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1 IMPACT OF THE EN-ECHELON FAULT  
2 CONNECTIVITY ON RESERVOIR FLOW  
3 SIMULATIONS

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12 **Abstract**

13 Limited resolution and quality of seismic data and time requirements for  
14 seismic interpretation can prevent a precise description of the connections  
15 between faults. We focus on the impact of the uncertainties related to the  
16 connectivity of en-echelon fault arrays on fluid flow simulations. We use a  
17 set of one hundred different stochastic models of the same en-echelon fault  
18 array. These fault array models vary in number of relay zones, relative posi-  
19 tion of fault segments, size of overlap zones and number of relay faults. We

20 automatically generate a flow model from each fault array model in four main  
21 steps: (1) stochastic computation of relay fault throw, (2) horizon building,  
22 (3) generation of a flow simulation grid, and (4) definition of the static and  
23 dynamic parameters. Flow simulations performed these stochastic fault mod-  
24 els with deterministic petrophysical parameters entail significant variability  
25 of reservoir behavior, which cannot always discriminate between the types of  
26 fault segmentation. We observe that the simplest interpretation consisting  
27 of one fault significantly yields significantly biased water cut forecasts at pro-  
28 duction wells. This highlights the importance of integrating fault connectivity  
29 uncertainty in reservoir behavior studies.

## 30 **Introduction**

31 During the interpretation of compartmentalized reservoirs, the characterization  
32 of fault connectivity is often critical to match production history and make reason-  
33 able forecasts of reservoir performance (e.g., Jolley et al. (2007)). In this context,  
34 fault connectivity concerns not only the large-scale pattern of faults, which can  
35 originate from several tectonic episodes (Sanderson and Nixon, 2015), but also the  
36 phenomenon of en-echelon faults, which results from the growth, overlap and linkage  
37 of several fault segments, see for instance Peacock and Sanderson (1991); Cowie and  
38 Scholz (1992); Cartwright et al. (1995); Childs et al. (1995); Fossen and Hesthammer  
39 (2000); Walsh et al. (2003); Giba et al. (2012).

40 In the subsurface, the characterization of these zones typically relies of 3D seis-  
41 mic data but may be limited by the seismic resolution and artifacts (Thore et al.,  
42 2002). Indeed, the relatively wide damage zones around overlapping fault segments  
43 (Kim et al., 2004; Rotevatn et al., 2007) tends to diffract seismic waves and make

44 relay fault interpretations very delicate. Significant literature about the description  
45 and statistics about en-echelon fault arrays may be used to drive the fault segment  
46 identification (e.g., Cartwright et al. (1995); Walsh et al. (2003); Soliva and Bene-  
47 dicto (2004)). However, in practice, limited interpretation time is also a source of  
48 uncertainties, which can be exacerbated by the insufficient use of geological concepts  
49 (Kattenhorn and Pollard, 2001; Bond et al., 2007; Bond, 2015).

50 The impact of fault overlap zones on reservoir behavior has been studied by sev-  
51 eral authors (Bense and Van Balen, 2004; Micarelli et al., 2006; Manzocchi et al.,  
52 2008a; Rotevatn et al., 2009a,b; Manzocchi et al., 2010; Fachri et al., 2013). Relay  
53 zones are often described as flow conduits between two fault blocks which would  
54 otherwise be isolated (Bense and Van Balen, 2004; Manzocchi et al., 2010). How-  
55 ever, the complexity and diversity of relay zones make it very challenging to define  
56 a general quantitative rule about their impact on fluid flow (Manzocchi et al., 2010;  
57 Bastesen and Rotevatn, 2012). Indeed, the overlap zones are usually associated with  
58 intense brittle deformation that can lead to the formation of a relay fault. Figure 1a  
59 shows a simplified view of a relay fold, which may be affected by fractures and com-  
60 paction bands, while Figure 1b shows a more mature structure where the relay has  
61 been breached by a relay fault. These two configurations correspond to soft-linked  
62 segments (Figure 1a) and hard-linked segments (Figure 1b). Such relay structures  
63 can act as barriers or drains depending on the fluid types, the rock nature and the  
64 amount and type of deformation. Geometrically, the existence or absence of a con-  
65 necting breach fault in an overlap zone can have a large effect on the juxtaposition  
66 of stratigraphic units on either sides of the fault zone. As a first approximation,  
67 the juxtaposition of two high permeability units increases the connectivity between  
68 two fault blocks, whereas a reservoir unit can be sealed due to its juxtaposition

69 with low permeability units. However, more complex effects can occur due to the  
70 possible occurrence of cataclastic deformation bands or the smearing of shale in the  
71 fault planes.

72 Representing the effects of all these features of reservoir flow model is challeng-  
73 ing, especially for multi-phase flow, see Manzocchi et al. (2010). A possible avenue  
74 is to integrate the effects of these features as deterministic or stochastic perturba-  
75 tions of transmissibilities between neighboring control volumes in the flow simulation  
76 grid. For example, Manzocchi et al. (2008a) capture the effects of small fault throw  
77 changes in a pillar-based reservoir grid and simulate relay zone frequency based on  
78 the mapped throw. In this paper, we instead explicitly create a new grid for each  
79 realization to capture the uncertainties.

80 For this, we build on a recent stochastic method that generates a set of possible  
81 segmentation configurations from a composite fault interpreted as one continuous  
82 structure (Julio et al., 2015). A segmentation configuration means here a 3D ge-  
83 ometric model composed of overlapping segments separated by breached or intact  
84 relay zones. The method uses the orientation variations of the composite fault as  
85 indicators of the occurrence of relay zones. The models generated by this method  
86 mainly vary in number of fault segments, relative position of the segments, size of  
87 overlap zones and number of relay faults. From each fault model and horizon data,  
88 we create a synthetic numerical flow model made of a flow simulation grid associated  
89 with static and dynamic parameters.

90 As compared to transmissibility-based approaches, our method is not *a priori*  
91 constrained by a reference flow simulation grid and allows considering the effects of  
92 fault segments on the static accumulations. It probably allows for more variability  
93 in the simulated geometry of relay zones, by exploiting the capabilities of recent

104 advanced gridding algorithms to integrate more complex fault descriptions than  
105 generally possible in pillar grids (Gringarten et al., 2008; Mallison et al., 2014). We  
106 also believe such an explicit geometric representation could be interesting in the  
107 future to integrate the effects of juxtaposition and damage zones on other physical  
108 processes (e.g., geomechanics or seismic wave propagation). In the context of the  
109 present paper which uses stair-step corner-point geometry flow grids, the method is  
110 suitable for local flow models or global flow models in which the separation between  
111 fault segments is larger than the areal grid resolution, as for instance in Rotevatn  
112 et al. (2009a).

103 In the following, we present the method to stochastically simulate relay zones and  
104 apply it to a reservoir model. Our approach extends the previous work by Julio et al.  
105 (2015). In particular, we capture the fault juxtaposition uncertainties in the relay  
106 zones by simulating possible throws of the relay fault, and we generate grids whose  
107 topology and geometry may vary for each realization. This allows us to perform  
108 a flow sensitivity analysis on all the simulated models to study the relationships  
109 between the types of segments and the flow behavior.

110 [Figure 1 about here.]

## 111 **Automatic generation of segmented reservoir mod-** 112 **els**

113 Reservoir modeling generally aims at transforming geophysical and borehole in-  
114 terpretations into a 3D reservoir flow grid. Standard workflows are roughly com-  
115 posed of four main successive steps. (1) The first step consists of building a reservoir  
116 structural model in which the geological interfaces, such as faults, horizons and un-

117 conformities, are represented as 3D surfaces (Mallet, 1988; Caumon et al., 2009).  
118 (2) Then, a corner-point grid widely used in reservoir simulation provide a 3D mesh  
119 of the reservoir volume. (3) From well data, the petrophysical properties of the rock  
120 are computed using deterministic interpolations or stochastic simulations (Pyrzcz and  
121 Deutsch, 2014). (4) Flow simulations may then be finally performed based on finite  
122 volume methods.

123 In this paper, we combine a new method to create a stochastic description of  
124 a 3D segmented fault (Julio et al., 2015) with standard existing methods for the  
125 steps 1-3. This section starts with a description of the data set used in our study  
126 and generated by the method of Julio et al. (2015). Then, we present the strategy  
127 applied to model the horizons. Indeed, as no horizon data points are available in  
128 relay zones, we propose to stochastically estimate the throw of the relay faults, and  
129 to use this estimation to constrain the interpolation of the horizon geometry in relay  
130 zones. Then, we explain how we create a conventional reservoir simulation grid for  
131 each of the stochastic structural models.

### 132 *Data set and stochastic fault model generation*

133 The proposed method is applied on a Middle East case study whose orientation,  
134 reservoir depth and fluid contact depth have been modified for confidentiality rea-  
135 sons. The data set used to model the reservoir is composed of: two horizon point sets  
136 and a normal fault  $\mathcal{F}$  (Figure 2). The two horizon point sets and the fault  $\mathcal{F}$  have  
137 been interpreted from a relatively low-quality onshore 3D seismic data set. These  
138 two horizons delimit a reservoir formation whose thickness is about 180 m and cover  
139 an area of 11 km by 1.1 km. The fault  $\mathcal{F}$  is a composite normal fault whose segmenta-  
140 tion could not be clearly identified from the seismic data. The global geometry of the

141 reservoir is a monoclinical horst striking N 140 (Figure 2). The fault  $\mathcal{F}$  strikes parallel  
142 to the main reservoir orientation and may be a potential flow barrier between the  
143 upper compartment and the lower compartment whose pressure is supported by an  
144 active aquifer located in the SW. The uncertainties associated to the exact location  
145 of this fault can also impact the OOIP because the top depth of footwall block is  
146 close to the oil-water contact depth. Therefore, small fault throw perturbation has  
147 a relatively large impact on reservoir closure. In the reservoir zone, the orientation  
148 of the fault  $\mathcal{F}$  locally shows some abrupt variations in the strike direction.

149 Julio et al. (2015) quantify these strike variations and interpret them as possible  
150 indicators of overlap zone occurrence. Their stochastic simulation method simulates  
151 possible fault segments from approximately planar areas in the fault surface using  
152 probabilistic descriptions about relative segment size and overlap/size relationships.  
153 This method has been applied to generate one hundred segmentation models of the  
154 fault  $\mathcal{F}$ . These models may have different number of fault segments, size of overlap  
155 zones, relative position of segments and segment geometry. The occurrence or not  
156 of a relay fault in an overlap zone is determined from the ratio between *overlap*  
157 (overlap zone length) and *separation* (overlap zone width). If this ratio is superior  
158 to a stochastically-chosen threshold, a relay fault is modeled in the middle of the  
159 corresponding overlap zone (Soliva and Benedicto, 2004). In the vertical direction,  
160 the relay faults have the same extent as the associated overlapping segments. Figure  
161 3 summarizes the generated configurations among the one hundred downscaled mod-  
162 els of the fault  $\mathcal{F}$ . The three main obtained segmentation configurations are: 28%  
163 are two hard-linked left-stepping segments, 25% are two soft-linked right-stepping  
164 segments, 16% are three soft-linked segments (Figure 3).

165 The downscaling method introduced by Julio et al. (2015) deals only with the



166 uncertainty related to faults (treated as slip surfaces), without consideration of the  
167 displacement in the relay zone that may be poorly-imaged on the seismic data.  
168 Therefore, we now present a new algorithm to manage uncertainties on the throw  
169 of relay faults, which can have a large impact on flow (Manzocchi et al., 2010).

170 [Figure 2 about here.]

171 [Figure 3 about here.]

### 172 *Stochastic computation of relay fault throws*

173 3D horizons are built by interpolation of input point sets extracted from 3D  
174 seismic data. However, in the majority of cases, the low quality of seismic data does  
175 not allow the characterization of the horizon geometry in overlap zones. In models  
176 with a continuous ramp in the relay, the geometry is computed by interpolation  
177 between horizon picks available on either side of the ramp. This is essentially similar  
178 to making a thin-plate assumption of the horizon geometry within the relay ramp.  
179 In models where the ramp is breached, the relay fault throw must be estimated  
180 before interpolating the horizon geometry.

181 For this, we propose to simulate points that will be used as interpolation con-  
182 straints for horizon building in breached relay zones. Consider a horizon denoted  
183  $\mathcal{H}$  and a relay fault denoted  $\mathcal{R}$ . The method computes the vertical displacement  
184 (denoted  $d$ ) of the horizon  $\mathcal{H}$  in the neighborhood of the relay zone, i.e. the total  
185 displacement away from the relay fault  $\mathcal{R}$ . This displacement  $d$  is computed from a  
186 sphere centered on the relay fault center and whose radius is input by the interpreter  
187 (Figure 4). The points associated with the horizon  $\mathcal{H}$  inside the sphere are selected  
188 and the algorithm differentiates the points located in the footwall of the relay fault

189 from the ones in the hanging wall. The mean difference in depth between these two  
 190 point sets gives an estimate of the vertical displacement  $d$ . If the sphere contains  
 191 no data point, it is enlarged until points are found. This methodology calls for reli-  
 192 able horizon picks in the vicinity of the fault, for example by eliminating potentially  
 193 erratic points within a certain distance of the fault surface.

194 The vertical displacement  $d$  corresponds to the sum of the throw ( $d_{Fault}$ ) of the  
 195 relay fault  $\mathcal{R}$  and of the vertical displacement ( $d_{Fold}$ ) associated with the ramp fold,  
 196 which is also termed “throw deficit” (Faure Walker et al., 2009). The ratio between  
 197 the relay fault throw  $d_{Fault}$  and the total displacement  $d$  at the relay fault center  
 198 is related to the maturity of the relay zone. In our method, we use a probability  
 199 distribution from which this ratio can be sampled to generate a particular realization.  
 200 In the vertical direction, this ratio is assumed to be maximal at the relay fault center  
 201 and to decrease vertically towards the relay fault tips. Consider a function  $\beta$  that  
 202 characterizes the ratio evolution (Figure 4a), and a parameter  $v$  that is the signed  
 203 difference between the relay fault center depth and the mean depth of the horizon  
 204  $\mathcal{H}$  inside the sphere. The value of the relay fault throw associated with the horizon  
 205  $\mathcal{H}$  is defined as:

$$d_{Fault} = \beta(v) \cdot d \quad (1)$$

206 The hanging wall and the footwall may differently accommodate the brittle defor-  
 207 mation. Therefore, we define a partition factor  $\gamma$  (between 0 and 1) as the proportion  
 208 of throw accommodated by the footwall (Georgsen et al., 2012; Laurent et al., 2013).  
 209 Thus, the values of throw in the footwall and in the hanging wall are:

$$d_{Fault}^{FOOT} = \gamma \cdot d_{Fault}, \quad (2)$$

210

$$d_{Fault}^{HANG} = (1 - \gamma) \cdot d_{Fault} \quad (3)$$

211 The values  $d_{Fault}^{FOOT}$  and  $d_{Fault}^{HANG}$  are used to add synthetic horizon points condition-  
212 ing the relay fault throw (Figure 4b). These new stochastic points and the initial  
213 point sets are used to interpolate the horizon geometry (Figure 4b). In terms of  
214 impact of these parameters, the value of  $\beta$  directly affects the geometry and the  
215 juxtaposition of rock units across the fault zone. The value of  $\gamma$  has probably less  
216 influence because it only affects the depth of the layers in the fault zone and not the  
217 juxtaposition.

218 In our application, the parameter  $\beta(0)$  characterizing the ratio between the relay  
219 fault throw and the total vertical displacement at the fault center is randomly chosen  
220 from a Gaussian distribution defined by a mean and a standard deviation equal to  
221 0.5 and 0.08, respectively. This means that the relative throw deficit due to the relay  
222 is assumed to vary between 34% and 56% of the global throw  $d$  in 95 % of the cases.  
223 The choice of these values are here arbitrary, so further studies should be made to  
224 define  $\beta(0)$  according to the lithology and to the intensity of the deformation. The  
225 partition factor  $\gamma$  is also chosen from a Gaussian distribution defined by a mean and  
226 a standard deviation equal to 0.5 and 0.08, respectively. Indeed, as the relay faults  
227 have been simulated in the middle of the overlap zones, we make the parsimonious  
228 assumption that, on average, the footwall and the hanging wall accommodate about  
229 the same quantity of deformation.

230

[Figure 4 about here.]

231 *Grid computation and petrophysical modeling*

232 Based on the API (Application Programming Interface) of the geomodeling soft-  
233 ware Gocad-SKUA, we have developed a plugin which implements the stochastic  
234 segmented fault downscaling approach described above and then automatically gen-  
235 erates a corner-point grid honoring these structures (Figure 5a). The gridding  
236 method generates stair-step corner-point grids as described in Gringarten et al.  
237 (2008). Essentially, the reservoir grids honor the stratigraphic layering and main-  
238 tain sub-orthogonal cell shapes suitable for conventional reservoir simulation. As a  
239 result, the faults are discretized as stair-step cell faces.

240 This allows us to efficiently build grids from a large set of stochastic structural  
241 models. The grid dimensions are globally equal to  $11 \text{ km} \times 3 \text{ km} \times 0.8 \text{ km}$ . Each  
242 grid is composed of the same number of cells ( $230 \times 30 \times 20 = 230,000$ ), yielding  
243 an average grid block size of  $48 \times 122 \times 8.6 \text{ m}$ . However, due to the topological and  
244 geometrical changes of the fault array, the number of active cells slightly varies in  
245 each model and is approximately equal to 112,000 (cells are considered dead if their  
246 pore volume is lower than  $100 \text{ m}^3$ ).

247 To isolate the effect of fault uncertainty on flow behavior, we have used the same  
248 synthetic petrophysical model in all the simulated grids. This petrophysical model  
249 assumes laterally continuous but vertically layered rock types as could exist for in-  
250 stance in turbiditic lobes. The Net-To-Gross values have been chosen constant and  
251 equal to 0.8. The porosity and the permeability have been simulated as stationary  
252 Gaussian random fields using a Sequential Gaussian Simulation (Figure 5b). We  
253 used spherical variogram models with ranges of 5 km, 3 km and 5 m in the N 140,  
254 N 230 and vertical directions, respectively. The porosity approximately follows a

255 normal distribution of average 0.13 and standard deviation 0.02. The horizontal  
256 permeability is isotropic and approximately follows a triangular distribution of min-  
257 imum 200 mD, mode 600mD and maximum 1500mD. It has a 0.98 rank correlation  
258 coefficient with the porosity values. The  $K_V/K_H$  ratio is taken constant and equal  
259 to 0.001 to compensate for the relatively coarse vertical grid resolution.

## 260 **Flow simulations results and interpretations**

### 261 *Fluid flow simulation parameters*

262 The en-echelon fault array completely crosses the reservoir from NW to SE (Fig-  
263 ure 5). The faults are considered as partially sealing with transmissibility multipliers  
264 assumed constant and equal to 0.05.

265 Two initial fluids, water and oil, are initially present in the reservoir. The initial  
266 water saturation in the oil zone is 0.05 and the residual oil saturation after water  
267 flooding is 0.24. The water oil contact vertically crosses the fault array (Figures 6  
268 and 7). At the SW, an aquifer maintains the reservoir pressure during oil production  
269 (Table 1).

270 The reservoir production scenario takes advantage of aquifer pressure support  
271 and only uses two production wells  $w_1$  and  $w_2$ , located in the NE near the top of the  
272 structure (Figure 5, Table 1). In the initial state, all the well perforations are located  
273 in the oil zone. The wells are controlled by the oil production rate but completions  
274 may be shut down if the bottom-hole becomes lower than an input threshold (Table  
275 1).

276 [Figure 5 about here.]

277 [Figure 6 about here.]

278 [Figure 7 about here.]

279 [Table 1 about here.]

### 280 *Fault segmentation impact on flow simulations*

281 From the 100 downscaled models, we obtained 93 flow simulations. The seven  
282 other models failed during the automatic grid generation step or the flow simulations.  
283 In this section, we compare the oil saturation and the water cut evolution of the  
284 different segmented reservoir models (Figures 9, 7, 10, 11).

285 **Range of initial conditions.** The stochastic estimate of relay fault throws and  
286 the interpolation between point sets involve some variations on the initial oil in place  
287 value of the stochastic downscaled models. The mean and the standard deviation  
288 are equal to  $176.8 \text{ Msm}^3$  and  $1.710 \text{ Msm}^3$ , respectively (Figure 8). These variations  
289 can be explained because the local throw and reservoir top depth variations directly  
290 affect the gross rock volume above the oil-water contact. The model composed of  
291 the single fault  $\mathcal{F}$  ( $177.3 \text{ Msm}^3$ ) is close to the mean (Figure 8).

292 [Figure 8 about here.]

293 **Range of dynamic responses.** After 30 years of production, the water cut values  
294 vary from 0.13 to 0.91 in well  $w_1$  and from 0.15 to 0.91 in well  $w_2$  (Figure 10a-  
295 b). This very high dispersion of water-cuts highlights the significant impact of  
296 fault segmentation on reservoir behavior. In the reservoir model composed of the  
297 continuous fault  $\mathcal{F}$  (before downscaling), the water-cut values are respectively equal

298 to 0.37 and 0.85 in wells  $w_1$  and  $w_2$  after 30 years of production (Figure 9). These  
299 two values are close to the extreme values of the statistics of downscaled models.  
300 Indeed, the deterministic water cut value (0.37) for the well  $w_1$  is inferior to the  
301 10th percentile (0.43) of the stochastic models, and, on contrary, the deterministic  
302 water cut value (0.85) for the well  $w_2$  is superior to the 80th percentile (0.81) of  
303 the stochastic models. Thus, performing flow simulations on the fault  $\mathcal{F}$  without  
304 consideration of the segmentation uncertainties may lead to major approximations  
305 in dynamic behavior predictions, and therefore in oil production estimates.

306 **Fault segmentation configurations and flow responses.** One of the outputs  
307 of the downscaling method is the probability of segmentation configurations (Figure  
308 3). These configurations can be seen as samples of discrete structural scenarios.  
309 Could these scenarios be discriminated from actual reservoir production data? To  
310 answer this question, for each of these configurations, we analyze the water cut  
311 evolution and the breakthrough time (considered occurring when the water fraction  
312 reaches 0.01 at producer wells).

313 Figure 10c-d shows the evolution for models composed of two hard-linked left-  
314 stepping segments and of two soft-linked right-stepping segments. In the well  $w_1$ ,  
315 the water cut at a given time is globally higher for two soft-linked than for two hard-  
316 linked segments. The opposite result is clearly observed for the well  $w_2$ . Figure 11  
317 shows statistics about water breakthrough times for the main different configura-  
318 tions, which confirm the previous observations. In the well  $w_1$ , the water break-  
319 through is earlier for two soft-linked segments than for two hard-linked segments  
320 (Figure 11a). The water delay is likely due to the relay fault that slows down the  
321 percolation of water across the ramp (Figure 7b). Conversely, in the well  $w_2$ , the  
322 water breakthrough is earlier for two hard-linked segments than for two soft-linked

323 segments (Figure 11b). This can be explained by the relatively large water produc-  
324 tion in the well  $w_1$  in the case of two soft-linked segments, allowing the well  $w_2$  to  
325 remain longer in the oil zone (Figure 7b-d).

326 We can also analyze the difference on dynamic behavior between three soft-linked  
327 segments (no ramp is breached) and two soft-linked segments (Figures 7c-d, 10e-f  
328 and 11). In the well  $w_1$ , the water breakthrough is, on average, earlier for three-  
329 segment models than for two-segment models (Figure 11a). This can be explained  
330 by the small throw of the central segments in three-segment configurations, leading  
331 to a significant juxtaposition area of reservoir layers (Figure 7c). As these segments  
332 are only partially sealing, they act as major preferential flow paths. In the well  
333  $w_2$ , no clear relationship appears between flow trends and segmentation patterns  
334 (Figures 10f and 11b).

335 Similarly, the configurations composed of three soft-linked segments are hardly  
336 differentiated using the water cut evolution (Figures 10g-h and 11). Nonetheless,  
337 as the models with such configurations are few, the corresponding statistics should  
338 be cautiously analyzed. Overall, the configurations composed of soft-segments are  
339 difficult to differentiate one from another. However, the configuration composed of  
340 two hard-linked left-stepping segments presents a dynamic behavior different from  
341 the other configurations analyzed in this section (Figure 11).

342 While segmentation patterns affect flow paths in the reservoir, a high variability  
343 of flow responses is also observed among models of a same pattern (Figures 10, 11).  
344 This is likely due to the large vertical variability of the permeability, which involves  
345 large changes in fault transmissibility as the throw changes. This may also stem  
346 from geometric variations of the segments, relay zone locations and local layer dip  
347 changes.



348 [Figure 9 about here.]

349 [Figure 10 about here.]

350 [Figure 11 about here.]

## 351 **Discussion and conclusions**

352 This paper presents a study of fault segmentation effects on flow simulations  
353 using a sample of possible configurations computed stochastically from a large-scale  
354 composite fault. For this, we have developed a new process that automatically  
355 generates structural models, flow simulation grids and petrophysical properties. This  
356 provides an alternative to methods which perturb the transmissibilities of a reference  
357 pillar-based reservoir simulation grid.

358 Several improvements could be added in the stochastic simulation method. At  
359 present, we have made the choice to always use the same geometric rules to gener-  
360 ate breach faults. As a result, simulated breach faults always have the same relative  
361 strike as compared to the fault segments. This could be made variable, as it has been  
362 shown to have an impact on strain localization during fault growth (Faure Walker  
363 et al., 2009). Also, the downscaling method does not presently use throw estimation  
364 to constrain the number of segments. As discussed in Julio et al. (2015), this infor-  
365 mation could either be integrated in the stochastic segmentation method or used as  
366 a criterion to assess the likelihood of the stochastic models after the simulation.

367 While the present study focuses on uncertainties related to fault connectivity,  
368 several additional sources of uncertainties could be addressed in future develop-  
369 ments. From a geometric standpoint, the horizons have been generated without  
370 consideration of interpretation and velocity uncertainties (e.g., Abrahamsen (1992);

371 Thore et al. (2002)). These sources of uncertainty could be incorporated into the  
372 stochastic process, for instance by the perturbation of the depth and thickness of  
373 the generated reservoir grids. A loop back computing synthetic seismic models from  
374 the realizations and comparing with the actual data could also be useful to rank the  
375 various stochastic interpretations generated by our approach.

376 In terms of petrophysics, the petrophysical and dynamic parameters were kept  
377 the same in all the generated reservoir models to highlight the impact of structural  
378 geometry uncertainties on flow simulations. However, a complete reservoir uncer-  
379 tainty study would definitely need to jointly assess the effects of fault segmentation  
380 and petrophysical uncertainty, by using also multiple petrophysical models. More-  
381 over, the effects of the various structural configurations on capillary rock properties  
382 in the fault and relay zones should in principle be overprinted to the depositional  
383 petrophysical model, both in the deformed neighborhood of the fault (Rotevatn  
384 et al., 2009b; Fachri et al., 2013) and on the fault surfaces themselves (Manzocchi  
385 et al., 1999, 2002; Myers et al., 2007). Adding these relationships to the flow mod-  
386 els could be interesting to better approach the true dynamic flow behavior of the  
387 simulated relay zones.

388 As compared to our approach, geometrical upscaling (Manzocchi et al., 2008b,  
389 2010) deals with relay uncertainty by direct editing of transmissibilities on a pillar  
390 grid, assuming that faults are vertically aligned on grid pillars. The methodol-  
391 ogy proposed in this paper makes fewer assumptions about the fault geometry but  
392 leaves the discretization problems to the chosen stair-stepped gridding algorithm  
393 (Gringarten et al., 2008). Although the details of both methods vary, they are es-  
394 sentially both limited by the reservoir grid resolution, which can only represent the  
395 effect of the fault features as constant permeability within each grid block or as a

396 transmissibility multiplier between rock volumes. At this point, in spite of its pil-  
397 lar approximation, geometrical upscaling may be more accurate than our present  
398 implementation because it does integrate fault features in the computation of trans-  
399 missibility multipliers. However, the possible effect of grid distortions in pillar grids  
400 may be a source of artifacts. Further comparison between our approach and geomet-  
401 rical upscaling is difficult because it strongly depends on implementation, so would  
402 certainly call for further studies. Nevertheless, other types of gridding algorithms  
403 could be used in our approach, such as the cut-cell method Mallison et al. (2014)  
404 for flow simulation. We also suggest that our workflow clears the path for more  
405 accurate modeling of coupled flow and mechanical processes in complex fault zones.  
406 Therefore, future work will aim to connect the stochastic workflow with unstructured  
407 gridding methods (Mustapha et al., 2011; Merland et al., 2014; Pellerin et al., 2014;  
408 Zehner et al., 2015) and advanced multiphysics codes (e.g., Matthäi et al. (2007);  
409 Paluszny et al. (2007)).

410 Nonetheless, the observed impact of fault segmentation on reservoir behavior  
411 confirms that relay zone uncertainties can be consequential for dynamic reservoir  
412 forecasts. This finding is consistent with many previous studies (e.g., Rotevatn et al.  
413 (2009a); Manzocchi et al. (2007); Myers et al. (2007); Manzocchi et al. (2008a)). The  
414 consequence of under-estimating fault uncertainty may lead to poor field develop-  
415 ment plans and inappropriate parameter selection in history matching tasks. The  
416 sensitivity study suggests that using only a small set of structural interpretations (or  
417 scenarios) may not be sufficient to capture the range of reservoir behavior uncertain-  
418 ties. This motivates further research to develop new interpretation and modeling  
419 approaches, for instance to integrate well tests early in the uncertainty assessment  
420 methodology to see if these allow to rule out some unrealistic structural scenarios.

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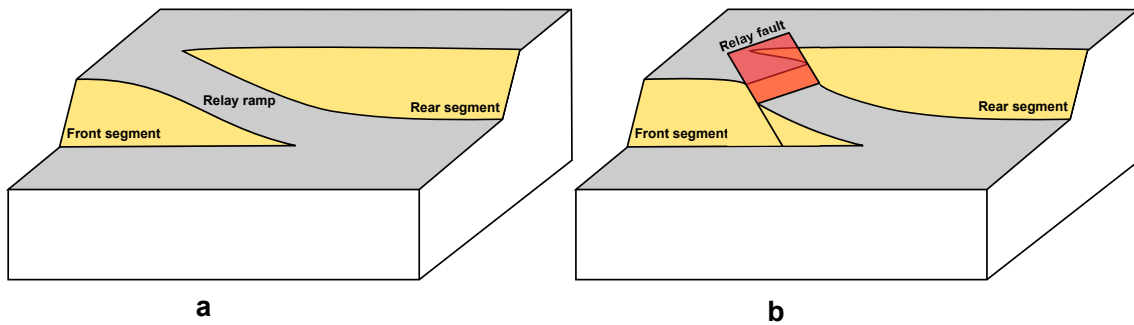


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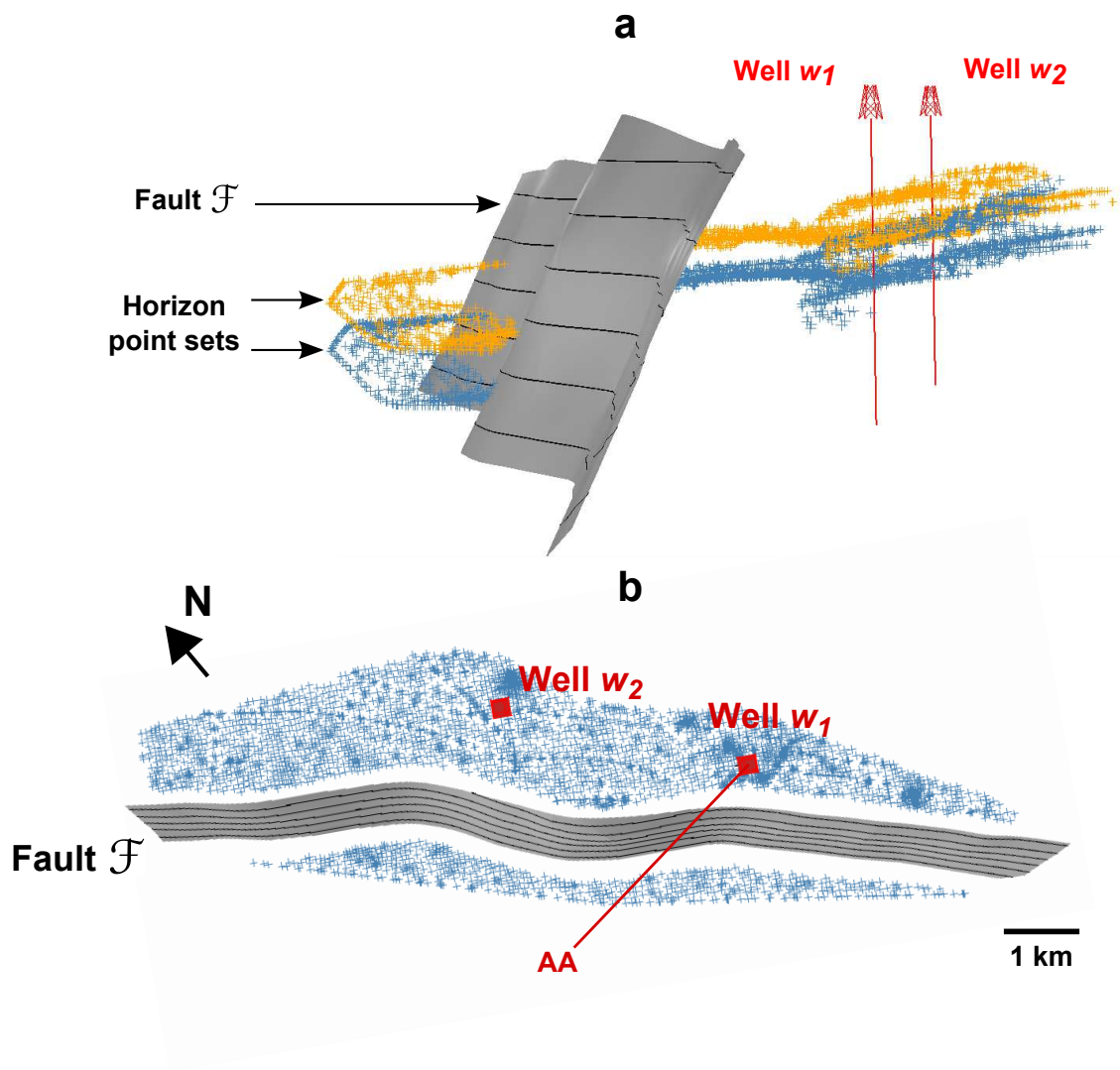


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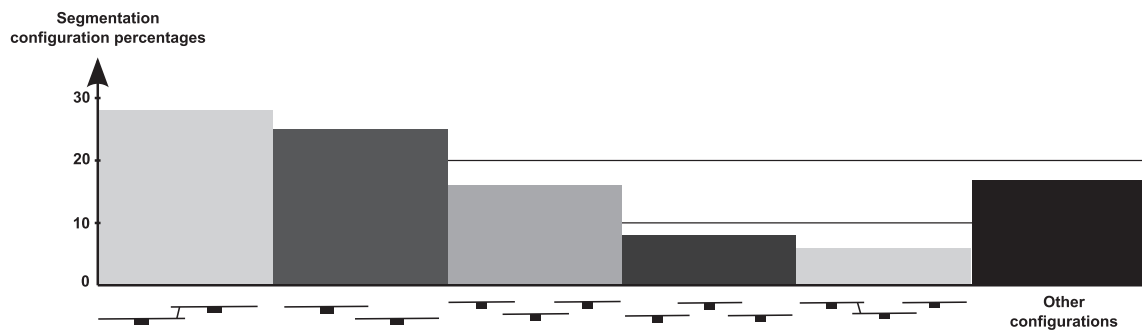


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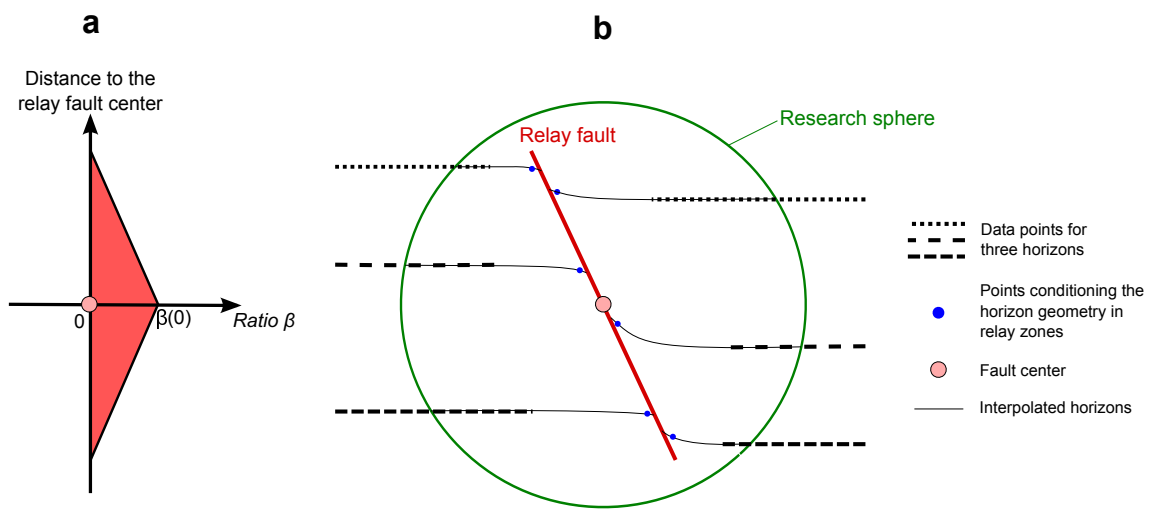


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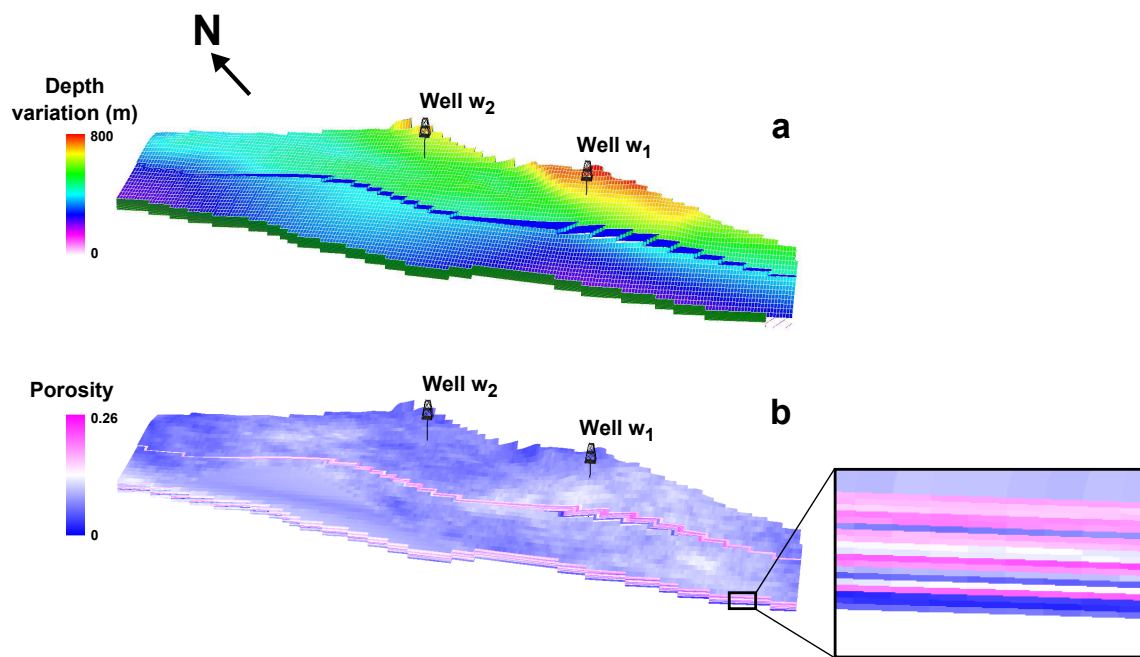


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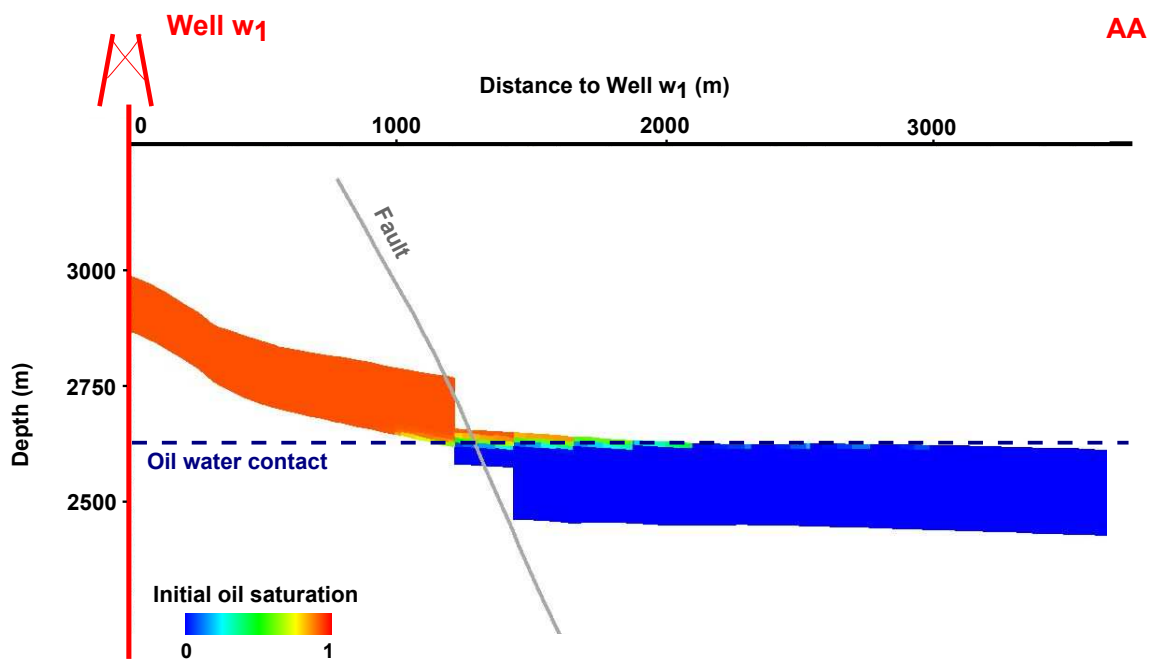


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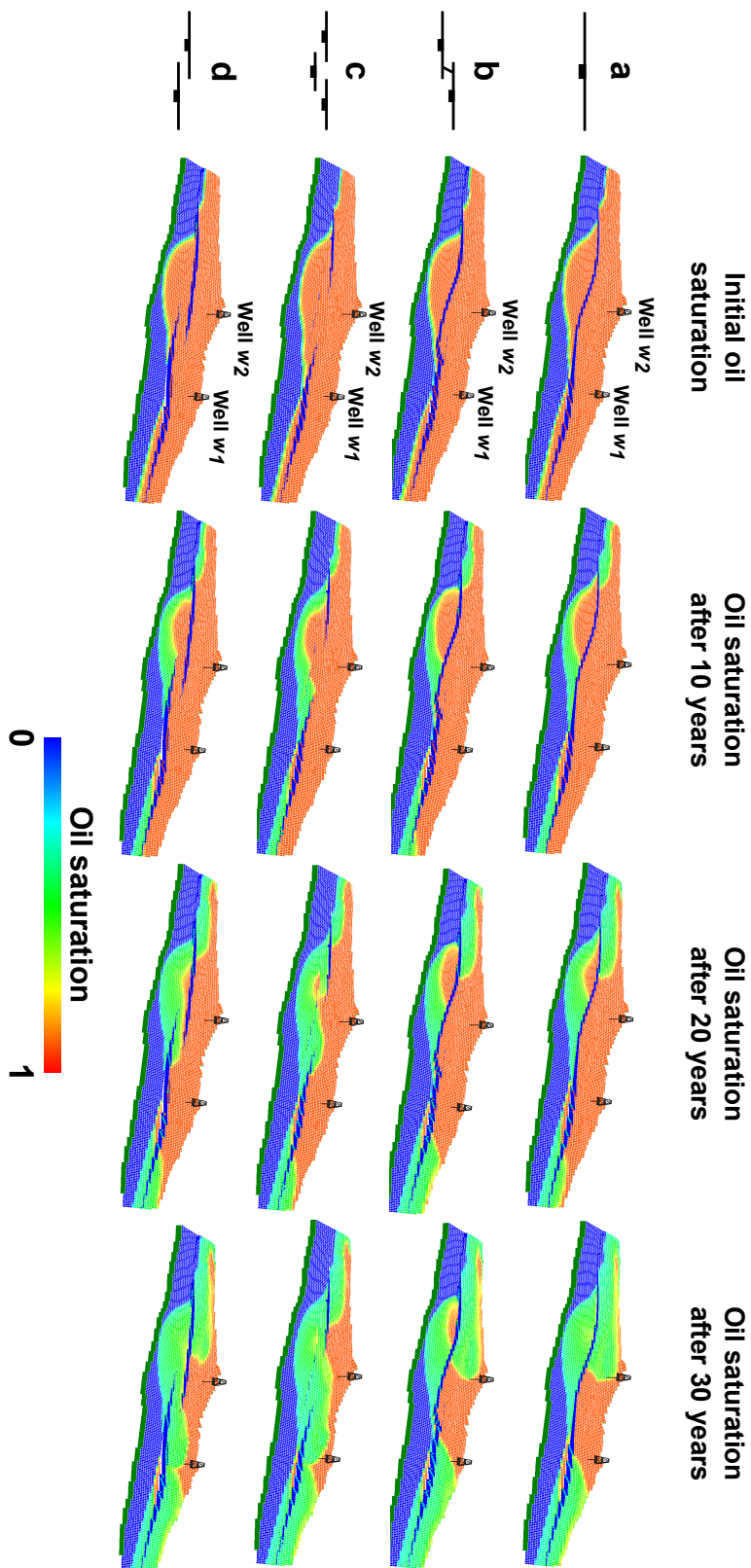


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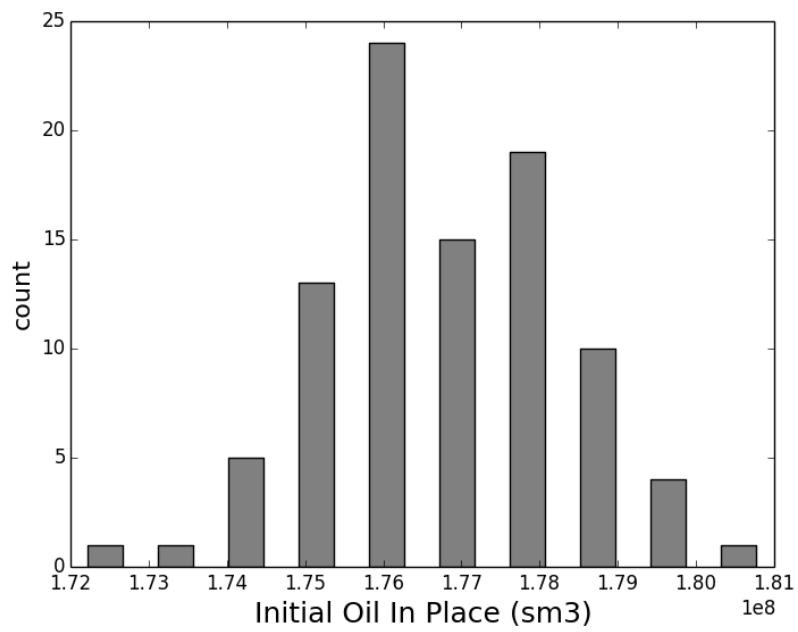


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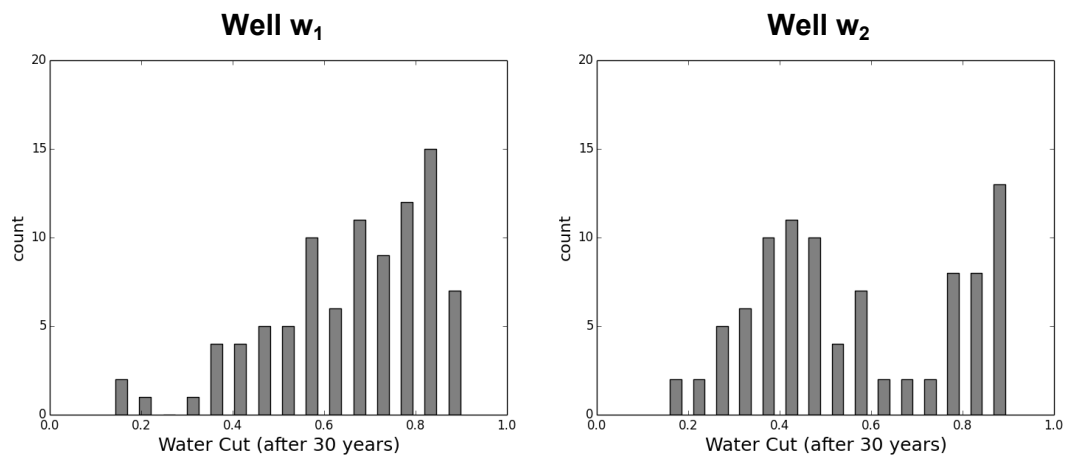


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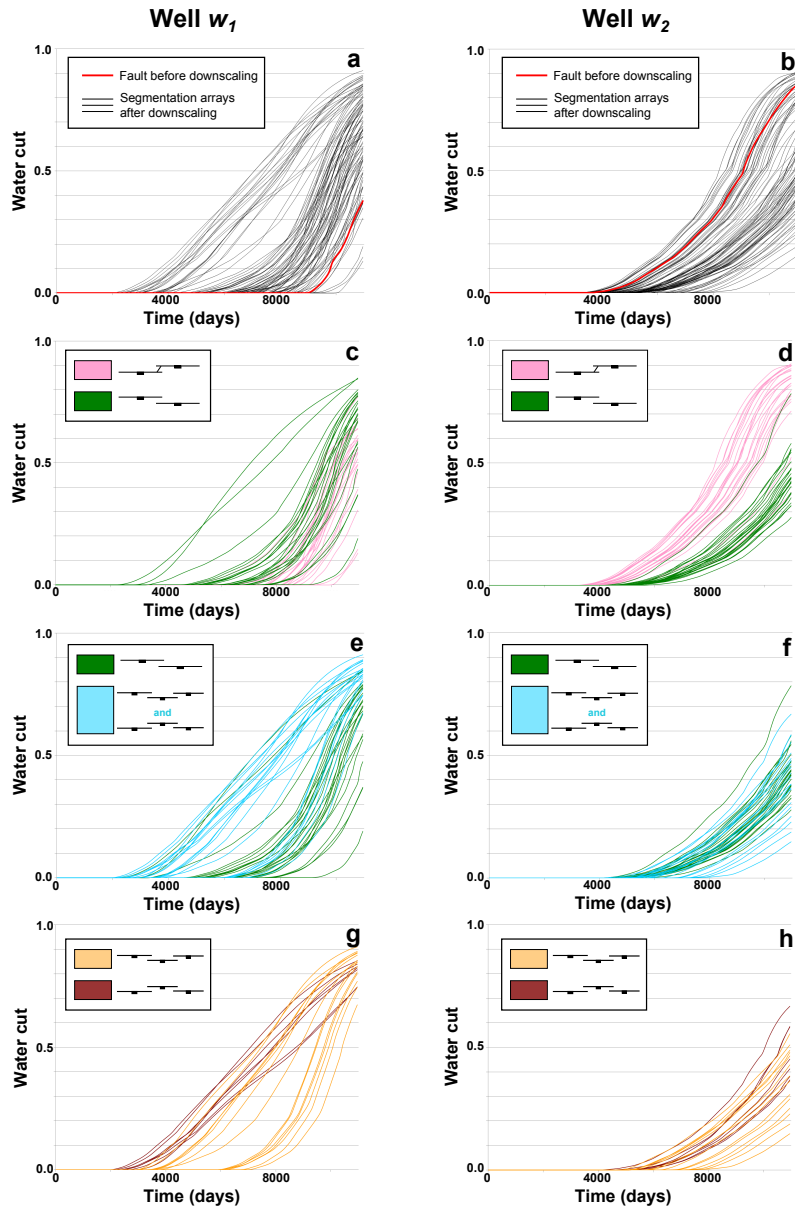


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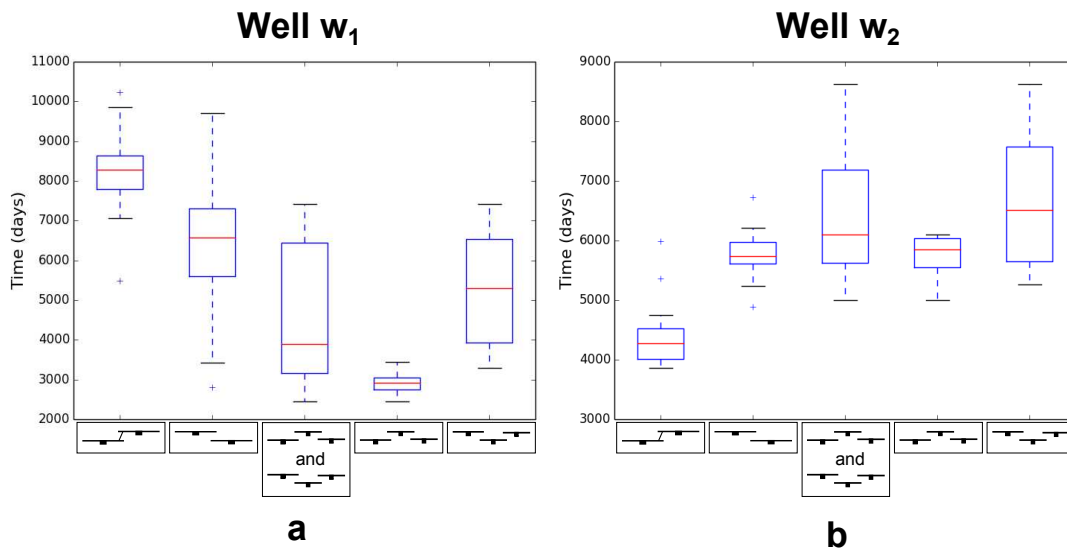


Figure 11: Statistics on the water breakthrough time according to the segmentation configurations. We have considered that the water breakthrough is reached when the water cut becomes superior to 0.01. (a) Well  $w_1$ . (b) Well  $w_2$ .

|                       |       |  |
|-----------------------|-------|--|
| <b>Run time</b>       |       | 30 years                                 |
| <b>Initial fluids</b> |       | water, oil                               |
| <b>Aquifer</b>        |       | Carter-Tracy model                       |
| Inner radius          |       | 50,000 <i>m</i>                          |
| Thickness             |       | 100 <i>m</i>                             |
| Permeability          |       | 300 <i>mD</i>                            |
| Porosity              |       | 0.18                                     |
| <b>Wells</b>          |       | 2 producers ( $w_1$ and $w_2$ )          |
| Initial control       | $w_1$ | Oil rate target control                  |
|                       | $w_2$ | Oil rate target control                  |
| Oil rate target       | $w_1$ | 4500 <i>sm</i> <sup>3</sup> / <i>day</i> |
|                       | $w_2$ | 3500 <i>sm</i> <sup>3</sup> / <i>day</i> |
| Lower BHP limit       | $w_1$ | 100 <i>barsa</i>                         |
|                       | $w_2$ | 100 <i>barsa</i>                         |

Table 1: Flow simulation parameters