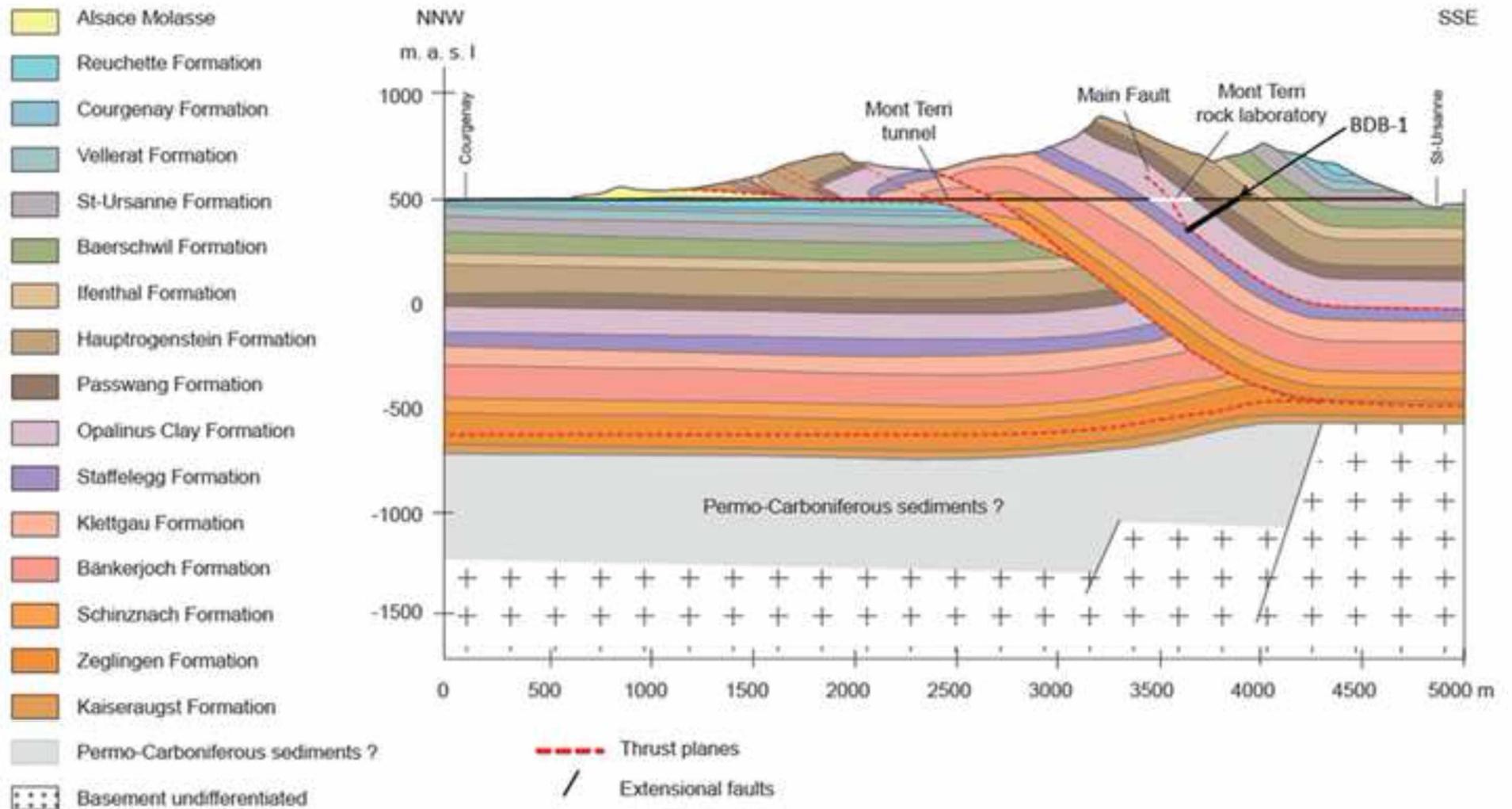
6 **Table 3:** Parameter estimates from BDB-1 borehole pulse withdrawal tests and constant rate
7 (CR) withdrawal tests (K [m s^{-1}]: hydraulic conductivity; Ss [m^{-1}]: specific storage; n: flow
8 dimension; t_s [cm]: skin thickness). Shaded cells represent unrealistically wide range of
9 uncertainties.

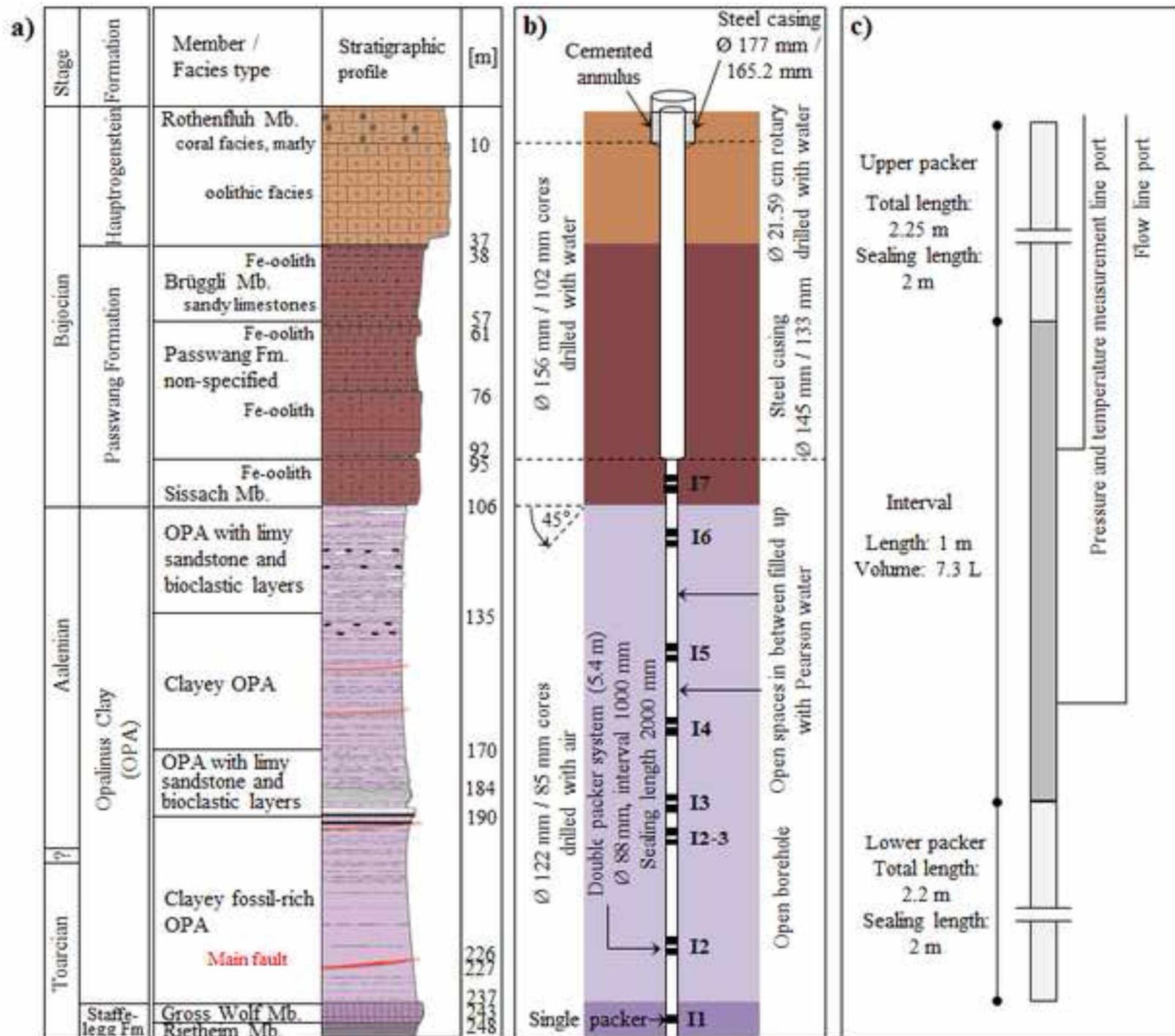
10 **Table 4:** Amplitudes of the tidal components with associated frequencies observed on BDB-1
11 pore pressure time series between 01/09/2014 and 10/03/2015.

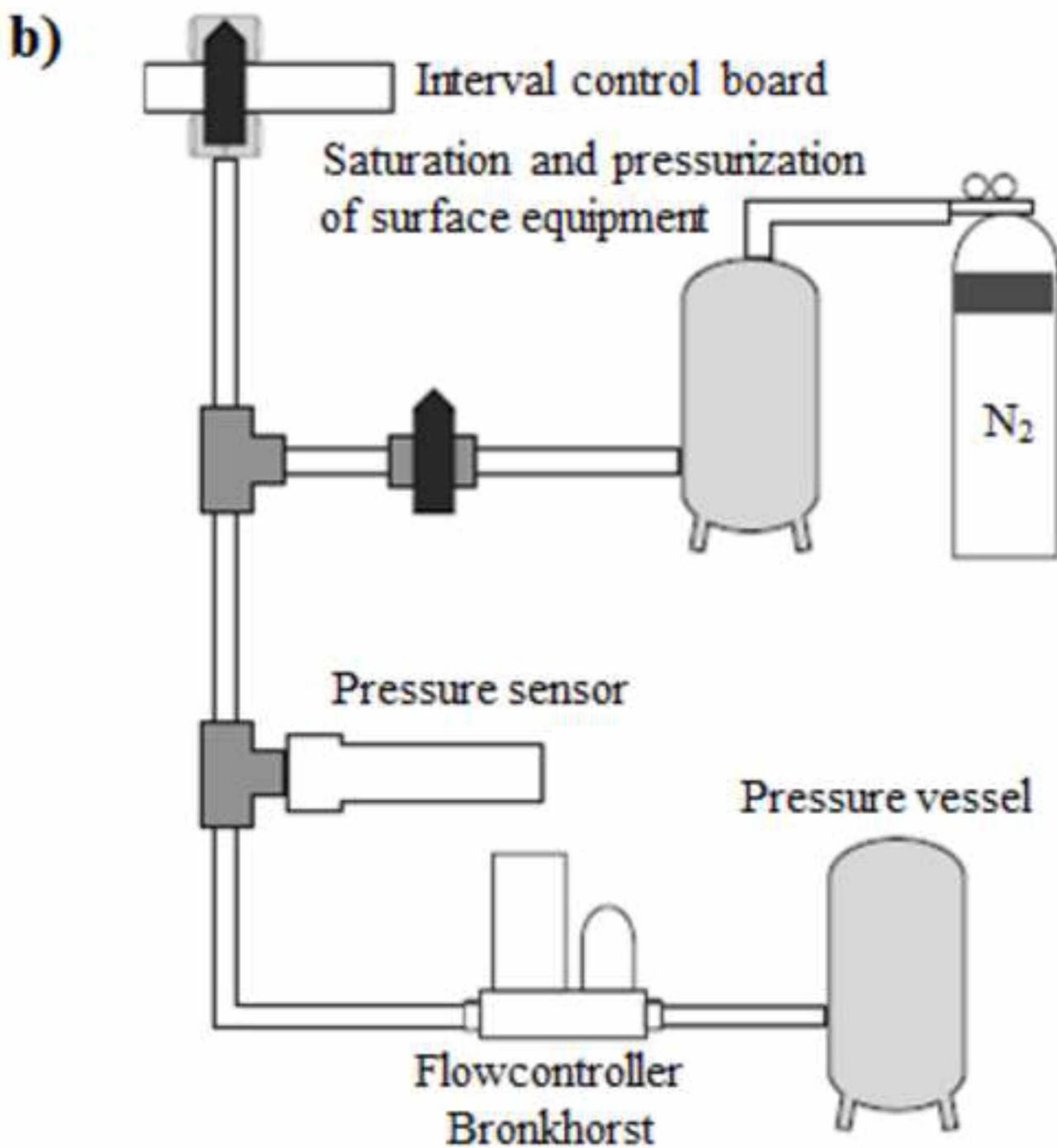
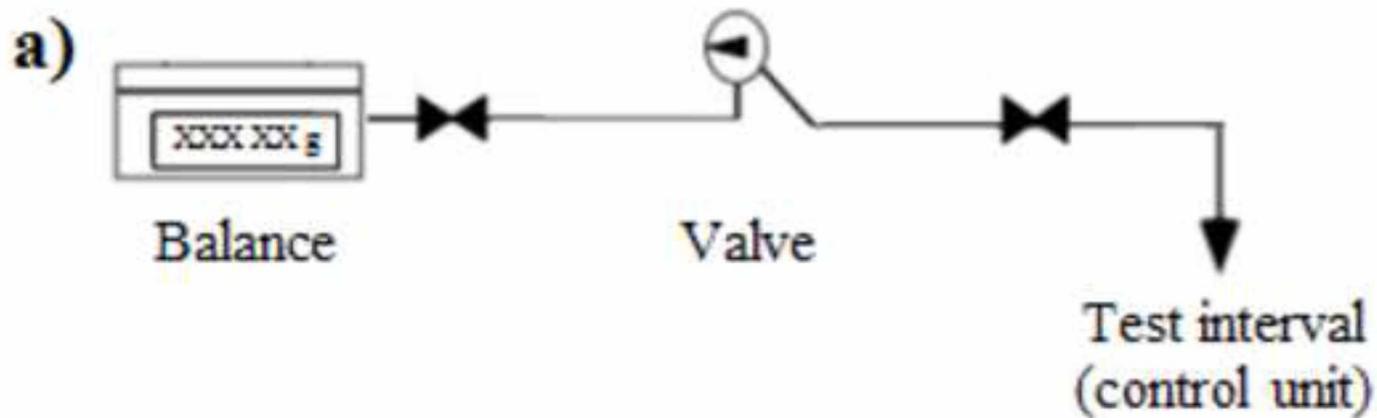
12 **Table 5:** Specific storage coefficients (S_s) estimated from absolute pore pressure signals for
13 BDB-1 borehole measuring intervals with corresponding formations and amplitudes of
14 pressure head fluctuations Δh .

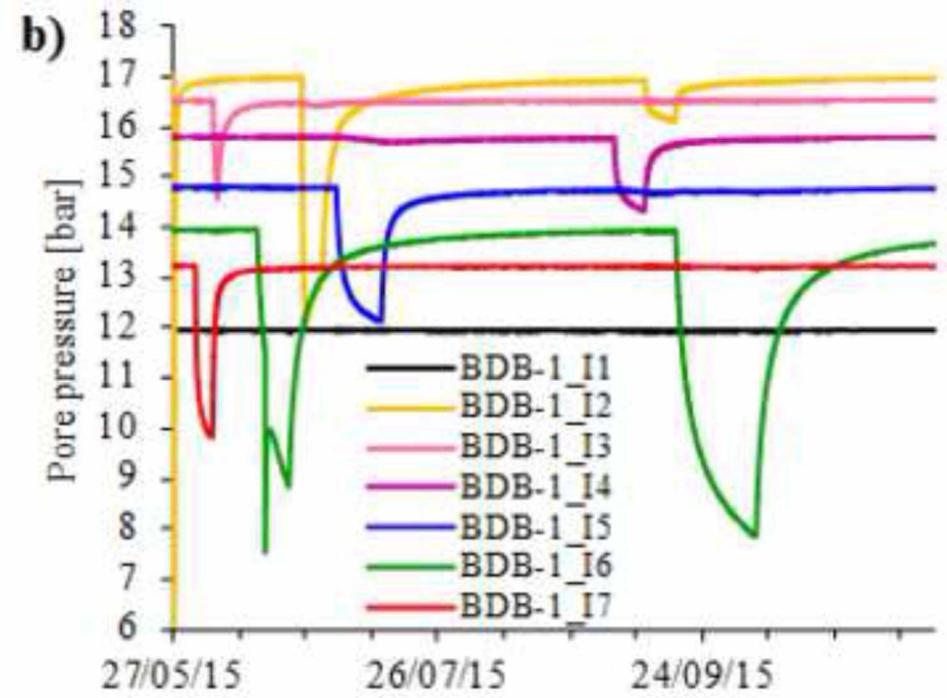
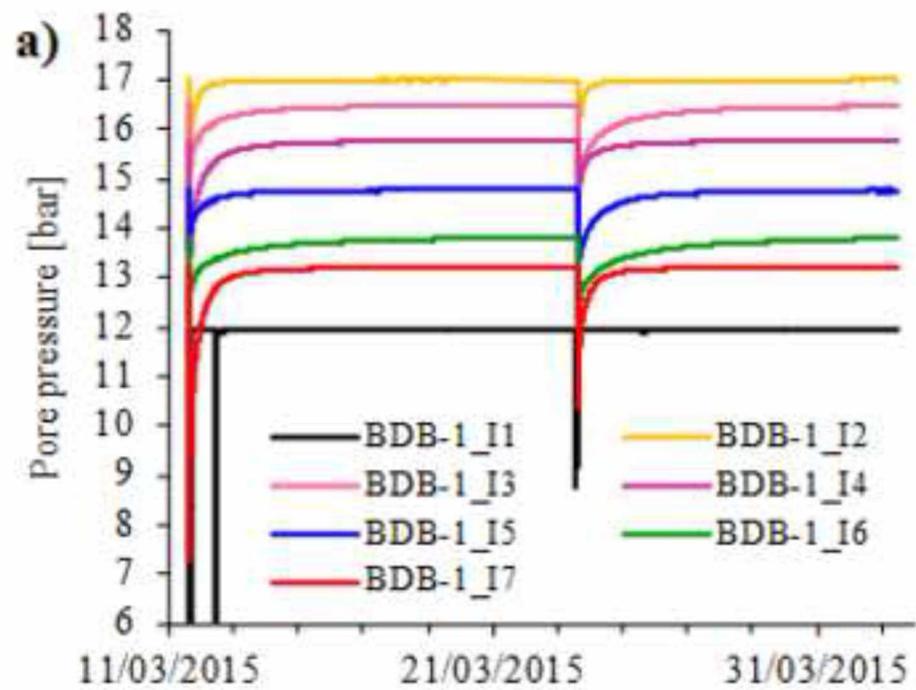
15 **Table 6:** Spectral coherence function (Coh), arithmetic mean of the specific storativity
16 coefficient (\tilde{S}_s), amplitude of the pore pressure signal 1 (A_{z1}), and of the pore pressure signal
17 2 (A_{z2}), vertical effective amplitude hydraulic conductivity (\tilde{K}_v^{Amp}) and vertical effective
18 phase hydraulic conductivity ($\tilde{K}_v^{\Delta\varphi}$), effective dynamic porosity (ω) obtained for the M_2 earth
19 tide for different couples of sensors in BDB-1 borehole. Mean water-loss porosity ($\omega_{\text{water loss}}$)
20 is given for comparison purposes. Shaded cells indicate spurious values.

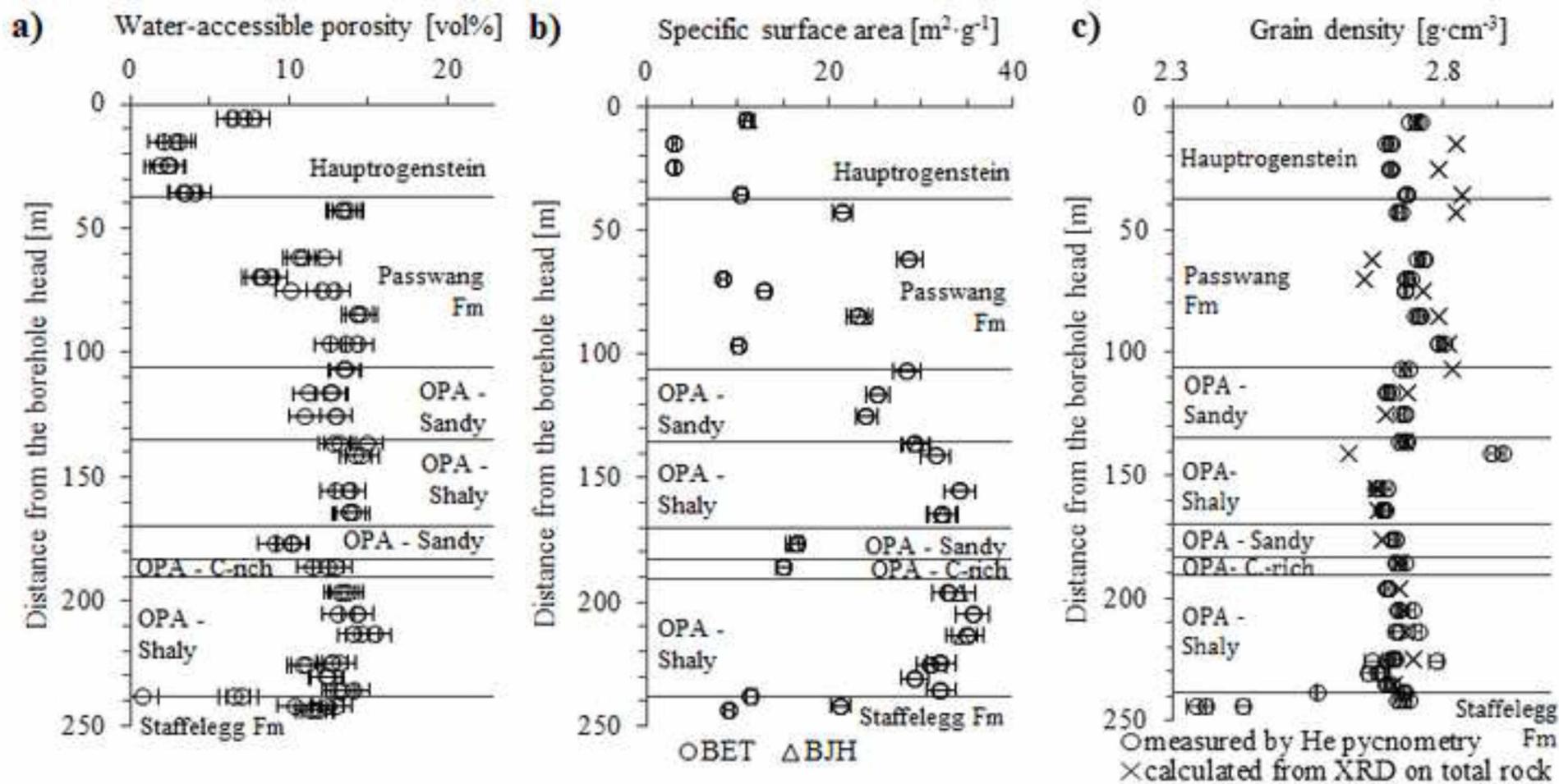
Figure 1

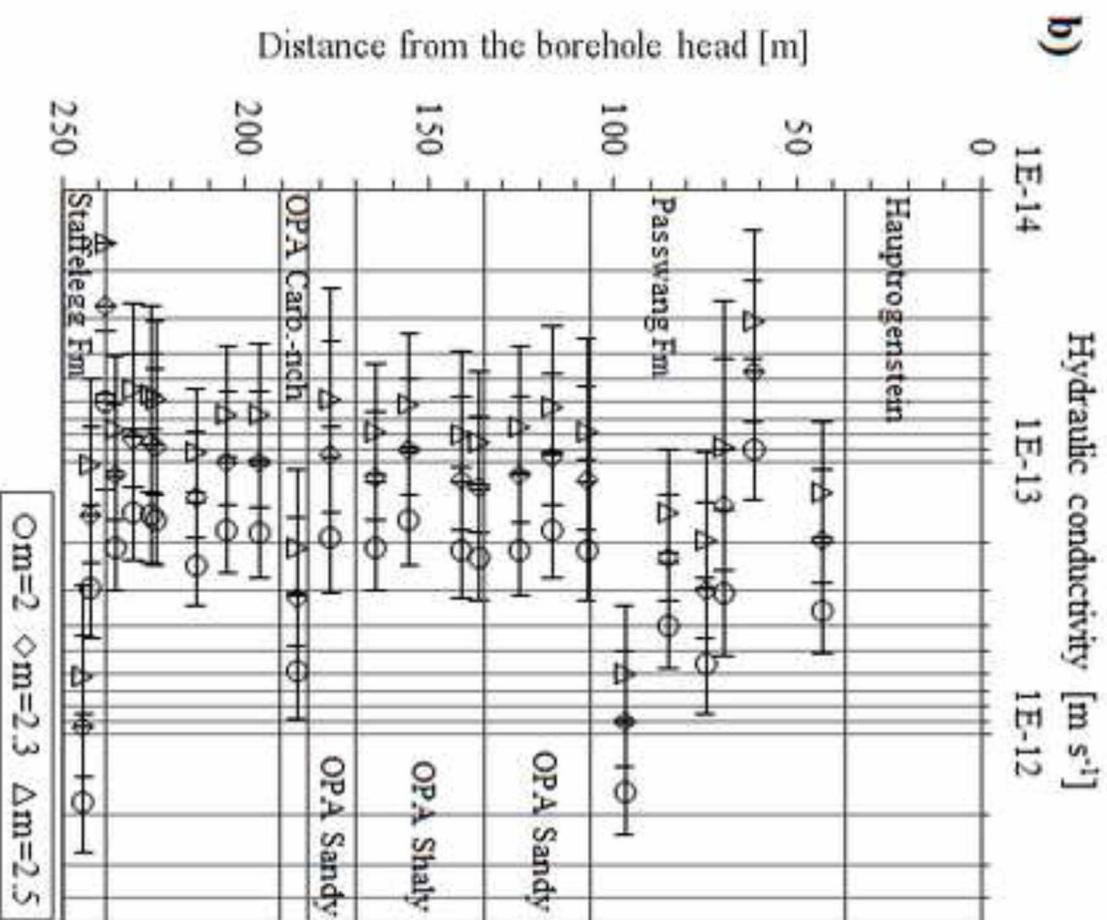
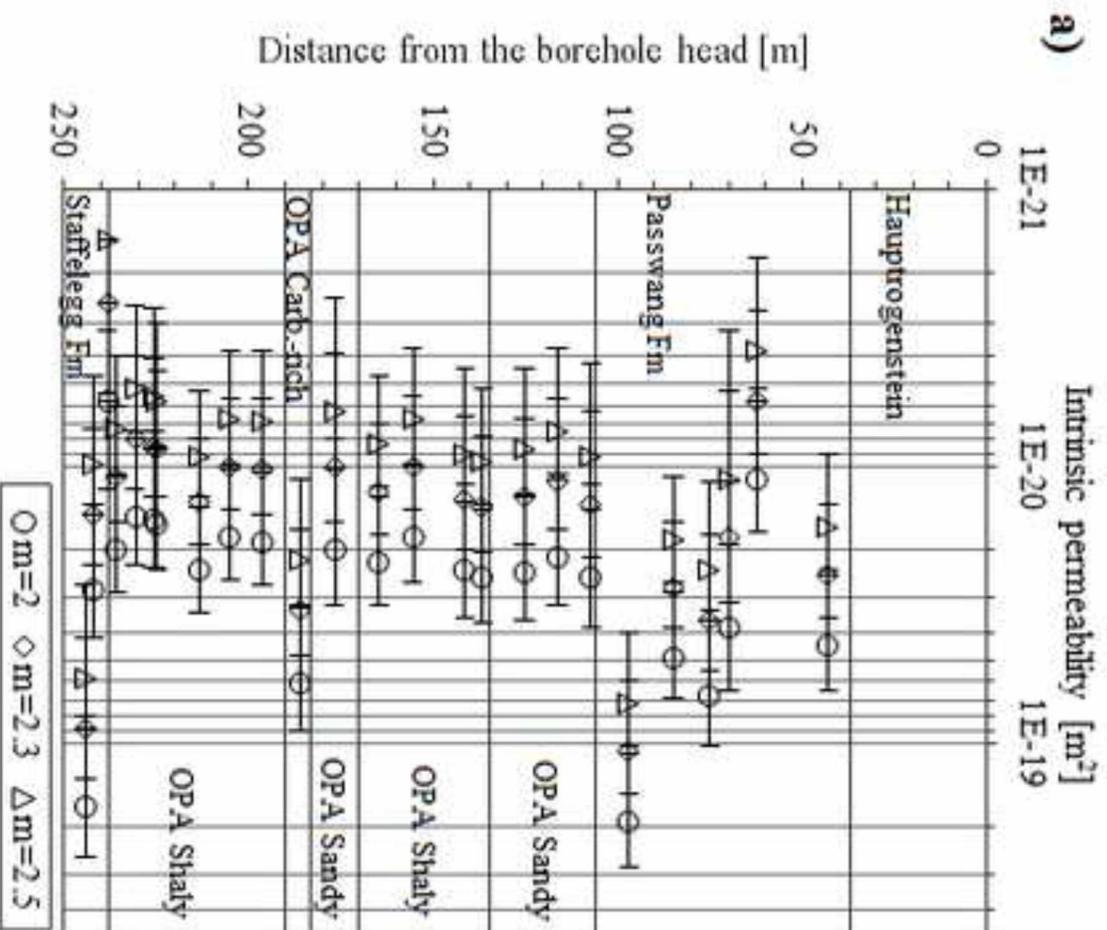


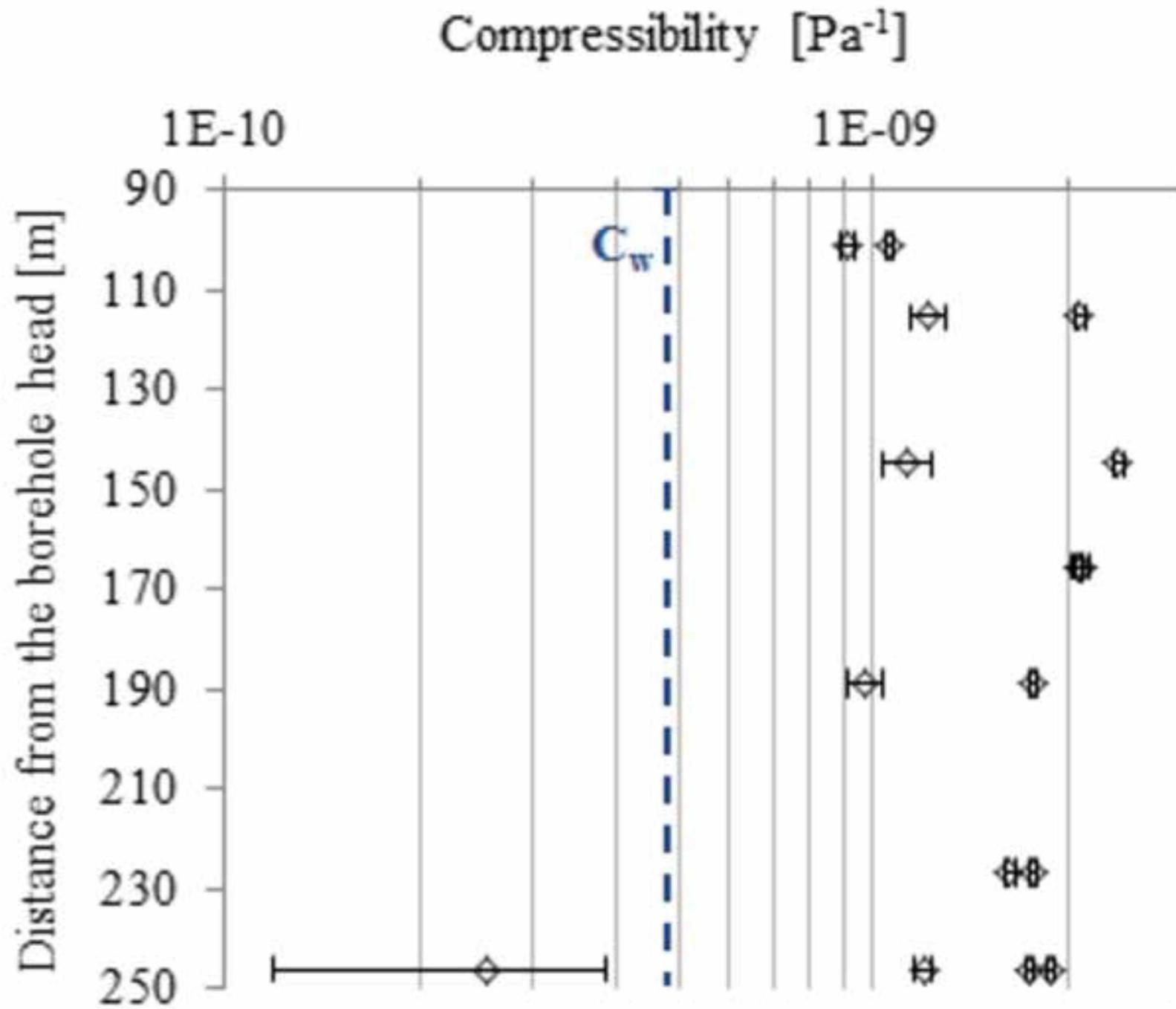


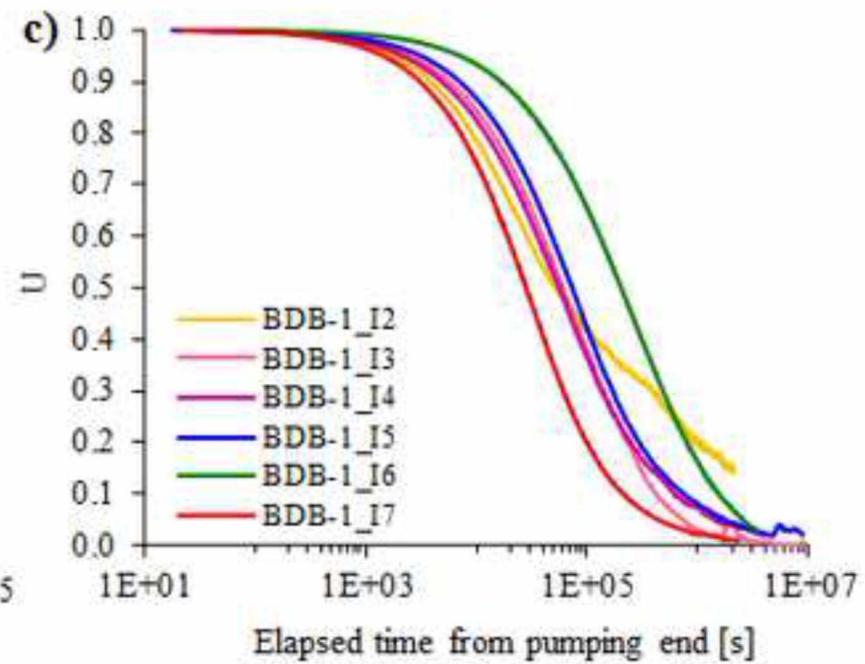
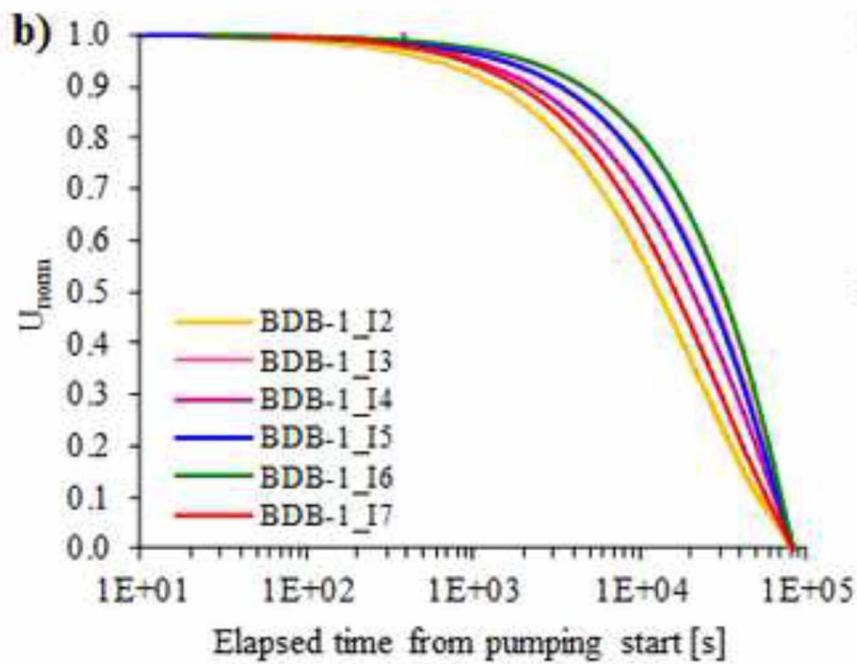
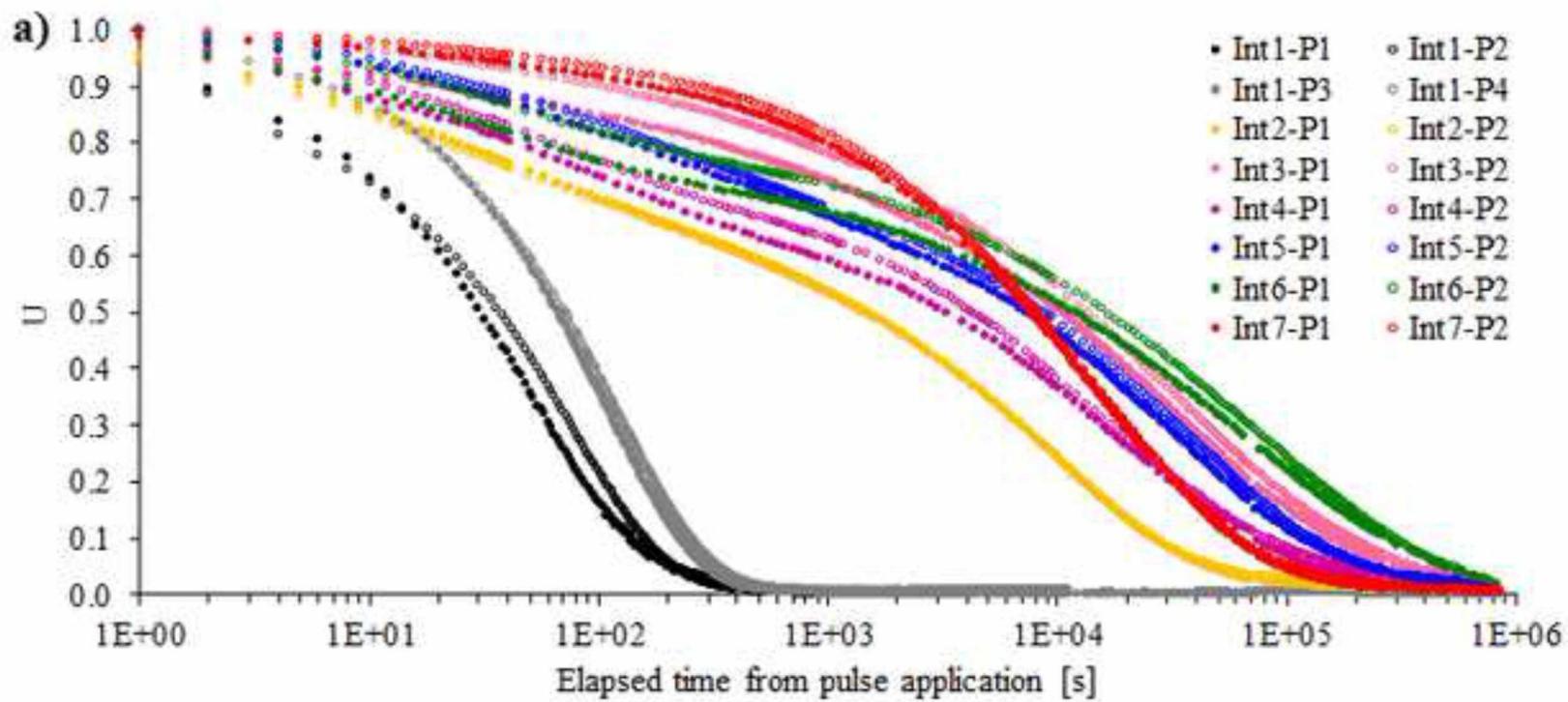


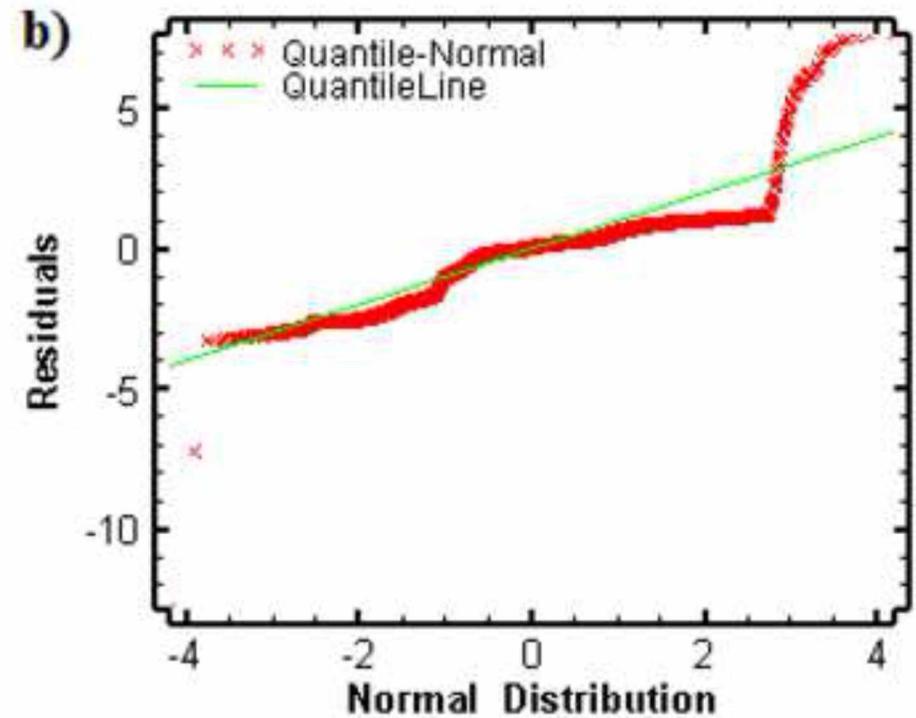
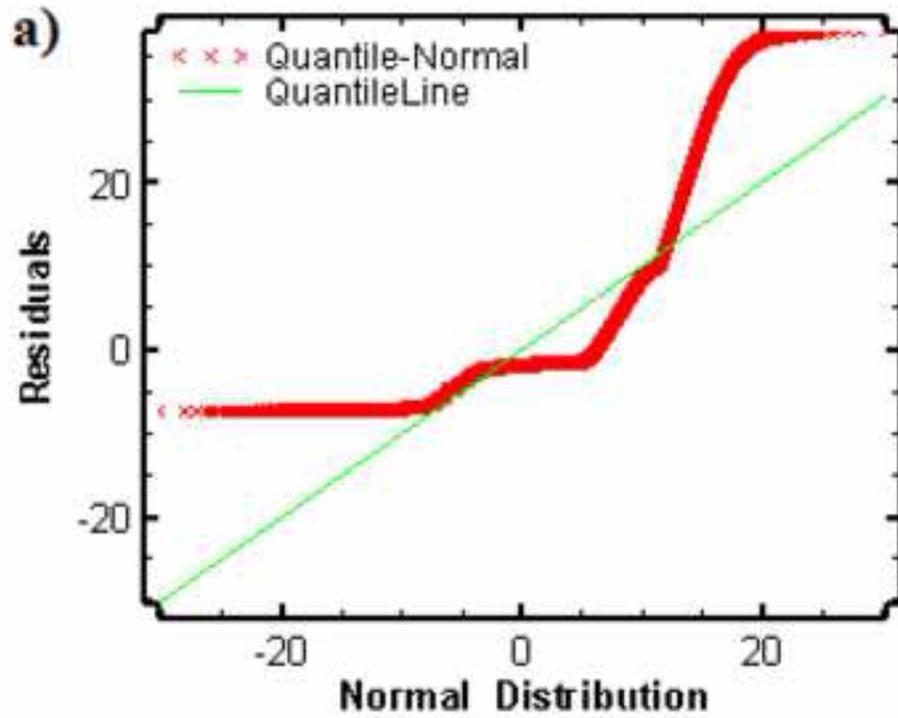


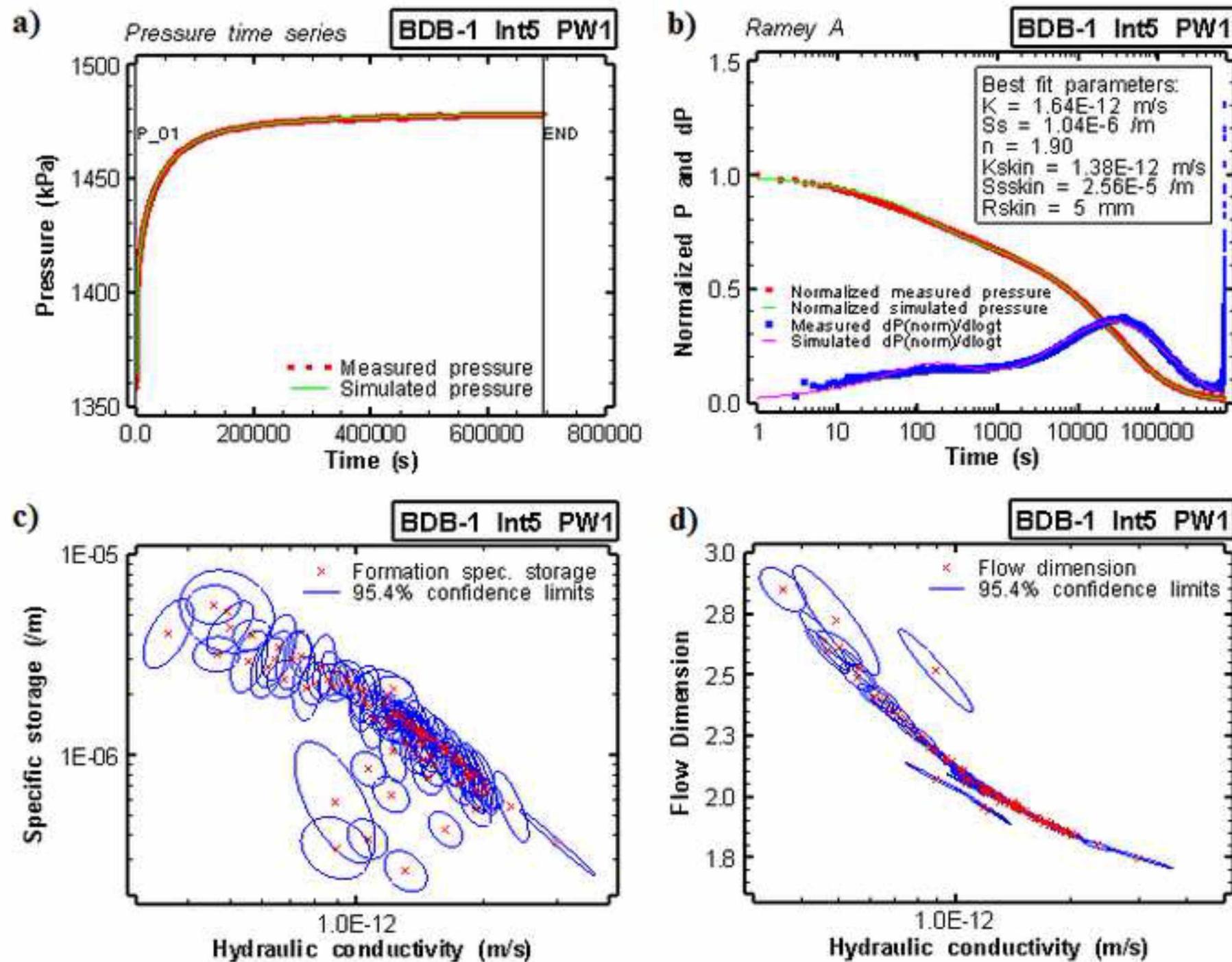


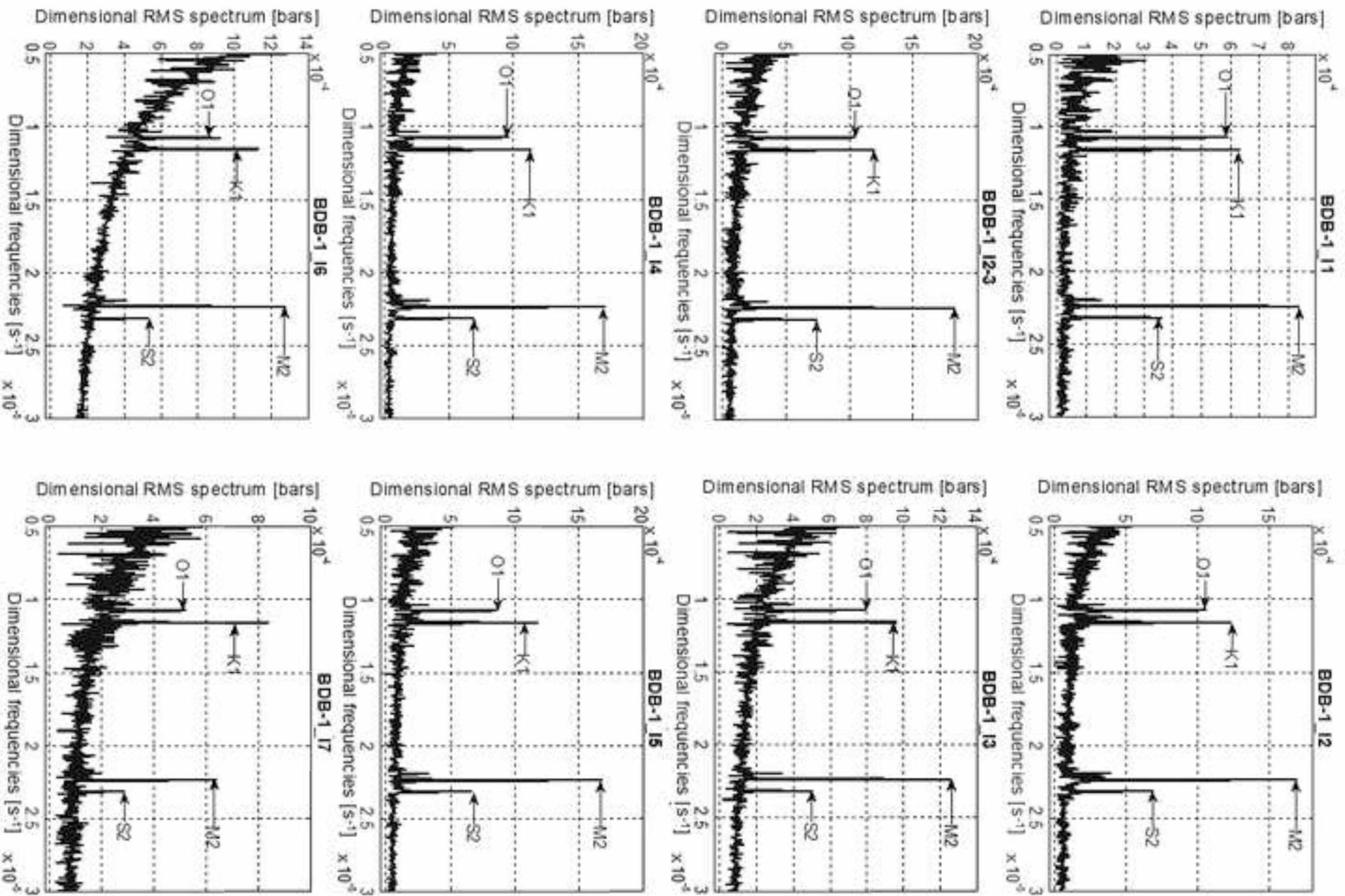


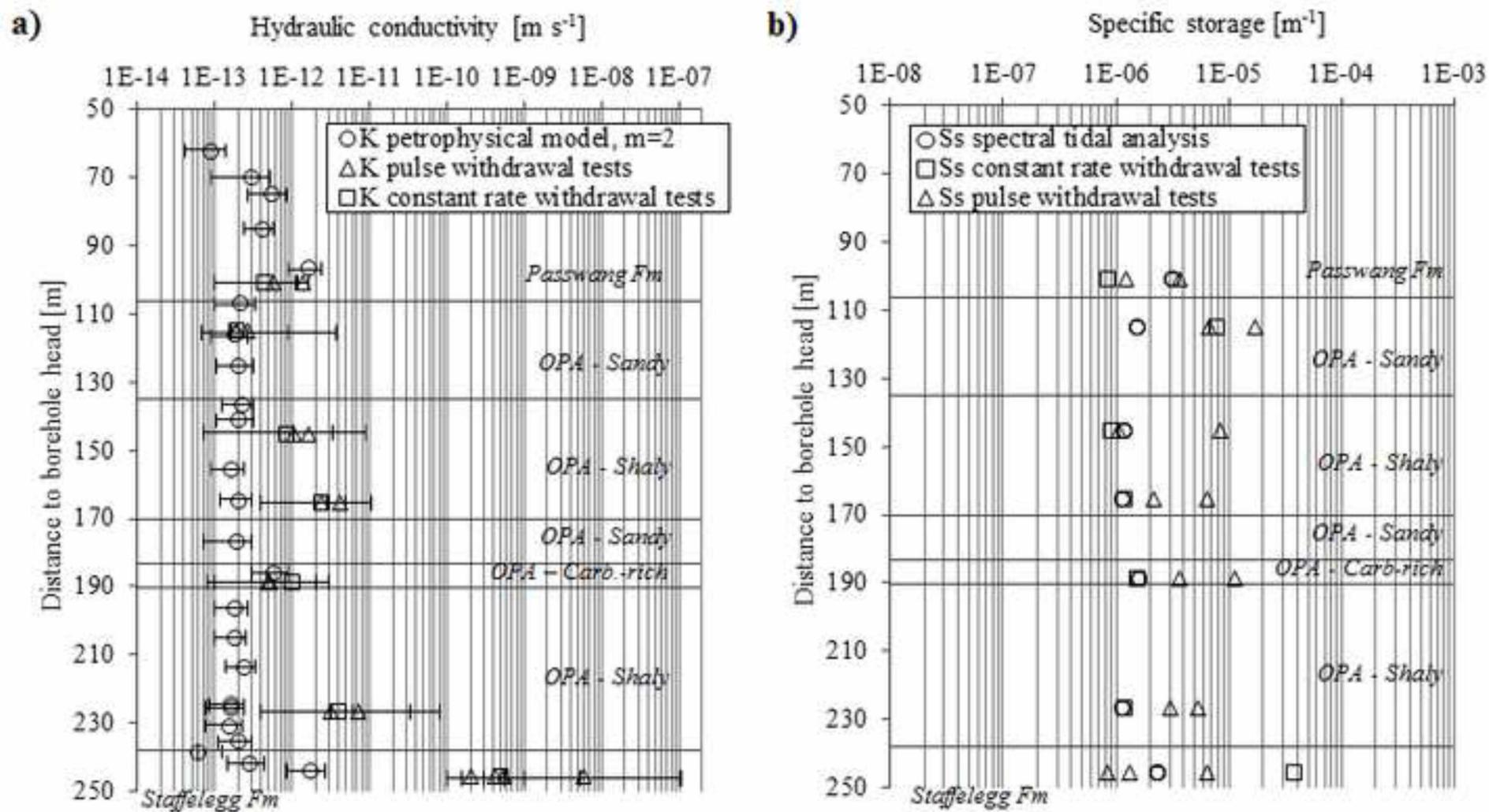












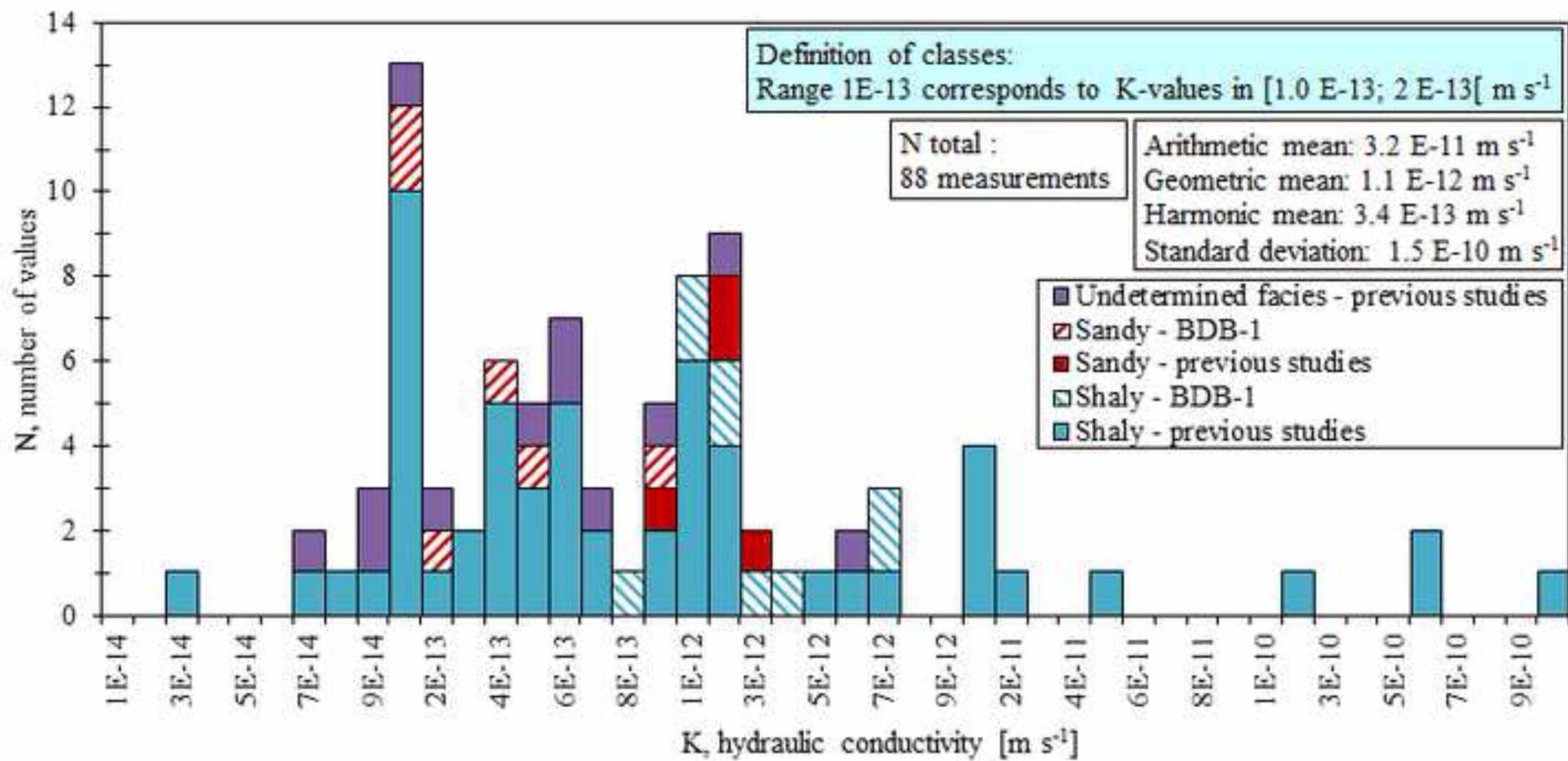


Table 1

Sensor type	Temperature	Pore pressure
Model	IST AG PT1000	Keller AG PAA-33X
Validity range	-50 - 650 °C	0 - 50 bars (absolute)
Accuracy	$\pm (0.15 + 0.002 T)$ °C	0.05% FS

1

Table 2

Fitted parameter		Plausibility range
K [m s ⁻¹]	Interval 1	10 ⁻¹³ - 10 ⁻⁸
	Interval 2 to 7	10 ⁻¹³ - 10 ⁻¹¹
Ss [m ⁻¹]		10 ⁻⁸ - 10 ⁻⁴
Flow dimension [-]		1 - 3.5
Skin thickness [cm]		0.5 - 30
External boundary radius [m]		0 - 5

1

Table 3

Test	Interval	t_s [cm]	K [m·s ⁻¹]		S _s [m ⁻¹]				n	
			Formation		Skin		Formation		Skin	
			Range	Best fit	Best fit	Range	Best fit	Best fit	Range	Best fit
Pulse										
C1-1	I ₁	-	1·10 ⁻¹⁰ - 3.5·10 ⁻¹⁰	2.1·10 ⁻¹⁰	-	6·10 ⁻⁹ - 6.3·10 ⁻⁸	1.4·10 ⁻⁸	-	1.9 - 2.7	2.2
C1-2	I ₁	-	1·10 ⁻¹¹ - 1·10 ⁻⁷	4.2·10 ⁻¹⁰	-		1.4·10 ⁻⁶	-		2.0
C1-3	I ₁	-	1·10 ⁻¹¹ - 1·10 ⁻⁷	5.6·10 ⁻¹⁰	-		6.3·10 ⁻⁸	-		2.4
C1-6	I ₁	-	3·10 ⁻¹¹ - 1·10 ⁻⁸	5.9·10 ⁻⁹	-		8.3·10 ⁻⁷	-		2.0
C2-1	I ₂	0.5	2·10 ⁻¹² - 3·10 ⁻¹¹	3.1·10 ⁻¹²	7.8·10 ⁻¹²	1·10 ⁻⁷ - 3·10 ⁻⁵	5.2·10 ⁻⁶	4.3·10 ⁻⁵	1.8 - 3.0	2.8
C2-2	I ₂	0.5	2·10 ⁻¹² - 1·10 ⁻¹⁰	7.3·10 ⁻¹²	1.0·10 ⁻¹¹	1·10 ⁻⁷ - 2·10 ⁻⁵	3.0·10 ⁻⁶	4.7·10 ⁻⁵	1.4 - 2.9	2.0
C3-1	I ₃	0.5	1·10 ⁻¹³ - 3·10 ⁻¹²	5.1·10 ⁻¹³	1.6·10 ⁻¹²	5·10 ⁻⁷ - 3·10 ⁻⁵	3.7·10 ⁻⁶	1.2·10 ⁻⁵	1.4 - 3.1	2.1
C3-2	I ₃	0.5	2·10 ⁻¹³ - 2·10 ⁻¹²	4.9·10 ⁻¹³	1.6·10 ⁻¹²	2·10 ⁻⁶ - 3·10 ⁻⁵	1.1·10 ⁻⁵	1.5·10 ⁻⁵	1.4 - 3.4	2.5
C4-1	I ₄	0.5	1·10 ⁻¹² - 9·10 ⁻¹²	2.3·10 ⁻¹²	5.7·10 ⁻¹²	2·10 ⁻⁶ - 1·10 ⁻⁵	6.4·10 ⁻⁶	5.5·10 ⁻⁵	1.7 - 3	2.3
C4-2	I ₄	2.0	7·10 ⁻¹³ - 1·10 ⁻¹¹	4.2·10 ⁻¹²	2.7·10 ⁻¹¹	1·10 ⁻⁶ - 2·10 ⁻⁵	2.2·10 ⁻⁶	9.7·10 ⁻⁶	1.5 - 3	2.0
C5-1	I ₅	0.5	4·10 ⁻¹³ - 4·10 ⁻¹²	1.6·10 ⁻¹²	1.4·10 ⁻¹²	3·10 ⁻⁷ - 8·10 ⁻⁶	1.0·10 ⁻⁶	2.6·10 ⁻⁵	1.8 - 2.9	1.9
C5-2	I ₅	0.5	4·10 ⁻¹³ - 3·10 ⁻¹²	1.0·10 ⁻¹²	2.7·10 ⁻¹²	1·10 ⁻⁶ - 3·10 ⁻⁵	8.5·10 ⁻⁶	4.7·10 ⁻⁵	1 - 3	2.5
C6-1	I ₆	1.5	8·10 ⁻¹⁴ - 8·10 ⁻¹³	1.9·10 ⁻¹³	1.4·10 ⁻¹¹	8·10 ⁻⁷ - 1·10 ⁻⁵	6.6·10 ⁻⁶	6.6·10 ⁻⁶	1.7 - 3	2.6
C6-2	I ₆	0.5	2·10 ⁻¹³ - 6·10 ⁻¹³	2.7·10 ⁻¹³	5.4·10 ⁻¹²	1·10 ⁻⁶ - 2·10 ⁻⁵	1.7·10 ⁻⁵	2.9·10 ⁻⁵	1.7 - 3	2.8
C7-1	I ₇	0.5	3·10 ⁻¹³ - 4.5·10 ⁻¹²	5.8·10 ⁻¹³	3.7·10 ⁻¹³	4·10 ⁻⁷ - 2·10 ⁻⁵	3.7·10 ⁻⁶	1.9·10 ⁻⁶	1.9 - 3.5	3.0
C7-2	I ₇	0.5	4·10 ⁻¹³ - 2.0·10 ⁻¹²	1.4·10 ⁻¹²	8.6·10 ⁻¹²	10 ⁻⁹ - 2·10 ⁻⁵	1.2·10 ⁻⁶	9.4·10 ⁻⁷	2.1 - 2.6	2.3
CR										
C1-7	I ₁	4.3	1·10 ⁻¹⁰ - 1·10 ⁻⁹	5.0·10 ⁻¹⁰	5.7·10 ⁻⁹	1·10 ⁻⁸ - 1·10 ⁻⁴	8.2·10 ⁻⁶	6.2·10 ⁻⁵	2.0 - 3.0	2.1
C2-2	I ₂	14.2	4·10 ⁻¹³ - 8·10 ⁻¹¹	3.9·10 ⁻¹²	3.5·10 ⁻¹¹		1.2·10 ⁻⁶	9.0·10 ⁻⁵	1.4 - 2.7	1.95
C3-3	I ₃	0.7	1·10 ⁻¹³ - 2·10 ⁻¹²	9.9·10 ⁻¹³	1.6·10 ⁻¹²	3·10 ⁻⁸ - 6·10 ⁻⁵	1.5·10 ⁻⁵	4.9·10 ⁻⁵	1.5 - 3.0	1.9
C4-3	I ₄	1.4	4·10 ⁻¹⁴ - 5·10 ⁻¹²	2.4·10 ⁻¹²	3.0·10 ⁻¹²	4·10 ⁻⁸ - 3·10 ⁻⁴	1.2·10 ⁻⁵	4.0·10 ⁻⁵	1.9 - 3.0	2.1
C5-3	I ₅	1.8	7·10 ⁻¹⁴ - 9·10 ⁻¹²	8.1·10 ⁻¹³	1.5·10 ⁻¹¹	1·10 ⁻⁷ - 3·10 ⁻⁵	8.9·10 ⁻⁵	2.4·10 ⁻⁵	1.9 - 3.0	2.3
C6-3	I ₆	0.5	1·10 ⁻¹⁴ - 4·10 ⁻¹²	2.2·10 ⁻¹³	1.1·10 ⁻¹²	1·10 ⁻⁷ - 2·10 ⁻⁵	7.7·10 ⁻⁶	9.9·10 ⁻⁵	1.5 - 2.9	2.5
C7-3	I ₇	0.6	1·10 ⁻¹³ - 1·10 ⁻¹²	4.4·10 ⁻¹³	8.2·10 ⁻¹³	3·10 ⁻⁸ - 4·10 ⁻⁶	8.5·10 ⁻⁶	2.3·10 ⁻⁵	2.1 - 3.0	2.7

Table 4

Formation / associated chamber	Amplitude on the RMS spectrum [bars]				Form ratio
	O ₁ (1.076·10 ⁻⁵ Hz)	K ₁ (1.161·10 ⁻⁵ Hz)	S ₂ (2.315·10 ⁻⁵ Hz)	M ₂ (2.236·10 ⁻⁵ Hz)	
Staffelegg Formation / I ₁	5.886·10 ⁻⁴	6.326·10 ⁻⁴	3.606·10 ⁻⁴	8.353·10 ⁻⁴	1.02
OPA - Shaly facies / I ₂	1.054·10 ⁻³	1.230·10 ⁻³	6.848·10 ⁻⁴	1.696·10 ⁻³	0.96
OPA - Shaly facies / I ₂₋₃	1.041·10 ⁻³	1.192·10 ⁻³	7.390·10 ⁻⁴	1.823·10 ⁻³	0.87
OPA - Carbonate-rich facies / I ₃	7.905·10 ⁻⁴	9.553·10 ⁻⁴	5.014·10 ⁻⁴	1.255·10 ⁻³	0.99
OPA - Shaly facies / I ₄	9.560·10 ⁻⁴	1.133·10 ⁻³	6.838·10 ⁻⁴	1.701·10 ⁻³	0.88
OPA - Shaly facies / I ₅	8.591·10 ⁻⁴	1.084·10 ⁻⁴	6.546·10 ⁻⁴	1.670·10 ⁻³	0.84
OPA - Sandy facies / I ₆	8.637·10 ⁻⁴	1.205·10 ⁻³	5.329·10 ⁻⁴	1.278·10 ⁻³	1.04
Passwang Formation / I ₇	5.200·10 ⁻⁴	7.206·10 ⁻⁴	2.825·10 ⁻⁴	6.360·10 ⁻⁴	1.35

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Table 5

Formation	Chamber	Δh [bar]	Δh [m]	S_s [m ⁻¹]
Upper Toarcian - Staffelegg Formation	I ₁	$8.353 \cdot 10^{-4}$	$8.52 \cdot 10^{-3}$	$2.35 \cdot 10^{-6}$
Upper Toarcian / Lower Aalenian - Opalinus Clay – Shaly facies	I ₂	$1.696 \cdot 10^{-3}$	$1.73 \cdot 10^{-2}$	$1.16 \cdot 10^{-6}$
Upper Toarcian / Lower Aalenian - Opalinus Clay – Shaly facies	I ₂₋₃	$1.823 \cdot 10^{-3}$	$1.86 \cdot 10^{-2}$	$1.08 \cdot 10^{-6}$
Lower Aalenian - Opalinus Clay – Carbonate-rich facies	I ₃	$1.255 \cdot 10^{-3}$	$1.28 \cdot 10^{-2}$	$1.56 \cdot 10^{-6}$
Lower Aalenian Opalinus Clay – Shaly facies	I ₄	$1.701 \cdot 10^{-3}$	$1.73 \cdot 10^{-2}$	$1.15 \cdot 10^{-6}$
Middle Aalenian - Opalinus Clay – Shaly facies	I ₅	$1.670 \cdot 10^{-3}$	$1.70 \cdot 10^{-2}$	$1.17 \cdot 10^{-6}$
Upper Aalenian - Opalinus Clay – Sandy facies	I ₆	$1.278 \cdot 10^{-3}$	$1.32 \cdot 10^{-2}$	$1.53 \cdot 10^{-6}$
Upper Aalenian - Passwang Formation	I ₇	$6.36 \cdot 10^{-4}$	$6.49 \cdot 10^{-3}$	$3.08 \cdot 10^{-6}$

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Table 6

Chamber	Coh	\tilde{S}_s	A_{z1}	A_{z2}	$\Delta\varphi$	\tilde{K}_v^{Amp}	$\tilde{K}_v^{\Delta\varphi}$	B	ω	$\omega_{\text{water loss}}$
	[-]	[m ⁻¹]	[bar]	[bar]	[rad]	[m·s ⁻¹]	[m·s ⁻¹]	[-]	[-]	[-]
I ₁ vs. I ₂	0.9985	1.75·10 ⁻⁶	8.35·10 ⁻⁴	1.70·10 ⁻³	-0.18220	4.7·10 ⁻⁸	7.2·10 ⁻⁷	0.2520	0.09	0.18
I ₂ vs. I ₂₋₃	0.9992	1.12·10 ⁻⁶	1.70·10 ⁻³	1.82·10 ⁻³	0.03573	2.5·10 ⁻⁶	1.0·10 ⁻⁵	1.0350	0.24	0.15
I ₂₋₃ vs. I ₃	0.9986	1.32·10 ⁻⁶	1.82·10 ⁻³	1.26·10 ⁻³	0.07658	1.4·10 ⁻⁷	3.3·10 ⁻⁶	0.3949	0.11	0.13
I ₃ vs. I ₄	0.9977	1.36·10 ⁻⁶	1.26·10 ⁻³	1.70·10 ⁻³	-0.06768	2.9·10 ⁻⁷	5.8·10 ⁻⁶	4.6810	1.33	0.12
I ₄ vs. I ₅	0.9930	1.16·10 ⁻⁶	1.70·10 ⁻³	1.67·10 ⁻³	0.02158	5.7·10 ⁻⁵	4.1·10 ⁻⁶	0.4758	0.12	0.14
I ₅ vs. I ₆	0.9965	1.36·10 ⁻⁶	1.67·10 ⁻³	1.28·10 ⁻³	-0.05037	6.4·10 ⁻⁷	1.8·10 ⁻⁵	0.2889	0.08	0.13
I ₆ vs. I ₇	0.9965	2.31·10 ⁻⁶	1.28·10 ⁻³	6.36·10 ⁻³	0.50810	3.9·10 ⁻⁸	7.3·10 ⁻⁸	1.6290	0.79	0.13

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