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1 HYDROLOGICAL BEHAVIOR OF A DEEP SUB-VERTICAL FAULT IN
2 CRYSTALLINE BASEMENT AND RELATIONSHIPS WITH
3 SURROUNDING RESERVOIRS

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18

19 ABSTRACT

20 Crystalline-rock aquifers generally yield limited groundwater resources. However, some highly
21 productive aquifers may be encountered, typically near tectonic discontinuities. In this study, we
22 used a multidisciplinary experimental field approach to investigate the hydrogeological behavior of a
23 sub-vertical permeable fault zone identified by lineament mapping. We particularly focused our
24 investigations on the hydrogeological interactions with neighboring reservoirs.

25 The geometry of the permeable domains was identified from geological information and hydraulic
26 test interpretations. The system was characterized under natural conditions and during a 9-week
27 large-scale pumping test. We used a combination of piezometric analysis, flow logs, groundwater
28 dating and tracer tests to describe the interactions between permeable domains and the general
29 hydrodynamical behaviors.

30 A clear vertical compartmentalization and a strong spatial heterogeneity of permeability are
31 highlighted. Under ambient conditions, the vertical permeable fault zone allows discharge of deep
32 groundwater flows within the superficial permeable domain. The estimated flow across the total
33 length of the fault zone ranged from 170 to 200 m³/day. Under pumping conditions, hydrological
34 data and groundwater dating clearly indicated a flow inversion. The fault zone appears to be highly
35 dependent on the surrounding reservoirs which mainly ensure its recharge. Groundwater fluxes were
36 estimated from tracer tests interpretation. This study demonstrates the hydrogeological capacities of
37 a sub-vertical fault aquifer in a crystalline context. By describing the hydrological behavior of a fault
38 zone, this study provides important constrain about groundwater management and protection of
39 such resources.

40 **Keywords:** Hydrogeology, crystalline rocks, lineament, fault zone, large scale pumping test,
41 sustainable groundwater resource.

42

43 1 INTRODUCTION

44 Crystalline rocks cover large areas throughout the world of about 35% of the continental surface
45 (Amiotte Suchet et al., 2003; Blatt and Jones, 1975) and may constitute a crucial water resource for
46 vast population. The porosity and permeability of primary crystalline rocks are extremely low, but
47 their hydraulic properties can be greatly modified as a result of secondary physical processes
48 (unloading, tectonic activities...) and/or geochemical processes such as weathering, fluid circulation
49 (Bahat, 1999; Caine et al., 1996; Evans et al., 1997; Henriksen and Braathen, 2005; Taylor and
50 Howard, 2002, 1999)... Various conceptual models of hydrogeological compartmentalization in
51 crystalline rock aquifers have been proposed (Chilton and Foster, 1995; Dewandel et al., 2006;
52 Maréchal and Wyns, 2004; Taylor and Howard, 1999; Wyns et al., 2004). They usually consist of two
53 main reservoirs: 1) a layer of alterites (<15 meters bgs), identified as a specific reservoir with a
54 relatively high porosity and storage, highly sensitive to rainfall recharge; 2) a superficial fractured
55 zone, of various thickness and which may be characterized by relatively dense sub-horizontal and
56 sub-vertical fracturing. This fractured reservoir has in general a higher permeability although well
57 yields are typically limited to less than 10 m³/h.

58 However, highly productive zones have been locally highlighted in regions exposed to past or current
59 tectonic activity, such as Brittany. In practice, although controversial (Gleeson and Novakowski,
60 2009), hydrogeologists often use fracture outcropping analysis or "lineaments" mapping to
61 determine drilling localization, especially when such lineaments result from extensive tectonic
62 activity (Gleeson and Novakowski, 2009; Henriksen and Braathen, 2005; Sander, 2006; Singhal and
63 Gupta, 2010). Many factors must be considered to ensure the viability of the resource such as rock
64 lithology affected by tectonic activity, stress fields and intensity of deformation. Such factors and
65 fluid flow processes determine fault zone permeability (Caine et al., 1996; Evans et al., 1997; Gleeson
66 and Novakowski, 2009; Goddard and Evans, 1995). Few hydrogeological studies examined
67 relationships between lineaments structures, hydrogeological flow organization and productivity

68 wells (Fernandes and Rudolph, 2001; Henriksen and Braathen, 2005; Holland and Witthüser, 2011;
69 Richard et al., 2002; Sander, 2006). Fault zones may act as conduits, barriers, or as combined
70 conduit-barrier systems that enhance or impede fluid flow (Bense and Person, 2006; Caine et al.,
71 1996) but can also significantly influence groundwater flow, spring discharge, and water-table
72 elevations (Apaydin, 2010; Gleeson and Novakowski, 2009; Melchiorre et al., 1999).

73 In some cases, aquifers near highly conductive fault zones and with relatively high production rates
74 for crystalline rocks (from 20 to 100 m³/h) have been described: Ploemeur aquifer, Brittany (Le
75 Borgne et al., 2006a; Leray et al., 2013; Ruelleu et al., 2010), the New Hampshire Bedrock Aquifer
76 (Richard et al., 2002), Crystalline Rock Aquifers in New England (Harte et al., 2008) and in the
77 Limpopo Province of South Africa (Holland and Witthüser, 2011).

78 The hydrodynamic functioning of fault structures in various geological contexts has been investigated
79 in several studies. In sedimentary media, Bense et al. (2006; 2003) showed the important effects of
80 the geometry and anisotropy of a fault zone on its hydraulic properties. Numerical studies, such as
81 those by Anderson et al. (Anderson and Bakker, 2008), also highlighted the influence of a vertical
82 fault on groundwater flow. In the crystalline context, some studies have described the permeability
83 architecture and hydrogeological functioning of fault zones for groundwater resources (Boutt et al.,
84 2010; Caine and Tomusiak, 2003; Evans et al., 1997; Ganerod et al., 2008; Stober and Bucher, 1999)
85 or hydrocarbon entrapment (Aydin, 2000). However, very few studies have analyzed the hydrological
86 functioning of faults in a water abstraction context. In this context, aquifer yields will mainly depend
87 on the ability of interactions between the fault and the surrounding reservoirs to allow recharge and
88 water availability. On the other hand, groundwater abstraction from a deep resource will
89 undoubtedly modify the hydrodynamic gradients and lead to mixing between the different
90 reservoirs. The hydrogeological influence of deep fault zones on overlaying reservoirs is poorly
91 known and is apparently difficult to characterize by field studies (Banwart et al., 1994; Carucci et al.,
92 2012; Folch and Mas-Pla, 2008; Gannon et al., 2011; Sophocleous, 2002). This question has been

93 tackled out only through few numerical studies, which have reported the hydrological efficiency of
94 fault zones to act as preferential flow zone that enhances recharge processes from surrounding
95 reservoirs (Folch and Mas-Pla, 2008; Leray et al., 2013).

96 The first aim of this study is to characterize the hydrodynamic functioning of a sub-vertical
97 permeable fault zone in crystalline basement from a large-scale field experiment. The main
98 objectives are to i) describe the architecture of the aquifer system, ii) define the flow organization
99 between the permeable zones and recharge processes towards the deep fault zone under natural
100 and pumping conditions and iii) characterize the origin of groundwater and mixing processes due to
101 groundwater abstraction. The experiment is carried out on a specific field site in Brittany (Western
102 France), identified by lineament observation (Carn-Dheilly and Thomas, 2008), where a permeable
103 fault zone at more than 100 meters depth is able to provide about 100 m³/h according to air-lift flow
104 measurements.

105 We first describe the characteristics of the groundwater system under ambient conditions to
106 highlight the hydrologic functioning of deep structures at the catchment scale. We then describe a 9-
107 week large-scale pumping test that was carried out to identify the hydraulic properties of the aquifer
108 system. During this test, various complementary experiments and measurements were conducted to
109 investigate flow interactions between the different reservoirs and to identify mixing processes.
110 Finally, the combined analyses from this multidisciplinary experiment are used to develop a
111 hydrogeological conceptual model of a sub-vertical fault zone in crystalline context.

112 2 GEOLOGICAL AND HYDROGEOLOGICAL SETTING

113 The experimental site of Saint-Brice en Coglès is located in the Mancellian Domain of the “*Massif*
114 *Armoricain*”, in Brittany (France), where it constitutes the north western French part of the
115 Cadomian and Variscan orogenies ((Figure 1a). This formation outcrops from western to central
116 Europe and is mainly composed of low to high grade (migmatite) metamorphic rocks, with regional-

117 scale magmatic intrusions (Cadomian granodiorites). The Mancellian Domain is limited in the north
118 by the English Channel, and to the south by the North Armorican Shear Zone (NASZ). The main
119 lithologies encountered are Precambrian (Brioverian) sedimentary rocks ((Figure 1a), composed of
120 alternating series of argillites/siltites and sandstones. These sedimentary rocks have been affected by
121 low grade metamorphism which has formed a metamorphic aureole around the Cadomian
122 granodiorites on a regional-scale (Ballèvre et al., 2009; Brun et al., 2001; Chantraine et al., 2001;
123 Cogné and Wright, 1980). The most important deformation zone corresponds to a major ESE-WNW
124 dextral strike-slip shear zone, the NASZ attributed to Hercynian orogeny. Secondary SW-NE reverse
125 faults are also found around this main shear zone. These terrains have been affected by Pyrenean
126 and Alpine orogenies that have generated a diffuse deformation characterized by half-graben basins
127 (Rennes basin, Landéan basin...) and NW-SE sub-vertical faults (Grellet et al., 1993; Van Vliet-Lanoë et
128 al., 1997).

129 The Saint-Brice en Coglès site is located in the epimetamorphism zone of a large Cadomian pluton
130 (Fougère granite). The rocks consist of Brioverian sediments metamorphosed into hornfels schists.
131 The vicinity of the site is characterized by parallel extensional N-S normal faults that form localized
132 extensional basins (Geological map, BRGM (Dadet et al., 1984), (Figure 1b).

133 **(Figure 1)**

134 Local geological structures were imaged by carrying out a structural analysis including landscape,
135 geological mapping and geophysical (electric and seismic tomographies) analysis. Sub-vertical faults
136 and extensional graben structures were clearly identified ((Figure 2a). In addition, three deep
137 boreholes (MFT20, MFT80 and, F3) were drilled using "Down Hole Air Hammer" drilling method.
138 Another deep borehole (FC4, 250 m), which has been entirely cored, has been drilled along a profile
139 perpendicular to the orientation of the main accident lineament (Figure 2b). The borehole
140 characteristics are detailed in (Table 1. Several shallow boreholes (labeled T in (Figure 2b) were also
141 drilled to characterize the shallow weathered compartment. The first 10 meters contained highly

142 weathered material with high clay and sand contents. Examination of the cores revealed that the
143 Brioverian rocks were highly deformed and fractured, and intruded by metric aplites, pegmatites and
144 quartz veins, oriented N 50° to N 70°. Particularly, in the vicinity of the fault outcropping, the
145 Brioverian rocks are affected by horizontal fractures, characterized by a density decrease with depth,
146 to an average of about 40-50 meters. The main fault zone was identified in each borehole as a highly
147 fractured and productive zone, ranging from a few meters thick (see core sampling in (Figure 2c) to
148 15 m in the outcropping part of the borehole ((Table 1 and (Table 2). The fault typically dips by 70° to
149 the NNW ((Figure 2c). Wells were completed with a slotted casing in the deep productive zones.

150 *(Figure 2)*

151 *(Table 1)*

152 3 MATERIAL AND METHODS

153 3.1 FIELD EXPERIMENT

154 The interactions between the fault zone and the other hydrologic domains were described and
155 quantified by investigating the site under natural conditions and during a large-scale pumping test. A
156 packer was placed 80m below the ground surface in borehole F3 to ensure that pumping was carried
157 out deep within the fault zone. As a result, water abstraction occurred principally from the fault zone
158 at 110 meters below ground surface ((Table 1). Pumping lasted for two months (63 days) at a flow
159 rate of about 45 m³/h. During the pumping test, total rainfall was limited to 40 mm, and potential
160 evapotranspiration was 90 mm (information available from Saint Mars-sur-la-Futaie weather station-
161 48°26'N 0°58'W, 30km north-east of the Saint-Brice site). Complementary experiments and analyses
162 carried out are described in the following.

163 3.2 WATER LEVEL MONITORING AND ANALYSIS

164 Water levels were recorded using a pressure sensor with barometric compensation (STS© and
165 Schlumberger© pressure transmitters). The altitude of the well was determined by differential GPS.
166 The estimated uncertainty for the absolute water level measurements was about a centimeter. The
167 mean hydraulic parameters of the system under pumping conditions were determined from classic
168 analytical models. In addition, a logarithmic derivative method of drawdown measurement was used
169 to analyze flow regimes (Bourdet and Ayoub, 1989; Renard et al., 2008; Spaine and Wurster, 1993).
170 This method also permitted identification of flow behaviors and an estimation of the system's
171 transmissivity based on Cooper and Jacob's approximation (Renard et al., 2008).

172 3.3 HIGH RESOLUTION FLOW AND TEMPERATURE LOGGING

173 Structural heterogeneity of fractured rocks induces flow partitioning within the aquifer system. To
174 examine preferential flow path and fracture connectivity we used high-resolution flow logging (Heat
175 Pulse Flowmeter, Geovista©) under ambient and pumping conditions (Le Borgne et al., 2006b;
176 Paillet, 1998). Single-borehole flowmeter tests provide information on the main inflow or outflow
177 zones in a well and measure the prevailing ambient flow conditions in the absence of pumping (Le
178 Borgne et al., 2006b; Paillet, 1998). During a pumping test, cross-borehole flowmeter tests (pumping
179 in a given well and measurement in another) are based on the observation that transient flow during
180 pumping in a given aquifer modifies the hydraulic head distribution with time in the different
181 permeable domains and produces measurable changes in the vertical flow profiles. The connectivity
182 and hydraulic properties of the main flow paths can be identified by transitory flow measurements
183 (Le Borgne et al., 2006b; Paillet, 1998).

184 To define flow paths and origin of the water, temperature logging was also used with a multi-
185 parameter Hydrolab probe (OTT©) and Ocean seven 303 CTD (Idronaut©). Differences in hydraulic
186 heads between the fractures in a borehole, under ambient conditions or during pumping, will modify
187 the temperature profile with respect to the geothermic gradient. Therefore these temperature

188 profiles are very useful to identify hydraulic connections between compartments and their evolution
189 through time (Anderson, 2005; Bense et al., 2008; Chatelier et al., 2011).

190 3.4 TRACER TESTS

191 To identify transfer time distribution and to characterize groundwater flows within the main
192 transmissive fault zone, tracer tests were performed between observation wells and the pumped
193 borehole. Tracer breakthrough concentrations were monitored in the pumped well (F3) within the
194 upper casing and below the pump with a flow-through field fluorometer developed by the University
195 of Neuchâtel (Schnegg and Costa, 2007; Schnegg and Flynn, 2002). The fluorometers had been
196 previously calibrated with tracer and local fresh water in the laboratory. To optimize injection, we
197 identified the main fractured part of the fault zone connected to the pumped well (F3) in each
198 observation wells (MFT80 and FC4). Uranine tracer solution was injected in front of the main inflow
199 zone and we checked that no tracer solution remained in the borehole after the injection by logging
200 concentration through borehole depth.

201 3.5 GEOCHEMISTRY AND GROUNDWATER DATING

202 To identify water origin and estimate mixing processes, we analyzed geochemistry and groundwater
203 dating data under ambient and pumping conditions. The apparent ages of water samples were
204 determined by measuring Chlorofluorocarbons (CFCs) concentrations. These anthropogenic gases
205 provide information on groundwater resident times up to 50 years and can give information on
206 mixing processes between different water sources during flow changes (Ayraud et al., 2008;
207 Busenberg and Plummer, 1992; Cook and Solomon, 1997; Cook et al., 2005; Jaunat et al., 2012).
208 Waters were sampled in stainless-steel ampoules after discarding at least three ampoule volumes,
209 and ensuring that there was no contact of the water with atmospheric gases.

210 Groundwater CFCs concentrations were measured by the Geosciences Rennes Laboratory (Labasque,
211 2006). Water samples were degassed by N₂ stripping and then injected into a gas chromatograph

212 equipped with an electron capture detector (GC–ECD). The CFC concentration obtained by
213 chromatographic analysis was converted to the atmospheric mixing ratio (pptv – Parts per Trillion by
214 Volume) by applying a solubility function (modified Henry’s Law for trace gases (Ayraud et al., 2008;
215 Bu and Warner, 1995; Warner and Weiss, 1985; Weiss and Price, 1980)). The CFC atmospheric mixing
216 ratios were then compared with the atmospheric evolution curve (Walker et al., 2000) to determine
217 the apparent recharge year, and thus the apparent age of the groundwater. Analytical uncertainty
218 for the CFC concentrations was estimated (Labasque, 2006) at around 3 % for recent water (<20
219 years) and 5 % for old water (between 55 to 30 years).

220 Major and trace elements were analyzed by ion chromatography (Dionex DX-100) and ICP-MS HP
221 4500 at the Geosciences Rennes Laboratory following standard laboratory methods. The analytical
222 uncertainty for major anions and cations was about 2%.

223 4 RESULTS

224 4.1 AMBIENT FLOW CONDITION

225 (Figure 3 shows the evolution of hydraulic head in the main boreholes representative of the
226 fractured domains (FC4, F3, MFT80 and MFT20) and in the upper weathered reservoir (T_i). The
227 seasonal evolution of hydraulic head is similar in all the aquifer system with a fast response to
228 rainfall during the recharge periods and a classic discharge regime observed during summer.

229 The hydraulic head gradient mostly follows the topography and indicates groundwater flow towards
230 the outcropping of the fault zone and discharge into the river (FC4-F3-MFT80 in (Figure 2b&c).
231 Measurements of the hydraulic gradient with depth revealed a higher hydraulic head in the deeper
232 boreholes ((Figure 3). This suggests a definite vertical compartmentalization of the aquifer system.
233 The three boreholes intersecting the permeable fault zone show similar hydraulic responses, with a
234 potential upward flow, according to the hydraulic gradient analysis. The MFT20 well, located at the

235 edge of the weathered and the fractured bed rock, remains under the influence of the fault zone.

236 The sub-surface aquifer situated within the upper weathered part (T_1 boreholes), appears to be much

237 less influenced by the deep structure.

238 The fault domain responds quickly to rainfall even though it is locally covered by the sub-surface

239 reservoir with lower hydraulic head. This suggests that the bed rock domain can respond rapidly to

240 recharge. The recharge area is certainly along strike and up topographic gradient through favorable

241 deep fractured zones.

242 **(Figure 3)**

243 A typical variation of flow rate with depth is shown in (Figure 4. All flow profiles obtained under

244 ambient conditions reveal upward flow, implying that hydraulic head is higher in the deep fractures

245 (235m for FC4) than in the upper fractures (45m for FC4). FC4 profile in ambient conditions show a

246 major inflow zone at 245 m deep and a major outflow zone at 49 m deep (Figure 4). No other

247 contributing fractures can be detected, either because of the limit of detection of the tool, or simply

248 because of the lack of any hydraulic head gradient between the head in the fractures and the head in

249 the borehole. In pumping conditions, and for a much lower hydraulic head in the borehole, few

250 others fracture may be detected between 160 and 215 meters deep. In any case, the flow rate

251 profiles obtained under pumping conditions confirms that the deep conductive fault zone provides

252 about 50 to 75% of the total productivity of each borehole ((Table 2). For all profiles, the fracture

253 transmissivity was determined by using the model developed by Paillet (1998). The transmissivity of

254 the deep productive sections in each well appeared to be relatively high, ranging between 6 and 9 x

255 10^{-4} m²/s ((Table 2).

256 **(Table 2)**

257 Groundwater dating by CFCs analyses also highlighted the influence of an old deep water origin, with

258 tracer concentrations close to the detection limit in all deep boreholes ((Table 3), including the 20m

259 depth well. The apparent water age is older than 55 years. Conversely, CFCs analyses in the first 10 m
260 of the weathered domain revealed recent waters and contamination with nitrate. Globally, the
261 apparent age determined in the upper weathered reservoir and based on a piston flow model, is 20
262 years. Moreover, the water age in this upper part of the aquifer system decrease uphill. This suggests
263 that the subsurface aquifer is partially influenced by deep groundwater discharge (more or less 25%
264 of old deep water).

265 **(Table 3)**

266 To summarize, three main hydraulic domains were highlighted at the Saint-Brice site: (1) the fault
267 zone which has a higher transmissivity, (2) the surrounding domain affected by secondary fractures
268 less transmissive and (3) the upper weathered part of the aquifer system, restricted to the first 10
269 meters. Under ambient conditions, the hydrogeological system is clearly driven by the discharge
270 from a deep groundwater system towards the upper part of the aquifer system and the local stream.

271 **(Figure 4)**

272 4.2 PUMPING CONDITION

273 4.2.1 EVOLUTION OF HYDRAULIC HEADS AND DIAGNOSTIC PLOT

274 During the 60-days pumping experiment, the hydraulic heads in the different boreholes were
275 recorded ((Figure 5). All wells located in or near the sub-vertical fault zone, including the shallow
276 piezometers in the sub-surface weathered domain, reacted quickly to pumping. During the first 10
277 days, drawdown was limited to a few meters and was similar in all boreholes. This suggests a good
278 connection between the upper and lower domains of the aquifer system. After 10 days of pumping,
279 drawdown has exceeded the depth of the sub-surface wells (<10 m deep), due to desaturation of the
280 upper weathered reservoir around the pumping well. As observed in all deep boreholes, drawdown
281 increased significantly during the last 50 days of pumping ((Figure 5).

282 **(Figure 5)**

283 Figure 6 displays the normalized drawdown (s/Q) of pumping well F3 and its derivative through time
284 in a log-log diagram. The evolution of the derivative curve provides information on flow behaviors
285 and on boreholes effects such as wellbore storage and skin effects. Such diagnostic curves can be
286 used to interpret different flow regimes (Bourdet et al., 1983; Renard et al., 2008), e.g. double
287 porosity, leakage effect, no-flows boundaries... Here, considering the specific geometry of the aquifer
288 system, we assumed that flow regimes can be described through a simple model developed for
289 fracture or strip aquifer embedded in lower permeable block (Butler and Liu, 1991; Escobar and
290 Hernández, 2010; Gringarten, 1996; Moench, 1984; Rafini and Larocque, 2009; Tiab, 2005). Such
291 fracture models involve generally three characteristic flow regimes: the early local response of the
292 fault zone, a period of transition controlled by the geometrical fault zone properties at larger scale
293 and finally the global hydraulic response of the system.

294 Flow behaviors can be detailed as follow through derivative description: ((Figure 6). 1) After the first
295 early-time where the drawdown response is influenced by wellbore storage and skin effects, a short
296 radial flow response is observed. This reflects the behavior of the local permeable fault zone, where
297 water was principally extracted from the local fracture storage and eventually fed by proximal matrix
298 storage and/or local leakage from overlaying aquifers. The constant derivative value suggests a
299 transmissivity around $10^{-3} m^2.s^{-1}$. The derivative decrease between 0.1 and 1 day can be the
300 consequence of preferential leaky flows from shallower reservoir. 2) Between 1 to 30 days of
301 pumping, the drawdown derivative curve is characterized by a transitory period with a strong
302 increase (derivative slope of $\frac{1}{2}$). This derivative increase can be interpreted as double porosity
303 behavior for which lateral inflows from surrounding reservoirs supply the permeable fault at larger
304 scale. The fault geometry can also influence the drawdown during this transitory period which
305 induces linear flow regime. 3) Finally, the system reached a radial flow condition during the last
306 month of pumping, where the whole system was solicited indicating that the major flow comes from
307 surrounding low-permeability domains (Butler and Liu, 1991). The normalized constant derivative of

308 0.18 m at the end of the test implies a global transmissivity of the aquifer system about
309 $10^{-4} m^2.s^{-1}$.

310 **(Figure 6)**

311 4.2.2 FLOWMETER TEST AND TEMPERATURE LOGGING

312 Flow and temperature logs under natural and pumping conditions are presented for MFT80 in (Figure
313 7. Other observation wells yielded similar results. Under ambient conditions, upward flows were
314 identified ((Figure 7 a₁), implying that the hydraulic head in the deeper part of the fault zone was
315 higher than in the upper part of the aquifer domain. During pumping, downward flows were
316 measured, indicating a greater decrease of the hydraulic head in the fault zone. Downward flow
317 could be even 3 times greater than the previous upward flow, which implied a clear inversion of flow
318 between the hydraulic permeable domains ((Figure 7 b₁). Nevertheless, the downward borehole
319 flows slowed down after a few days, in conjunction with the decrease in head gradient between the
320 two compartments ((Figure 7 c₁).

321 Temperature logs ((Figure 7₂), carried out under ambient conditions and during pumping in all
322 observation wells, showed a clear temperature decrease of about 0.2 to 1°C with pumping. The
323 homogeneity of the profiles, with lower temperatures than under ambient conditions, suggests that
324 the deep aquifer domain was fed by colder water coming from the sub-surface domain ((Figure 7 b₂
325 and c₂). This confirms that pumping is initiated within the fault zone at depth and that the upper
326 aquifer domain is supplying the deeper structure.

327 **(Figure 7)**

328 4.2.3 PUMPING TEST MODELING

329 The hydraulic parameters of the aquifer system were evaluated by fitting the drawdown data with
330 classic analytical models. Different solutions were applied to interpret the dataset at different times
331 ((Figure 8). in view to characterize the two main flow behaviors involved during the test, previously

332 characterized by the derivative interpretation: 1) the fault storage response, supported by leaky flow
333 from the weathered part of the aquifer system (<10 days of pumping) and 2) the global double
334 porosity response of the aquifer system during long term pumping.

335 For the first 10 days of pumping, the double porosity analytical solution according to Moench's
336 model (Moench, 1984) was used to model the local fault zone response. This model is based on the
337 concept of a fracture embedded within blocks of lower permeability, characterized by matrix
338 storage. Solutions are presented in equations 19 and 20 from the Moench paper of 1984 and plotted
339 for the early time in MFT80 for both drawdown and its derivative in (Figure 8a. Quadratic head losses
340 were estimated by a variable rate pumping test at $2.5 \cdot 10^4 \text{ m}^5 \text{ s}^{-2}$. Hydraulic parameters deduced from
341 all wells are listed in (Table 4. These parameters confirm that, during the first days of pumping, flow
342 is controlled by a relatively high transmissivity ($T1 = 7 \cdot 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$) fault zone embedded in lower
343 permeability blocks ($Kb = 2 \cdot 10^{-8} \text{ m} \cdot \text{s}^{-1}$). A strong fracture skin value (set to 1) was required to
344 model the first times of both drawdown and derivative, which suggest a strong delay contribution
345 between surrounding blocks to the fractured zone (Moench, 1984).

346 **(Table 4)**

347 We also used the "Two Aquifer-System" model developed by Hunt and Scott (2007) to characterize
348 drainage flows from weathered reservoir to the fractured domain. This model assumes a screened
349 well in an aquifer overlain by an aquitard and an unconfined aquifer which may represent here the
350 upper weathered reservoir. A mean transmissivity of $T1 = 5 \cdot 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$ for the deeper aquifer
351 domain, and transmissivity and porosity estimates of $6 \cdot 10^{-5} \text{ m}^2 \cdot \text{s}^{-1}$ and 2% respectively, for the
352 superficial aquifer was required to fit both drawdowns and derivatives (plot in (Figure 8a, results in
353 (Table 4).

354 For modeling the hydraulic behavior of the hydrological system at global scale after the first 8 hours
355 of pumping, Moench's model (Moench, 1984) proved to be the simplest and most efficient model to
356 reproduce the data ((Figure 8b). The estimated transmissivity of the fractured system is $T1 =$

357 $10^{-4}m^2.s^{-1}$, embedded within a reservoir (matrix) with a lower permeability of $Kb = 2.10^{-8}m.s^{-1}$
358 and a relatively high specific storage of $Sb = 10^{-3}m^{-1}$. A high value of fracture skin is still necessary
359 to reproduce the transitory flow regime observed during transitory pumping times (Figure 6). The
360 transmissivity deduced for long times pumping tends to the transmissivity of the global permeable
361 system (Butler and Liu, 1991).

362 Note that the estimation of storativity in adjacent blocks based on Moench's model is relatively large.
363 However, storativity is in general difficult to estimate in heterogeneous crystalline rocks (Burbey,
364 2003; Le Borgne et al., 2006a; Meier et al., 1998; Neuman, 1979). This higher value may also reflect
365 the fact that only two main compartments (fracture and matrix) were used in the model, whereas
366 several capacitive domains, including a superficial one in the weathered rocks, may actually be
367 involved in the response to pumping.

368 **(Figure 8)**

369 4.2.4 GEOCHEMISTRY AND GROUNDWATER DATING

370 Chemical analyses of major ions revealed Ca-Mg-CO₃ in water from the fault zone and Ca-Mg-CO₃
371 SO₄-Cl, characteristic of anthropogenic activities, in water from the shallower weathered domain. A
372 clear evolution of groundwater chemistry was observed during pumping, due to the mixing of water
373 of different origins. In particular, mixing with the upper weathered reservoir was clearly apparent
374 during the first ten days of pumping. The geochemical response after a longer period was dependent
375 both on shallower and "matrix" contributions and modified by reactivity processes. Description of
376 geochemical evolution will require a much more detailed analysis and will be published in another
377 article (Roques et al., "In Preparation"). Our main focus here is to highlight changes in the apparent
378 age of groundwater, using conservative anthropogenic tracers such as CFCs to highlight the mixing
379 processes.

380 The evolution of groundwater apparent age was deduced from the CFC-12 and CFC-113
381 concentrations in samples taken at the pumping wellhead (

382 (Figure 9). An asymptotic increase in CFCs concentrations was observed, implying a decrease in
383 apparent age, given the assumption of a piston flow model. Under ambient conditions, the CFCs
384 concentrations in the F3 well were negligible, close to the measurement uncertainty, and
385 characteristic of an apparent age exceeding 55 years. After 60 days of pumping, the mean apparent
386 age of water sampled at the outflow was about 40 years. This clearly confirms the influence of the
387 recent water solicited during pumping. Since old water was found in most of the boreholes, this
388 recent water must come from the upper weathered aquifer (<10m). The result also confirms the
389 relatively fast transfer time between compartments.

390 **(Figure 9)**

391 The contribution of the weathered aquifer may easily be estimated by considering a simple binary
392 mixing assumption. We first assumed that mixing occurred between i) water of high apparent age
393 i.e., 55 years (CFC12 concentrations of 0 to 50 pptv) the representative signature of deep fault water,
394 and ii) water from the upper weathered compartment with a mean apparent age of 20 years (CFC12
395 concentrations of 550 pptv measured in the superficial boreholes before pumping). Based on these
396 assumptions, the estimated contribution of the upper weathered aquifer was around 15-20% at the
397 end of pumping (last 30 days, CFC concentration = 105 pptv).

398 These observations clearly demonstrate that the superficial compartment contributes to the global
399 mixing process when the deep fault zone aquifer is pumped. It is difficult to clearly define the
400 contribution of each compartment without a detailed analysis of the mixing process (Roques et al., in
401 preparation), which is beyond the scope of the present work. However, both the geochemistry
402 evolution and groundwater dating suggest that after one month of pumping about 20% of the
403 pumped water comes from the upper part of the aquifer system.

404 4.2.5 TRACER TESTS

405 Two tracer tests were performed during pumping. Uranine tracer was injected in the main
406 productive fault zone in two observation wells: MFT80 and FC4 at 55 and 235 meters depth
407 respectively. (Figure 10 displays the evolution of normalized concentrations with time for the two
408 breakthrough curves. In the first tracer test (MFT80 towards F3), the tracer was detected 4 hours
409 after injection while the maximum concentration occurred at about 16 hours. The estimated travel
410 distance between the injection point in MFT80 and the main inflow zone in F3 was around 53 meters,
411 implying an average flow velocity of about 3.3 m/h. In the second test (FC4 to F3), the tracer
412 appeared 20 hours after injection and the peak concentration was apparent after about 220h. A
413 slight double peak was observed, certainly due to different flow paths between the two wells. Taking
414 into account a travel distance of about 135m, the estimated average flow velocity in the deep
415 structure was 0.6 m/h, i.e. 5.5 times slower than in the upper part of the fault zone. This implies
416 either that the Darcy velocities were much lower in the deeper compartment or that porosity in the
417 deeper compartment was much higher.

418 The Becker and Charbeneau (2000) solution for converging radial flow was used to compute the
419 present breakthrough curves (Figure 10). The use of this model is justified for highly dispersive
420 system like this one (Peclet number are around 5, where $Pe = R/\alpha$, with R is the travel distance and α
421 the dispersivity). The modeling objectives are to derive first order transport parameters and to
422 estimate roughly flow partitioning within the permeable fault zone ((Figure 10). The modeling was
423 achieved by setting the injected mass to the restitution rate (around 85% for MFT80 and 45% for
424 FC4). It was not possible to use the same set of parameters to fit the two breakthrough curves
425 ((Figure 10). Firstly, dispersivity was apparently two times higher during the deeper tracer test (FC4).
426 This increase in dispersivity can be explained by a scaling effect that is classically observed in large
427 scale tracer tests (Gelhar, 1992) and due to the integration of heterogeneities along pathways.
428 Secondly, fitting both curves would require either constant flow rates or constant parameters for the
429 fault zone (thickness and porosity). Assuming an average fault thickness of 6 meters and a constant

430 porosity of around 1 to 2% we were able to obtain a relatively good match for both breakthrough
431 curves ((Figure 10). Porosity values obtained in this case appears relatively high for crystalline rocks,
432 but still reasonable, considering FC4 cores samples (Figure 2), which show that the productive zones
433 are highly fractured and open. The difference in restitution time between the two tracer tests could
434 be honored in this case only by using different effective flowrates for the two tracer tests. This
435 interpretation would imply that the flow-rate from the upper of the aquifer system represented
436 about 2/3 of the total pumping rate while the flow rate from the deeper part was limited to the
437 other 1/3.

438 Note that the difference in restitution time could be similarly modeled by assuming a permeability
439 decrease with depth or a porosity increase with depth. However, an increase of porosity with depth
440 would be difficult to explain, and permeability, as deduced from previous single borehole tests,
441 appears to remain relatively constant with fault deepening ((Table 2). Such differences may be also
442 partly the results of fault zone heterogeneities. Nevertheless, in both cases tracer injection were
443 done in fractured zone of similar local permeability values. It therefore seems more reasonable to
444 model both tracer tests by assuming flow partitioning through depth.

445 **(Figure 10)**

446

447 5 DISCUSSION: CONCEPTUAL MODEL

448 The results obtained in the previous sections were synthesized to derive a global conceptual model
449 of the Saint-Brice en Coglès aquifer system. Our aim was to describe the hydraulic functioning of this
450 steep fault zone under ambient and pumping conditions, and to estimate the groundwater resources
451 actually available.

452 5.1 SUB-VERTICAL STRUCTURE PROPERTIES AND IMPACT ON GROUNDWATER FLOW

453 The main permeable structure has developed along an extensive normal fault zone. Boreholes at
454 different depth (MFT80, F3 and FC4) were used to investigate the fault zone properties. The fault
455 permeability appears relatively constant with depth and constitutes a sub-vertical strip fractured
456 zone embedded in low-permeability domains and overlain by a weathered horizontal unconfined
457 domain which does not exceed 10 meters depth (T₁ piezometers).

458 Various complementary approaches were used to characterize the discharge of deep groundwater
459 through the sub-vertical permeable fault zone. Geochemistry and groundwater dating indicated the
460 presence of an old water signature in the fractured domain from 250 to 20m. As the hydraulic heads
461 in the deeper part are higher, the deep water finds a preferential flow path along the permeable
462 fault zone and is discharged towards the subsurface aquifer domains in the watershed outlet (**Figure**
463 **11a**). Fluxes from the deeper part of the aquifer system can be quantified from the fault zone
464 permeability deduced from hydraulic tests and the mean hydraulic gradient between the deep and
465 subsurface domain. Assuming that the flowrate is constant along the length of the fault (about
466 1000m deduced from the estimated lineament length), the discharge ranges between 170 and
467 200 m³/day. Although this amount of natural flux along fault zones is significant, it is generally poorly
468 known, and is not usually considered in the local hydrogeological balance.

469 (**Figure 11**)

470 5.2 FLOW BEHAVIOR AND RELATIONSHIPS BETWEEN COMPARTMENTS UNDER PUMPING

471 CONDITIONS

472 A multi-disciplinary approach was adopted to investigate flow behavior and water exchanges
473 between the different aquifer domains which enabled us to derive a conceptual model of the
474 hydraulic behavior of this deep permeable fault zone.

475 The most relevant observation is that the sub-vertical fault is clearly connected with the sub-surface
476 reservoir and the two compartments are therefore highly dependent on each other. Globally,
477 pumping in the deep structure induces downward groundwater flow from the upper aquifer domain
478 (**Figure 11b**). Due to the limited storage in the fault zone, water fluxes during pumping are mainly
479 supported by the overlaying reservoir and/or adjacent domains. After two months of water
480 extraction, it is clear that pumping involves contributions from the surrounding compartments, which
481 implies sub-surface and lateral inflows (matrix storage) towards the sub-vertical structure. Tracer test
482 analyses showed that about 2/3 of the water flow originates from the upper part of the aquifer
483 system. This partition of fluxes seems to be governed mainly by hydraulic boundary conditions which
484 limit the deep supply during pumping. As a result, the superficial part of the aquifer seems to
485 constitute a key reservoir supplying the faulted bedrock domain during pumping. The lateral
486 influence of pumping seems to be limited to 300 meters from the fault, as observed in some
487 subsurface boreholes. Thus, in the case of a fault with a large dip (approximately 70°) and a high
488 permeability contrast with surrounding compartments, the radial expansion of the drawdown and
489 pressure variation is preferentially transferred along the fault zone. In the present case, pressure
490 variations diffuse mainly along the graben structure, in the lower topographic zone where the
491 wetland has developed (**Figure 11b**). This behavior implies that fault zones, when they are
492 permeable, may allow pressure diffusion along the fault plane that can act almost as a boundary
493 condition to drain groundwater from the surrounding reservoirs. Similar behavior has been described
494 through numerical modeling of groundwater flow in fault zones (Leray et al., 2013).

496 CONCLUSIONS

497 In this study, we used a multidisciplinary approach to investigate the hydrogeologic behavior of a
498 sub-vertical permeable fault and quantify its interactions with surrounding reservoirs, under ambient
499 and pumping conditions. This study provides a good example of the functioning of a sub-vertical fault
500 determined from lineament mapping.

501 Our results suggest that sub-vertical fault and sub-surface reservoirs are highly dependent on each
502 other. Under ambient conditions, the fault allows the discharge of regional old water into superficial
503 aquifer domains. The natural discharge rate of the fault zone is estimated to be around 170 to 200
504 m^3/day . Although relatively low, this value should be taken into account when estimating water
505 fluxes, hydrologic budget and solute transport at the watershed scale. During the early stages of
506 pumping, the hydrological system is strongly dependent on storage from the sub-surface weathered
507 reservoir. Once the upper weathered reservoir has become mainly unsaturated, the system acts as a
508 classic dual porosity medium with a highly transmissive structure embedded in lower permeable
509 compartments. Thus, this high permeability fault zone appears to be an efficient thin permeable
510 domain that permits rapid diffusion of pressure but is strongly dependent on sub-surface and
511 adjacent domains of higher storativity. All field measurements suggest that under pumping
512 conditions, most of the flow comes from superficial domains and from the vicinity of the fault zone,
513 with a recharge area located at the surface mainly along the fault zone. Moreover, such steep fault
514 zones, although of relatively high transmissivity, remain relatively limited in terms of groundwater
515 yield. In this study, the pumping test was carried out for 2 months at a flow-rate of $45 \text{ m}^3/\text{h}$, but the
516 piezometric analysis indicates that this rate was certainly too high to be sustainable. A better
517 estimate of sustainable flowrate would be around 20 to $30 \text{ m}^3/\text{h}$. This is a much lower value than
518 some other fault zone aquifers, such as gently dipping fault zones which may provide higher
519 groundwater resources (Le Borgne et al., 2006a; Ruelleu et al., 2010). This difference confirms the

520 role of the dip of the fault-zone that may greatly increase borehole yield in some circumstances
521 (Leray et al., 2013).

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534

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1 *Figure 1: a) Location map and regional geological map. Star symbol indicates the St Brice Field site,*
2 *48°25'N 1°22'W, alt. 90m a.s.l. (modified from Chantraine, (Chantraine et al., 2001)). b) Local*
3 *geological map with main lineaments identified (modified Dadet, (Dadet et al., 1984) & IGN©).*

4
5 *Figure 2: Geological conceptual model of the St Brice field site. a) Conceptual geological structure in a*
6 *3D diagram representation, b) local geological map and boreholes location and c) cross-section of the*
7 *structure perpendicular to the main identified lineament.*

8
9 *Figure 3 : Typical hydraulic head variations measured in the different boreholes at Saint-Brice and*
10 *precipitations measured during the same period. Rainfall was measured at the nearest*
11 *meteorological station located 30 kilometers from Saint-Brice.*

12
13 *Figure 4: Flowrate profiles in FC4 borehole under (a) ambient conditions (before pumping), measured*
14 *with a Heat-Pulse-Flowmeter, and (b) pumping conditions, measured with an Impeller Flowmeter*
15 *Geovista©. The blue straight line represents the modeled flow using Paillet solutions (Paillet, 1998).*

16
17 *Figure 5 : Drawdown in the pumping well (F3, blue triangle dots), in observation wells intersecting the*
18 *fault zone aquifer (FC4, MFT80 and MFT20, gray points) and observation wells located in the shallow*
19 *aquifer (T1, T2, T3, T5, T6 and T7, black lines)*

20
21 *Figure 6 : Diagnostic plot in Log scales showing drawdown (blue straight line) normalized by flow rate*
22 *(s/Q), and its derivative (blue point symbol) measured during the long term pumping test in F3.*

23

24 *Figure 7: Flow and temperature profiles under ambient (grey lines) and pumping conditions (after 9*
25 *and 63 days of pumping) in observation well (MFT80).*

26

27 *Figure 8 : Drawdown (s) evolution with time and its derivative (s') during pumping. Observations*
28 *come from MFT80 observation well. Moench and Boulton (modified Hunt) analytical models were*
29 *used to fit both drawdown and derivative curves. In a) only the first ten days were fitted while in b)*
30 *Moench's model was fitted to pumping results obtained at later times.*

31

32 *Figure 9 : Apparent age of water sampled at the outflow and deduced from CFC analysis.*

33

34 *Figure 10 : Tracer test data between the shallow aquifer (MFT80, gray point symbol) and the deep*
35 *fracture (FC4, gray triangle symbol), modeled with the Welty and Gelhar solution (gray straight lines).*
36 *Parameters used in the model are presented in the table (Welty and Gelhar, 1994).*

37

38 *Figure 11 : Conceptual model of groundwater flow at the St-Brice site under a) ambient conditions*
39 *and b) pumping conditions*

40

41 Table 1: Borehole descriptions

42

43 Table 2: Transmissivity results obtained by modeling borehole flow profiles using Paillet solutions
44 (Paillet, 1998).

45

46 Table 3: CFC and SF6 concentrations converted into atmospheric concentration (PPTV, (Bu and Mark
47 J Warner, 1995; M.J. Warner and Weiss, 1985)).

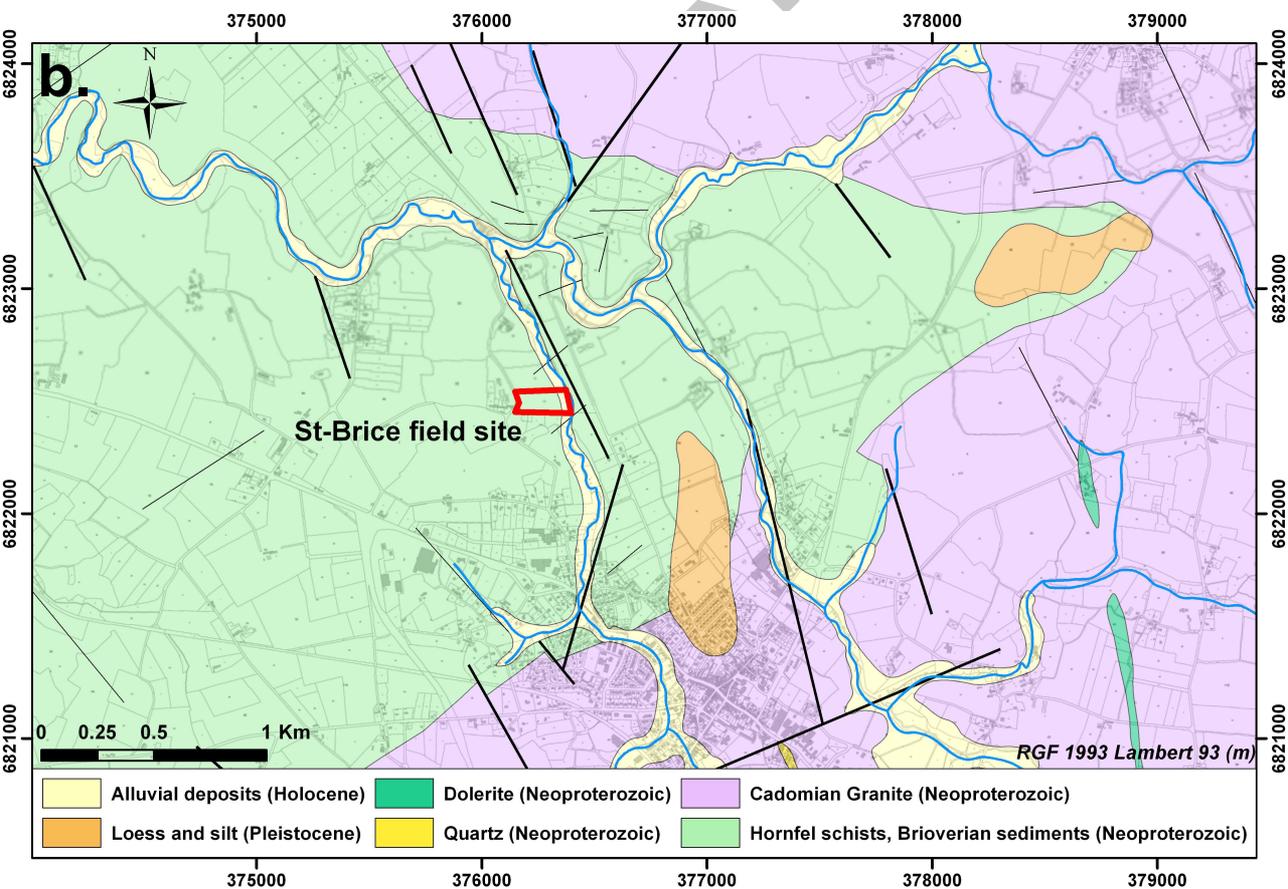
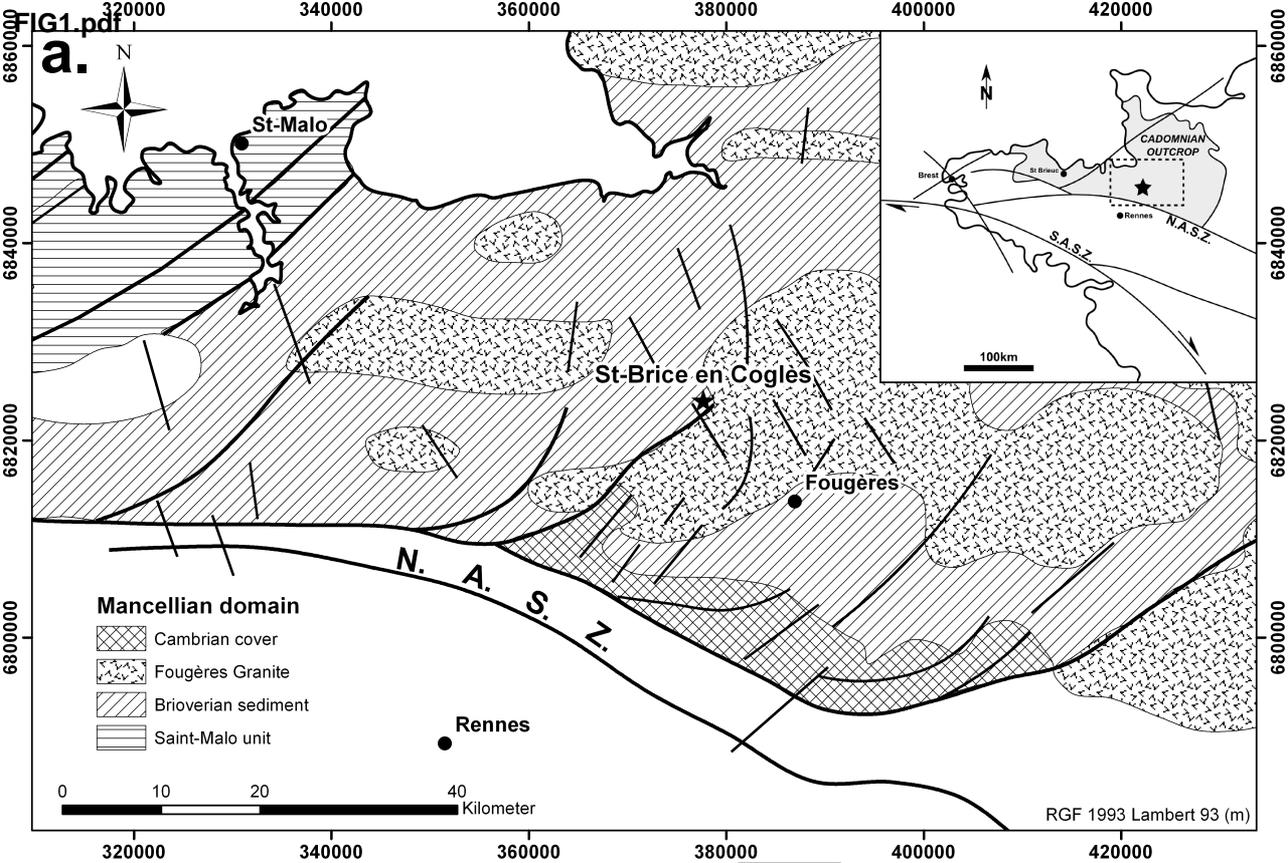
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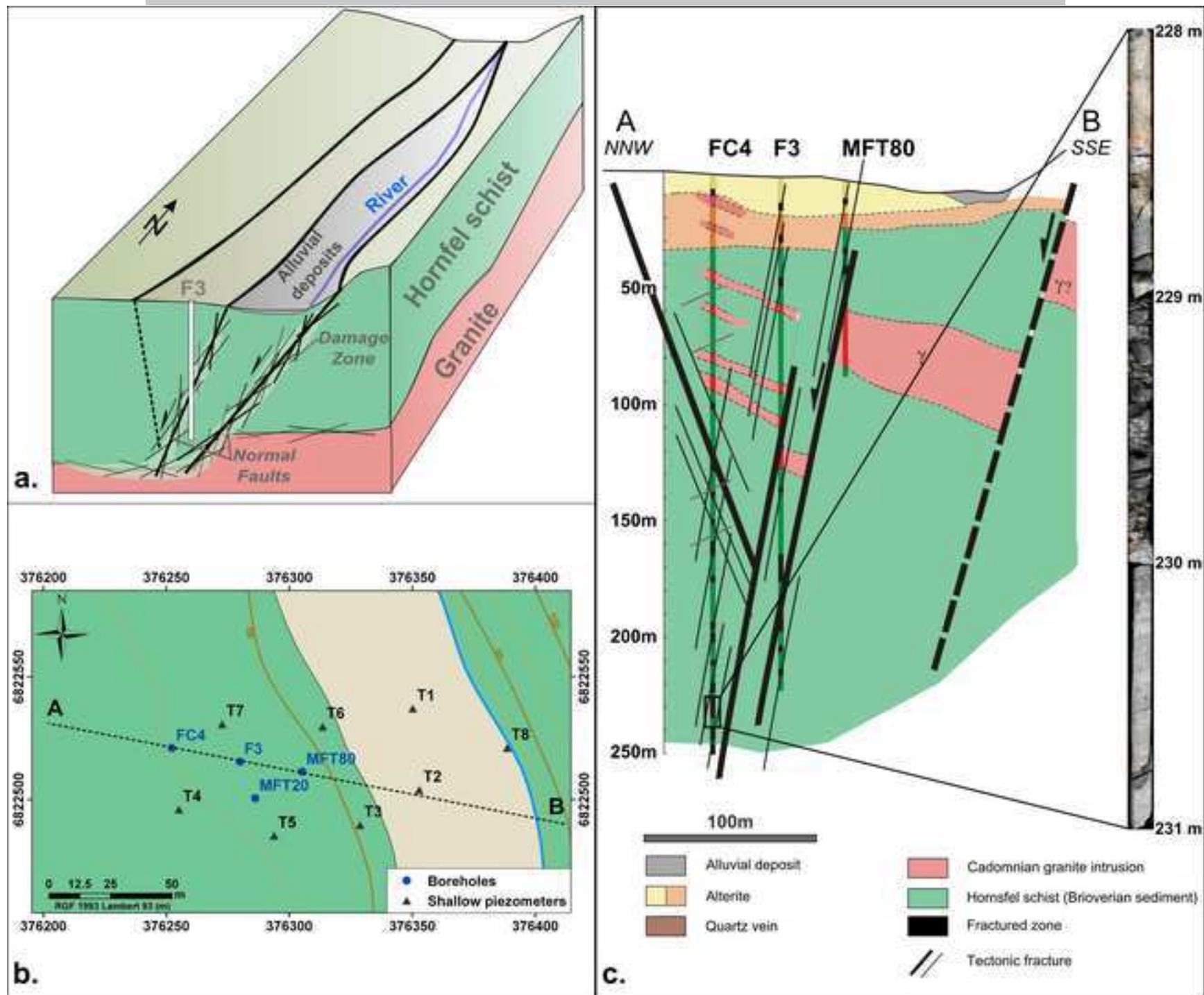
49 Table 4: Pumping test results for pumping well F3 and observation wells MFT80, FC4 and MFT20.

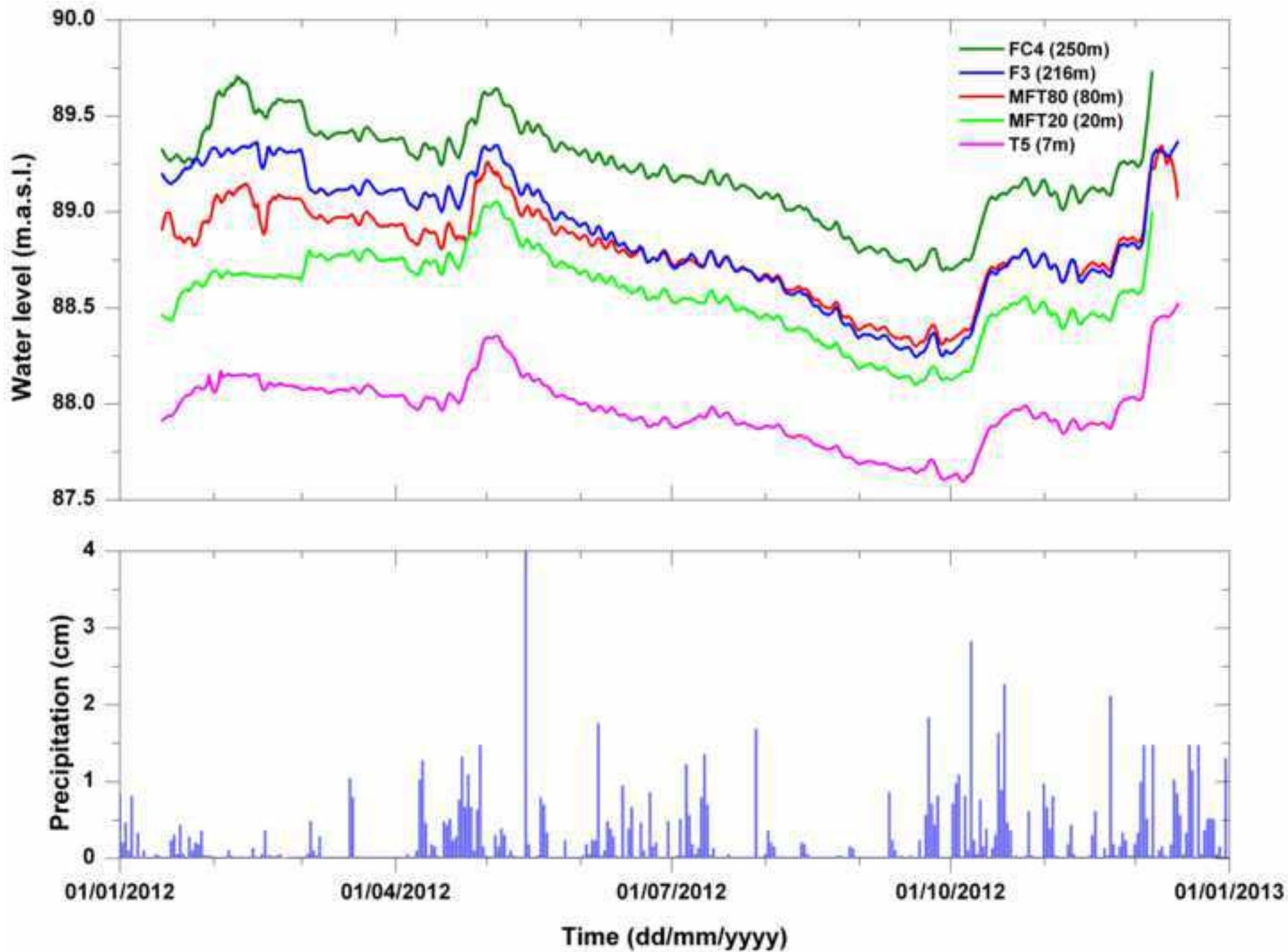
50 RMSE is calculated over the analyzed part of the pumping test.

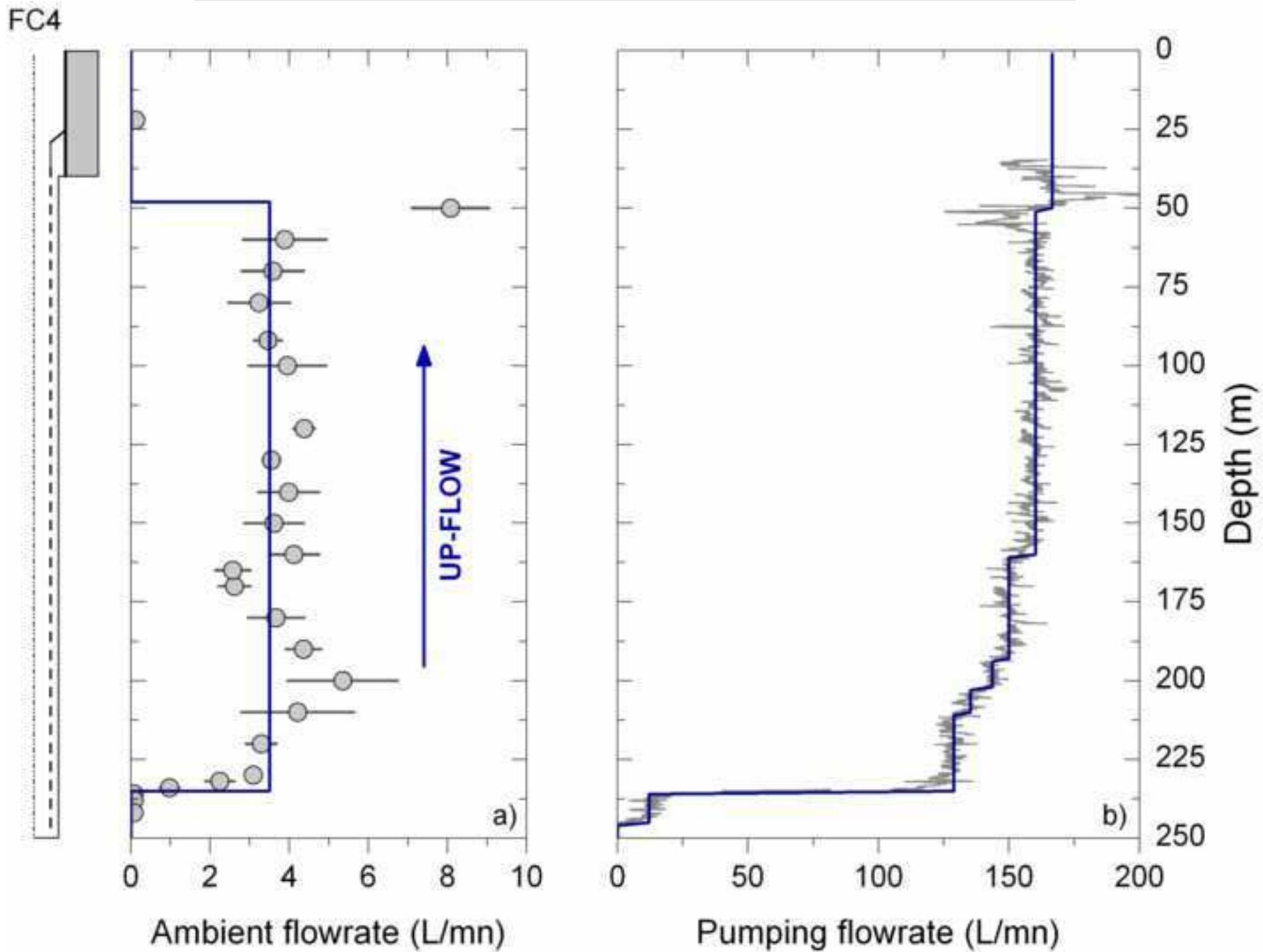
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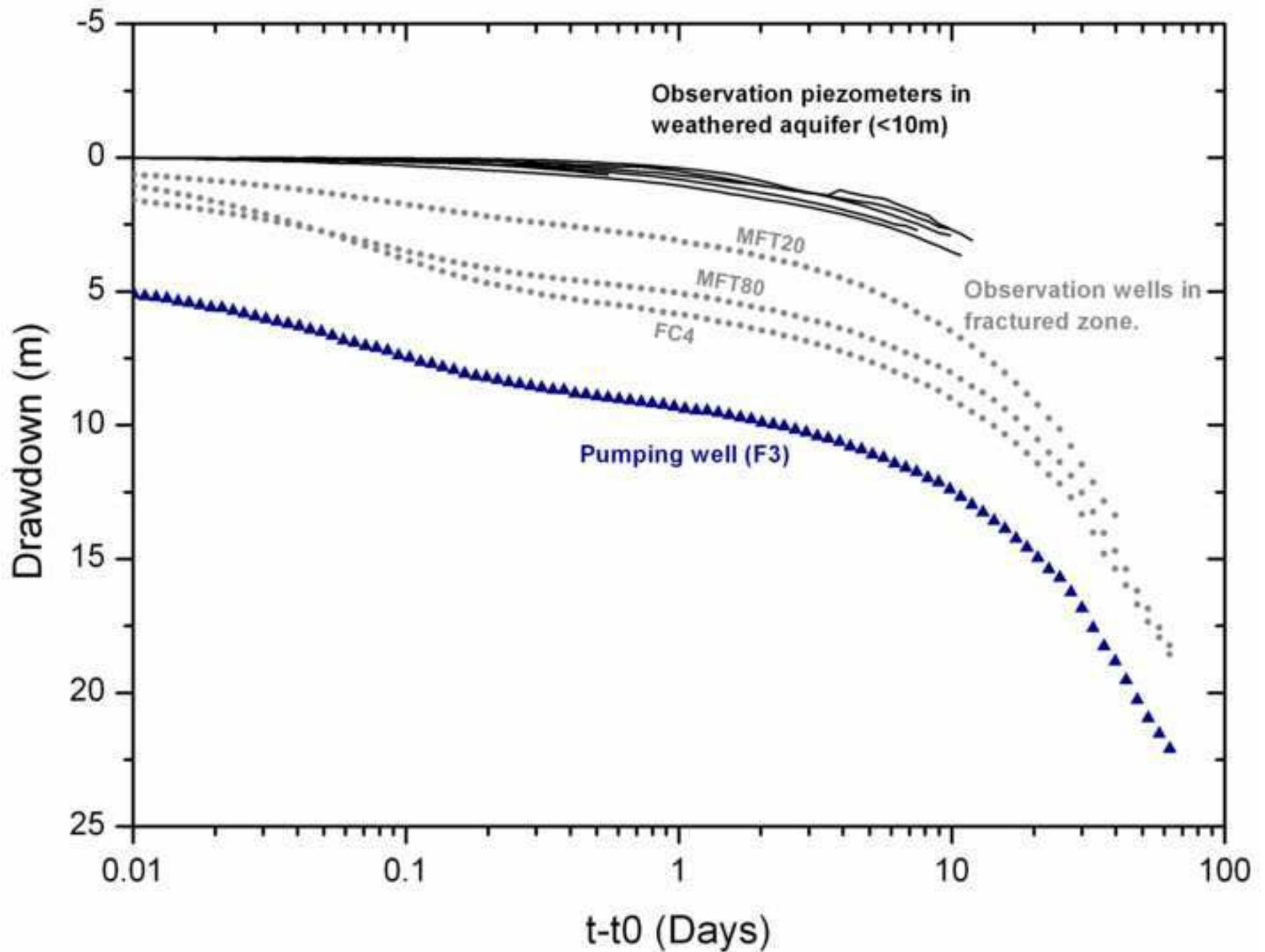
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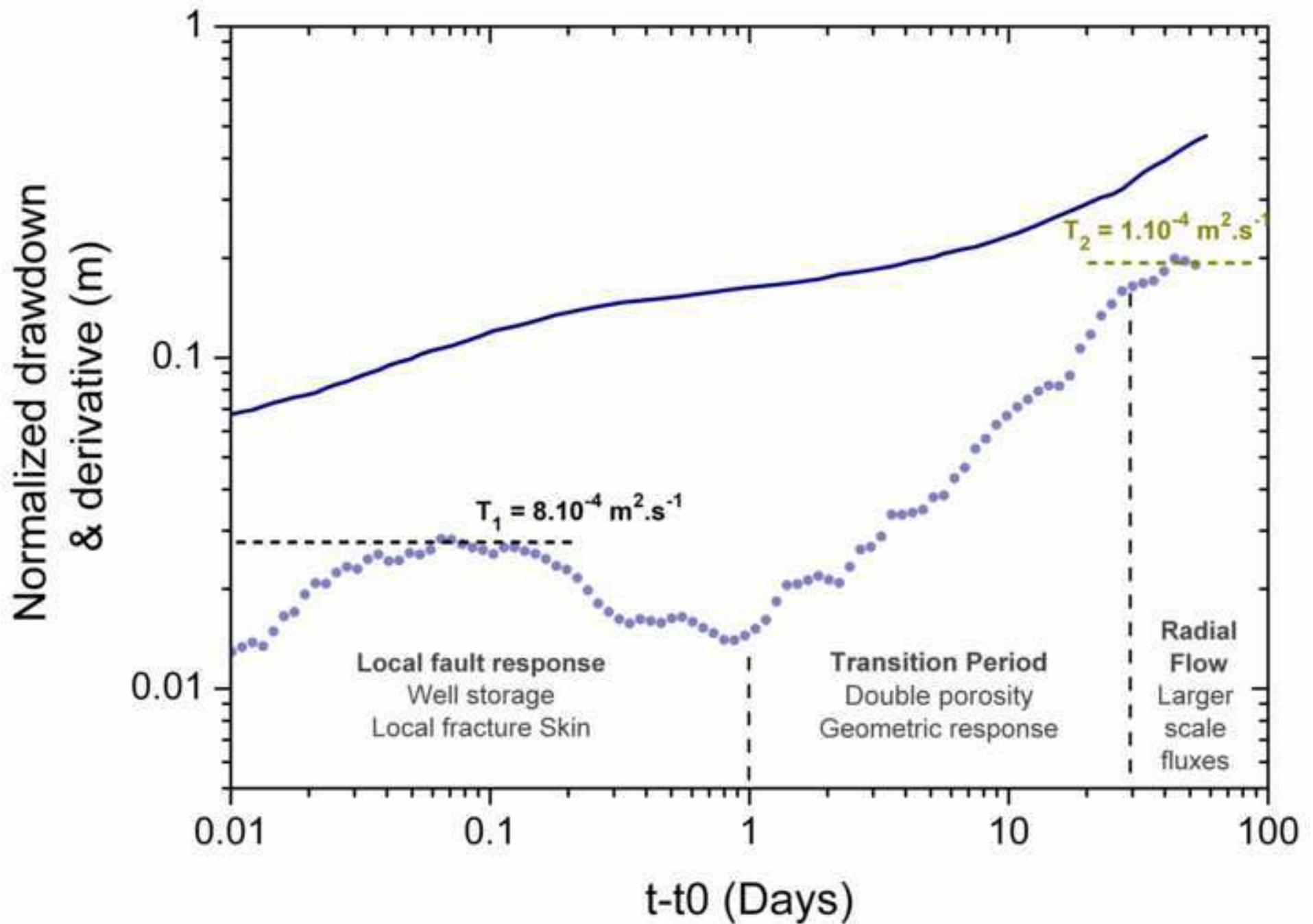




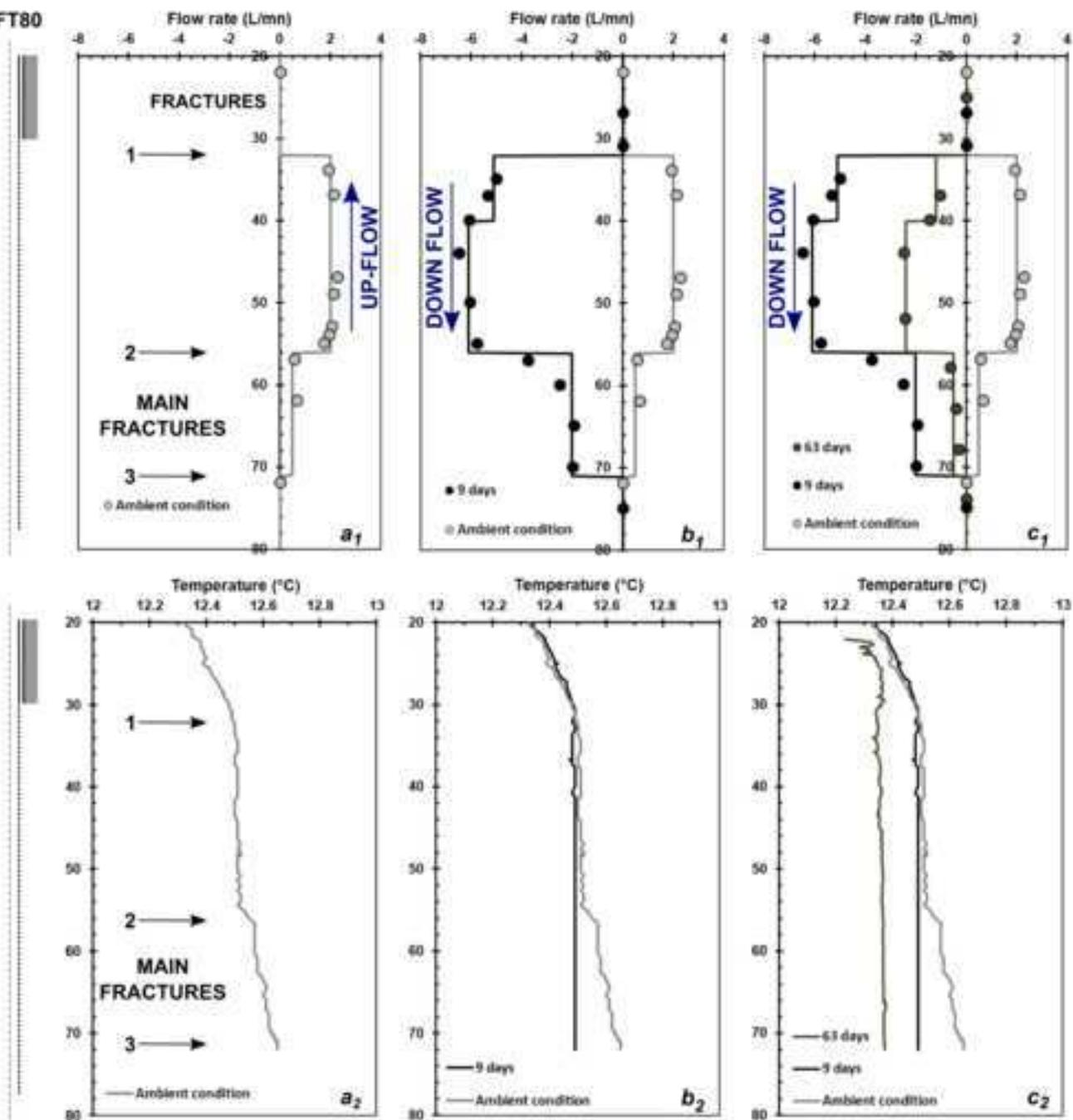


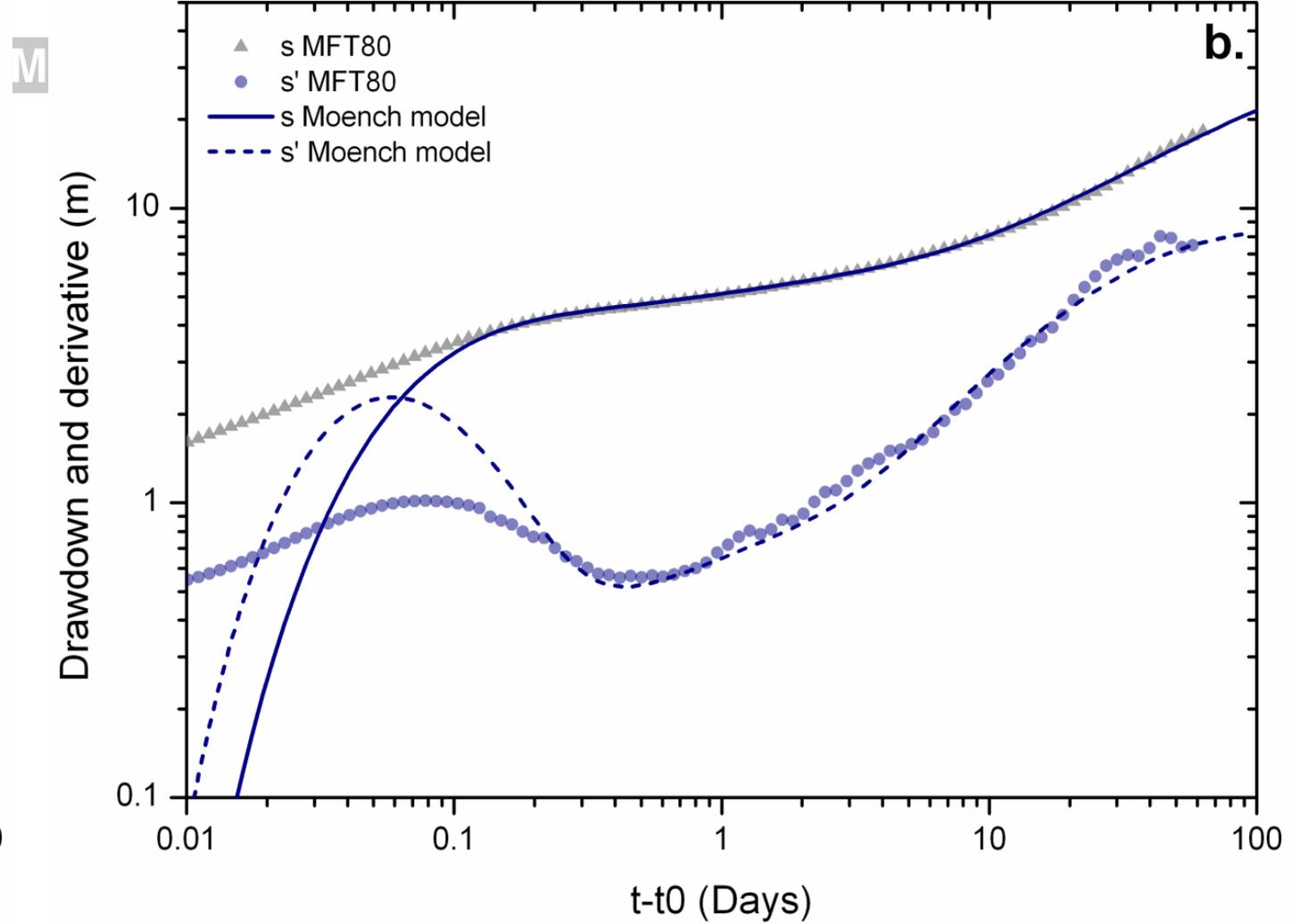
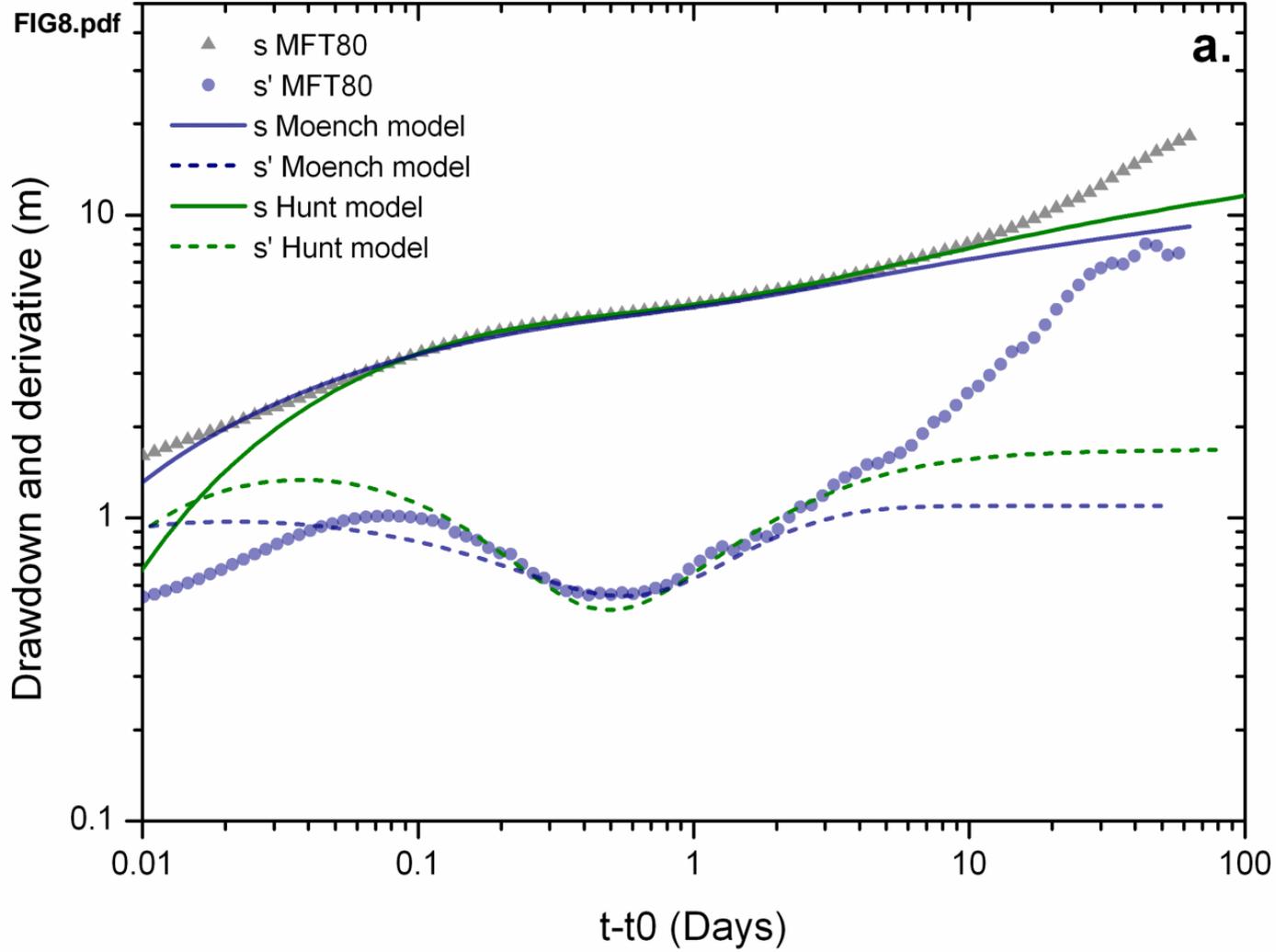


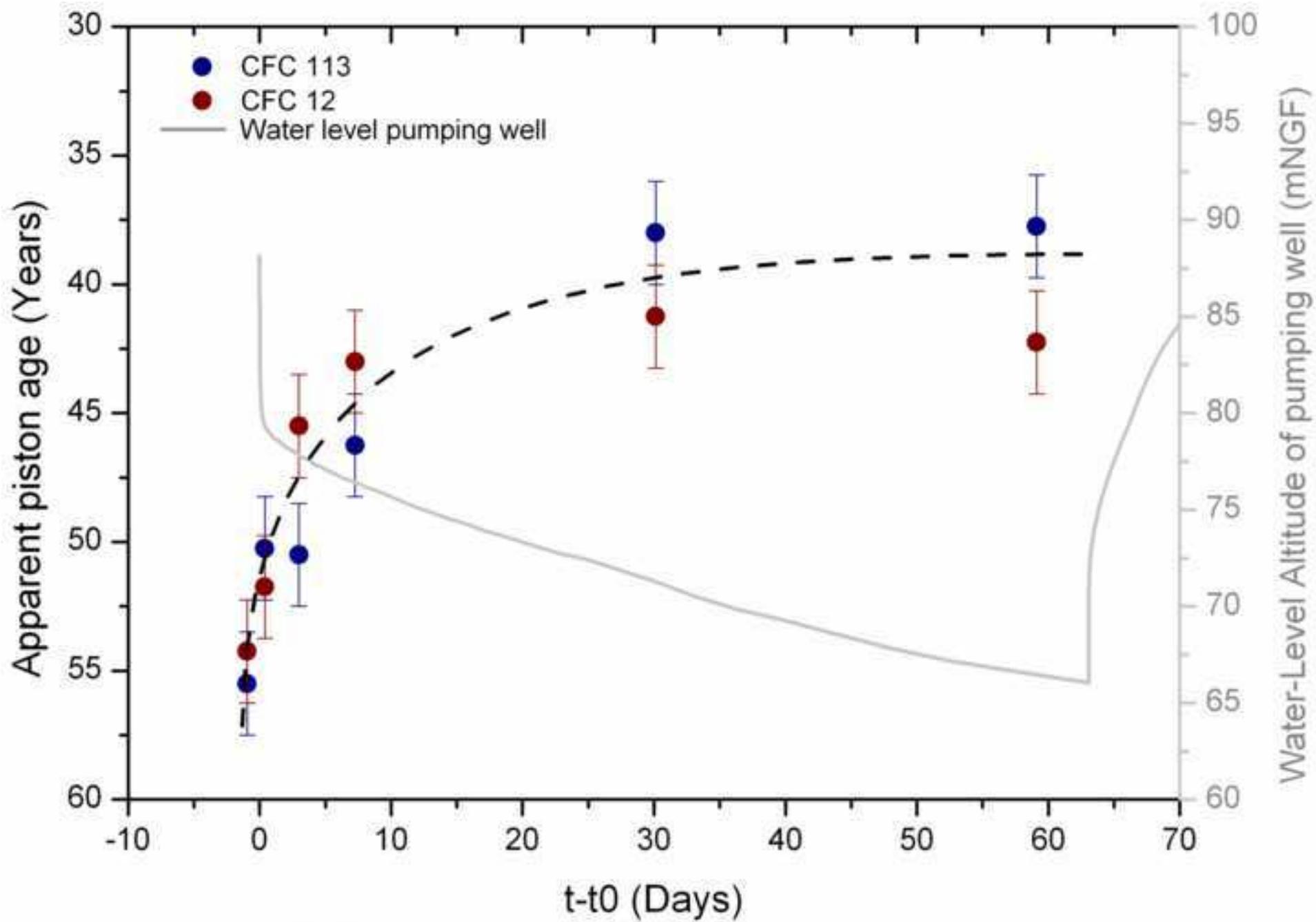


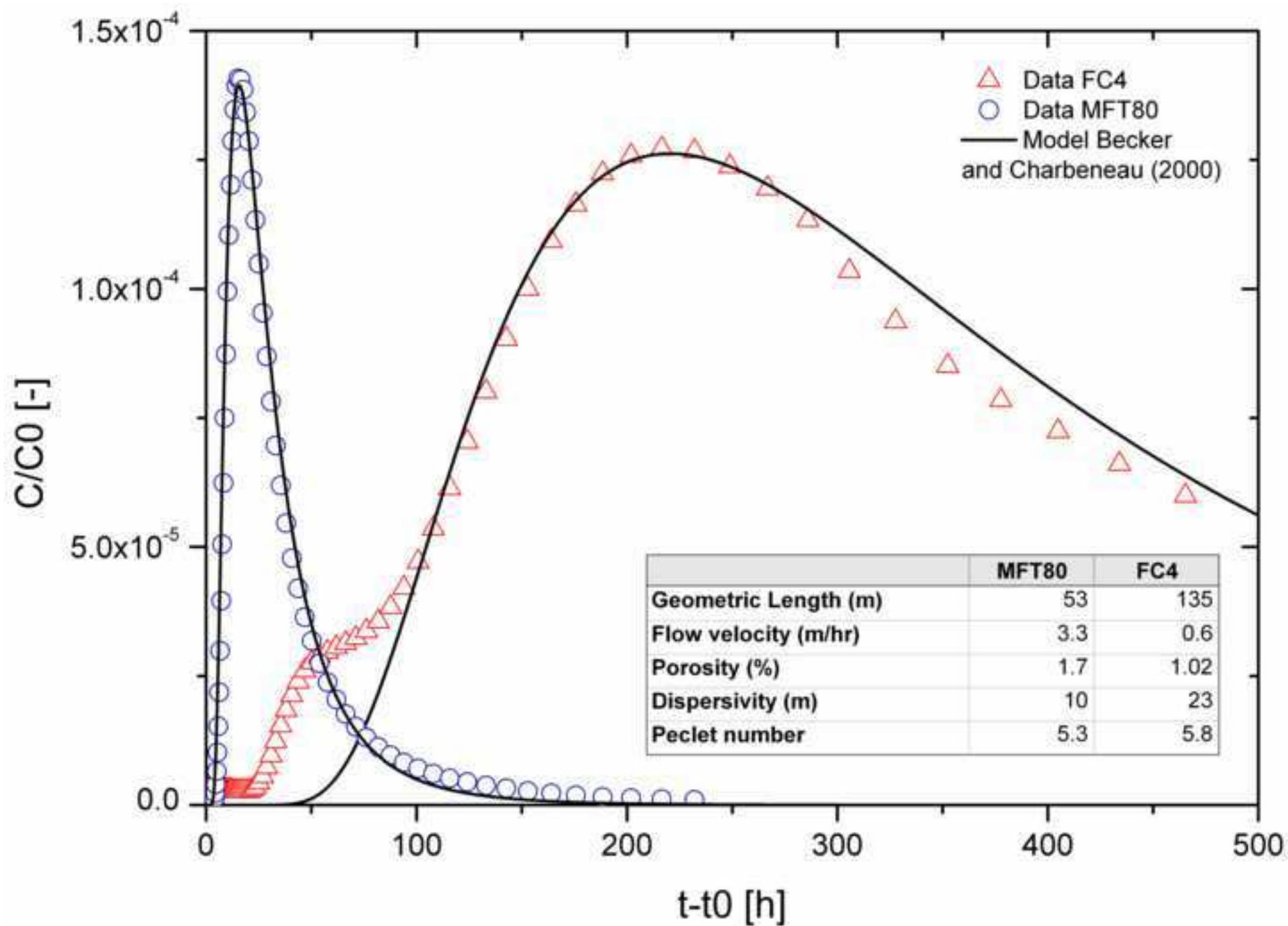


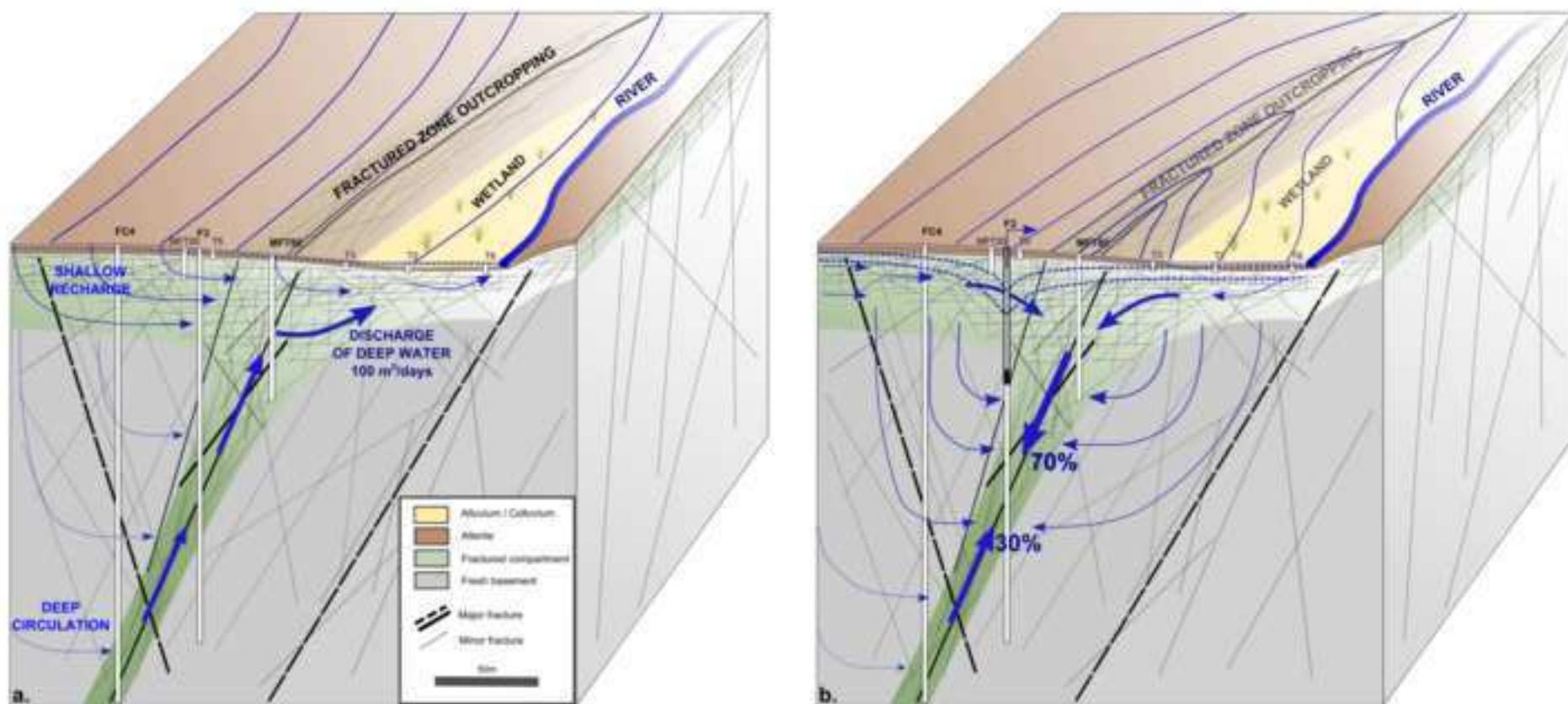
MFT80











Well	X (LAMB93)	Y (LAMB93)	Z (a.s.l.)	Depth (m)	Geology	Slotted zone (m)	Main fracture depth (m)
F3	376280	6822515	93.53	216	Brioverian bed rock	30 to 216	110; 135 ;160; 169; 180; 192
FC4	376252	6822521	95.1	250	Brioverian bed rock	40 to 250	160; 204; 235
MFT20	376286	6822500	93.68	20	Brioverian bed rock	10 to 20	-
MFT80	376305	6822511	91.14	80	Brioverian bed rock	30 to 80	52; 69
T1	376350	6822537	88.22	6	Alluvial deposits (wetland)	1 to 6	-
T2	376353	6822504	88.27	8	Alluvial deposits (wetland)	2 to 6	-
T3	376329	6822490	89.57	6	Alterites	3 to 6	-
T4	376255	6822496	95.55	8	Alterites	4 to 8	-
T5	376294	6822485	93.54	7	Alterites	4 to 7	-
T6	376314	6822530	89.63	7	Alterites	2 to 6.5	-
T7	376273	6822531	93.02	9	Alterites	5 to 9	-
T8	376389	6822521	88.06	3	Alluvial deposits (wetland)	0.5 to 3	-

Well	Depth of fault zone (m)	Ambient Flowrate (L/mn)	Total transmissivity (m ² /s)	Fractured zone transmissivity (m ² /s)	Part of total productivity
FC4	235	3.5	1.3x10 ⁻³	9.8x10 ⁻⁴	75%
F3	90-116	3.5	1.8x10 ⁻³	8.8x10 ⁻⁴	50%
MFT80	48-53	2	7.9x10 ⁻⁴	5.9x10 ⁻⁴	75%

Well	SF6 (pptv)	CFC-12 (pptv)	CFC-11 (pptv)	CFC-113 (pptv)
F3	0	50.13	6.03	14.47
FC4	0	19.85	5.83	31.04
MFT20	0.87	48.29	6.64	21.48
MFT80	0.5	52.93	5.11	24.22
T's (mean)	2.79	458.79	271.52	56.66

Wells	Analytical models	Fault aquifer		Blocks parameters		Superficial aquifer			Error
		T (m ² /s)	S (dless)	Kb (m/s)	Sb (1/m)	T0 (m ² /s)	Sy (dless)	Kv (m/s)	RMSE [m]
F3	Moench early time	7.00E-04	-	2.47E-08	2.62E-04	-	-	-	0.98
	Hunt early time	4.79E-04	-	-	-	8.13E-05	-	-	0.55
	Moench global	1.05E-04	7.00E-03	-	-	-	-	-	0.95
MFT80	Moench early time	7.38E-04	7.00E-04	1.34E-09	1.15E-05	-	-	-	0.59
	Hunt early time	4.84E-04	1.80E-03	-	-	8.10E-05	0.02	1.09E-07	0.37
	Moench global	9.03E-05	1.75E-03	1.28E-08	1.18E-03	-	-	-	0.56
FC4	Moench early time	6.25E-04	8.40E-04	8.47E-10	9.84E-06	-	-	-	0.93
	Hunt early time	3.87E-04	1.61E-03	-	-	6.94E-05	0.02	8.00E-08	0.21
	Moench global	1.13E-04	1.61E-03	8.15E-09	6.53E-04	-	-	-	0.57
MFT20	Moench early time	6.02E-04	1.05E-02	3.35E-08	2.62E-04	-	-	-	0.69
	Hunt early time	7.27E-04	1.17E-02	-	-	5.79E-05	0.05	8.04E-07	0.19
	Moench global	9.78E-05	7.00E-03	6.33E-08	3.07E-03	-	-	-	0.57

- 1 We propose hydrogeological conceptual model of fault aquifer in crystalline basement.
- 2 We characterize interactions between a fault aquifer and surrounding compartments.
- 3 Sub-vertical fault resource is strongly dependent on superficial aquifer storage.
- 4 We estimate groundwater resource availability.

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