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1 Inter-well scale natural fracture geometry and 2 permeability variations in low-deformation 3 carbonate rocks

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8 **Keywords:** natural fractures, equivalent permeability, aperture, discrete fracture networks,
9 Potiguar basin, shallow-water carbonates

10 **Abstract**

11 Regional natural fracture networks often show variations on a scale below that captured by
12 seismic reflection data. This variability is not considered in most reservoir models, but likely
13 impacts uncertainties in permeability. We quantify this uncertainty using a database of 13,000
14 fractures in nine outcrops digitised in the carbonate Jandaíra Formation (Potiguar basin,
15 Brazil). Distance between outcrops is on average 11 km, with a minimum of 300 m, which is
16 comparable to the distance between wells in naturally fractured reservoirs. In between
17 outcrops, significant variations exist in orientation, intensity, length and topology. Using
18 discrete fracture-matrix flow models, we model the permeability of each deterministic pattern
19 and find that small changes in geometry and topology result in permeability variations that
20 are not captured by connectivity-based analyses such as percolation probabilities, particularly
21 when the matrix is permeable. The permeability variations associated with subseismic-scale
22 fracture variability are not captured in conventional stochastic models, but can be captured
23 using deterministic outcrop models with flow through discrete fractures. The deterministic
24 models provide a permeability range associated with subseismic fracture variability, that can

25 be assigned to grid cells of fractured reservoir flow models, as an alternative to assuming
26 constant permeability in the absence of subseismic-scale deformation.

27 **1. Introduction**

28 Wells in naturally fractured reservoirs produce from multiscale fracture systems that are
29 partly or completely below the resolution of seismic reflection data (Bonnet et al., 2001;
30 Makel, 2007). Natural fractures can be measured in wells, but these data typically only
31 provide a 1-D, or 3-D in the case of borehole images, characterisation that does not fully
32 capture the spatial and size distributions of 3-D fracture networks at scales larger than the
33 borehole (Bourbiaux et al., 2002; Gauthier et al., 2002). The existence of common
34 heterogeneities in fracture networks is well-known from large-scale outcrops of fractured
35 rocks, such as those in the Bristol Channel in the UK or the Burren in Ireland (Cosgrove,
36 2001; Gillespie et al., 2001; Belayneh and Cosgrove, 2010). Overall spatial trends in
37 geometry with associated porosity and permeability are often captured in reservoir models by
38 relating fracture orientation and intensity to characteristics and development history of larger-
39 scale host structures such as folds or faults (Price, 1966; Bergbauer, 2007; Smart et al., 2009;
40 Shackleton et al., 2011).

41 Relations between seismic-scale deformation and fracture networks help to capture
42 km-scale trends in fracture intensity and orientation that are observed in some reservoirs, but
43 outcrops typically indicate that, at a subseismic scale, variability of fracture network
44 geometry does not simply relate to the geometry of the larger, seismic-scale folds or faults
45 (Bisdom et al., 2014). With respect to this matter, we focus on fractured carbonate reservoirs
46 that experienced very little tectonic deformation and consider the inter-well scale (i.e. several
47 hundred metres to less than ten kilometres), where fracture variability is not easily quantified,
48 but may impact permeability (Peacock, 2006; Lei and Wang, 2016). Obtaining a better

49 understanding of the impact of this scale of fracture variability on permeability should help to
50 quantify appropriate uncertainty ranges for permeability that otherwise can often not be
51 entirely quantified in subsurface datasets (Belayneh et al., 2009). The impact of subseismic-
52 scale variability in network geometry on permeability has been studied before, particularly
53 for the assessment of leakage risks for storage of CO₂ and nuclear waste, where even a small
54 subset of conductive fractures poses significant risks (Long and Billaux, 1987; Nussbaum et
55 al., 2011; Bond et al., 2013). These studies require high-resolution datasets of subseismic
56 fracture networks, which can sometimes be characterised from subsurface datasets provided
57 that data are available from a dense network of wells (Bond et al., 2013), or from subsurface
58 study sites (Long and Billaux, 1987; Nussbaum et al., 2011; Follin et al., 2014; Laurich et al.,
59 2014). These subsurface sites provide exposures on the scale of metres, but to incorporate
60 datasets that better constrain the issue, uninterrupted exposures of fracture networks covering
61 several hundred by several hundred metres are needed. To our knowledge, no studies have
62 used such large exposures to focus explicitly on the variability in fracture network
63 characteristics at the scale of the domain between wells in a typical fractured reservoir, for
64 flow modelling through deterministic fracture patterns without any stochastic component.

65 Conventional workflows for modelling permeability in fractured reservoir models can
66 be based on extracting geometrical distributions from outcrops for stochastic Discrete
67 Fracture Networks (DFNs) and upscaling to effective properties, where seismic-scale
68 variability in fracture patterns is constrained by considering the resultant structural
69 geometries and implications of kinematic and mechanical forward models (Sanders et al.,
70 2004; Shackleton et al., 2009; Bond et al., 2013; Watkins et al., 2015; Ukar et al., 2016).
71 Subseismic trends in fracture network geometry on permeability have been studied in
72 outcrops, both with and without matrix flow, albeit without application to DFNs (Odling,
73 1997, 2001; Odling et al., 1999). These works found that in addition to density and

74 orientation, connectivity impacts permeability, even if fractures are disconnected (Odling and
75 Roden, 1997). Stochastic DFNs are ideal for subsurface datasets, where typically 1-D fracture
76 geometry distributions are available that need to be extrapolated to 3-D reservoir models, but
77 they are less apt at representing the variability in outcrop-scale fracture geometry, as for
78 example, they do not allow for the control that older fractures have on the geometry of
79 younger fractures and they typically consider fractures as purely straight segments (e.g.
80 Belayneh et al., 2009; Bonneau et al., 2016a; Hardebol et al., 2015). This limitation can be
81 partly overcome by combining stochastic models with rules for the generation of the fracture
82 network based on geomechanical requirements for fracture formation (Bonneau et al., 2016).
83 Alternatively, we propose to use deterministic networks digitised from 2-D outcrops that
84 capture the natural variability and complexity of fracture networks for inclusion in the
85 permeability-focused models. We use actual patterns from closely-spaced outcrops in a
86 setting where the regional stress and lithological boundary conditions were approximately
87 constant, to quantify the impact of fracture network variability on permeability variability.

88 The datasets are acquired from the Jandaíra Formation in the Potiguar basin (NE
89 Brazil), which is a flat-lying carbonate that is exposed in km-scale outcrops in the region
90 south and west of the city of Mossoró (Figure 1). The post-rift formations have experienced
91 limited faulting and folding, but the regional fracture network nonetheless has a high intensity
92 (de Graaf et al., 2017). Whereas syn-rift deformation in the region is influenced by pre-
93 existing basement faults, these relations seem mostly absent for fracture networks in the
94 younger and shallower Jandaíra Formation (Kirkpatrick et al., 2013; Soden et al., 2014). We
95 collect a multiscale dataset of fracture geometries using an Unmanned Aerial Vehicle (UAV)
96 to image the large outcrops, combined with photogrammetry to construct georeferenced
97 outcrop images. A total area of $8.8 \times 10^5 \text{ m}^2$ is covered, where fracture length scales between
98 0.1-300 m are captured. The minimum distance between outcrops is 300 m.

99 We use this unique dataset to quantify the implications for permeability in Naturally
100 Fractured Reservoir (NFR) flow modelling, focusing on uncertainties related to i) Inter-well,
101 subseismic-scale natural variations in fracture network geometry; and ii) The impact of
102 matrix permeability on the validity of geometry-based percolation methods. The aim is to
103 provide an improved understanding of the quantitative impact of these uncertainties for
104 permeability determined from subsurface NFR modelling workflows, focusing on the inter-
105 well scale, which normally lacks direct measurements of fracture geometry and permeability.

106 Flow is modelled using Discrete Fracture and Matrix (DFM) models (Matthäi and
107 Nick, 2009; Geiger et al., 2010). Contrary to Discrete Fracture Network (DFN) models,
108 which do not consider flow through the matrix, we consider the possible flow exchange
109 between fractures and a permeable matrix. This additional consideration incorporates flow
110 contributions from fractures disconnected from the main percolating network (Nick et al.,
111 2011; Bisdorn et al., 2016c). As the apertures of the outcropping fractures are not
112 representative of the apertures that would be present in the subsurface fractures due to
113 ambient stress conditions, we use geomechanical stress-aperture models to provide apertures
114 for our networks (Bisdorn et al., 2016a). The resulting permeability is summarised as
115 equivalent permeability in 2-D, which can be compared to the effective permeability of grid
116 cells in conventional reservoir flow models (Matthäi and Belayneh, 2004; Matthäi et al.,
117 2007; Matthäi and Nick, 2009). This equivalent permeability captures matrix and fracture
118 flow combined in a single parameter, including sub-gridcell trends in fracture permeability
119 associated with geometry variations. These variations are less easily captured in conventional
120 fracture flow modelling approaches based on the ODA method (Oda, 1985). Moreover,
121 ODA-based methods require the use of dual-permeability grids.

122 We also compare these results with predictions made by percolation methods, which
123 are often applied to predict the reservoir permeability associated with a DFN geometry

124 (Robinson, 1983, 1984; Berkowitz and Balberg, 1993; de Dreuzy et al., 2000; Berkowitz,
125 2002). These analytical methods are computationally inexpensive and can be applied to
126 reservoir-scale DFNs, but as percolation is only an indirect proxy for flow, it may not always
127 yield representative results. Using our DFM models, we define the fracture network
128 geometries and matrix conditions for which percolation accurately describes the permeability
129 modelled using the DFMs.

130 **2. Geological setting**

131 The Potiguar basin is a rift basin in NE Brazil, formed during the crustal break-up of
132 Gondwana (Ojeda, 1982; Matos, 1992). The onshore part of the basin has a width of 350 km,
133 measured along the coast, and consists of several NE-SW trending grabens that continue 200
134 km inland, with individual widths of 100 km (Figure 1) (Reis et al., 2013).

135 *2.1. Tectonics*

136 The basin is part of the Equatorial Atlantic, a shear margin that connects the south and central
137 Atlantic (Matos, 1992). It is one of three NE-SW trending intracontinental basins in NE
138 Brazil, which are bounded by transfer faults (Brito Neves et al., 1984). Basin-scale NE-SW
139 striking basement faults define the structure of the main horst and grabens of the Potiguar
140 basin (Matos, 1992; Reis et al., 2013). Rifting started in the Early Cretaceous, followed by a
141 post-rift transition phase in the Aptian and a drift phase from the Albian onward (Reis et al.,
142 2013). Maximum burial of the post-rift Jandaíra Formation is difficult to constrain but, based
143 on Fourier Power Spectrum analysis of burial-related horizontal stylolites it is found to be
144 less than 1500 m in the study area (Ebner et al., 2009; de Graaf et al., 2017).

145 Uplift of the post-rift sediments started in the Cenozoic (Bezerra and Vita-Finzi,
146 2000; Gurgel et al., 2013). At present, the basin is experiencing a strike-slip regime where a
147 maximum horizontal stress strikes E-W in the east of the basin and rotates to NW-SE in the

148 western part (Assumpção, 1992; Bezerra et al., 2007). Within the area of interest in the
149 western part of the basin, NW-SE and NE-SW striking faults are present, but these faults are
150 not known to be active as a result of the present regional stress field (Reis et al., 2013). Also,
151 the studied rock pavements of the post-rift Jandaíra Formation dip consistently sub-
152 horizontally at about 3°, indicating that these exposed layers in this part of the basin have not
153 been folded (Figure 1).

154 2.2. *Stratigraphy*

155 Post-rift deposition started with the Albian Açu Formation, which consists of fluvial-
156 estuarine sandstones and mudstones (Ojeda, 1982). This non-marine phase was followed by
157 transgression and deposition of the Jandaíra carbonate platform from the Turonian to
158 Campanian (Matos, 1992). The Jandaíra Formation consists of mudstones, packstones and
159 grainstones with a depositional thickness of up to 700 m in the onshore part of the basin
160 (Fernandes et al., 2015; Santos Filho et al., 2015). Most of the studied outcrops are composed
161 of packstones-grainstones with only small variations in grain size, except for two outcrops
162 (Mossoró 1 and 2 in Figure 1) in the northwest, where the lithology is mainly dominated by
163 mudstones. Bedding orientation in all outcrops is sub-horizontal, with an average dip of 3°
164 towards the north and a scatter of less than 3°. Within most outcrops, only a single
165 stratigraphic layer is exposed, but limited vertical exposures and Ground Penetrating Radar
166 data show that the lithology is relatively constant in vertical and horizontal directions
167 (Fernandes et al., 2015).

168 **3. Fracture network analysis**

169 Outcrops in the basin show heterogeneous fracture patterns, even though lithology is mostly
170 constant, layers are sub-horizontal and most outcrops consist of a single stratigraphic layer
171 with no significant changes in bedding (Figure 2a). The outcrops contain bed-perpendicular

172 fractures, often with indications of mixed shearing and opening-mode deformation (Figure
173 2b), and both tectonic and burial-related stylolites (Figure 2c,d).

174 3.1. *Data acquisition and database*

175 Mapping of the fracture networks was done through a multiscale approach combining UAV
176 imagery and measurements at the outcrop surface. The UAV is a multi-rotor vehicle equipped
177 with a compact camera and positioning sensors. During 20-minute pre-programmed flights at
178 an altitude of 50 m above the outcrops, between 100 and 150 images with more than 50%
179 overlap were taken of areas up to 200 x 200 m. At this altitude, the image resolution of our
180 camera is 1.4 cm/px, which is sufficient to capture the barren fracture network (i.e. fractures
181 that presently have a visible aperture). Features such as stylolites and veins without colour
182 variation could not be resolved consistently in this imagery, as most outcrops are weathered,
183 creating clints and grikes (Figure 2e) (Jones, 1965).

184 The UAV images were merged into georeferenced orthomosaics using
185 photogrammetry software (Agisoft® PhotoScan®). Georeferencing was done using
186 positioning sensors in the UAV and outcrop markers measured by laser range finders or
187 GNSS (Global Navigation Satellite System). Fractures were manually digitised using the
188 GIS-based software DigiFract (Hardebol and Bertotti, 2013), from which length, orientation
189 and spatial distributions were extracted. For mutually crosscutting fractures, which are
190 abundant, length was defined from fracture end-point to end-point. Fracture digitisation was
191 done manually to ensure that individual fractures were accurately represented, instead of
192 using automatic interpretation methods, which are typically faster, but introduce artefacts into
193 the fracture trace network due to the software algorithms (Kemeny and Post, 2003; Hodgetts,
194 2013; Vasuki et al., 2014).

195 Using the UAV imaging approach, we digitised nine outcrops that cover a total area
196 of $8.8 \times 10^5 \text{ m}^2$, with individual outcrops sizes between $1.6 \times 10^4 - 2.1 \times 10^5 \text{ m}^2$. The outcrops are
197 mostly in the western part of the basin, which we further subdivide into three regions (Figure
198 1):

- 199 1. Two *Mossoró* outcrops, west of the city of Mossoró, are in the central part of the
200 basin.
- 201 2. Five *Apodi* outcrops, north of the town of Apodi, are closer to the southern edge of the
202 basin.
- 203 3. Two *Dix-Sept* outcrops are in between Apodi and the town of Dix-Sept Rosado, and
204 are slightly more towards the centre of the basin compared to the Apodi outcrops.

205 The total dataset consists of 13,223 fractures. Each outcrop contains between 500-2600
206 fractures covering three orders of magnitude for length and intensity.

207 3.2. *Spatial variations in outcrop geometries*

208 3.2.1. *Orientation*

209 The combined orientation distribution of the entire dataset shows a distinct N-S and a lesser
210 E-W fracture trend, particularly when considering length-weighted orientation data. These
211 trends represent 55% of the total orientation population (Figure 3). Three out of nine outcrops
212 contain predominantly fractures with the N-S and E-W orientations (Apodi 3-4 and Dix-Sept
213 1), but the distribution is more scattered in the other outcrops (Figure 3b). Spatially,
214 orientation does not show a systematic trend between the different outcrops.

215 3.2.2. *Length*

216 Fracture length varies strongly across the basin (Figure 4a). Average length varies from 17.4
217 m (Apodi 1) to 3.5 m (Mossoró 1), with the smallest average lengths in the Mossoró outcrops
218 (Figure 4). This difference is not related to sampling artefacts as most outcrops have similar

219 dimensions and all images were acquired from a constant altitude, ensuring constant image
220 resolution. Still, while the variation in average length is about a factor of five, it is not
221 geographically systematic (Figure 4a-d).

222 Length was further analysed using frequency and cumulative frequency distributions
223 (Figure 4b-e). We use a density frequency distribution for the entire dataset, which is more
224 representative than cumulative frequency distributions (Bonnet et al., 2001), but the
225 individual outcrops were analysed using cumulative distributions because they do not contain
226 sufficient fractures for density distributions. Although the outcrop images cover areas of up to
227 $2 \times 10^5 \text{ m}^2$ with a resolution sufficiently high to trace fractures as small as 10 cm, the deviation
228 from the straight segments in the log-log plots indicate that the fracture length distributions
229 suffer from censoring and truncation artefacts (Figure 4b-e). Although some fractures with
230 lengths down to 10 cm have been interpreted in the images, not all fractures of this length
231 scale could be interpreted, resulting in truncation artefacts (Ortega et al., 2006). For
232 cumulative length distributions of individual outcrops, the truncation limit can be as large as
233 10 m (Apodi 2 in Figure 4b) and the censoring limit is down to 60 m (Dix-Sept 2 in Figure
234 4c). However, for all fractures from all outcrops combined, a density frequency distribution is
235 derived that covers length scales between 2 and 100 m with no censoring or truncation
236 (Figure 4e). The cumulative length frequency distribution for individual outcrops indicates
237 that for the part of the distribution that is not censored or truncated, a power-law function best
238 fits the data (Figure 4b-d). The individual exponents are close to 2.0, with the exception of
239 Apodi 3 and Mossoró 1-2, which have exponents between 2.1 and 2.3 (Figure 4a). The
240 fracture length distribution for the entire dataset from all outcrops combined is studied by
241 plotting the entire dataset in a density frequency distribution, constructed by dividing the
242 dataset into linear bins of lengths (Bonnet et al., 2001). The frequency distribution of all
243 measured fractures in the basin, filtered for censoring and truncation artefacts, follows a

244 power-law scaling distribution with a relatively high exponent of 2.4 (Figure 4e). Since the
245 length domain that is not censored or truncated in the frequency and cumulative frequency
246 distributions is limited to less than three orders of magnitude, we cannot determine whether
247 the variability is natural or related to the artefacts, even though the original dataset covers
248 more than four orders of magnitude in length. Because of censoring and truncation, stochastic
249 DFN models based on these 1-D distributions use only part of the original dataset. However,
250 for our deterministic models, all digitised fractures are included, in addition to a permeable
251 matrix to take into account the smaller fractures that are not digitised.

252

253 3.2.3. *Fracture intensity*

254 The spatial distribution is defined by P_{21} intensity (Dershowitz and Einstein, 1988), which is
255 defined as the cumulative length of fractures within a given area (Wu and Pollard, 2002). We
256 use the box-counting method to define the spatial distribution (Bonnet et al., 2001), where
257 each outcrop is discretised by a rectangular grid containing several thousand cells. The P_{21}
258 intensity is calculated within each cell and the resulting distribution is plotted in frequency
259 and cumulative frequency distributions (La Pointe, 1988; Walsh and Watterson, 1993;
260 Bonnet et al., 2001; Darcel, 2003).

261 On average, P_{21} is close to 0.19 m^{-1} (Figure 5). Intensity is least in Apodi 5 at 0.06 m^{-1}
262 and greatest in Dix-Sept 1 at 0.31 m^{-1} . Intensity in the other outcrops ranges between 0.13 -
263 0.21 m^{-1} , without apparent spatial trends in between outcrops across the basin.

264

265 3.2.4. *Connectivity*

266 P_{21} intensity is more representative of the spatial fracture distribution compared to P_{10} , which
267 is typically used to define intensity in cores and along scanlines. However, neither definition

268 considers the spatial arrangement of fractures or whether the fractures form a percolating
269 network for flow. To consider the connectivity of the network to measure percolation, we
270 define percolation probability as the ratio between the number of intersections and the
271 number of fractures, normalised for the outcrop area, where a greater value indicates a greater
272 percolation probability (Robinson, 1983, 1984; Berkowitz, 1995; de Dreuzy et al., 2002).

273 The percolation probability is relatively large in outcrops with scattered orientation
274 distributions (e.g. Apodi 1-2 and Dix-Sept 1), which is to be expected because a larger scatter
275 in orientation increases the likelihood of fractures intersecting (Figure 6a vs. Figure 3c). This
276 likelihood also increases when fractures are relatively long, such as in Apodi 1 and Apodi 2,
277 but overall no relation exists between percolation probability and average length or P_{21}
278 (Figure 6b). The percolation probability is greatest in Apodi 5, which has the smallest P_{21}
279 intensity (Figure 6b). Similarly, Dix-Sept 2 and Mossoró 2 have the smallest percolation
280 probabilities but average intensities compared to other outcrops (Figure 5 vs. Figure 6b).

281 In addition to variations in intensity and percolation, we have described
282 heterogeneous length and orientation distributions in different parts of the basin (Table 1).
283 These variations cannot be related to regional trends in the basin or seismic-scale structural
284 features. However, the geometry variations are sufficiently large to likely impact
285 permeability, and therefore need to be accounted for in models that consider the flow
286 properties of a reservoir that hosts such a fracture population. Conventional stochastic DFNs
287 do not typically consider these variations.

288 **4. Impact of intrinsic fracture network variability on** 289 **permeability**

290 The digitised fracture networks form a database of structural variation at about the scale of
291 inter-well spacing in fractured reservoirs. Although all outcrops experienced the same

292 tectonic history, we observe a large scatter in geometric characteristics from one outcrop to
293 another which cannot be linked to explanations that could be generated by considering
294 regional deformation or lithology variations. In some outcrops, the dominant fracture
295 orientations are aligned to nearby faults, such as WSW- and WNW-striking fractures in
296 Apodi 1 and 2 respectively, and SE and NE striking fractures in Apodi 5 (Figure 3).
297 However, the majority of fractures in most outcrops are not aligned with nearby faults.
298 Similarly, fracture size or intensity are not a function of distance to the regional faults (Figure
299 4 and Figure 5). We therefore attribute these geometric variations to factors that operated at
300 the subseismic scale and could vary locally, such as stress perturbations associated with stress
301 shadows of existing fractures that influence and perturb the development of subsequent
302 fractures.

303 Using DFM models, we quantify the impact of this variability on permeability. In
304 addition, we compare the results with the percolation probabilities. Four fracture networks are
305 selected for fluid-flow modelling. The characteristics that they share, are minimal internal
306 censoring artefacts (see supplemental material containing the original fracture maps), good
307 connectivity of fractures in terms of intersections with model boundaries (Figure 7), to ensure
308 that flow is characterised as part of a larger connected network, and an abundance of the N-S
309 and/or E-W trending fractures (Figure 3c). Each outcrop contains at least several hundred
310 fractures, and the spatial distribution varies strongly between outcrops and sometimes within
311 outcrops. The windows for each of the four outcrops that satisfy these criteria are illustrated
312 in Figure 7:

- 313 i) Apodi 2, which contains N-S, NE-SW and NW-SE striking fractures (Figure 7a);
- 314 ii) Apodi 3, with large partly intersecting fractures striking approximately NE-SW,
315 and smaller E-W striking fractures that are mostly limited to the SW part of the
316 outcrop (Figure 7b);

- 317 iii) Apodi 4, with an orthogonal fully percolating fracture system striking N-S and E-
318 W (Figure 7c); and
- 319 iv) Dix-Sept 1, with scattered orientations where many small fractures are abutting
320 against less intense, larger WNE-ESE fractures (Figure 7d).

321 The other outcrops contribute to our documentation that geometric variation is quite prevalent
322 for fracture networks across the study area, but were not needed for the permeability
323 modelling because these four outcrops served to show the variation while having some
324 similarities for consideration.

325 4.1. *Modelling methodology*

326 Rather than conventional upscaling of geometry to effective flow properties, we model flow
327 through a discrete network of fractures in a permeable matrix, based on the four outcrops
328 (Figure 7). Flow is modelled in 2-D, representative of horizontal permeability between wells,
329 as an analogue for production from a fractured reservoir. We consider single-phase flow,
330 which is representative for early production from a hydrocarbon reservoir, but may not be
331 applicable to secondary recovery methods (Gong and Rossen, 2016). The present surface
332 fracture apertures are not representative of subsurface conditions because of stress-relief
333 during exhumation and aperture enhancement due to recent weathering, hence we use a
334 stress-sensitive aperture model based on estimated subsurface stress representative of pre-
335 exhumation conditions for the conditions that we are modelling.

336 4.1.1. *Aperture modelling*

337 Some preserved veins are found in the Jandaíra Formation, which have shear and opening
338 components (Figure 2b). Based on these observations, we model apertures as a function of
339 stress using the Barton-Bandis model, which describes the opening of sheared fractures with
340 irregular fracture walls (Barton, 1976; Barton and Bandis, 1980). It assumes that, in the

341 absence of high fluid pressures, fractures have an intrinsic roughness that prevents complete
342 closing when some shear occurs, resulting in hydraulic apertures of up to 0.5 mm (Olsson and
343 Barton, 2001; Barton, 2014). This aperture magnitude corresponds to the limited
344 measurements of veins with matching boundaries made from thin sections (de Graaf et al.,
345 2017).

346 Barton-Bandis aperture is a function of intrinsic fracture properties, predominantly the
347 fracture roughness (Joint Roughness Coefficient JRC) and strength (Joint Compressive
348 Strength JCS), and the local normal and shear stresses (Barton and Bandis, 1980). We use a
349 constant JRC of 15, representative of somewhat irregular fracture walls corresponding to
350 qualitative observations of veins in small preserved sections of outcrops, and a JCS of 120
351 MPa, representative of non-weathered surfaces. We approximate local normal and shear
352 stresses using a method that does not require Finite Element modelling, but instead uses far-
353 field stresses in combination with the local network geometry (Bisdom et al., 2016a). For all
354 networks, constant stress boundary conditions and mechanical rock properties are used, with
355 a horizontal maximum stress of 30 MPa, representative of stress conditions at depths of
356 around 2.5 – 3 km in the Potiguar basin (Reis et al., 2013). For a fully elastic rock matrix
357 with a Young's modulus of 50 GPa and a Poisson's ratio of 0.3, a Poisson's stress of 10 MPa
358 is generated. The resulting ratio between shear displacement and normal stress then defines
359 the hydraulic aperture (Olsson and Barton, 2001; Bisdom et al., 2016c). As the models are
360 limited to 2-D horizontal sections, overburden stresses are not considered.

361 4.1.2. *Permeability modelling*

362 To model flow through the fracture network we generate a mesh that is conformable to a
363 selected fracture geometry using ABAQUS® (Dassault Systèmes®). Each outcrop model is
364 meshed with 2-D triangular elements representing the matrix and 1-D line elements
365 representing fractures (Bisdom et al., 2016c). Intrinsic fracture permeability is calculated

366 from local apertures using the cubic law, assuming flow between parallel plates (Snow,
367 1969). To account for potential flow from disconnected fractures, we assume a constant
368 matrix permeability of 1 mD, which is later increased to up to 100 mD to study the impact of
369 matrix flow, and calculate along each fracture element the flow exchange between fracture
370 and matrix.

371 Flow is modelled using the Complex Systems Modelling Platform (CSMP++; Matthäi
372 et al., 2007), which models the fluid-pressure distribution for single-phase incompressible
373 flow through fractures and matrix (e.g. Matthäi and Belayneh, 2004). A fluid pressure
374 gradient is applied in the directions parallel to the model edges (e.g. E-W and N-S; Figure 8).
375 This choice does not necessarily capture the maximum permeability, but our aim is to
376 characterise relative permeability trends between different networks. From the fluid-pressure
377 gradient, we derive the equivalent permeability in the two horizontal directions, which is the
378 permeability representative of combined fracture and matrix flow within the model (Paluszny
379 and Matthäi, 2010; Nick and Matthäi, 2011).

380 4.2. Results

381 4.2.1. Variability in inter-well scale permeability

382 For the applied boundary conditions and fracture properties, Barton-Bandis apertures range
383 between 0-0.28 mm (Figure 7). The corresponding equivalent permeability in a 1 mD matrix
384 is quantified as the ratio between equivalent permeability and matrix permeability in the E-W
385 and N-S directions (Figure 9a). Except for Apodi 2, permeability is anisotropic and greatest
386 in the N-S flow direction. Anisotropy is greatest in Apodi 3, which contains predominantly
387 long N-S striking conjugates and joints. The limited number of E-W striking fracture traces in
388 this outcrop have small lengths so E-W-directed connectivity is weak. Permeability is nearly
389 isotropic in Apodi 4, which has an orthogonal system of N-S and E-W striking fractures with
390 a homogeneous intensity, and Dix-Sept 1, which has a scattered orientation distribution with

391 no prominent modal orientations, resulting in the lack of a preferential flow direction. In
392 Apodi 2, fewer fractures strike N-S compared to the other outcrops, resulting in a more
393 isotropic permeability distribution.

394 The contribution of fracture flow to equivalent permeability, averaged over the two
395 flow directions, ranges from 3.5 to 8, as compared to matrix flow (Figure 9b). We found no
396 relation between geometry, specifically length and intensity, and permeability (Figure 9b).
397 The outcrop with the greatest permeability does have the largest P_{21} intensity (Apodi 4), but a
398 small average fracture length, whereas Apodi 3, which has a similar intensity and
399 significantly larger average length, has the lowest permeability. Although particularly
400 intensity is generally considered to determine permeability, we found no correlation between
401 permeability and intensity for these networks in a 1 mD permeable matrix.

402 4.2.2. *Percolation probability as a proxy for permeability*

403 As permeability variations cannot be related to a single geometrical parameter, we compared
404 the permeability results with the percolation probabilities, which encompass fracture count
405 and connectivity, to assess whether percolation probability is a more representative proxy for
406 permeability than intensity or length. In addition to the percolation probability defined by
407 (Robinson, 1983, 1984), we consider a second definition, network saturation (Hürxkens,
408 2011). Network saturation is defined as the ratio between the area of the cluster and the total
409 outcrop area, and ranges between 0-100%. Network saturation was calculated using
410 FracMan® (Golder Associates®).

411 The percolation probability defined by Robinson (1983) has a positive correlation
412 with permeability for three outcrops, although the correlation is not fully linear (Figure 10a).
413 Moreover, percolation significantly underestimates the flow potential of Apodi 4. This
414 method implicitly accounts for intensity, length and orientation, as a large scatter in

415 orientation and long fractures increase the probability of intersecting fractures. However, the
416 intersection count can also be large when fractures are short and clustered, but if these
417 fractures do not form a connecting network from one side of the model to the other boundary,
418 permeability will be low even though the percolation probability is high.

419 Defining the percolation probability as network saturation improves the relation with
420 equivalent permeability in a 1 mD matrix (Figure 10b). Contrary to the previous method, this
421 method considers the spatial arrangement explicitly. However, since both methods assume
422 that the matrix is impermeable, the correlation between connectivity and permeability does
423 not hold for larger matrix permeabilities (Figure 10c,d). This outcome is further illustrated by
424 outcrops Apodi 2 and Dix-Sept 1, which have similar network saturations and a similar
425 equivalent permeability in a 1 mD matrix (Figure 10b), but permeability of the two networks
426 differs noticeably when matrix permeability increases (Figure 10c,d).

427 **5. Discussion**

428 The large permeability variations between different outcrops that are only 300 m to several
429 km apart, illustrate the impact of natural fracture variability on permeability (Figure 9a).
430 Outcrops Apodi 3 and 4, which are less than 2 km apart, have the largest contrast in
431 permeability, whereas the Dix-Sept 1 and Apodi 2 have comparable permeabilities although
432 they are nearly 20 km apart. Equivalent permeability as a ratio of matrix permeability ranges
433 from 3.5 to 8, which reflects the combined impact of orientation, intensity, length and
434 connectivity, but cannot be related to any of these parameters individually, nor to definitions
435 of percolation probability that consider multiple geometrical parameters (Figure 9b). Note
436 that the aperture range predicted by Barton-Bandis is relatively narrow, and that the
437 permeability contrasts between outcrops likely increases for other aperture definitions
438 (Bisdom et al., 2016b).

439 Conventional DFN modelling based on 1-D geometry distributions cannot account for
440 this intrinsic variability of geometry. Using a combination of representative power-law
441 exponents for fracture length and the fractal dimension does introduce more variability into
442 the system (Darcel, 2003), but most fracture datasets do not contain a sufficient number of
443 fractures covering several orders of magnitude in length and intensity to usefully constrain
444 these parameters. Even the dataset in this study, containing an average of nearly 1,500
445 fractures per outcrop, has sampling and truncation artefacts that limit the orders of magnitude
446 of fracture length and intensity.

447 Instead of trying to capture multidimensional fracture patterns and their intrinsic
448 variability in 1-D distributions that subsequently need to be extrapolated to 2-D or 3-D for
449 DFN models, we propose to use a multiscale approach to capture fracture patterns in 2-D and
450 directly use these deterministic patterns as input for flow models to better understand the
451 impact of geometry variations on permeability, and to derive lessons for subsurface analogue
452 reservoirs. The limitation that outcrops are not a direct proxy for flow is overcome by using a
453 stress-sensitive aperture model representative of fractures in reservoirs with shear-induced
454 fractures and low pore pressures, where Barton-Bandis is considered most representative.

455 The applied DFM flow modelling approach quantifies the uncertainty range in
456 permeability associated with intrinsic network variability without a need for upscaling, but as
457 this method is computationally expensive, its application is limited to relatively small-scale
458 models (Geiger et al., 2010; Geiger and Matthäi, 2012). When matrix permeability is small or
459 absent, geometry-based percolation methods can be a good proxy for permeability in
460 reservoir-scale models, but they should ideally account for the 2-D or 3-D spatial distribution
461 (e.g. de Dreuzy et al., 2000) rather than 1-D distributions. Individual geometrical parameters,
462 such as P_{21} intensity, are insufficient as a proxy for permeability (Figure 9b).

6. Conclusion

The geometrical and flow analysis of the fracture patterns in the Potiguar basin illustrates the impact of natural variability of fractures on uncertainties in permeability. A scatter in geometry that is only partly related to seismic-scale deformation such as regional faults leads to significant variations in the equivalent permeability ratio, with a ratio between 3.5 and 8 in outcrops that are only several hundred metres to several kilometres apart from each other. In fractured reservoir models, these areas typically represent several upscaled grid cells in between wells. The effective fracture-flow properties of these cells are controlled by geometrical trends defined by seismic-scale folds or faults, but they rarely consider the intrinsic variability of fractures. Outcrop analogues do illustrate this variability, but most studied outcrops are too small to quantify this variability usefully for inclusion in models. The fracture patterns in the Potiguar basin are an excellent example of intrinsic variability of natural fracture patterns, providing sub-horizontal exposures of several hundred by several hundred metres where more than 13,000 of fractures were mapped.

Within each outcrop and between different outcrops, differences in intensity and length of barren fractures exist that cannot be related to the large-scale structural position of each outcrop in the basin. Conventional DFN modelling using 1-D probability distributions does not capture this scatter. To quantify the impact of intrinsic fracture geometry variations on reservoir permeability, we model the equivalent permeability in the digitised deterministic fracture networks using Discrete Fracture-Matrix (DFM) flow modelling, where fractures are represented as discrete features with a heterogeneous aperture distribution derived from geomechanical relations. These models consider that natural fractures have an intrinsic roughness that creates a hydraulic aperture even when fluid pressure is low, as long as fractures experienced some shear displacement.

487 We find that in between outcrops that are several hundred metres apart, a large scatter
488 occurs in equivalent permeability and permeability anisotropy. The distance between these
489 outcrops is comparable to well spacing in large fractured carbonate reservoirs in for example
490 the Middle East, and the results illustrate that even in reservoirs with relatively little regional-
491 scale deformation, fracture permeability varies greatly at an inter-well scale. Percolation
492 probabilities record this scatter, but we find that percolation is only representative of
493 permeability when fractures are the only features that contribute to permeability in a
494 reservoir. Alternatively, defining permeability as an equivalent permeability that includes
495 flow through fractures and matrix, as well as subseismic-scale variations in fracture
496 geometry, the permeability of fractured reservoirs can be more accurately modelled at
497 reservoir-scales, using conventional grid-based flow models.

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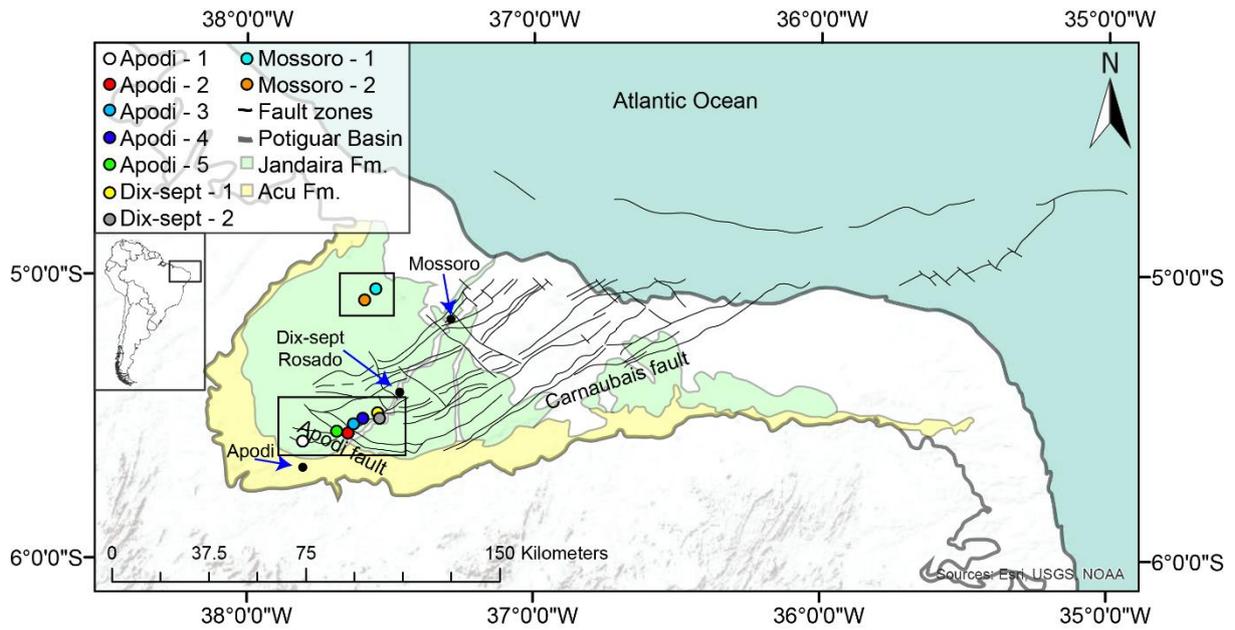
771 **Tables**

772 *Table 1 Summary of the average geometrical parameters (strike, length, intensity and*
 773 *percolation probability) for each outcrop.*

	Orientation (strike) [°]	Length [m]	Intensity [m ⁻¹]	Percolation probability [-]
Apodi 1	94	17.4	0.17	1.7
Apodi 2	81	16.6	0.17	2.0
Apodi 3	121	20.0	0.20	0.9
Apodi 4	82	7.1	0.21	1.5
Apodi 5	86	5.7	0.06	2.4
Dix-sept 1	81	5.5	0.31	1.7
Dix-sept 2	63	6.8	0.16	0.8
Mossoro 1	86	3.5	0.13	1.0
Mossoro 2	164	3.6	0.16	0.8

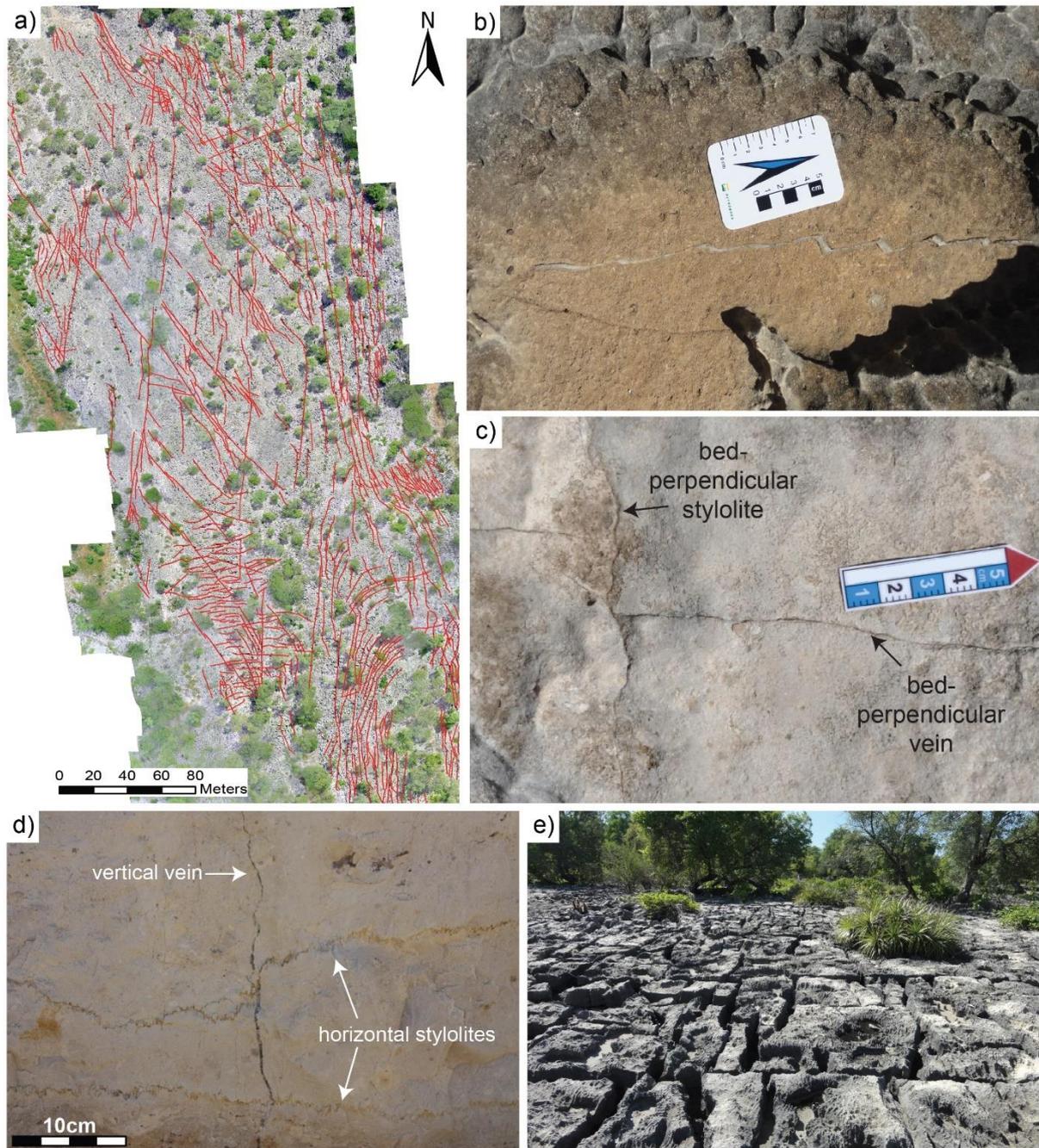
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775 **Figures**



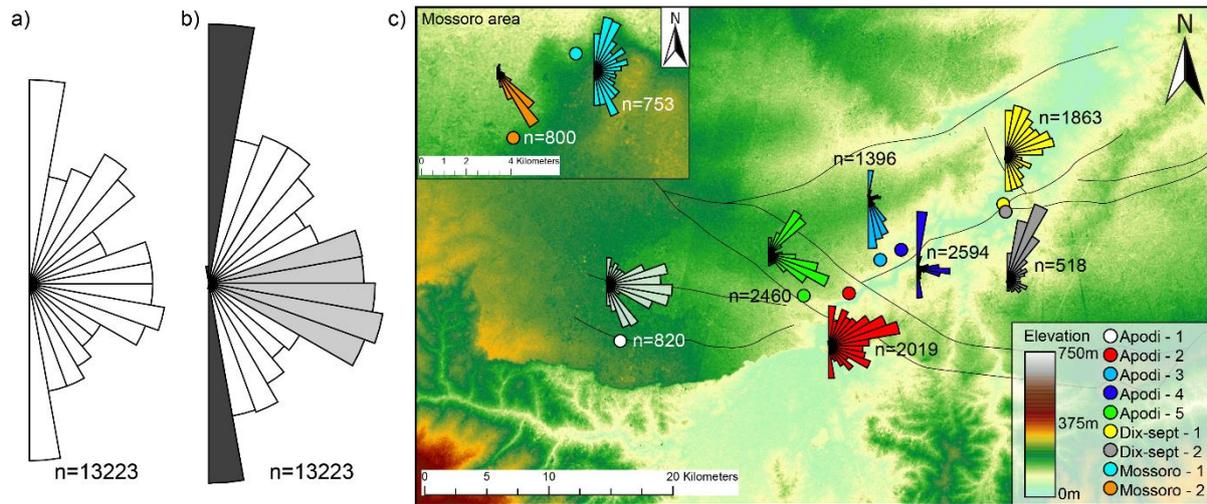
776

777 *Figure 1 The Potiguar basin, containing NE-SW and NW-SE faults that are part of a graben*
 778 *system. The coloured areas indicate where the Jandaíra and Açú Formations outcrop.*
 779 *Coloured dots are locations for sampled fracture networks.*



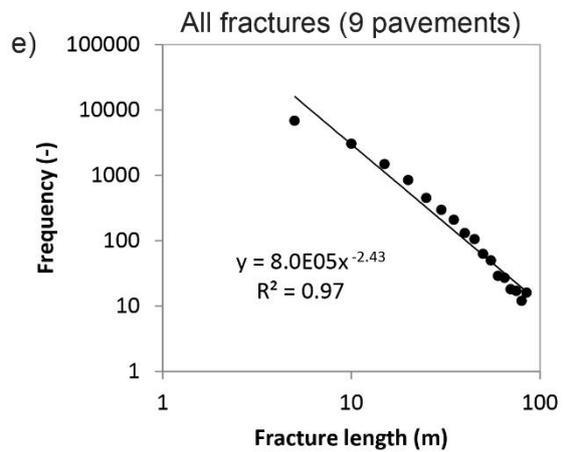
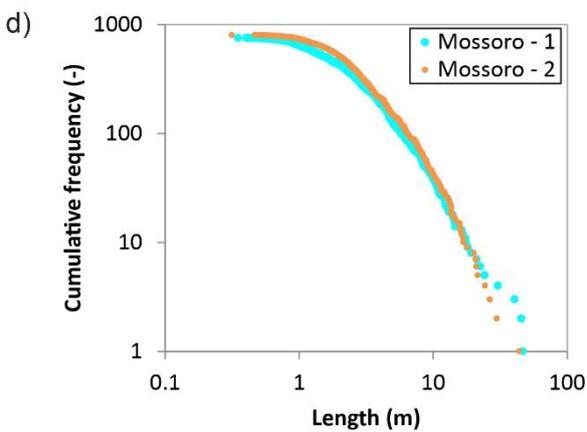
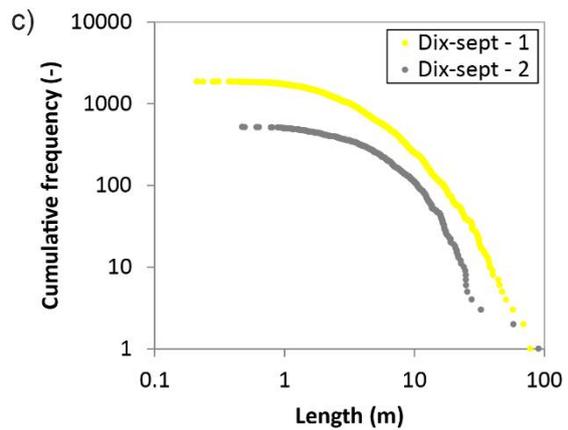
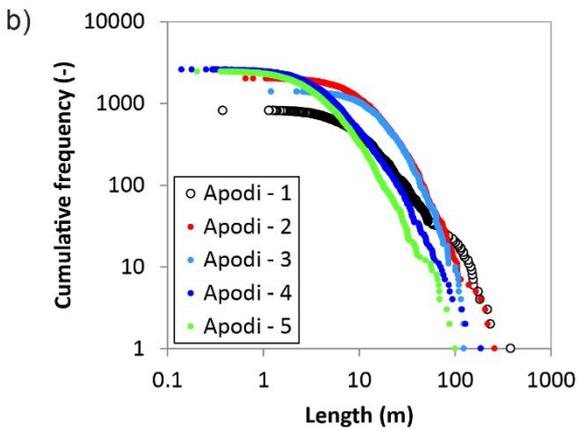
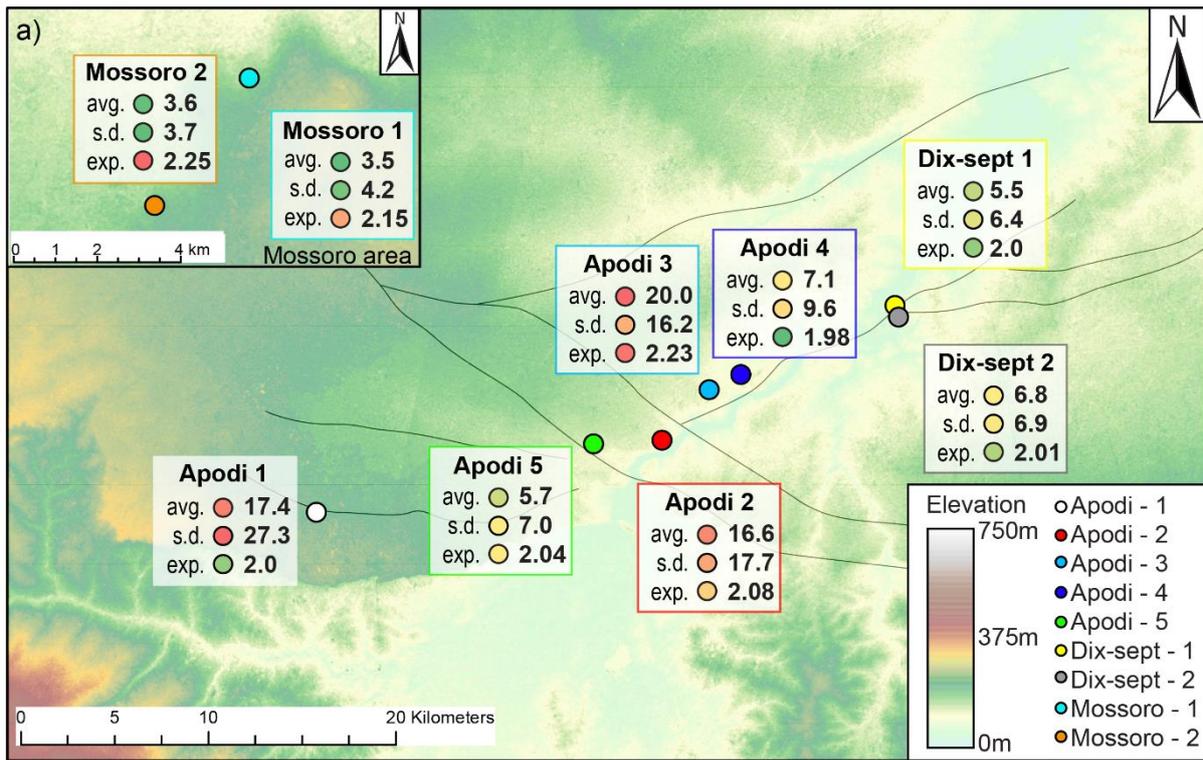
780

781 *Figure 2 Fracturing in the Jandaíra Fm.: a) Example of large-scale network digitised from*
 782 *UAV imagery (Apodi 3); b) N-S striking bed-perpendicular vein with opening and shear*
 783 *mode components; c) Top view of a detail from Apodi 4 showing a N-S striking bed-*
 784 *perpendicular vein that is displaced by an E-W striking bed-perpendicular tectonic stylolite;*
 785 *d) Vertical section showing a vertical vein that is cut by two horizontal stylolites; e) Detail of*
 786 *Apodi 4, with dm-scale apertures related to clints and grikes.*



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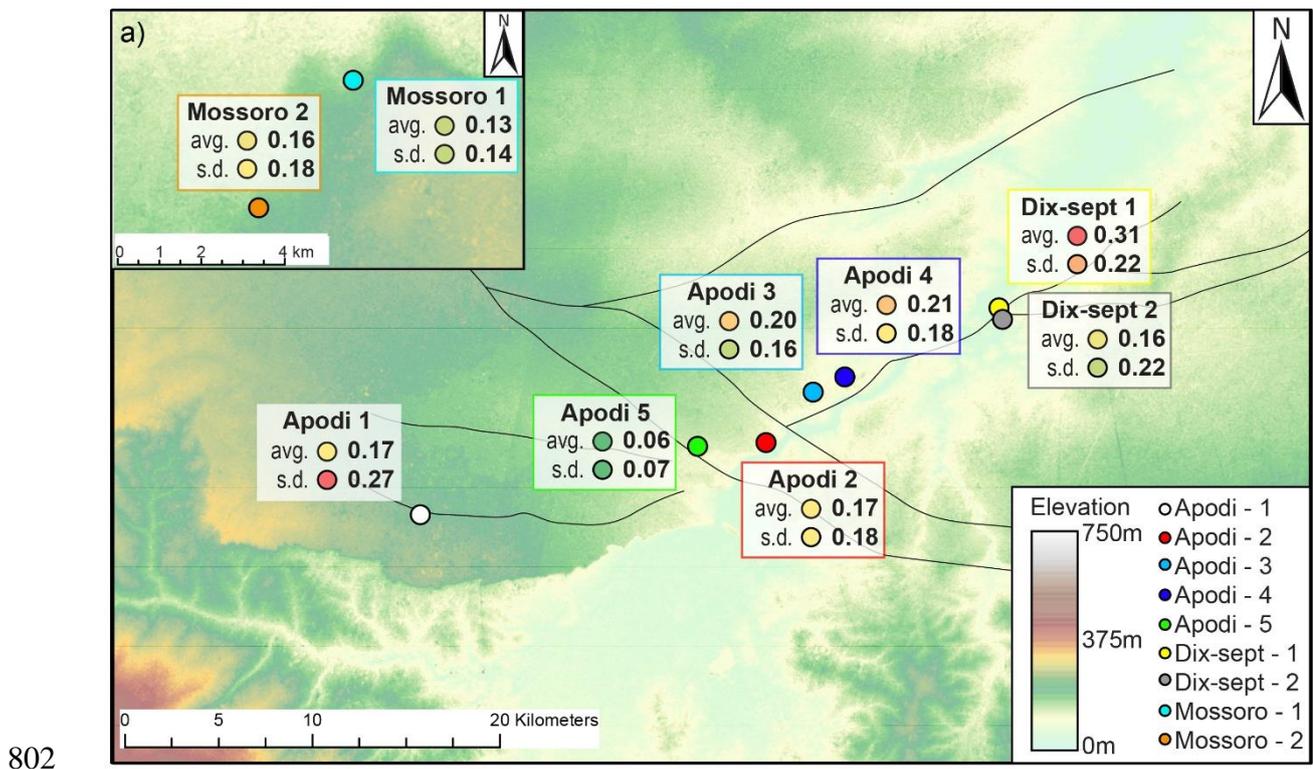
788 *Figure 3 Orientation distribution of barren fractures: a) Rose diagram of all 13,223 barren*
 789 *fractures digitised in ten outcrops; b) Length-weighted rose diagram showing the*
 790 *contribution of the two main N-S and E-W striking orientation trends to the length-weighted*
 791 *distributions; c) False-colour map of a detail of the basin, showing the Apodi and Dix-Sept*
 792 *outcrops, with the Mossoró outcrops in the top left inset. Regional faults indicated in black.*
 793 *For each outcrop, the fracture orientations are shown in length-weighted rose diagrams,*
 794 *with the number of digitised fractures.*



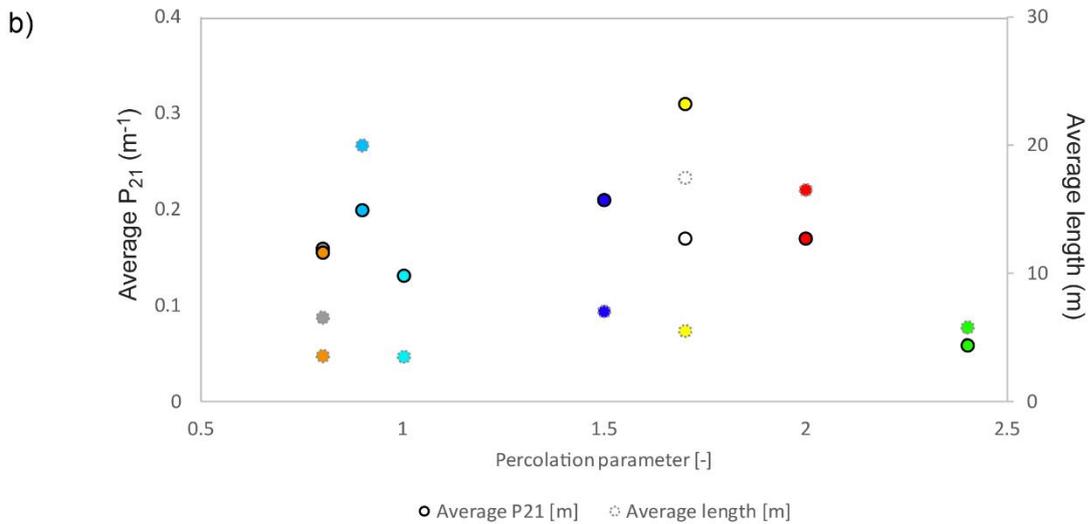
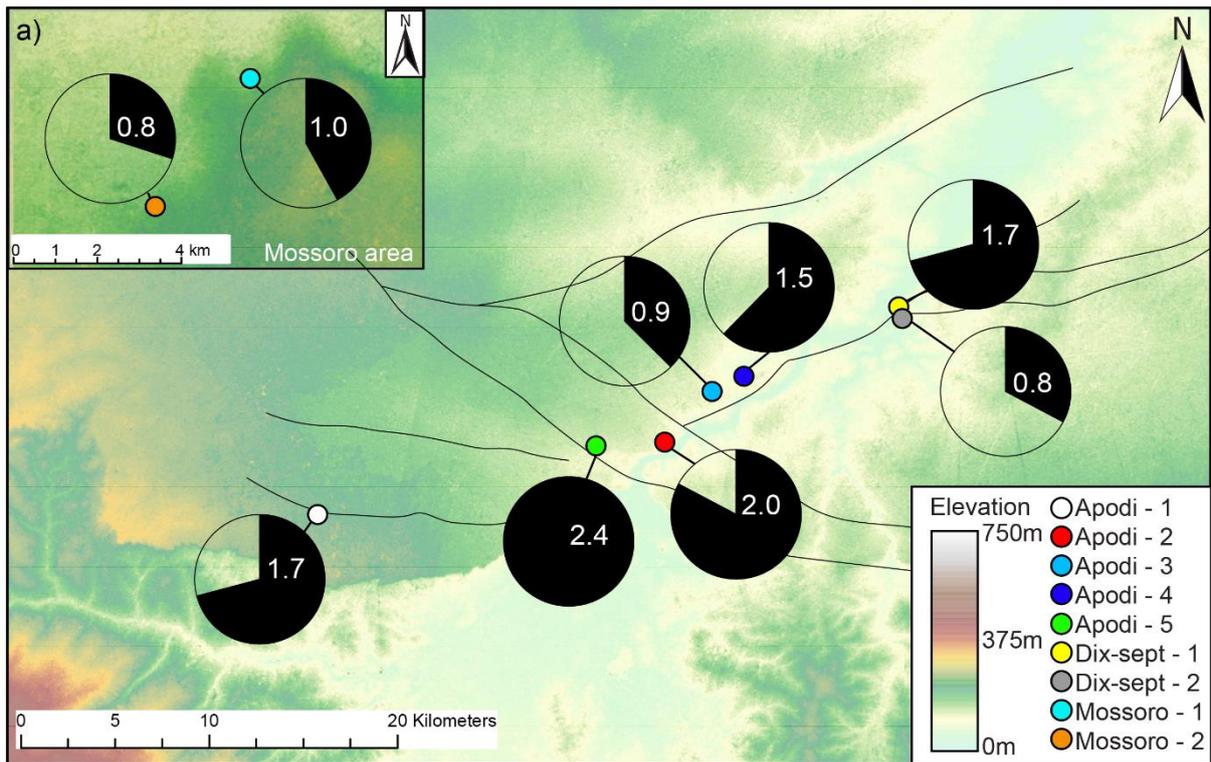
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796 *Figure 4 Analysis of fracture length: a) Spatial variations in length attributes (average*
 797 *length, standard deviation, and the power-law scaling exponent) in the individual outcrops,*

798 where the bar plots indicate relative trends in between the outcrops; b) Cumulative frequency
 799 distributions for the Apodi outcrops; c) Cumulative frequency for the Dix-Sept outcrops; d)
 800 Cumulative frequency for the Mosorro outcrops; e) Combined frequency distribution for
 801 fractures from all outcrops.



803 *Figure 5 Spatial variations in P_{21} intensity attributes (average and standard deviation).*



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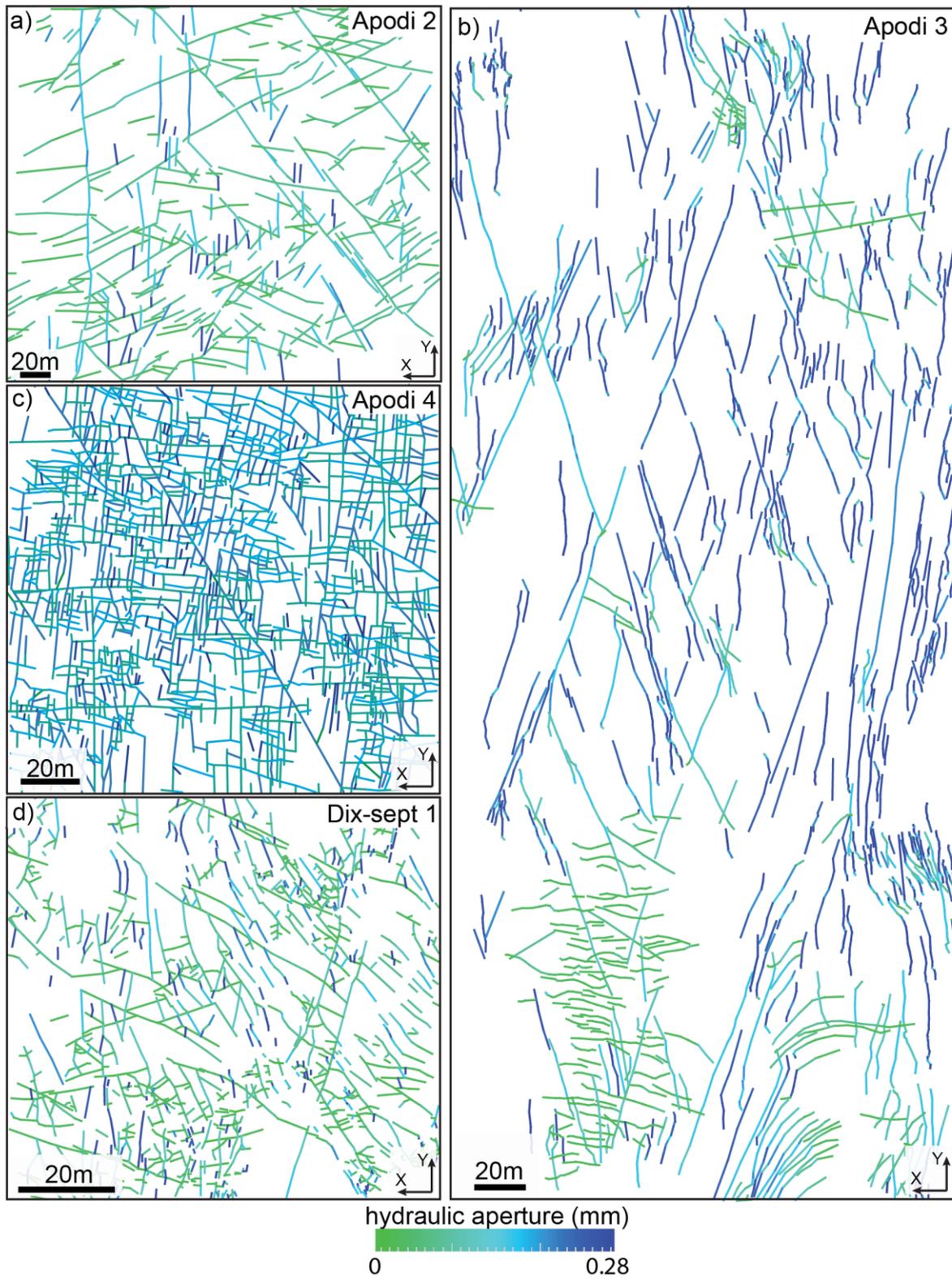
805 *Figure 6 Percolation parameters (intersections versus fracture count) for all outcrops: a)*

806 *The normalised percolation probability stated in each pie chart.;*

807 *versus average P_{21} (left vertical axis, circular symbols have solid black border) and average*

808 *length (right axis, circular symbols have dashed grey border) for all outcrops. Colour coding*

809 *of symbols corresponds to outcrop colours in (a).*



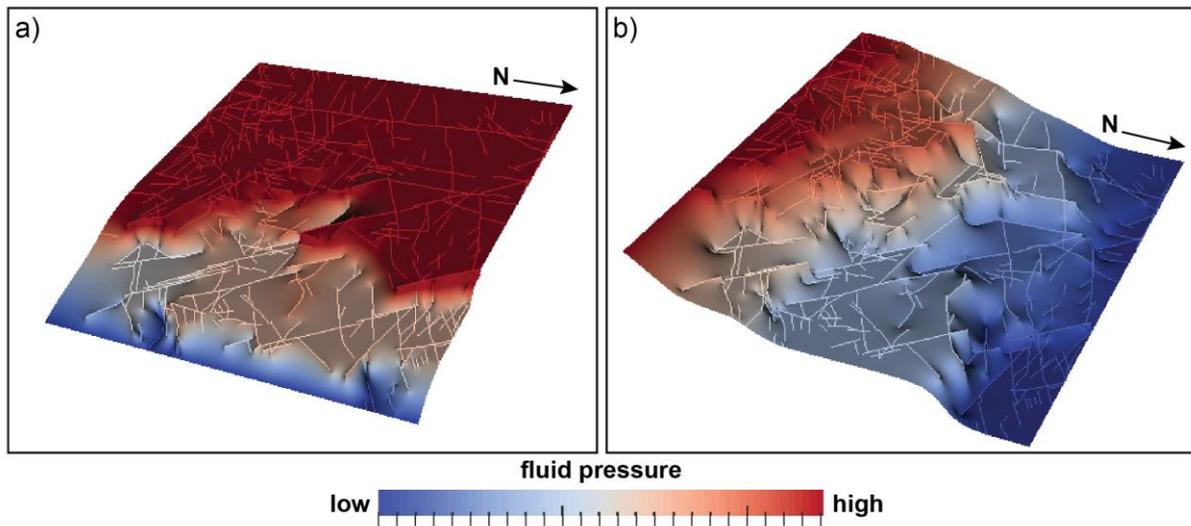
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811 *Figure 7 The hydraulic aperture distribution calculated using the Barton-Bandis shear*

812 *aperture model, applied to the exhumed fracture networks of: a) Apodi 2; b) Apodi 3; c)*

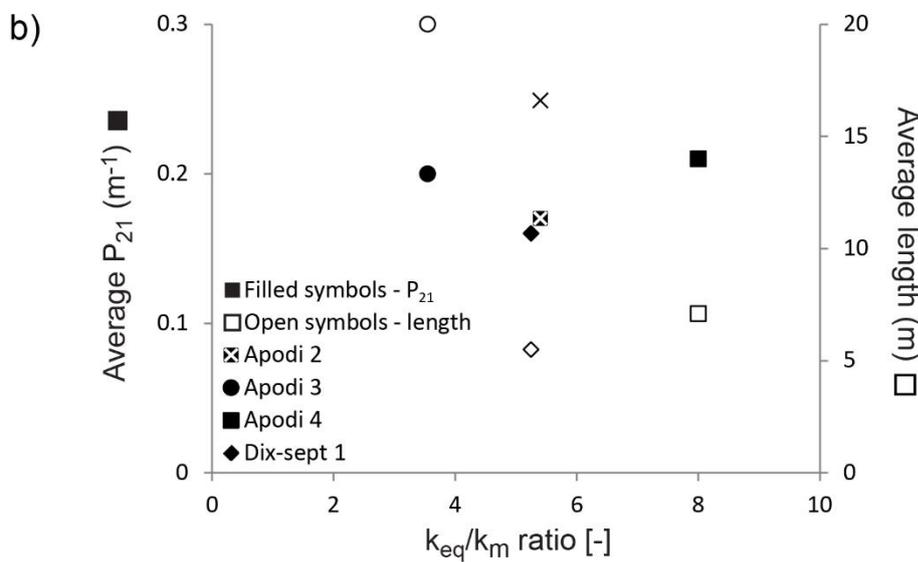
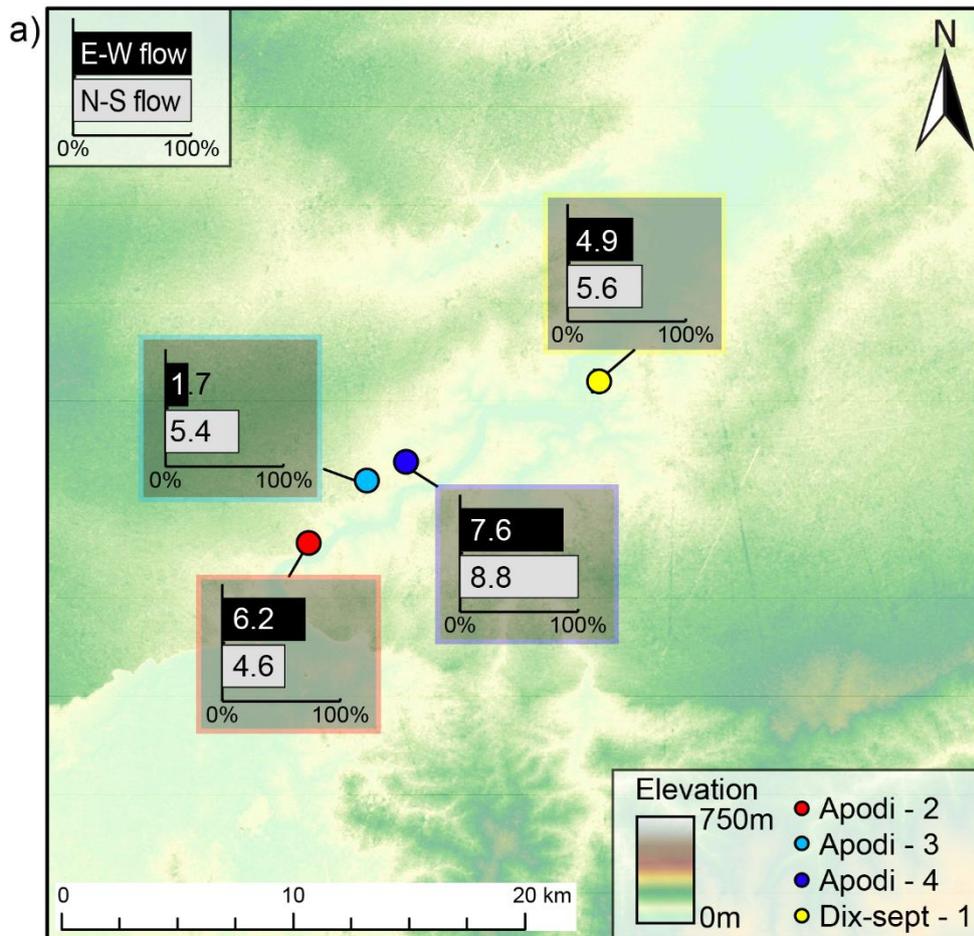
813 *Apodi 4; d) Dix-Sept 1. Adapted from (Bisdorn et al., 2016b). The colour range represents the*

814 hydraulic aperture calculated for the stress boundary conditions and rock properties used in
815 this study.



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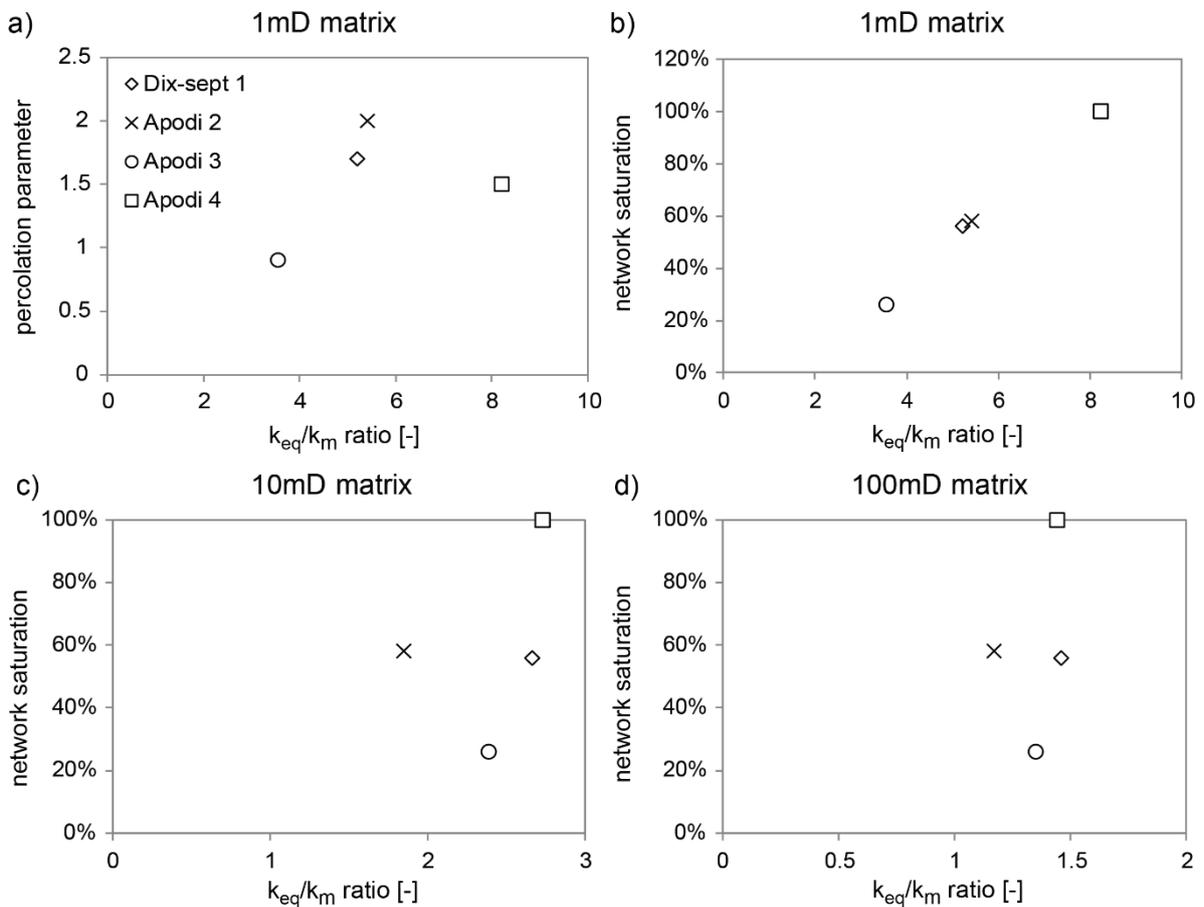
817 *Figure 8 Fluid pressure distributions for Apodi 2 with a 1 mD matrix permeability and*
818 *fracture permeability derived from the aperture distribution in Figure 7a: a) E-W fluid*
819 *pressure; b) N-S fluid pressure.*



820

821 Figure 9 a) Ratio between equivalent permeability and matrix permeability in the E-W and
 822 N-S directions for four outcrops with barren fractures. The bar plots show the relative
 823 differences in different outcrops and different directions, normalised for the largest

824 permeability; b) Relation between the permeability ratio for each outcrop (average of the two
 825 directions) and average length (open symbols) and P_{21} intensity (filled symbols).



826

827 *Figure 10 Relation between connectivity and the ratio between equivalent permeability k_{eq}*
 828 *and matrix permeability k_m , derived from the four outcrops: a) Percolation parameter as*
 829 *defined by (Robinson, 1983) versus equivalent permeability in an impermeable matrix; b)*
 830 *The degree of network saturation derived from cluster analysis versus the equivalent*
 831 *permeability ratio in a 1 mD matrix; c) Network saturation versus permeability ratio for a 10*
 832 *mD matrix; d) Network saturation versus permeability ratio for a 100 mD matrix.*