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**Coupling fracture facies with in-situ permeability measurements to generate stochastic simulations of tight carbonate aquifer properties: Example from the Lower Cretaceous aquifer, Northern Provence, SE France**

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20           **Coupling fracture facies with in-situ permeability**  
21           **measurements to generate stochastic simulations of tight**  
22           **carbonate aquifer properties: example from the Lower**  
23           **Cretaceous aquifer, Northern Provence, SE France.**

24

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32

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34   *reservoir, carbonates*

35

36           **Abstract**

37   The relationships between fracture facies and permeability distribution have been explored  
38   using a well-constrained 3D implicit structural model of hemipelagic low porosity/low  
39   permeability carbonate from the Northern Provence region, SE France. Fracture and  
40   permeability facies were determined using an extensive dataset of 99 hydrogeological  
41   boreholes wells.

42   Data processing was undertaken using a step-by-step approach, involving: i) identification of  
43   the fracture facies based on well logs detailing structure and stratigraphy ; ii) determination of

44 permeability facies from the a priori correlation between the dimension of the hydraulic  
45 radius of influence (deduced from slug test analyses) and the type of reservoir heterogeneity  
46 (fissure, fracture, fault zone, etc.); iii) three dimensional plot of fracture and permeability  
47 facies in the geological model using a variographic analysis of data.

48 Thirty-three sequential indicator simulations (SIS) based on geostatistic analyses were  
49 realised on both fracture and permeability facies. Finally, a connectivity algorithm was  
50 developed to compute the probability of connection between selected infiltration areas and the  
51 major aquifer springs via moderate-to high-permeability geological bodies.

52 Key results are: i) fault zones have a greater role in controlling permeability facies  
53 distribution than on fracture facies repartition; ii) there is little correlation between  
54 permeability and fracture facies distributions ; iii) connectivity results highlight the  
55 compartmentalization of aquifers in the Cadarache area, the extensions of permeable  
56 geological bodies being limited by the N130 faults.

57

## 58 **1. Introduction**

59 Understanding fluid flow in aquifers is of primary importance in the context of current water  
60 demand increases and in tracking the subsurface spread of materials introduced into the  
61 subsurface, including pollutants. Accurate flow predictions require key geological  
62 heterogeneities that affect the aquifer at different scales to be correctly identified and  
63 represented in flow models. To a first approximation, aquifers are defined by the distribution  
64 of host rock (or matrix) petrophysical properties (porosity and permeability) that can be  
65 represented in flow models by flow units that correlate with rock type and depositional facies.  
66 Such porous aquifers differ from fractured or karstified aquifers [1] where fracture and cave  
67 conduits may or may not be localized in specific rock types. The reality of aquifers containing  
68 fractures and caves can be complex. Workers have used double [2] or even triple porosity

69 models [3, 4] where flow heterogeneity reflects variability in both the matrix and some  
70 combination multi-scale structural objects. Often these models do not take completely into  
71 account the subsurface reality which can be partly due to the presence and the effectiveness  
72 (or not) of structural features. For example Rzonca [6] studied a highly productive carbonate  
73 aquifer in the Holy Cross Mountain in Poland. He demonstrated that the matrix in this  
74 example is inactive and pointed out the singularity of this situation - as usually the matrix act  
75 as storage capacity in carbonate rock massifs. In the oil and gas industry, unconventional and  
76 fractured reservoirs with low matrix porosity and permeability can release huge amount of  
77 fluids [7]. This experience highlights the importance of both very small pores ranging down  
78 to the nanometre scale [8, 9] and fracture populations that can be very complex [10]. Small  
79 faults and populations of opening-mode fractures can vary markedly in length, height (and  
80 heights pattern), aperture, the degree and pattern of mineral fill, as well as in density and  
81 spacing patterns and these relations can vary systematically with with the stratigraphy [for  
82 example, 11]. Such fracture population complexity could affect fluid flow. Guerriero et al.  
83 [12] in their study of carbonates rocks from the Sorrento Peninsula (Italy) show a hierarchical  
84 organisation of permeable structures in a reservoir analogues and discriminate the relative role  
85 of these structures in fluid flow. Therefore it remains challenging to represent these highly  
86 heterogeneous media at depth when only fragmentary data are available. The question of how  
87 to represent the dimensions of these heterogeneities in acquifers can benefit from the use of  
88 tools developed in the petroleum industry, such as 3D modelling and geostatistics that can  
89 provide an interesting alternative to simpler conceptual models. The generation of multiple  
90 equiprobable models in a well-constrained structural framework will lead to a better  
91 representativity of the subsurface heterogeneity. The applicability of these methods to  
92 groundwater modelling was broadly investigated in several papers [13, 14]. Here to better  
93 account for structural and petrophysical heterogeneities we use a three-dimensional model to

94 represent the reservoir architecture, including stratigraphic surfaces and faults, to describe the  
95 Lower Cretaceous limestone aquifer in Northern Provence. Our pixel-based stochastic  
96 method, such as the one used in sedimentary facies simulation, is seldom considered to model  
97 faults and fractures in reservoirs [14, 15]. These methods require generating a large number of  
98 equiprobable models to be reliable, which is time consuming and requires high performance  
99 software. In this paper, we address the question how stochastic reservoir simulation can be  
100 used to predict dimension, location and degree of connectivity of flowpaths in a tight  
101 carbonate aquifer by defining an approach that allows restricting the numerical flow  
102 calculations to a reduced number of significantly different cases of static reservoir  
103 heterogeneities.

104

## 105 **2. The Durance hemipelagic carbonates hydrogeological context**

106 The area of interest is located 80 km North of Marseille, in the Durance Valley (SE France,  
107 Fig. 1). Its paleogeographic location is in the southern limb of the Vocontian Basin, where  
108 Berriasian to Valanginian sediments are interpreted to have been deposited in a slope-to-basin  
109 transition zone [16, 17]. Previous work of Bruna et al. [18] defined 2 groups of formations:  
110 mud-dominated (Upper Berriasian - Mid-Lower Valanginian age) 150 m thick, and grain-  
111 dominated (Mid-Lower Valanginian – end of Lower Valanginian age) 130 to 150 m thick  
112 (Fig. 1). Mud-dominated formations were deposited in low hydrodynamism environments,  
113 and are characterised by a low 0 to 4% porosity micritic matrix. This group is composed of 2  
114 sedimentary formations:

- 115 - Meyrargues Limestones Formation (1) is composed of metric to plurimetric grey to  
116 yellow planar beds, alternating with centimeter to pluri-centimeter thick laminated  
117 purple colored beds.
- 118 - Beaumont-de-Pertuis Limestones Formation (2) displays metric light brown nodulous

119 beds alternating with meter to plurimeter thick yellow platy-limestone beds.  
120 Grain-dominated formations correspond to higher energy environments and are typically  
121 characterised by significantly larger porosities up to 9%. This group is composed of 2  
122 sedimentary formations:

- 123 - Saint Paul-lès-Durance Limestone Formation (3) is composed of pluri-centimeter to  
124 meter thick beds that form pluri-decameter lens-shaped bodies.
- 125 - Saint Eucher Limestones Formation (4) is composed of gray limestone made by one  
126 meter thick sand waves stacking.

127

128 The present day structure of the South-East of France records a complex and polyphased  
129 tectonic history. Deformation of the sedimentary succession produced E-W oriented anticlines  
130 separated by quiet zones [19] and major N030 transfer faults which have been reactivated  
131 during polyphase deformation (Middle Durance Fault). The studied aquifer is located in a low  
132 deformation zone of the northern flank of the Vautubière Mountain (E-W - Southward  
133 verging anticline). This zone is affected by series of N120-N140 and N040-N060 faults.  
134 N120-N140 faults lengths (map traces) vary from 1.8 km to more than 6.5 km, and fault zone  
135 spacing is 1 to 2 km. These faults display strike-slip movement with normal apparent offsets  
136 [20, 21]. In the *CEA Cadarache* area, faults bound a dissymmetric graben filled with Tertiary  
137 and Quaternary deposits. N040-N060 faults are divided in two classes: major faults displaying  
138 lengths exceeding 1000 metres and a 1064 metres spacing and minor faults displaying lengths  
139 smaller than 150 metres and a 260 metres spacing. All of the N040-N060 faults display strike-  
140 slip movements with a slight vertical component associated with low vertical offsets. The  
141 fracturation was studied on two quarry outcrops located in the Abéou Valley (Fig. 1). Two  
142 families of plurimetric open fractures respectively N040-N050 and N140 were measured. The  
143 fractures spacing varies from 10 centimetres to more than three metres.

144

145 Upper Berriasian to Lower Valanginian carbonates host a regional aquifer drained by four  
146 perennial springs with a maximum high-water outflow of  $300 \text{ l} \times \text{s}^{-1}$ . Three springs outflow in  
147 the Abéou River, which is a Durance's tributary. Drilling of more than 300 piezometric wells,  
148 by the *CEA Cadarache* (set on the aquifer watershed; Fig. 1), identified three reservoir units:  
149  $\approx 12$  m thin shallow Quaternary alluvium, 20–250 m thick Tertiary clastic deposits, and  
150 1200 m thick Cretaceous-Jurassic limestone. In the Cadarache Valley, sectors of interest  
151 correspond to Quaternary and Tertiary deposits. According to Cartalade [22] and to  
152 Guyonnet-Benaize [20], the Tertiary and the Quaternary aquifers are considered highly  
153 permeable reservoirs ( $10^{-7}$  to  $>10^{-4} \text{ m.s}^{-1}$ ). Possible connections between the Tertiary aquifer  
154 and the deep Cretaceous-Jurassic aquifer may occur in the study area. Hydrogeological  
155 boundaries in the study area are formed by the Boutre Fault, Mirabeau-Vautubière Anticline  
156 (Fig. 1), Triassic argillaceous and evaporitic layers, and the Callovian–Oxfordian marls are all  
157 considered impermeable boundaries. The lower Cretaceous aquifer, which is the main focus  
158 of this study, is interpreted to be exclusively controlled by fractures. Large exposures of the  
159 lower Cretaceous carbonate series which outcrop in the Abéou valley and ninety-nine wells  
160 that give access to the aquifer geology and hydraulic properties at depth were used in this  
161 work (Fig.1).

162

### 163 **3. Method: Three-Dimensional coupling of geological and hydrological** 164 **data**

165

#### 166 **3.1. Building the three-dimensional structural model**

167 The implicit modeling method [23] was used to build the 3D structural model. Implicit  
168 surfaces (faults or stratigraphic units) are isovalues of a 3D scalar function field [24, 25]. The

169 modeling is performed in a defined volume of interest (VOI), in which a UVT Transform®  
170 algorithm converts x,y,z coordinates into u,v,t coordinates, where (u,v) isovalue planes  
171 represent the stratigraphy and t a pseudo-time (chronology). Therefore, modeled horizons are  
172 then considered as paleo-geochronological surfaces. Several authors [26-28] have pointed out  
173 the importance of representing complex geological structures for reliable groundwater flow  
174 studies. In this paper, the used modeling approach allows consistent modeling of complex 3D  
175 grids embedding “Y” faults and other complex tectonic structures by compiling different data  
176 sources in a unified framework. The SKUA® (Subsurface Knowledge Unified Approach)  
177 plug-in integrates the UVT technology and was used in the present study.

178 The 3D model dimension is  $21 \times 8 \times 0.5$  kilometres. The resolution of the structural model  
179 was defined at 70 m in aerial and vertical directions. The 3D environment is limited by the top  
180 of the Callovian-Oxfordian surface (500 to 700 metre depth), considered as the bottom  
181 boundary of the model according to Guyonnet-Benaize [20], and by the highest point of the  
182 topography ( $Z_{max} = 555$  metres, northern flank of the Vautubière Mountain) considered as  
183 the top of the model. This model is limited Southward by the Vautubière Mountain and  
184 Northward by the Verdon River (Fig. 1). It is limited Eastward by the Ginasservis Graben and  
185 Westward by the Mirabeau Anticline (Fig. 1). The model is centered on the Cadarache Valley  
186 and includes the Abéou Valley and the Southern zone of Verdon River (Cadarache Federal  
187 Forest). The dataset contains 1D, 2D and 3D data. The 1D data are lithostratigraphic sections  
188 and outcrop observations from the Abéou Valley and from the Boudre Fault zone (Fig. 1).  
189 Seven lithostratigraphic sections (ranging from 10 to 130 m thick) have been logged in detail  
190 (1:100) in the Abéou Valley sector. Due to shallow dip of the Lower Cretaceous sedimentary  
191 strata, the complete stratigraphic succession has never been sampled. Nevertheless, all  
192 contacts between two successive units were observed and a synthetic log was proposed (Fig.  
193 1).

194 Marker horizons in wells from Cadarache Valley supplement these data. The well data  
195 contains information of Tertiary/Quaternary to Secondary rock contacts. Such contacts were  
196 used as marker horizons in order to constrain the base of the Tertiary/Quaternary erosive  
197 surface. All data have been referenced in the field using the Global Positioning System  
198 (WGS84) with a horizontal precision less than five meters. Location data were converted into  
199 the local coordinate system (Lambert III).

200 The 2D data comprise a *CEA Cadarache* map, two BRGM geological maps of Pertuis [29]  
201 and of Tavernes [30], and an accurate geological map at 1:5000 centered in Abéou Valley and  
202 in the Boudre fault (Fig.1).

203 Two hundred and fifty four samples were collected from lithostratigraphic sections or  
204 randomly sampled in the field. Petrographic studies on each sample were undertaken in order  
205 to describe and map sedimentary facies types and to define petrophysical properties [18]. A  
206 series of 2 regional and 3 local balanced cross-sections were integrated to the 3D structural  
207 model. The 3D data comprises a compilation of point-sets and surfaces extracted from  
208 existing models [20] and corrected with new data detailed above.

209 A grid was then generated to be consistent with field observations conducted on the outcrops.  
210 Consequently the dimensions of each grid cell are  $11 \times 11 \times 10$  metres.

211

### 212 **3.2. Geostatistical analyses**

213 Stochastic simulations aim at generating several models of property or facies, conditioned to  
214 available data, for statistical analyses and risk assessment. In this paper, simulations were  
215 performed following the SIS algorithm (Sequential Indicator Simulation) [31]. The SIS  
216 method considers discrete variables. These variables are first kriged, then the algorithm  
217 chooses an occurrence probability for the considered variable on each cell of the gridded  
218 model. Advantages of this method are: fast realisation, high potential for matching hard

219 conditioning data, and capacity to reproduce different facies geometries in a model. The SIS  
220 presented in this paper is conditioned to well data only (hard conditioning data), variograms  
221 and global proportions.

222

223       • **Fracture facies**

224 An extensive database of 99 wells drilled between 1984 and 2010 (part of a hydrogeological  
225 survey network) was provided by the *CEA Cadarache*. These wells are partially screened and  
226 these intervals are mainly shallow (mean depth is 75.4 metres with a standard deviation of 57  
227 metres). Check-in quality (camera) and re-habilitation of wells were done every year since  
228 2009. Each well has an associated drilling log, its resolution and precision dependent on the  
229 operator, the drilling type (destructive or cored) and the location of the well. Several well  
230 reports contain additional information such as physical parametres of the drilling machine  
231 (velocity of the drilling tool = VIA), detailed well logs, identification of major structures  
232 (karst and faults), camera investigation, core investigations, geotechnical tests (Lefranc,  
233 Lugeon tests) and estimation of the permeability (Cassan's method) [32].

234 A first step analysis of well logs and reports allowed identifying three main fracture facies:

- 235       • Facies FF1 is a non-fractured facies. FF1 has been assigned when well logs describe  
236       the host rock (fracture devoided or containing negligible amount of sealed fracture);
- 237       • Facies FF2 is a fractured facies composed of various fracture types and sizes,  
238       including faults.
- 239       • Facies FF3 is a karstified facies, represented by empty or filled-with-clay cavities.

240 The main challenge of this first step analysis was to synthesize and to attribute a degree of  
241 confidence to well logs and descriptions. In order to evaluate this parameter, the study  
242 focused on both the interval length where facies is defined and the available additional  
243 information (Fig. 2). A score of 0 to 1 was attributed to each facies interval and is summarised

244 in Table 1. For instance, if the description of FF1 in a few metre long intervals is consistent  
245 with a camera investigation and/or drilling velocity, it is given a better mark than the same  
246 facies defined on a hundred metre long interval without any additional information.

247 When the mark is lower than 0.5, the facies description was not considered with confidence,  
248 and was identified as a null value (-99999).

249 Some log descriptions are very accurate and allow the separation of fractures in regard to their  
250 dimension. Consequently, the FF2 facies was divided in two additional facies:

- 251 • Facies FF2a is a fissure facies that contains multi-centimetre long fractures with small  
252 aperture (generally >0.5 cm and considered as matched by drilling operators);
- 253 • Facies FF2b is a fracture facies that contains multi-decimetre to metre-long fractures  
254 with large aperture (generally >1 cm and considered as open fracture by drilling  
255 operators).

256

- 257 • **Wells permeability**

258 The hydraulic property of wells used for fractures facies identification has been investigated  
259 during two hydraulic slug test campaigns in 2010 and 2012. Slug tests were used to evaluate  
260 local hydraulic properties of the aquifer. The protocol is to quickly change the static level of  
261 an aquifer by injecting a known quantity of water [33] and to monitor the return to the static  
262 water table. This study used the Cooper-Papadopoulos-Bredehoeft solution available on the  
263 Hytool® software [34], to re-interpret the variation of the water level versus time and to  
264 estimate the transmissivity and the storage of the aquifer. This solution assumes that the tested  
265 aquifer is an ideal porous media with a radial transmissivity and consequently could be  
266 considered as an infinite medium. In addition, Bredehoeft and Papadopoulos [35] solution  
267 considers aquifers with very low storage capacity (tight rocks). This solution also gives an  
268 estimate of the storage coefficient of a given aquifer by taking into account the well

269 equipment compressibility [36]. The method used is consequently more accurate than a  
270 simple Cooper solution. Permeability values were deduced by dividing the transmissivity with  
271 the well screen thickness.

272 The fracture dataset defined in wells was formatted to compare the fracture facies with the  
273 well permeability. Permeability was averaged from slug test results on the whole screened  
274 interval of each well. Well screen thickness is highly variable (standard deviation of  
275 approximately 31 metres) and induces significant bias on the permeability estimation. To  
276 reduce this bias, the following two-step protocol was used:

277 1) Work of Yang and Gates [37] demonstrates that the slug test radius of influence can be  
278 correlated with particular geological features. Consequently, classes of permeability ranging  
279 from  $10^{-14}$  to  $>10^{-5}$  m.s<sup>-1</sup> has been defined as following:

- 280 • CK1 corresponds to permeability values of  $10^{-14}$  to  $10^{-11}$  m.s<sup>-1</sup> representative of matrix  
281 effects (Fig. 3);
- 282 • CK2 corresponds to permeability values of  $10^{-10}$  to  $10^{-9}$  m.s<sup>-1</sup> representative of the  
283 fissure effects (Fig. 3);
- 284 • CK3 corresponds to permeability of  $10^{-8}$  to  $10^{-6}$  m.s<sup>-1</sup> representative of fracture effects  
285 (Fig. 3);
- 286 • CK4 corresponds to permeability values above  $10^{-5}$  m.s<sup>-1</sup> representative of fault and  
287 karst effects (Fig. 3).

288 2) These classes were compared with the fracture facies classification for each well. The  
289 method was to attribute the permeability value measured at the screen interval scale to a facies  
290 interval (Fig. 2). When the measured permeability did not match any facies described in the  
291 well, a null value was attributed to the entire well (Fig. 2).

292 The main caveat in this method was that the reduction of the intervals induced large decreases  
293 of available point data for further simulations. This is mainly due to the quality of the well

294 geological reports. For instance, if a well was described with open fractures on the entire  
295 screened interval and a permeability of  $10^{-12}$  m.s<sup>-1</sup>, the well geological report was considered  
296 inconsistent. In order to increase the sampling rate, the matrix hydraulic properties were  
297 introduced into the dataset. When the matrix was identified with a high degree of certainty  
298 (occurrence probability over 0.6, see section 3.2.1) this facies was assigned a  $10^{-11}$  m.s<sup>-1</sup>  
299 permeability (lowest dataset value).

300

### 301 **3.3. Comparison of simulations with field data**

302 Thirty-three SIS simulations were generated for fracture and permeability facies. These  
303 simulation, analysed on one E-W cross-section and on a horizontal map of the top of the  
304 model were based on variogram analyses [31, 38, 39]. Different experimental variograms are  
305 computed and analysed in different directions to capture the facies anisotropy. Gringarten and  
306 Deutsch (2001) proposed an integrated protocol to analyse variograms. This approach was  
307 used in this paper to perform the variogram analyses. Variogram ranges represent an averaged  
308 estimate of facies dimensions [40]. The spatial correlation is defined at short (range,  
309 correlation) but also at long distance (sill, simple variance). Analysing these parameters and  
310 the different variogram allows the geological structure geometries and organisation to be  
311 estimated.

312 A “connectivity algorithm” was developed to evaluate connectivity between selected areas in  
313 the fractured geobodies, identified in the stochastic modeling, and the major springs. This  
314 algorithm considers the degree of static connectivity, the dimensions and the rank of  
315 connected geobodies. Nevertheless, several other definitions exist [41, 42] and a review of  
316 connectivity definitions is proposed in Renard and Allard [43]. In this study, the static  
317 connectivity corresponds to the case where two cells with the same facies are connected if a  
318 continuous path (straight or tortuous) exists between these cells. In three dimensions, the

319 connectivity is effective if only two surfaces of the cells are linked. The interface between  
320 Tertiary/Quaternary units and Cretaceous-Jurassic units was considered here as connected but  
321 recent work conducted on site tend to show that this hypothesis may not be verified  
322 everywhere.

323

## 324 **4. Results**

325

### 326 **4.1. Three-dimensional structural model**

327 The model contains 25 faults observed and measured in the field. Additional faults were  
328 observed but not considered here because of their poor surface expression or their relatively  
329 insignificant impact (offset) on the sedimentary succession. Vertical extent of these faults has  
330 been estimated based on the map trace length, related offset and dominant direction of  
331 movement. The model shows that N050 oriented faults measured in the Abéou Valley display  
332 only a very slight offset.

333 This solution reflects the consideration of the fault movement and the geological map realised  
334 in the area of interest. This is not the case for N130 faults that display large vertical offset of  
335 100 to 400 metres.

336 The 3D structural model displays a contrast between the North and the South of the  
337 Cadarache Valley. Tertiary or Quaternary units seal the faults. This results in a duality  
338 between the south of the area of interest where faults are observable (where the Cretaceous  
339 rocks are exposed) and the northern part where the faults affecting Mesozoic terranes are  
340 under-cover (where the Tertiary or Quaternary rocks crop out).

341

342 Eight stratigraphic horizons starting from the top of Callovian-Oxfordian layer to the  
343 topography are represented. The Secondary sedimentary succession is conformable and shows

344 little thickness variation in the whole model. This is consistent with the present-day structural  
345 style of Provence, where fold and thrust belts are separated by wide, tabular, relatively  
346 undeformed zones [19].

347 The Lower Cretaceous layers are relatively thin (< 350 m thick) compared to the whole  
348 Mesozoic succession (from 2000 to 2500 metres thick from base Triassic to the top of the  
349 Lower Cretaceous). This implies that the Lower Cretaceous stratigraphy needs to be carefully  
350 modelled to provide an accurate framework for stochastic simulation process. SKUA®  
351 software allows modulation of the data point weight with the fitting factor. Using a high  
352 fitting factor, modeled horizons match very well the point data rather than with a low fitting  
353 factor where horizons are smoothed. Thus, outcrop and cross section data points were  
354 implemented with a very-high fitting factor in order to tightly constrain horizons close to  
355 these points. This process sometimes produces artifacts at the data location that have been  
356 corrected manually by a local smoothing of the surfaces.

357 Figure 4, shows a thickness map of Formations (1), (2) and (3) and the histogram of thickness  
358 value distribution.

- 359 - Formation (1) displays the lowest standard deviation on the thickness values (8 m).  
360 The median value (49 m) is consistent with the 50 m observed value in the Grignantes  
361 quarry [18].
- 362 - Formation (2) shows the highest value of standard deviation (16 m). Nevertheless, the  
363 median value is here again consistent with outcrop measurements. The standard  
364 deviation value for Formation (2) is explained by extreme values repartition  
365 emphasising boundary and fault effects.
- 366 - Formation (3) thickness median value (101 m) is slightly above the measured average  
367 value (80 m). This is consistent with previous interpretations of the depositional  
368 environment [18] and field observations. Indeed, Formation 3 was interpreted as

369 turbiditic-contouritic deposit by the previous authors (Fig. 4)  
370 These deviations are linked to the modelling process and mainly to the chosen resolution  
371 defined in the implicit modelling workflow. The provided thicknesses are in the same order of  
372 magnitude than the measured sections in the field. This makes the 3D structural framework  
373 consistent with the geological available information.  
374 Appropriate cell dimensions were chosen in regard to stochastic simulations. Cells measure  
375  $11 \times 11 \times 10$  metres with a total volume of more than 89 million of cells. Because the Lower  
376 Cretaceous is the target of the present study, the Upper Jurassic successions were substracted  
377 from the grid. Stochastic simulations were not computed for Tertiary and Quaternary units  
378 (excluded as a region in the grid) but these volumes were afterwards used in the connectivity  
379 calculations as a one-cell volume connected with underlying units. The sampling of wells in  
380 the 3D grid was established in each cell centre along the well log. Fracture facies simulations  
381 have been performed with 2278 samples and permeability simulations with 878 samples.

382

#### 383 **4.2. Spatial anisotropy and variogram analyses**

384 Global proportions calculated from well data are the following: non-fractured facies (FF1) is  
385 42.8%, fractured facies (FF2) is 55.7% and karstified facies (FF3) is 1.5 %; low permeability  
386 (CK1) is 52.1%, moderate permeability (CK2) is 21.9%, high permeability (CK3) is 20.4%  
387 and very high permeability (CK4) is 5.6%.

388 Following the SIS algorithm, fracture facies were investigated with three variables (FF1 to  
389 FF3). Permeability facies were provided with four variables (CK1 to CK4). Variograms were  
390 computed in the vertical and in several horizontal directions (N055, N068, N077, N090,  
391 N100, N110, N125, and N180; Table 2). Parametres of the ellipsoid issued from variogram  
392 modelling are: the first axis ( $Ra$ ), the second axis ( $Rb$ ) and the third axis ( $Rc$ ).

393

394 *1/ Fracture facies variograms:*

395 The spherical variogram model was chosen to fit experimental variograms (issued from  
396 dataset) of FF1-FF2-FF3 facies (Appendix 1). Sills vary widely for each facies and express  
397 large scale variability (zonal anisotropy). Due to the grid resolution and the isolated  
398 occurrence of karstified facies (FF3), the main structure displays a binary arrangement: when  
399 the non-fractured facies is expressed, the fractured facies is absent and conversely.

400 FF1 and FF2 vertical variograms displays an erratic behavior (Table 2) meaning that the sill is  
401 largely below the sampling variance. Such a behavior implies a high vertical continuity of  
402 FF1 and FF2 facies.

403 Therefore, the range of the variogram model was extended to a very high lag distance in order  
404 to reproduce the continuity effect. The horizontal variogram is erratic within the N068, N077,  
405 N090, and the N100 directions implying a lack of representative pairs of data points in these  
406 directions. Yet, the variability could be more important in these directions rather than in the  
407 other ones. N110, N125 and N180 directions show a well-expressed hole-effect (Table 2)  
408 indicating a cyclicity in the facies occurring in these directions. The ellipsoids of FF1 and FF2  
409 facies are oriented in the N055 direction (maximal correlation distance between pairs of  
410 points). Modelled geobodies emphasise an anisotropy where  $Ra = 2170$ ,  $Rb = 369$  and  $Rc =$   
411  $340$  for FF1 facies, and  $Ra = 2015$  metres,  $Rb = 369$  metres and  $Rc = 349$  metres for FF2  
412 facies (Fig. 5). The FF3 vertical variogram displays a similar behavior as previously observed  
413 in FF1 and FF2 but is smaller and rare in the model. Horizontal variograms highlight the low  
414 amount of available data points. Consequently, their behavior is erratic in each computed  
415 directions (Table 2). Geobodies issued from variographic analyses emphasise a marked  
416 anisotropy where  $Ra = 612$  metres,  $Rb = 369$  metres and  $Rc = 242$  metres (Fig. 5).

417

418 *2/ Permeability variograms:*

419 The exponential model was chosen to fit experimental variograms of CK1-CK2-CK3-CK4  
420 facies (Appendix 2). Vertical variograms of these facies display a sill largely below the  
421 sampling variance. The same processing as the one applied for fracture facies was used in this  
422 case.

423 The CK1 horizontal variogram (Table 2) displays an erratic behavior in N055, N068, N077,  
424 and N090. A slight hole-effect is identified in the N110 and N125 azimuths. The experimental  
425 variogram is slightly below the model in the N100 azimuth. This zonal anisotropy implies that  
426 the variability is not visible in such direction. The maximum range is reached for the N055  
427 variogram. The variability of range within this facies implies a geometric anisotropy for CK1.  
428 The variographic behavior is represented by an anisotropic ellipsoid with a  $Ra = 820$  metres,  
429  $Rb = 407$  metres and  $Rc = 260$  metres (Fig. 5).

430 The CK2 vertical variogram is under the variance sill (zonal anisotropy) on N055, N068,  
431 N077, and N090 azimuths. N110 and N125 directions display hole-effects behaviors. CK2  
432 horizontal variogram shows the same range in all directions (Fig. 5; Table 2). The  
433 representative ellipsoid is more isotropic than in the CK1 facies with a  $Ra = 497$  metres,  $Rb =$   
434  $490$  metres and  $Rc = 194$  metres (Fig. 5).

435 The CK3 horizontal variogram is erratic in the N068, N077, and N090 directions. N100 and  
436 N180 directions record a slight zonal anisotropy. The CK3 horizontal variogram (Table 2)  
437 displays a maximum range in the N055 direction. The ellipsoid representative of CK3 is  
438 clearly anisotropic with a  $Ra = 728$  metres,  $Rb = 498$  metres and  $Rc = 318$  metres (Fig. 5).

439 CK4 horizontal variogram is erratic in almost all directions due to the punctual and the non-  
440 abundance of data points. The Direction N180 displays a zonal anisotropy and allows fitting  
441 the range. CK4 experimental variogram (Table 2) has a single range. The ellipsoid is here  
442 again highly anisotropic with a  $Ra = 490$  metres,  $Rb = 97$  metres and  $Rc = 39$  metres (Fig. 5).

443

### 444 **4.3. Organisation of fracture and permeability facies stochastic maps**

445 Thirty-three fracture and permeability facies simulations have been performed to obtain a  
446 statistically representative population of 3D models. Fracture and permeability facies were  
447 investigated in details in an area that contained 50 of the 99 wells (Fig. 1). While simulation is  
448 a 3D process, a 2D view is shown, in order to observe the horizontal variability, the  
449 recurrence, and the dimensions of facies geobodies. In order to conduct such an analysis, the  
450 reference ellipsoid defined for each facies by the variographic analysis was compared to the  
451 facies maps resulting from the simulations (Fig. 6, summary in Table 3). In the case of  
452 fracture facies, the ellipsoid shape and orientation are the same between non-fractured facies  
453 (FF1 facies) and fractured facies (FF2 facies) (Fig. 6). Ellipsoids can be classified in three  
454 types: isolated ellipsoids; amalgamated ellipsoids representing large geobodies; and bands of  
455 amalgamated geobodies crossing the entire zone. The amalgamated geobodies correspond to  
456 FF1 and FF2 facies with a larger proportion of FF2 facies. These are large and  
457 discontinuous/tortuous geobodies oriented N055 with a limited and cyclic aerial extension  
458 (Fig. 6). These geobodies have a periodic spacing of 500 to 1500 metres which is close to the  
459 periodicity of the faults observed in the field.

460 Concerning permeabilities, only moderate- to high-permeability facies CK2 and CK3 were  
461 investigated. Ellipsoids display the same dominant N055 orientation. However, the CK2 and  
462 CK3 facies ellipsoids axis parameters are different. The anisotropy in CK2 is less important  
463 than in CK3 (Fig. 6). This variation in axis dimensions implies a differential behavior of the  
464 associated geobodies. CK2 facies geobodies display mainly linear N055 orientations (Fig. 6).  
465 An alternative secondary N120-N140 direction is also apparent in this facies. CK3 facies  
466 geobodies display comparable behavior to FF2 facies being mainly organized in groups of  
467 several geobodies that constitute a 1.5-2 km wide and 1 km long geobodies (Fig. 6).

468

#### 469 **4.4. Connectivity of simulated high permeability zones**

470 Seven areas were selected to investigate the connectivity along and between fractured  
471 geobodies (sector 1 to sector 7): results obtained from the static connectivity algorithm (see  
472 section 3.3) are synthesized in Figure 7.

473 The probability of a connection between the different sectors and the Grignantes Spring is  
474 very low, ranging from 3 to 18 %. This spring appears to be disconnected from these areas,  
475 even though sector 4 is oriented in the close direction of fractured geobodies.

476 The Font Reynaude Spring is connected to sectors 1 via CK2 facies (45%) and 7 via CK3  
477 facies (42%). These sectors are closely oriented (azimuth N065 and N053) in the same axes as  
478 fractured geobodies (N055) and accounts for the high probabilities of connectivity displayed  
479 in this case.

480 The Laurons Springs are mainly connected with sectors 1 (54%, via CK2), 7 (60%, via CK3),  
481 4 (48%, via CK2 and 54%, via CK3) and 3 (42%, via CK2). Sectors 1 and 7 are closely  
482 oriented in the direction of fractured geobodies explaining the static connections within  
483 permeable geobodies through the western part of the Combe Fault system. Sectors 3 and 4 are  
484 not connected via the same direction (~N090). This direction does not correspond to the main  
485 fracture orientation. This implies that the connectivity in that direction is controlled by  
486 another parameter (smaller scale fracture, sedimentary body).

487 The Grande Bastide Spring is principally connected with sectors 1 (72%, via CK2 and 57%,  
488 via CK3), 7 (66% via CK2 and 48%, via CK3), 6 (57 % via CK2), 5 (57 % via CK2) and 2  
489 (51 % via CK2). Sector 1 is connected to the spring via a fault system parallel to the  
490 Cadarache Valley orientation (filled by Tertiary porous deposits). It is notable that sector 2, 5  
491 and 6 are strongly connected with the spring. Low probabilities were obtained for  
492 connectivity between these sectors and springs located on the south of Cadarache Valley. This  
493 implies that a hydraulic barrier occurs between the northern and southern part of Cadarache

494 Valley.

495 The connectivity with the different sectors can be summarized as follows:

496 - The connectivity with the Grignantes Spring is very low (6-11%).

497 - The connectivity with the Grande Bastide springs is higher via CK2 facies (58%) than  
498 via CK3 facies geobodies, suggesting a greater effectiveness of the CK2 facies  
499 geobody in the domain.

500 - The connectivity with the Laurons Spring is slightly higher via a CK3 than via a CK2  
501 geobody.

502 - The connectivity with the Font Reynaude Spring is similar between CK2 and CK3  
503 geobodies.

504 These results will be discussed in terms of their influence on the global water flow in the  
505 hydrogeological basin in section 5.4.

506

## 507 **5. Discussion**

508

### 509 **5.1. Benefit of the input of *a-priori* data in stochastic model?**

- 510 • Fracture vertical proportion curve

511 As proposed by Cherubini et al. [44] and by Yarus et al. [45], the facies vertical proportion  
512 curve (VPC) can be a powerful tool to integrate geological heterogeneity in a 3D model. The  
513 aim of this cumulative histogram is to visualize the facies variability within the sedimentary  
514 succession or within selected stratigraphic units. This method was applied to the fracture  
515 facies FF1 to FF3. One of the objectives was to identify possible intra stratigraphic variability  
516 of fracture proportion and to use it as *a-priori* knowledge to force the model.

517 The obtained VPC emphasises the bias induced by the depth and the repartition of wells. This  
518 is because wells are dedicated to a hydrogeological network survey and are therefore mainly

519 superficial. Moreover, the screened interval is highly variable. Consequently, the number of  
520 usable samples for the VPC is 182 in the Formation (3), 142 in Formation (2), and 37 in  
521 Formation (1). This bias prevented us to use VPC as a secondary dataset for the model input.

522

523 • Relationship between Fracture density and faults location

524 As Proposed by Caine et al. [46], a fault zone is defined as the volume composed by a fault  
525 core and a damaged zone. The damaged zone is a key conduit or barrier for fluid flow  
526 conferring a marked local anisotropy to the permeability tensor. Yet, the thickness of these  
527 zones remains of prime importance in order to define fluid drains. For instance, Matonti et al.  
528 [47] conducted a petrophysical and structural characterisation of a fault zone in the South-East  
529 of France. They emphasized that the porous and permeable zone could be defined, on average,  
530 as a 20 metre thick zone on both sides of the fault core. Similar petrophysical features were  
531 investigated here at the scale of the 3D model. Firstly, fractures orientation measured at the  
532 outcrop scale was compared to the main faults orientation. Fractures display two main  
533 orientations N040-N060 and N130-N140 comparable to fault orientations observed in the  
534 field and introduced in the 3D structural model. This observation matches the model of  
535 Micarelli et al. [48], who studied highly porous carbonates from the Hyblean Plateau (Italy)  
536 and defined the damaged zone as an intense fault related fracture zone. Consequently, a  
537 second investigation was conducted here, focusing on the relationship between the distance to  
538 the fault and the proportion of fractured facies in wells. Due to the low amount of available  
539 data close to faults, the first region starts at 20 metres from the fault plane. Then, regions are  
540 computed every 10 metres from 20 to 100 metres, every 20 metres from 100 to 200 metres,  
541 and every 200 above 200 metres from fault. Error bars were calculated for each data point and  
542 range from 0 to 18% (Fig. 8). Data with error bars lower than 11% only (arbitrary cut-off  
543 avoiding most pronounced errors) are plotted and shows 3 zones:

- 544 i) zone of intense fracturing with a fracture facies proportion higher than 88%;
- 545 ii) fractured zones far from faults with a proportion of non-fractured and fractured facies
- 546 slightly varying around 40-60% respectively;
- 547 iii) unexpected proportion zones where the fractured to non-fractured facies ratio is the
- 548 opposite of what is expected.

549

550 The proximal 0 to 30 metres zone is consistent with the previously defined fault zone. In this

551 interval, the highly fractured facies are abundant. Nevertheless, between 30 and 40 metres the

552 proportion changes drastically with the proportion of non-fractured facies increasing to 94%.

553 Between 40 and 90 metres, the proportion of fractured facies resumes to a proportion

554 comparable to the one observed close to the fault. Between 90 and 120 metres from the fault,

555 the fracture facies to non-fractured facies ratio decreases again. The proportion of each facies

556 reach values comparable to the mean proportion value calculated with the entire well dataset

557 (42% non-fractured, 55% fractured). Between 120 and 130 metres to the fault, another

558 inversion occurs. The fractured facies reaches 100 %. Finally, above 130 m, non-fractured and

559 fractured facies again reach mean values observed at the whole dataset scale.

560 This investigation highlights the complexity of the relationship between faults and fractures,

561 and the difficulty to constrain this relationship given the well data arrangement. Nevertheless,

562 the 0 to 30 metres from fault region is consistent with the definition of a fault damaged zone.

563 Since it cannot be extended to 100 metres (which is the size of the model elementary grid),

564 damage around the main faults was not considered in the simulation processes.

565

## 566 **5.2 Geological meaning of variographic analyses**

567 Gringarten and Deutsch, [49] introduced variograms as a widely used tool to model the multi-

568 scale heterogeneity in reservoirs. A major part (around 90 %) of the geostatistical properties

569 simulations of a reservoir are based on variographic analyses. The methodology generally  
570 adopted to interpret the variogram in order to compare to geological structures is to identify:  
571 i) Small-scale correlations, mainly represented by the "nugget effect"; ii) the intermediate-  
572 scale correlation corresponding to a geometric anisotropy; and iii) the large-scale variability  
573 attributed to zonal anisotropy, hole-effect and trend behavior [39].

574 In the present case study, no small-scale correlations have been identified. This indicates that  
575 the fractures facies and the permeability facies display intermediate to large scale anisotropy  
576 only. Field observations conducted on fractures are consistent with this approach. The small-  
577 scale heterogeneity described in previous studies [18, 22] was not taken into account because  
578 the upscaling process requiring interpolation of small-scale heterogeneity at the reservoir-  
579 scale was beyond the scope of this study. The reservoir behavior in this case was therefore  
580 considered as fracture flow driven only.

581 The intermediate-scale variability is obvious in the geometric anisotropy in FF1 and FF2  
582 facies and in CK1 and CK3 facies (Appendix 1 and 2). For all these facies, the maximum  
583 range is oriented in the N055 direction which matches the N040-N060 oriented faults. The  
584 maximum range of FF1 and FF2 is much higher than the range of CK1 and CK3. This is quite  
585 surprising because CK1 and CK3 represent permeability values of matrix and fractured facies,  
586 respectively. This finding shows that the repartition of the permeability in fractured facies is  
587 heterogeneous.

588 Another interesting point is that moderate- and high-permeability facies (CK2-3) do not  
589 always match with fractured facies geobodies (FF2) (Fig. 6). This emphasises a paradox: the  
590 representation of FF1 and FF2 only reflects a part of the organisation of the fractured  
591 geobodies; or the high permeability values (CK3) could be located in non-fractured areas.  
592 Indeed, high values of permeability could be attributed to porous intervals of Formation (3)  
593 ranging from 0 to more than 8%. The porosity values measured in several locations in

594 Formation (3) are randomly distributed and could also correspond to isolated patches of high  
595 permeability. This configuration is in agreement with work from Ellis et al. [50],  
596 demonstrating that long and open fractures can occur in damaged zones in a rock that is  
597 elsewhere nearly devoid of fractures.

598 The large-scale variability is represented by the hole-effect and the zonal anisotropy  
599 (Appendix 1 and 2). In the case study, hole-effects are visible on the N180-125-110 azimuths  
600 only. The periodicity of the hole-effect is 50% higher in the N180 azimuth than in the two  
601 other directions. This is consistent with the observed periodic occurrence of N040-060 faults  
602 displaying a double period of 300 metres and of 1000 metres, indicating that the fault pattern  
603 should also affect the Northern part of the Cadarache Valley where the faults were not  
604 observed because of the Tertiary sedimentary covering.

605 The zonal anisotropy was observed in all the vertical variograms and a trend in some  
606 horizontal directions could explain a decreasing or an increasing of the intensity of a facies in  
607 the direction where the trend is defined (Appendix 1 and 2). In both cases, these behaviors  
608 imply a continuity of a given facies in the considered direction. Zonal anisotropy or trend  
609 direction are generally associated to a perpendicular hole-effect [20], which occurs in FF2 and  
610 CK2 facies. Indeed, the FF2 facies display a slight trend in N077 direction and a zonal  
611 anisotropy in N180 direction. The CK2 facies display a zonal anisotropy in N055 direction  
612 and a hole-effect on N125 direction. Consequently, fractured geobodies and moderate  
613 permeability geobodies are mainly vertical and restricted to small-extended areas.

614 This type of analysis is uncommon because it uses SIS to represent fracture and permeability  
615 facies. Several authors proposed methods to simulate fractures as surfaces distributed in the  
616 model according to density and dimension distribution [25, 51]. On the other hand, the SIS  
617 technique is a stochastic procedure commonly used for reproducing facies organisation [20,  
618 52]. In this paper, the SIS technique is used to reproduce the geometry and the organisation of

619 fracture and permeability facies in the targeted area. In that way, fractures are not considered  
620 as punctual objects but as volume of fracture facies. This appears to be particularly useful  
621 when diffuse fracturation takes place as well as fracturation linked to fault damaged zones.

622

### 623 **5.3. Hydrogeological data representativity**

624 Slug tests are widely used in hydrogeology because they are a low cost and quick tool to  
625 investigate the transmissivity and the storage capacity of aquifers. Interpretation of this kind  
626 of test has been extensively investigated by several authors [53-57] in both homogeneous and  
627 fissured aquifers. Yet, an accurate characterisation of transmissivity in fractured media  
628 implies considering a wide range of parameters linked to the intrinsic fracture heterogeneity  
629 (complex combination of various sizes, apertures, filling materials, orientations, occurrence  
630 frequency). Such complexity is rarely considered in models of fractured aquifers. Some  
631 authors discussed this paradox and developed recommendations to best describe the aquifer  
632 heterogeneity. Shapiro and Hsieh [58] compare transmissivity values obtained from slug tests  
633 realised on variable screened intervals ranging from 5 to 160 metres in length. Transmissivity  
634 values obtained in these intervals vary over 5 to 6 orders of magnitude. The authors linked  
635 these variations to the presence of fractures. In order to decipher the impact of the model used  
636 to interpret the slug test in a fissured aquifer, the authors compare: i) a mathematical solution  
637 considering the homogeneity of the aquifer and ii) a Laplace Transform model taking into  
638 account fractures in the reservoir. It appears that transmissivity values obtained from both  
639 models always displayed less than one order of magnitude difference.

640 Previous study [18] highlights the strong variability in fracture type in the studied aquifer.  
641 According to Shapiro and Hsieh [58], considering all these parameters generates an  
642 unpracticable complex model. A choice of most prominent fracture parameters is therefore  
643 required to represent the aquifer heterogeneity. Yet, the most transmissive fracture need

644 prioritized, bearing in mind that the connectivity of the fracture network formed in part by  
645 smaller and less active faults will exert a strong control on solute contaminant transport  
646 especially in case of exchange between the fracture and the matrix [59, 60] Then, the  
647 permeability heterogeneity related to the permeability of Lower Cretaceous hemipelagic  
648 limestones matrix ranging from  $10^{-14}$  to  $10^{-11}$  m.s<sup>-1</sup> [22] need to be addressed. The matrix  
649 heterogeneity was not introduced in the present models because of a paucity of data available  
650 to describe its repartition.

651 The question of the hydrogeological data representativity is also linked to the influence radius  
652 of a slug test. Due to the relatively low amount of water injected in the borehole, the  
653 investigated zone is limited. Guyonnet et al. [61] studied the volume of porous media  
654 investigated by a slug test in 3 theoretical cases. They note that the influence radius is easily  
655 identifiable in the case of homogeneous aquifers. They compared the return time to the static  
656 level in Cretaceous slug tests and the measured transmissivity of the aquifer. They were able  
657 to calculate influence radii ranging from millimetre to hectometre scales, highlighting that the  
658 increase of both permeability and influence radii is linked to geological structures such as  
659 matrix, fracture, fissures, faults and karsts. In our study, the influence radius previously  
660 described was used to define permeability ranges. In addition, fractures were taken into  
661 account by synthesizing structural information gained from well logs and attributing specific  
662 well intervals to permeability ranges. This method reduced the bias induced by using  
663 averaged permeability values in the whole screened interval of the borehole.

664

#### 665 **5.4. Interest of the connectivity algorithm**

666 The connectivity algorithm developed in this study is a useful tool to investigate the links  
667 between different permeable geobodies in a heterogeneous aquifer. It is of particular interest  
668 in the hydrogeological characterisation of highly discontinuous aquifers (fractured or karstic

669 aquifers for example) where the number of data is in most cases not sufficient or difficult to  
670 integrate in a reservoir model (interference tests or tracer tests data).

671 Static connections between geobodies in a reservoir have already been used in several studies.  
672 Lee et al. [62] use static connectivity in particularly high-K facies in California fluvial  
673 context. Results of this type of calculations may help identifying potential groundwater flow  
674 pathways and consequently preferential transport conduits in the reservoir. This assumption is  
675 conditioned by the use of dynamic data which were not developed in this study. Regarding  
676 other possible techniques of simulation on which connectivity should be applied, [63]  
677 proposed a comparative study between outcrop evaluation of connected bodies and several  
678 simulation algorithms, including SIS simulation and concluded that the connectivity is often  
679 slightly overestimated in the case of SIS compared to other algorithms.

680 This is due to small-scale noise produced by this algorithm. We show in our study that this  
681 algorithm provides good results in static connectivity overview. The variability in volume of  
682 generated fractured and permeable geobodies illustrates that their dispersion does not display  
683 a strong variability (Fig. 9). This assumption gives weight to connectivity interpretations.

684

685 A map of the Cretaceous aquifer water table was produced, based on the monitoring of 68  
686 piezometers connected to the Cretaceous aquifer, corresponding to April 2009 high water  
687 table (Fig. 10). Flow gradients display a first order direction from the SE towards the Durance  
688 River and a second order anomaly characterised by a complex high hydraulic gradient in the  
689 Moure-Frais Valley towards the Durance (NW) and the Bete ravine (NNE). This high  
690 gradient can highlights (i) a low permeability zone parallel to the orientation of the valley that  
691 could correspond to the Tertiary deposits filling the up to 100 metres thick paleo-valley  
692 incised in the Cretaceous formations and/or (ii) a high permeability (fractured) drainage zone  
693 in the Cretaceous aquifer located on the left side of the valley (Fig. 10).

694 The regional hydraulic flow does not follow the trend obtained from facies simulations. Then  
695 the uncertainties induced by the clustering and by the shallow depth of investigation of the  
696 hydrogeological survey could play a role on these results. Nevertheless, it seems that the  
697 boundary conditions (topography in the SE and the Durance River in the NW of the domain)  
698 have a stronger influence on the hydraulic gradient than the distribution of the reservoir  
699 properties. Interestingly, the high hydraulic gradient in the Mourre-Frais Valley matches a  
700 high fracture and fault density zone that was identified on 39% of the fracture facies  
701 simulations, and 41% of the permeability facies simulations, and where connected permeable  
702 geobodies are oriented parallel to the valley azimuth (Fig. 10).

703

## 704 **6. Conclusions**

705 Coupled integration in a three-dimensional geostatistical model of hydrogeological data (slug  
706 test method) and geological informations (sedimentary and fracture facies) from wells is an  
707 efficient way to characterise fissured aquifers. The 3D structural model first is way to  
708 integrate 1D, 2D and 3D data. Using the implicit method allows reducing artifacts close to  
709 geological unconformities, and gives the opportunity to quickly update the model.

710 This method results in a highly consistent stratigraphic grid even if modeling strategy is  
711 strongly influenced by the compromise between model resolution and computational  
712 performance that in the case of a highly fractured and faulted reservoir, may lead to the  
713 minimisation of fault offsets and smoothing of stratigraphic undulations.

714 An evaluation of the data consistency by comparison between field and well information  
715 provided before statistical modeling showed no unequivocal results that could be input into  
716 the model as secondary data. Consequently, simulations were only based on variographic  
717 anisotropy calculations and were realised for both fracture and permeability facies. We  
718 consider that this may be one of the most general cases since in much highly documented case

719 there may be some potential correlations between facies and reservoir properties.  
720 The key result of this modeling was to highlight the contrasted effects of fractures and faults  
721 on the reservoir permeability, permeable geobodies displaying a complex arrangement are  
722 much more influenced by faults than by fractured geobodies. The information provided by the  
723 model in terms of fracture anisotropy will be taken into account in hydrogeological modelling  
724 of the area.  
725 The connectivity algorithm developed in this study allows computing the static connectivity  
726 between geobodies identified in the geostatistical modeling. The main flow orientation in this  
727 particular case does not follow the fracture and permeability facies because the piezometric  
728 gradient is primarily influenced by the topographic heights (SE) to the Durance River (NW).  
729 Such algorithms results still remain of great interest for pre-dynamic modelling study  
730 currently used to characterise highly heterogeneous reservoirs.

731

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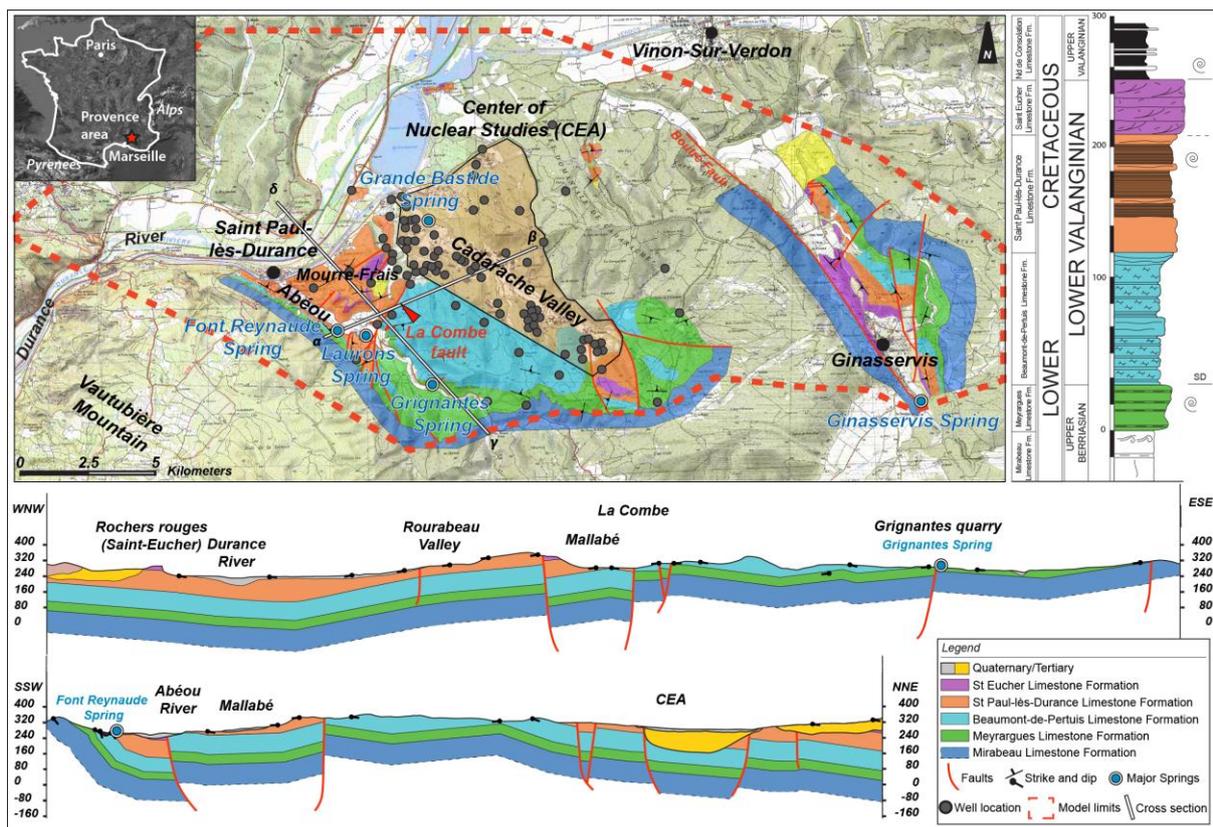
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746

### 747 Figure captions

### 748 Figure 1

749 Geological map of the Durance region including the dimensions of the 3D geological model  
750 and the location of boreholes. Synthetic lithostratigraphic column of the Tithonian to  
751 Valanginian interval ages on the right side of the log are based on ammonites and  
752 calpionellids biostratigraphic charts. Orthogonal cross sections through the area of interest  
753 emphasize the structural style and the thickness variations of the sedimentary units



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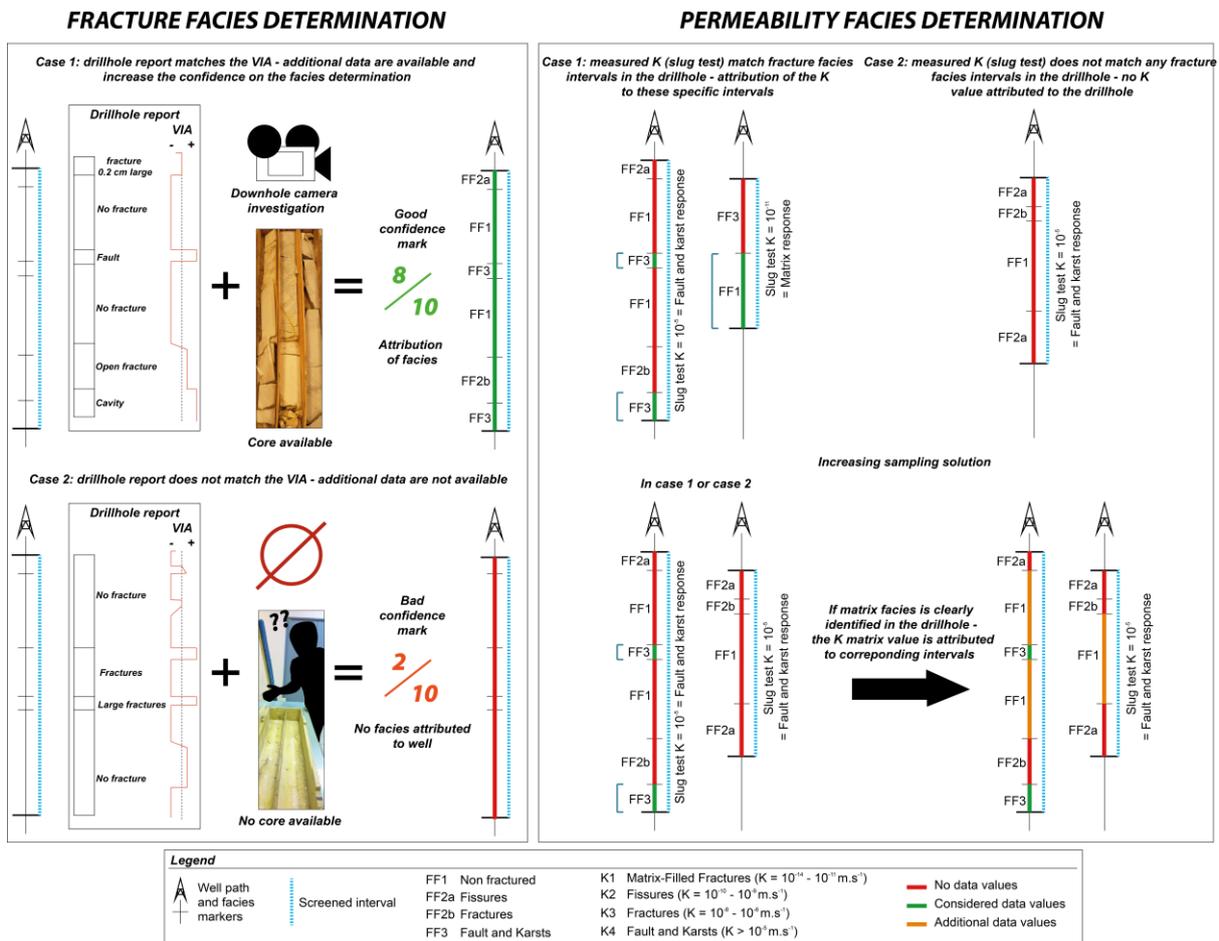
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759 **Figure 2**

760 Methodology used to define the permeability intervals in the well screened interval. Sketches  
 761 highlight the solution found to increase the sampling rate by taking into account well-defined  
 762 non-fractured intervals.



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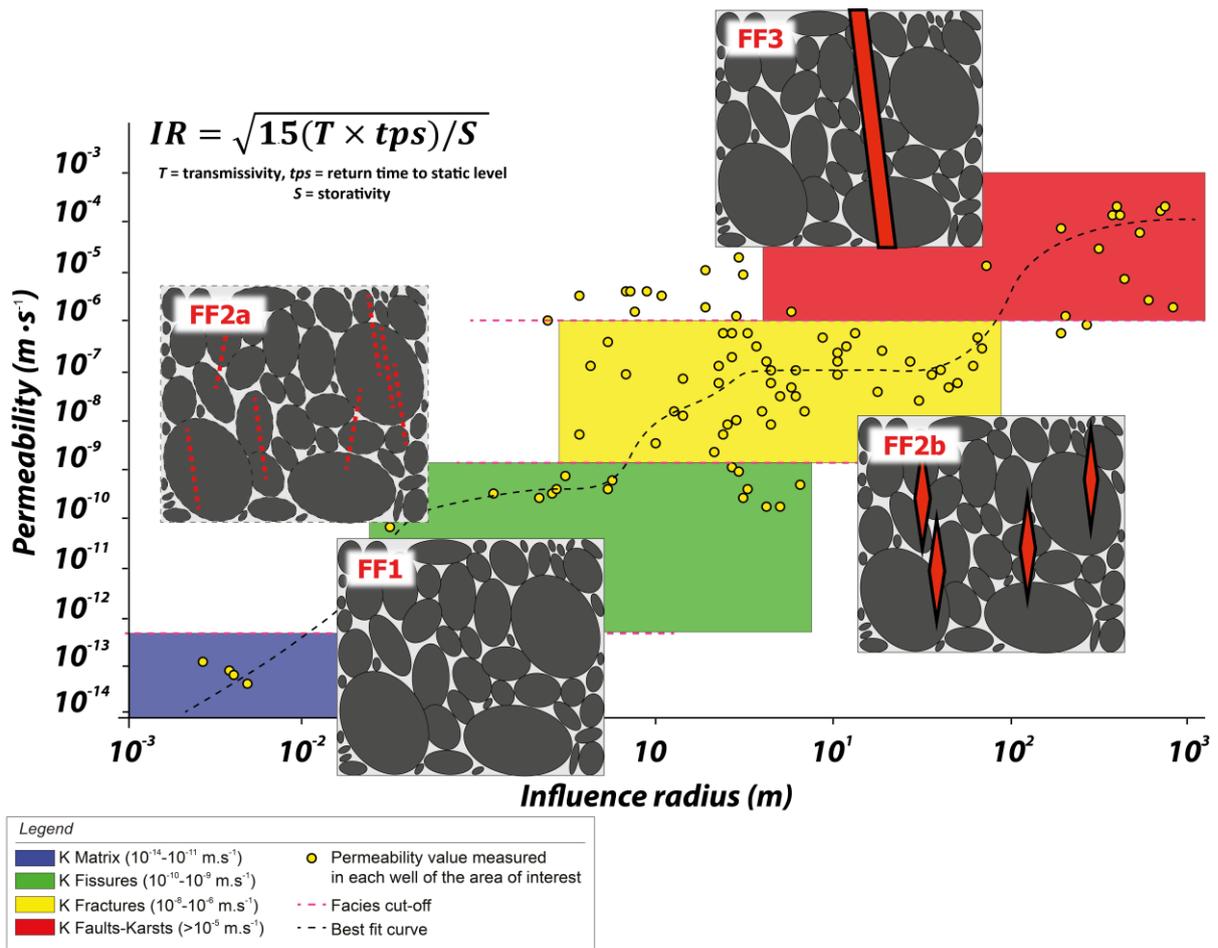
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772 **Figure 3**

773 Link between fracture facies and slug tests influence radii. Yellow dots are measured  
 774 permeability value in the studied wells. FF1 facies (matrix) is then characterized by a small  
 775 influence radius close to the borehole ( $10^{-3}$  to  $10^{-2}$  m) and with a low range of permeability  
 776 ( $10^{-14}$  to  $10^{-13}$  m.s<sup>-1</sup>). Facies cuts-offs were established in regards of the slug tests permeability  
 777 curve inflexion.



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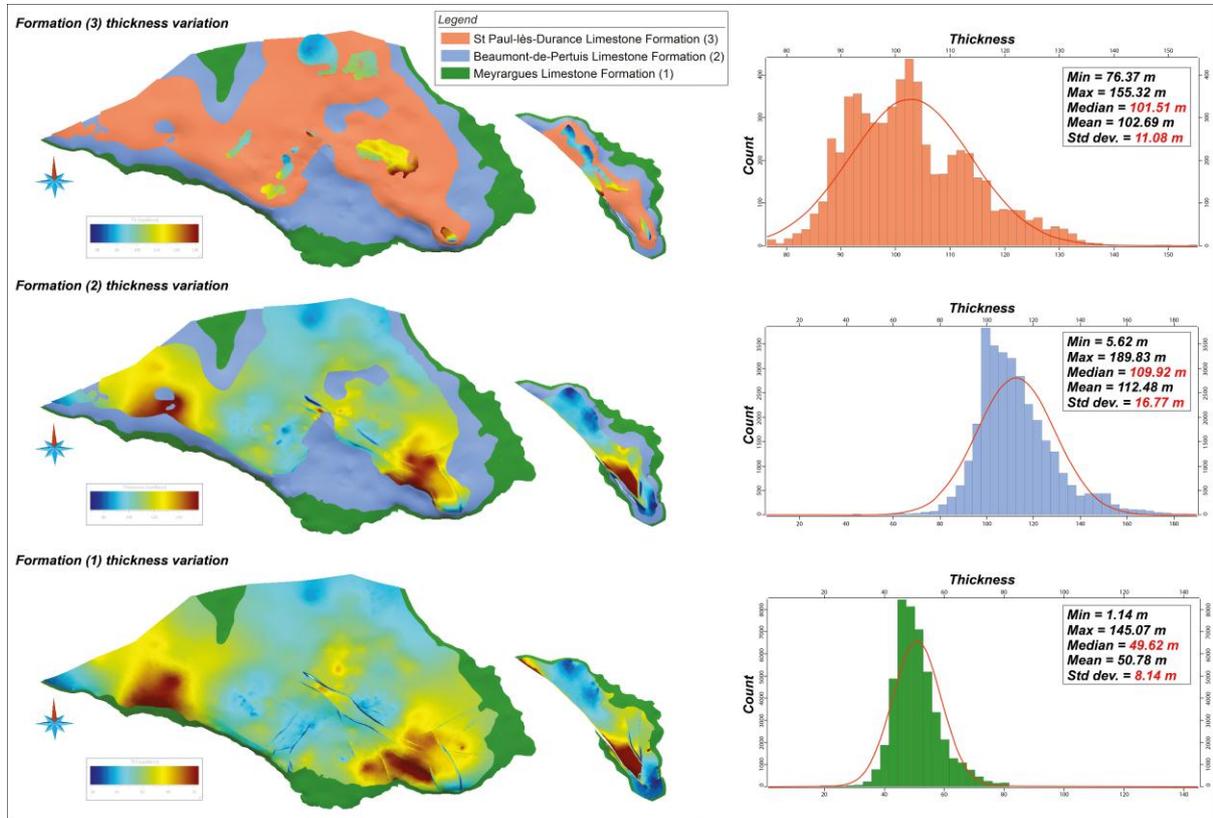
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785 **Figure 4**

786 Thickness maps of Formations (1) to (3). Main statistical data are indicated for each thickness

787 maps.



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800 **Figure 5**

801 Variogram parametres synthesis including the model used to fit the experimental variograms,  
 802 range and sill values, length of the ellipsoid axes and orientation of the great axis and  
 803 representation of the relative size of facies ellipsoids.

		<i>Facies FF1</i>	<i>Facies FF2</i>	<i>Facies FF3</i>	<i>Facies CK1</i>	<i>Facies CK2</i>	<i>Facies CK3</i>	<i>Facies CK4</i>
	Global proportions	42.80%	55.70%	1.50%	52.10%	21.90%	20.40%	5.60%
	Variogram model	Spherical	Spherical	Spherical	Exponential	Exponential	Exponential	Exponential
	Sill	0.24	0.24	0.025	0.249	0.16	0.18	0.07
	Vertical range (dimensionless)	> 0.25	> 0.25	> 0.25	> 0.25	> 0.25	> 0.25	> 0.25
	Horizontal range 1 (dimensionless)	0.16	0.15	0.028	0.06	0.023	0.043	0.004
	Horizontal range 2 (dimensionless)	0.02	0.02	0.028	0.02	0.023	0.03	0.004
Ellipsoid parameters	A <sub>1</sub>	2168	2015	612	820	497	728	490
	A <sub>2</sub>	369	369	369	407	490	498	97
	A <sub>3</sub>	340	349	242	260	194	318	39
	Orientation	N055	N055	N055	N055	N055	N055	N180
Ellipsoide representation	<div style="border: 1px solid black; padding: 5px; margin-top: 10px;"> <p><b>Legend</b></p> <ul style="list-style-type: none"> <li><span style="color: red;">—</span> First great axis of the ellipsoid (A<sub>1</sub>)</li> <li><span style="color: green;">—</span> Second intermediate axis of the ellipsoid (A<sub>2</sub>)</li> <li><span style="color: blue;">—</span> Thrid small axis of the ellipsoid (A<sub>3</sub>)</li> </ul> </div>							

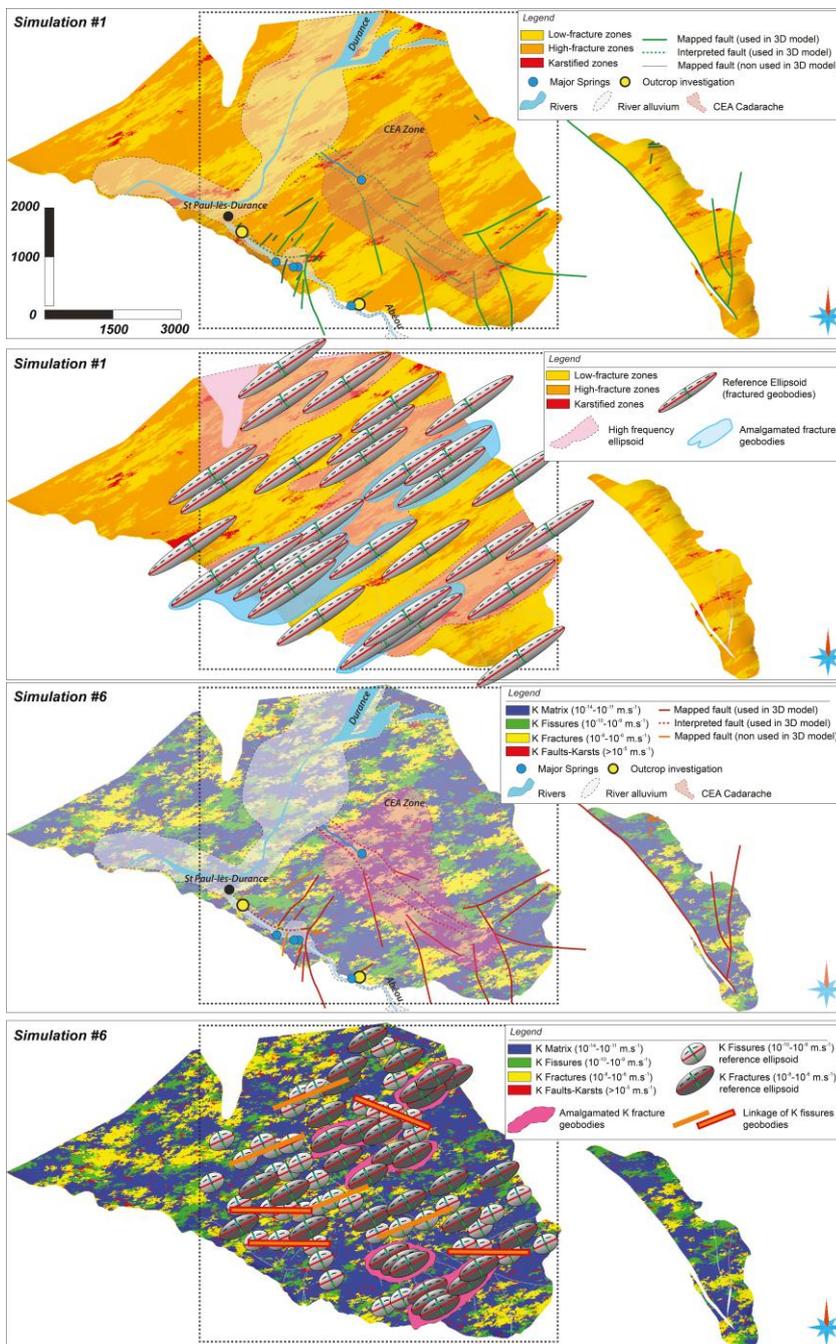
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807 **Figure 6**

808 Geobodies size and organisation in the well-documented area limited by the maximal  
809 extension of borehole data. The reference ellipsoid of fractured facies was chosen to show  
810 geobodies repartition in the fracture facies simulation. Moderate and high permeability facies  
811 reference ellipsoid was chosen to evidence geobodies organisation in the permeability facies  
812 simulation.



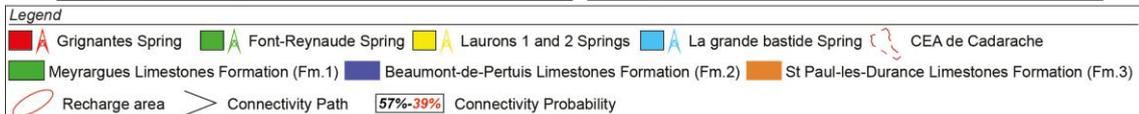
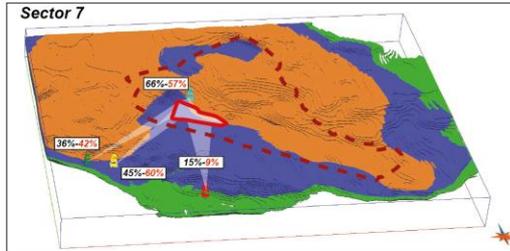
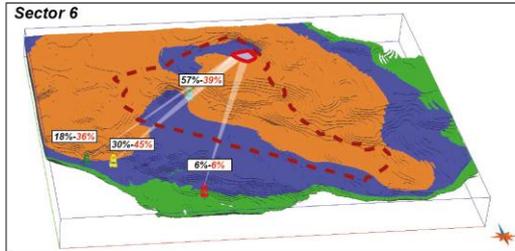
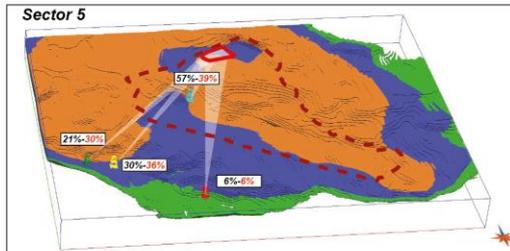
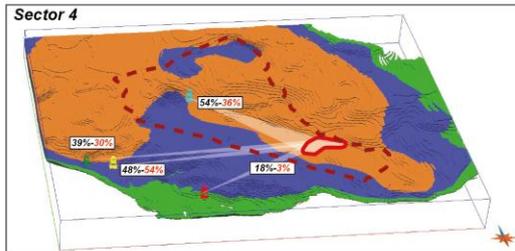
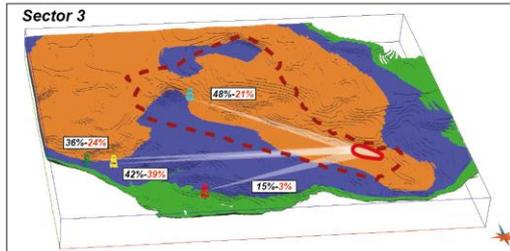
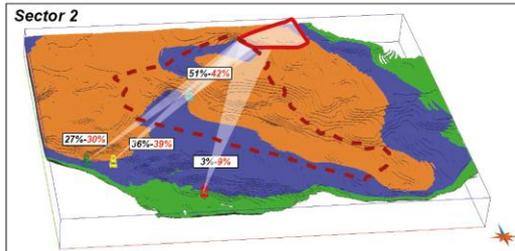
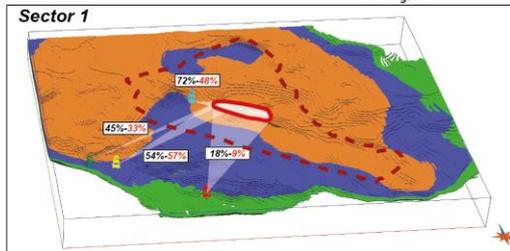
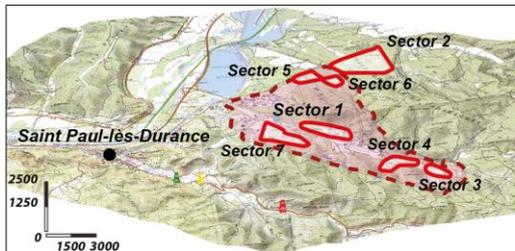
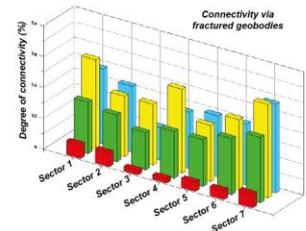
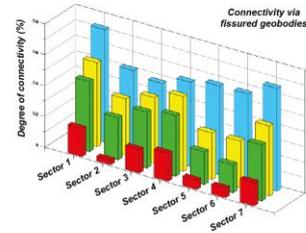
813

814 **Figure 7**

815 Bar diagram and map of static connectivity probability inside and between geobodies

816 containing major springs and seven sectors in the domain.

	Sp Grignantes			Sp Font-Reynaud		
	Fissures	Fractures	Azimuths	Fissures	Fractures	Azimuths
Sector 1	0.18181818	0.09090909	N021	0.4545455	0.33333333	N065
Sector 2	0.03030303	0.09090909	N029	0.2727273	0.30303030	N052
Sector 3	0.15151515	0.03030303	N076	0.3636364	0.24242424	N094
Sector 4	0.18181818	0.03030303	N064	0.3939394	0.30303030	N090
Sector 5	0.06060606	0.06060606	N022	0.2121212	0.30303030	N051
Sector 6	0.06060606	0.06060606	N015	0.1818182	0.36363636	N043
Sector 7	0.15151515	0.09090909	N000	0.3636364	0.42424224	N053
Average values	0.11688312	0.06493506		0.3203463	0.324675325	
Standard deviation	0.06411215	0.02726471		0.100286	0.057267344	
	Sp Laurons			Sp Grande-Bastide		
	Fissures	Fractures	Azimuths	Fissures	Fractures	Azimuths
Sector 1	0.54545455	0.57575758	N059	0.7272727	0.48484848	N115
Sector 2	0.36363636	0.39393939	N047	0.5151515	0.42424224	N057
Sector 3	0.42424242	0.39393939	N092	0.4848485	0.21212121	N125
Sector 4	0.48484849	0.54545455	N087	0.5454545	0.36363636	N127
Sector 5	0.30303030	0.36363636	N045	0.5757576	0.39393939	N061
Sector 6	0.30303030	0.45454546	N035	0.5757576	0.39393939	N041
Sector 7	0.45454546	0.60606061	N041	0.6666667	0.57575757	N175
Average values	0.41125541	0.47619048		0.5844156	0.406926407	
Standard deviation	0.09234082	0.09852647		0.0851982	0.111830284	



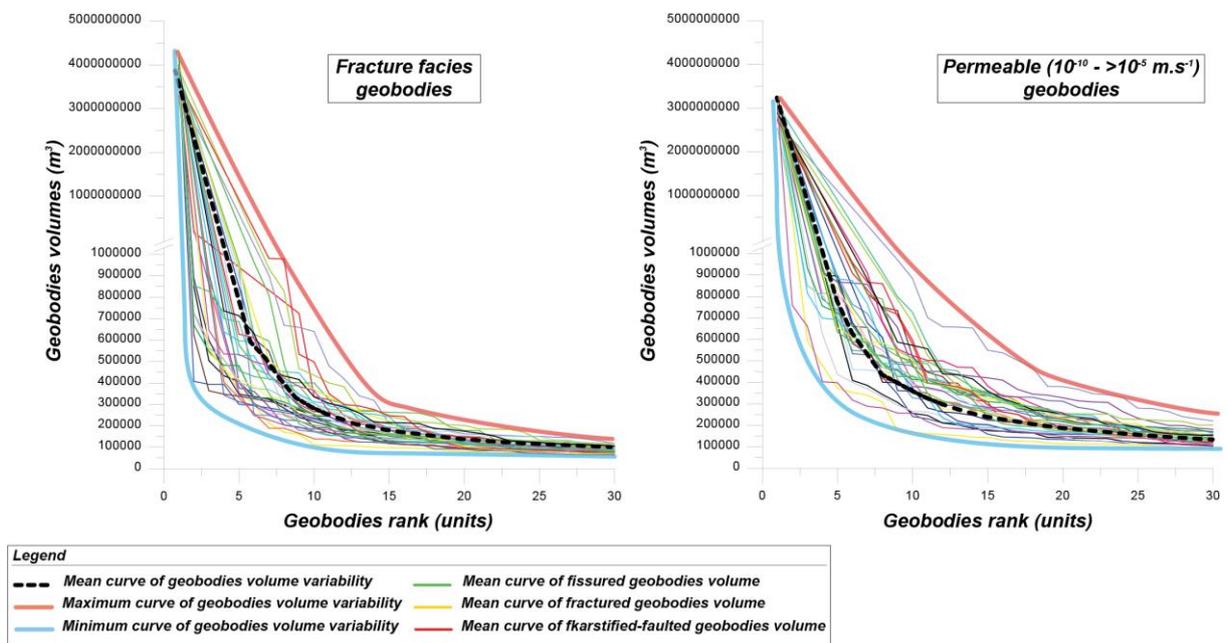
817

818 **Figure 8**

819 Graph representing the facies proportion vs. the fault distance. Yellow dots are non-fractured  
820 facies, orange dots are fractured facies and red dots are karstified facies. Red zones are intense  
821 fracturation zones. Yellow zones represent the average proportion of fractured versus non-  
822 fractured facies calculated in all the boreholes.

823 **Figure 9**

824 Geobodies sizes and ranks from the 33 simulations. Each colored curve represents the data  
825 extracted from one simulation.

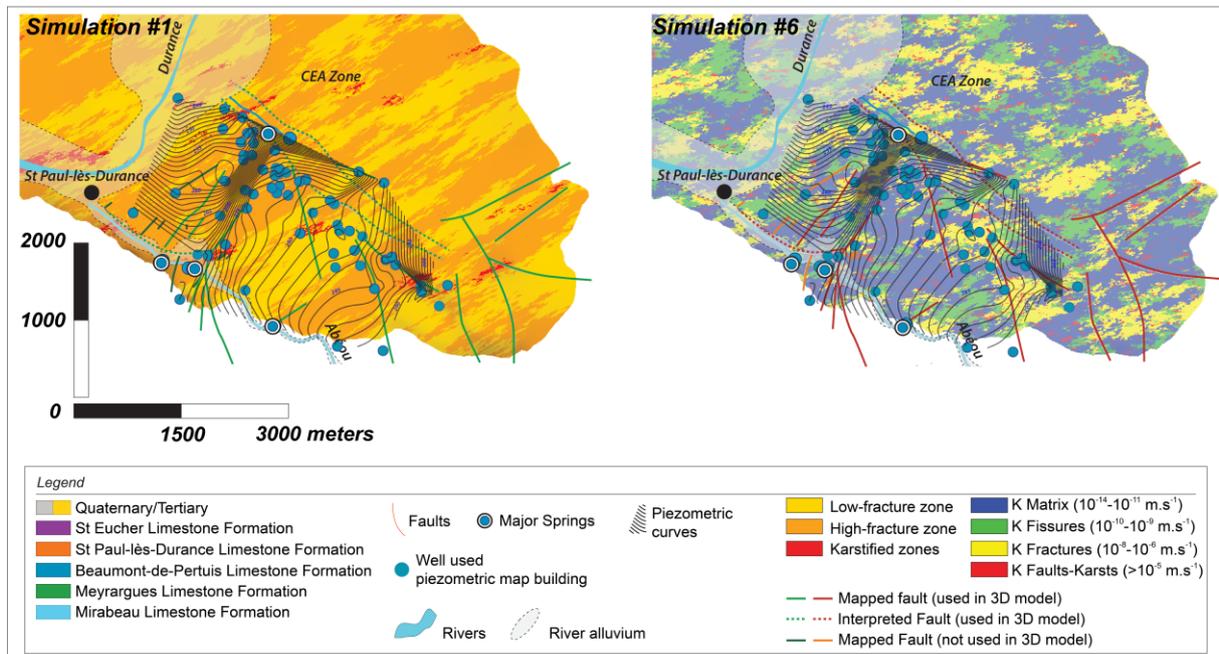


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828 **Figure 10**

829 Geological map associated with piezometric levels measured in Lower Cretaceous aquifer in  
830 high water mark context (April 2009). Piezometric map is compared to fracture facies and  
831 permeability facies simulation in order to explain the tightening of isovalues of hydraulic  
832 head close to the Mourre-Frais zone.



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835 **Table 1**

836 Definition of the occurrence probability of fracture facies. The same method was applied to  
 837 permeabilities facies investigation.

Probability	Observation interval				Additional Tool								
	Localised/ systematic	<5 m	<10 m	<20 m	>20 m	Core observe	Detailed report	VIA-Geophysical tool	Camera	Overlapped	K Hytool	K CASSAN	High confidence to K curves
<i>1 Non fractured limestones (FF1)</i>													
0.1					O (present)								
0.2					O								
0.3			O										
0.4		O			O		O/N (optional)	O/N					
0.5					O		O/N	O/N					
0.6			O		O/N		O/N	O/N					
0.7		O	O/N				O/N	O/N				O	O
0.8		O	O/N				O	O			O		O
0.9		O	O/N				O	O		O			O
1.0		O	O/N			O/N	O	O	O/N	O/N			O/N
<i>3 fractured/faulted limestones (FF2)</i>													
0.1													
0.2													
0.3													
0.4			O/N		O			O/N					
0.5		O/N		O				O/N					
0.6			O				O/N	O/N					
0.7		O					O/N	O/N					
0.8	O	O/N					O	O/N				O	O
0.9	O	O/N				O/N	O	O/N	O/N		O		O
1.0	O	O/N				O	O	O	O	O			O
<i>3 karstified limestones (FF3)</i>													
0.1													
0.2													
0.3													
0.4													
0.5													
0.6													
0.7		O						O/N					
0.8	O/N	O						O/N				O/N	O/N
0.9	O	O/N					O	O/N			O		O
1.0	O	O/N				O	O	O/N	O	O			O

838

839

840 **Table 2**

841 Synthesis of variograms behavior. ZA is a Zonal Anisotropy, GA is a Geometric Anisotropy,  
 842 HE is a Hole-Effect behavior, T is a Trend behavior, and E is an Erratic repartition of points  
 843 in the experimental variogram. Small letters indicate that the observed behavior is not clearly  
 844 defined.

	Vertical variogram	Az N180 variogram	Az N125 variogram	Az N110 variogram	Az N100 variogram	Az N090 variogram	Az N077 variogram	Az N068 variogram	Az N055 variogram	Other behaviour
<b>Facies FF1</b>	ZA-E	HE	he	he	za	E	E	E	BF-E	GA
<b>Facies FF2</b>	ZA-E	HE	he	HE	E	E	t	E	BF-E	GA
<b>Facies FF3</b>	ZA	E	Za	E	E	E	E	AZ	bf-E	
<b>Facies CK1</b>	ZA	E	he	he	ZA	E	E	E	bf	GA
<b>Facies CK2</b>	ZA	E	HE	he	E	ZA	bf-ZA	ZA	ZA	
<b>Facies CK3</b>	ZA	E	E	ZA	ZA	E	E	E	BF-E	GA
<b>Facies CK4</b>	ZA	ZA	E	E	t	E	E	bf-E	E	

845

846

847 **Table 3**

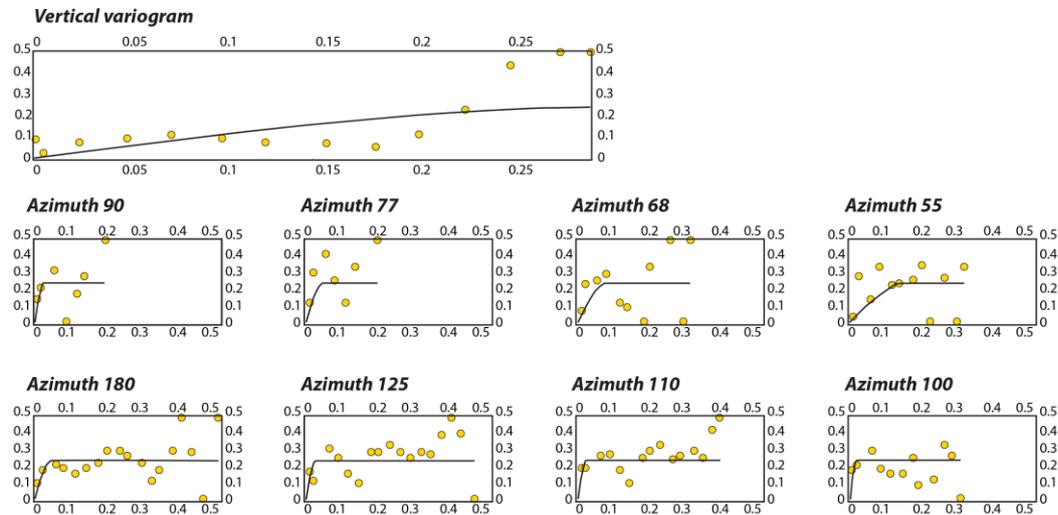
848 Synthesis of simulations matching field fault pattern. The table emphasises the type of  
 849 geobody organisation deduced from each simulation for both fracture and permeability facies.

Facies Fracture simulation				Facies permeability simulation			
# of realisation	Fitting (Y-N)	Type of fitting	Aspect of non fitting (between Combe fault E-W parts)	# of realisation	Fitting (Y-N)	Type of fitting	Aspect of non fitting (between Combe fault E-W parts)
1	Y	Amalgamated		1	Y	Amalgamated-linear	
2	Y	Isolated		2	Y	Amalgamated	
3	N		Homogeneous	3	N		Inverse-linear
4	N		Homogeneous	4	Y	Amalgamated	
5	N		Homogeneous	5	N		Homogeneous
6	Y	Isolated		6	Y	Linear	
7	Y	Isolated		7	N		Homogeneous
8	Y	Amalgamated		8	Y	Amalgamated	
9	Y	Amalgamated		9	Y	Amalgamated	
10	N		Homogeneous	10	N		Homogeneous -linear
11	N		Inverse of expected	11	N		Homogeneous
12	Y	Isolated		12	Y	Amalgamated	
13	N		Inverse of expected	13	N		Homogeneous
14	N		Inverse of expected	14	N		Homogeneous
15	N		Homogeneous	15	Y	Amalgamated	
16	N		Homogeneous	16	Y	Amalgamated-linear	
17	Y	Amalgamated		17	Y	Amalgamated	
18	N		Homogeneous	18	N		Homogeneous-linear
19	N		Homogeneous	19	N		Homogeneous-linear
20	N		Homogeneous	20	N		Homogeneous
21	Y	Isolated		21	Y	Amalgamated	
22	N		Inverse of expected	22	N		Homogeneous
23	Y	Amalgamated		23	Y	Amalgamated	
24	Y	Amalgamated		24	N		Homogeneous-linear
25	N		Inverse of expected	25	Y	Amalgamated-linear	
26	N		Inverse of expected	26	Y	Amalgamated-linear	
27	N		Inverse of expected	27	N		Inverse-linear
28	N		Homogeneous	28	N		Homogeneous-linear
29	Y	Amalgamated		29	N		Homogeneous-linear
30	N		Homogeneous	30	Y	Linear	
31	N		Inverse of expected	31	N		Inverse
32	N		Non conform	32	N		Inverse-linear
33	N		Homogeneous	33	N		Homogeneous-linear

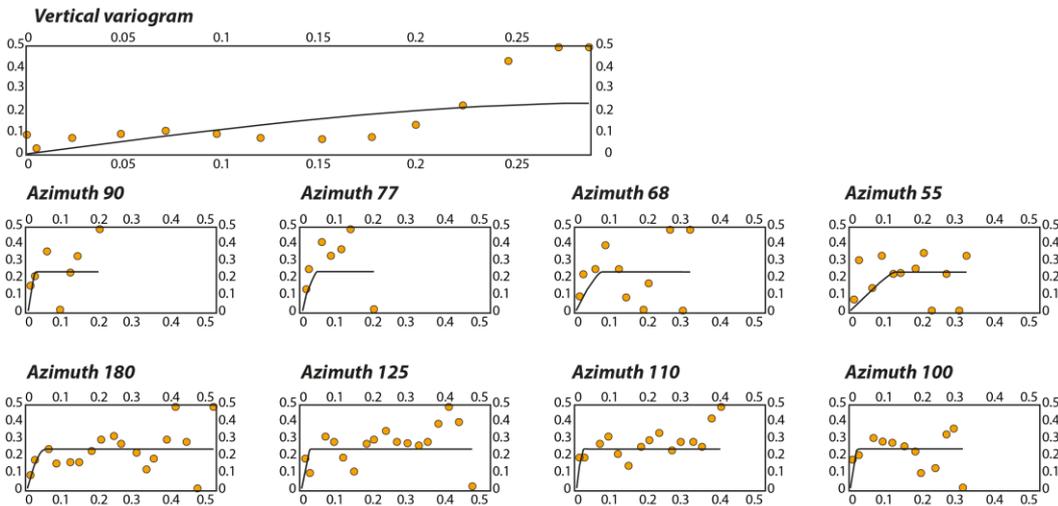
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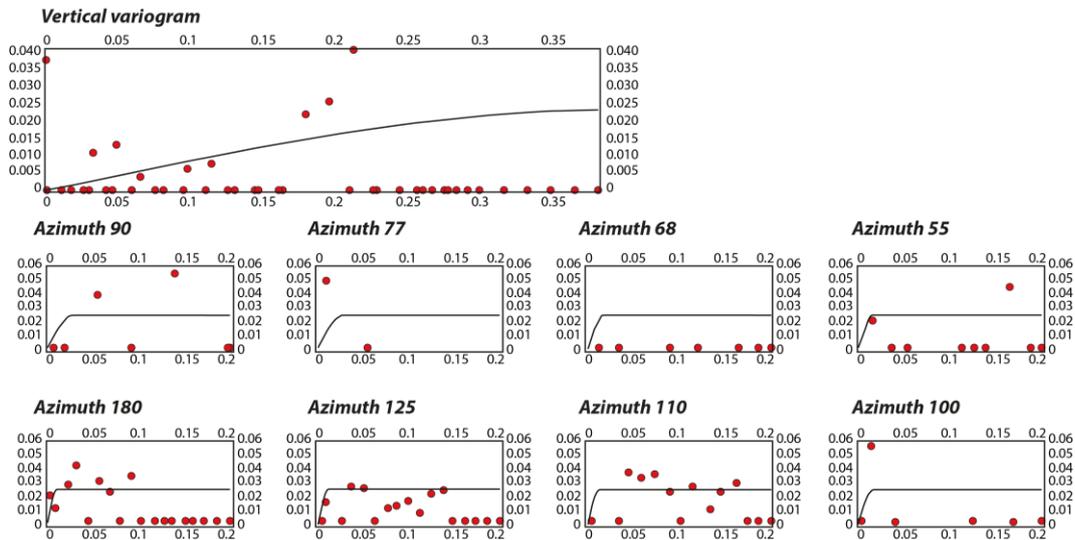
**Low-fractured Facies**

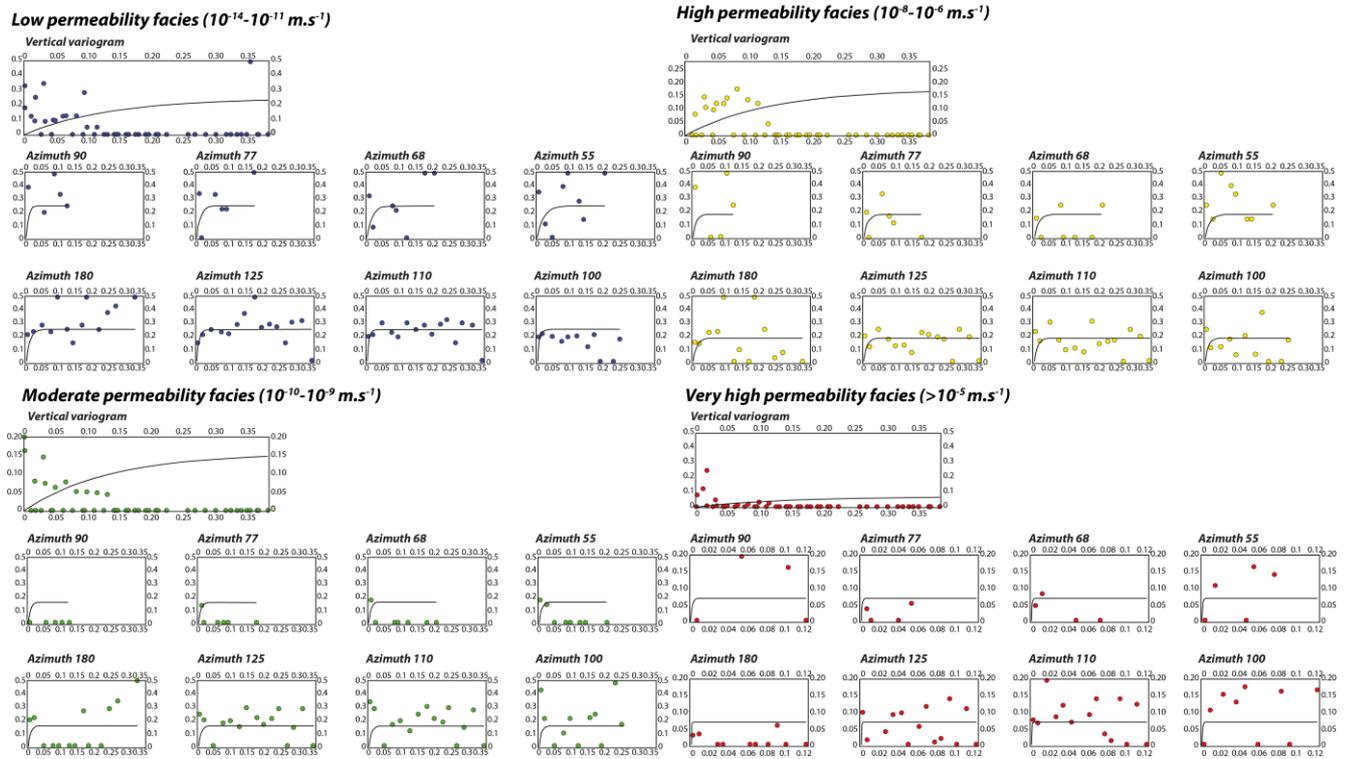


**Fractured Facies**



**Karstified Facies**





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860 **References**

- 861 [1] Gilli E, C Mangan, J Mudry. Hydrogéologie: objets, méthodes, applications. Second  
 862 edition, Dunod, Paris, France, 2008.
- 863 [2] Carniero JF. Numerical simulation on the influence of matrix diffusion to carbon  
 864 sequestration in double porosity fissured aquifers. International Journal of Greenhouse Gas  
 865 Control. 3 (2009) 431-43, doi:10.1016/j.ijggc.2009.02.006
- 866 [3] Motyka J, A Pulido-Bosch, S Borczak, J Gisbert. Matrix hydrogeological properties of  
 867 Devonian carbonate rocks of Olkusz (Southern Poland). Journal of Hydrology. 211 (1998)  
 868 140-50.
- 869 [4] Wu Y-S, HH Liu, GS Bodvarsson. A triple-continuum approach for modeling flow and  
 870 transport processes in fractured rock. Journal of Contaminant Hydrology 73 (2004) 145– 79,  
 871 doi:10.1016/j.jconhyd.2004.01.002.
- 872 [5] Berkowitz B. Characterizing flow and transport in fractured geological media: A review.  
 873 Advances in Water Resources. 25 (2002) 861–84.
- 874 [6] Rzonca B., Carbonate aquifers with hydraulically non-active matrix: A case study from  
 875 Poland: Journal of Hydrology. 355 (2008) 202-13.
- 876 [7] Zou C. Unconventional Petroleum Geology. First edition, Elsevier Inc, China, 2013
- 877 [8] Nelson PH, Pore-throat sizes in sandstones, tight sandstones, and shales. AAPGs Bulletin.

878 93 (2009) 329-40 DOI: 10.1306/10240808059  
879 [9] Loucks RG, RM Reed, SC Ruppel, U Hammes. Spectrum of pore types and networks in  
880 mudrocks and a descriptive classification for matrix-related mudrock pores. AAPG Bulletin.  
881 96 (2012) 1071-98.  
882 [10] Laubach SE, JE Olson, MR Gross. Mechanical and fracture stratigraphy. AAPG  
883 Bulletin. 93 (2009) 1413-26.  
884 [11] Hooker JN, SE Laubach, R Marrett. Fracture-aperture size-frequency, spatial  
885 distribution, and growth processes in strata-bounded and non-strata-bounded fractures,  
886 Cambrian Mesón Group, NW Argentina. Journal of Structural Geology. 54 (2013) 54-71.  
887 doi.org/10.1016/j.jsg.2013.06.011.  
888 [12] Guerriero V, S Mazzoli, A Iannace, S Vitale, A Carravetta, C Strauss. A permeability  
889 model for naturally fractured carbonate reservoirs. Marine and Petroleum Geology. 40 (2013)  
890 115-134,  
891 [13] Biteman S, DW Hyndman, MS Phanikumar, GS Weissmann. Integration of  
892 sedimentologic and hydrogeologic properties for improved transport simulations, in Aquifer  
893 Characterization. SEPM Special Publication. 80 (2004) 4-13,  
894 [14] Renard P. Stochastic hydrogeology; what professionals really needs? Ground Water. 45  
895 (2007) 531-41.  
896 [15] Pöppelreiter MC, MA Balzarini, B Hansen, R Nelson. Realizing complex carbonate  
897 facies, diagenetic and fracture properties with standard reservoir modelling software. The  
898 Geological Society, London, Special Publications, The Future of Geological  
899 Modelling in Hydrocarbon Development. 309 (2008) 39-49, doi: 10.1144/SP309.3.  
900 [16] Stampfli GM, GD Borel. A plate tectonic model for the Paleozoic and Mesozoic  
901 constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and  
902 Planetary Science Letters. 196 (2002) 17-33, doi: [http://dx.doi.org/10.1016/S0012-](http://dx.doi.org/10.1016/S0012-821X(01)00588-X)  
903 [821X\(01\)00588-X](http://dx.doi.org/10.1016/S0012-821X(01)00588-X).  
904 [17] Gréselle B, B Pittet. Sea-level reconstructions from the Peri-Vocontian Zone (South-east  
905 France) point to Valanginian glacio-eustasy. Sedimentology. 57 (2010) 1640-85.  
906 [18] Bruna P-O, Y Guglielmi, J Lamarche, M Floquet, F Fournier, J-P Sizun, A Gallois, L  
907 Marié, C Bertrand, F Hollender. Porosity Gain and Loss in Unconventional Reservoirs:  
908 example of rock typing in Lower Cretaceous hemipelagic limestones, SE France (Provence).  
909 Marine and Petroleum Geology. 48 (2013) 186-205.  
910 <http://dx.doi.org/10.1016/j.marpetgeo.2013.08.008>  
911  
912 [19] Lamarche J, APC Lavenu, BDM Gauthier, Y Guglielmi, O Jayet. Relationships between  
913 fracture patterns, geodynamics and mechanical stratigraphy in Carbonates (South-East Basin,  
914 France). tectonophysics. (2012), doi: 10.1016/j.tecto.2012.06.042.  
915 [20] Guyonnet-Benaize C. Modélisation 3D multi-échelle des structures géologiques de la  
916 région de la Faille de la Moyenne Durance (SE, France). Marseille: Université de Provence;  
917 2011.  
918 [21] Masse J-P, M Masse. Notice du crétacé inférieur de la Basse-Durance. Université de  
919 Provence, Marseille, 2009. pp. 19.  
920 [22] Cartalade A. Modélisation des écoulements dans les aquifères fracturés, développement  
921 d'un modèle multi-continua (problèmes directs et inverse) et application au site du  
922 CEA/Cadarache. Montpellier: Université de Montpellier II; 2002.  
923 [23] Calcagno P, JP Chilès, G Courrioux, A Guillen. Geological modelling from field data  
924 and geological knowledge: Part I. Modelling method coupling 3D potential-field interpolation  
925 and geological rules. Physics of the Earth and Planetary Interiors. 171 (2008) 147-57, doi:  
926 <http://dx.doi.org/10.1016/j.pepi.2008.06.013>.  
927 [24] Caumon G, P Collon-Drouaillet, C Le Carlier de Veslud, S Viseur, J Sausse. Surface-

928 based 3D modeling of geological structures. *Mathematical Geosciences* 41 (2009) 927-45,  
929 doi:10.1007/s11004-009-9244-2.

930 [25] Cherpeau N, G Caumon, B Lévy. Stochastic simulations of fault networks in 3D  
931 structural modeling. *Comptes Rendus Geoscience*. 342 (2010) 687-94, doi:  
932 <http://dx.doi.org/10.1016/j.crte.2010.04.008>.

933 [26] Spottke I, E Zechner, P Huggenberger. The southeastern border of the Upper Rhine  
934 Graben: a 3D geological model and its importance for tectonics and groundwater flow.  
935 *International Journal of Earth Sciences*. 94:4 (2005) 580-593.

936 [27] Bayer P, P Huggenberger, P Renard, A Comunian. Three-dimensional high resolution  
937 fluvio-glacial aquifer analog: Part 1: Field study. *Journal of Hydrogeology*. 405:1-2 (2011) 1-  
938 9.

939 [28] Comunian A , P Renard, J Straubhaar, P Bayer. Three-dimensional high resolution  
940 fluvio-glacial aquifer analog: Part 1: Field study. *Journal of Hydrogeology*. 405:1-2 (2011)  
941 10-23.

942 [29] Arlhac P, F Catzigras, E Colomb, J Gervais, C Gouvernet, S Guierard, et al. Carte  
943 géologique de Pertuis au 1/50 000e. Carte géologique détaillée de la France. in: Brgm,  
944 (Ed.).1970.

945 [30] Mennessier G, D Modret, J Goguel. Carte géologique de Tavernes au 1/50 000e. Cartes  
946 géologiques détaillées de la France. in: Brgm, (Ed.).1966.

947 [31] Goovaerts P. *Geostatistics for natural resources evaluation*, New-York, 1997.

948 [32] Cassan M., *Les essais de perméabilité sur site dans la reconnaissance des sols, Tome I*  
949 *réalisation et interprétation*. Eyrolles, Presse des ponts et chaussées, 1978.

950 [33] Chapuis RP. Overdamped slug test in monitoring wells: review of interpretation methods  
951 with mathematical physical and numerical analysis of storativity influence. *Canadian*  
952 *Geotechnical Journal* 35 (1998) 697-719.

953 [34] Renard P. *Hytool: a hydrogeological toolbox*. University of Neuchâtel, Switzerland2003.

954 [35] Bredehoeft JD, SS Papadopulos. A method for determining the hydraulic properties of  
955 tight formations. *Water Resource Research*. 16 (1980) 233-8, doi:  
956 10.1029/WR016i001p00233.

957 [36] Mejías M, P Renard, D Glenz. Hydraulic testing of low-permeability formations. A case  
958 study in the granite of Cadalso de los Vidrios, Spain. *Engineering Geology*. 107 (2009) 88-97,  
959 doi: 10.1016.

960 [37] Yang YJ, TM Gates. Wellbore skin effect in slug-test data analysis for low-permeability  
961 geologic materials. *Ground Water*. 35 (1997) 931-37.

962 [38] Armstrong M. *Basic linear geostatistics*, Berlin, Germany, 1998.

963 [39] Gringarten E, CV Deutsch. Teacher's Aide, Variogram Interpretation and Modeling.  
964 *Mathematical Geology*. 33 (2001) 507-33, doi: 0882-8121/01/0500-0507\$19.50/1.

965 [40] Guo H, CV Deutsch. Fluvial channel size determination with indicator variograms.  
966 *Petroleum Geoscience*. 16 (2010) 161-9.

967 [41] Deutsch CV. Fortran programs for calculating connectivity of three-dimensional  
968 numerical models and for ranking multiple realizations. *Computers & Geosciences*. 24 (1998)  
969 69-76, doi: [http://dx.doi.org/10.1016/S0098-3004\(97\)00085-X](http://dx.doi.org/10.1016/S0098-3004(97)00085-X).

970 [42] Knudby C, J Carrera. On the relationship between indicators of geostatistical, flow and  
971 transport connectivity. *Advances in Water Resources*. 28 (2005) 405-21, doi:  
972 <http://dx.doi.org/10.1016/j.advwatres.2004.09.001>.

973 [43] Renard P, D Allard. Connectivity metrics for subsurface flow and transport. *Advances in*  
974 *Water Resources*. 51 (2013) 168-96.

975 [44] Cherubini C, F Musci, N Pastore. Checking simulations of a geolithological model  
976 obtained by means of nested truncated bigaussian method. *International Journal of*  
977 *Mathematical Models and Methods in Applied Sciences* 3(2009) 152-61.

978 [45] Yarus JM, RL Chambers, M Maucec, G Shi. Facies Simulation in Practice: Lithotype  
979 proportion mapping and Plurigaussian Simulation, a powerful combination. Ninth  
980 International Geostatistics Congress, Oslo, Norway, 2012.

981 [46] Caine JS, JP Evans, CB Forster. Fault zone architecture and permeability structure.  
982 *Geology*. 24 (1996) 4.

983 [47] Matonti C, Y Guglielmi, J Lamarche, L Marié. Structural and petrophysical  
984 characterization of mixed drain/barrier fault zones in carbonates: Example from the Castellás  
985 Fault (SE France) *Journal of Structural Geology*. (2012).

986 [48] Micarelli L, A Benedicto, CAJ Wibberley. Structural evolution and permeability of  
987 normal fault zones in highly porous carbonate rocks. *Journal of Structural Geology*. 28 (2006)  
988 1214-27, doi: <http://dx.doi.org/10.1016/j.jsg.2006.03.036>.

989 [49] Gringarten E, CV Deutsch. Methodology for Variogram Interpretation and Modeling for  
990 Improved Reservoir Characterization. in: SoP Engineers, (Ed.). Society of Petroleum  
991 Engineers Annual Technical Conference and Exhibition Houston, Texas, 1999. pp. 1-13.

992 [50] Ellis, M.A., Laubach, S.E. Eichhubl, P., Olson, J.E. & Hargrove, P., 2012, Fracture  
993 development and diagenesis of Torridon Group Applegarth Formation, near An Teallach, NW  
994 Scotland: millennia of brittle deformation resilience? *Journal of the Geological Society*,  
995 London. v. 169, no. 3, p. 297-310. doi: 10.1144/0016-76492011-086.

996 [51] Bonneau F, V Henrion, G Caumon, P Renard, J Sausse. A methodology for pseudo-  
997 genetic stochastic modeling of discrete fracture networks. *Computers & Geosciences*. 56  
998 (2013) 12-22.

999 [52] Felletti F. Statistical modelling and validation of correlation in turbidites: an example  
1000 from the Tertiary Piedmont Basin (Castagnola Fm., Northern Italy). *Marine and Petroleum*  
1001 *Geology*. 21 (2004) 23-39.

1002 [53] Papadopoulos IS, JD Bredehoeft, HH Cooper. On the analysis of slug test data. *Water*  
1003 *Resources Research*. 9 (1973) 1087-9.

1004 [54] Cooper HH, Jr., Bredehoeft, J.D., , IS Papadopoulos. Response of a finite diameter well to  
1005 an instantaneous change of water. *Water Resources Research*. 3 (1967) 263-9.

1006 [55] Black JH. The interpretation of slug tests in fissured rocks. *Quarterly Journal of*  
1007 *Engineering Geology and Hydrogeology*. 18 (1985) 161-71.

1008 [56] Warner JW, C Tamayo-Lara, E Khazaei, F Manghi. Stochastic management modeling of  
1009 [57] Brauchler R, R Hu, T Vogt, D Al-Halbouni, T Heinrichs, T Ptak, et al. Cross-well slug  
1010 interference tests: An effective characterization method for resolving aquifer heterogeneity.  
1011 *Journal of Hydrology*. 384 (2010) 33-45, doi: <http://dx.doi.org/10.1016/j.jhydrol.2010.01.004>

1012 [58] Shapiro AM, PA Hsieh. How good are estimates of transmissivity from slug tests in  
1013 fractured rocks? *Ground Water*. 36 (1998) 37-48.

1014 [59] Parker, B.L., Chapman, S.W., Cherry, J.A., 2010. Plume persistence in fractured  
1015 sedimentary rock after source zone removal. *Ground Water*, 48(6): 799-808.

1016 [60] Parker, B.L., Cherry, J.A., Chapman, S.W., 2012. Discrete fracture network approach for  
1017 studying contamination in fractured rock. *AQUA mundi*, 3(2): 101-116.

1018 [61] Guyonnet D, S Mishra, J McCord. Evaluating the volume of porous medium investigated  
1019 by slug tests. *Ground Water*. 31 (1993) 627-33.

1020 [62] Lee S-Y, FC Carle, GE Fogg. Geologic heterogeneity and a comparison of two  
1021 geostatistical models: Sequential Gaussian and transition probability-based geostatistical  
1022 simulation. *Advances in Water Resources*. 30 (2007) 1914-32.

1023 [63] Falivene O, P Arbués, A Gardiner, G Pickup, JA Muñoz, L Cabrera. Best practice  
1024 stochastic facies modeling from a channel-fill turbidite sandstone analog (the Quarry outcrop,  
1025 Eocene Ainsa basin, northeast Spain). *AAPG Bulletin*. 90 (2006) 1003-29, doi:  
1026 10.1306/02070605112.

1027