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Scaling of fault damage zones in carbonate rocks

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Key words: *fault damage; displacement; carbonates; scaling law; segmentation*

18 **Abstract**

19 A renewed interest in fault damage zones is aimed at better understanding stress
20 perturbation around faults, earthquake ground motions and fluid flow in the upper crust. In
21 this study, we analyse fault/fracture systems at the outcrop and map scale and define
22 *displacement - thickness (D-T)* scaling of fault damage zones using scanlines, in carbonate
23 rocks in France and Spain. We determine fault displacement and damage zone thickness
24 perpendicular to fault planes and far from fault tips for 12 selected faults in four study sites.
25 The data show a logarithmic decrease of fracture frequency from the fault cores. This
26 decrease is characterized by local frequency peaks corresponding to variably-linked
27 secondary fault segments and abandoned tips within the fault damage zone. *D-T* data
28 comprised between 0 and 100 m of net fault displacement show a nearly linear scaling with
29 very little scattering. Including two additional data for $D > 100$ m, the best fit corresponds
30 better to a power law. We propose a new model based on fault segmentation and linkage to
31 explain the linear scaling observed up to 100 m displacement, and we discuss the non-linear
32 behaviour with respect to the role of mechanical layer thickness and the inhibition of the
33 segmentation process down dip for large-scale faults.

34

35

36 **1. Introduction**

37 Deformed rock volumes in fault zones are usually classified as two distinct zones, the Core
38 Zone (CZ) and the Damage Zone (DZ) (Shipton and Cowie, 2001; Billi et al., 2003; Kim et
39 al., 2004; Berg and Skar, 2005). The core zone is generally characterised by the presence of
40 fault rocks (e.g. Sibson, 2000; Fossen, 2016) with variable comminution degree and
41 frequently well-developed cementation, generally acting as a barrier of permeability when the

42 fault is dormant. The damage zone develops through different processes such as initiation,
43 propagation/interaction of faults or seismic ruptures (Cowie and Shipton, 1998; Peacock,
44 2001; Shipton and Cowie, 2003; Kim et al., 2004; Peacock et al., 2017). Depending on the
45 nature of the deformed rock and the applied state of stress, a wide diversity of damage
46 structures can be found such as tensile fractures, layer folding, stylolites, dilation, shear and
47 compaction bands. These structures may produce significant and variable impacts on
48 permeability anisotropy in and adjacent to faults and therefore on fault-related fluid flow
49 (Chester and Logan, 1986; McGrath and Davison, 1995; Caine et al., 1996; Sibson, 2000;
50 Jourde et al., 2002; Kim et al., 2004; Agosta et al., 2007; Faulkner et al., 2010; Ballas et al.,
51 2015). Despite their importance for economic fluids, fault damage zone 3D structure, their
52 scaling and flow properties remain poorly known and still debated.

53 The geometry of damage zones has been described, from map, outcrop and microstructural
54 analyses (McGrath and Davison, 1995; Billi et al., 2003; Micarelli et al., 2003; Johansen and
55 Fossen, 2008; Choi et al., 2016). The *Damage zone thickness* (T) is defined as the total
56 adjacent rock volume on both sides of the fault core containing brittle damage structures
57 related to the fault (Shipton and Cowie, 2001, 2003; Berg and Skar, 2005; Schueller et al.,
58 2013; Choi et al., 2016). Many studies indicate that T seems to evolve with the net fault
59 *Displacement* (D) (e.g, Evans, 1990; Knott et al., 1996; Shipton and Cowie, 2003; Manighetti
60 et al., 2004; Mitchell and Faulkner, 2009, 2012; Faulkner et al., 2011; Savage and Brodsky,
61 2011; Torabi and Berg, 2011; Perrin et al., 2016) and some of them even reveal a proportional
62 relationship between T and D for $D < 150$ m (Shipton and Cowie, 2003; Mitchell and
63 Faulkner, 2009, 2012; Savage and Brodsky, 2011; Schueller et al., 2013). For $D > 150$ m, T
64 seems to stabilize at a few hundred metres. However, despite this evidence for a D - T
65 relationship and associated trends, the processes and mechanics causing this remain difficult
66 to constrain because of the large scattering of data used, about two orders magnitude (Savage

67 and Brodsky, 2011). Many factors can be responsible for this scattering. Firstly, the
68 methodologies used to measure or quantify T vary between studies with no systematic
69 consensus. By combining many different published studies into a large scanline database,
70 damage can be described by undifferentiated structures such as tensile fractures and
71 deformation bands, whose frequency decreases with distance from the CZ (e.g. Chester and
72 Logan, 1986; Beach et al., 1999; Schueller et al., 2013). Then, the external limit of the
73 damage zone is defined as the point where the fracture frequency reaches the background
74 fracture frequency value (Beach et al., 1999; Berg and Skar, 2005; Faulkner et al., 2006; de
75 Joussineau et al., 2007; Mitchell and Faulkner, 2009) although background fracture frequency
76 is usually difficult to determine, adding errors in the assessment of T . Secondly, the fault
77 damage types (tip damage, wall damage, link damage) in the sense of Kim et al. (2004) or in
78 the synthesis from Mitchell and Faulkner (2009) (also see Wilson et al., 2003; Blenkinsop,
79 2008), are not differentiated, probably also explaining a part of the D - T data scattering.
80 Thirdly, differences in rock type could also produce a strong effect on fault zone architecture
81 and potentially on the D - T scaling (e.g. Soliva et al., 2006; Roche et al., 2012; Ballas et al.,
82 2014). Most of the studies whose aim is to characterize the D - T scaling law are mainly based
83 on faults in siliciclastic lithologies (e.g. Knott et al., 1996; Fossen and Hesthammer, 2000; Du
84 Bernard et al., 2002; Berg and Skar, 2005; de Joussineau and Aydin, 2007; Mitchell and
85 Faulkner, 2009). Although carbonate fractured reservoirs are common and the understanding
86 of fracture network complexity represents a major issue for exploration/production of
87 georesources, the fault damage zones and their scaling properties are poorly constrained for
88 this lithology (Micarelli et al., 2003; Micarelli et al., 2006; Balsamo et al., 2016; Maqbool et
89 al., 2016).

90

91 In this paper, we focus on the analysis of fault damage in carbonate rocks. We first provide
92 a map scale analysis of fault segmentation geometry and damage using analysis based on
93 remote sensing orthophotos and outcrops. Secondly, we analyse small-scale fracture damage
94 using scanlines adjacent to fault, cores far from fault tip zones, and on outcrops where
95 displacement can be measured. This enabled the identification of 12 faults, on which we
96 define the D - T relationship. We analyse the resulting scaling laws and discuss their properties
97 with respect to the map scale observations and previous models proposed in the literature.
98 Finally, we propose new explanations based on fault growth processes, and especially fault
99 segmentation and linkage.

100

101

102 **2. Geological setting**

103 In this study, we focus on two areas located in the south of France (Languedoc) and close
104 to the Eastern coast of Spain (Sant Mateu and Maestrat). These two sites show normal faults
105 due to the Oligocene Mediterranean Sea opening and some reverse and strike-slip faults from
106 the Paleogene Pyrenean orogeny contraction, all in Tethysian mudstone carbonates.

107

108 *2.1 Languedoc (south of France)*

109 The Languedoc region is located in the former western gulf of the Tethys Ocean (Fig. 1a).
110 Most of the outcrops in the region contain marine sediments comprising stratified carbonate
111 rocks (Fig. 1a). The Mesozoic sedimentary cover can reach a total thickness up to 3,000 m. In
112 this study, the analysed faults only affect Jurassic and Cretaceous rocks. The Jurassic section
113 is characterized by sublithographic marine limestones and is several hundred metres thick.

114 The Cretaceous rocks are characterized by marl and massive limestone alternations with
115 ammonites and brachiopods fossils.

116 The Mesozoic cover was affected by Pyrenean shortening, expressed by three phases of
117 deformation from Paleocene to Oligocene (Petit and Mattauer, 1995; Séranne et al., 1995;
118 Benedicto et al., 1999). The first one is characterized by well-marked N020E-oriented
119 fractures (Taha, 1986; Arthaud and Laurent, 1995), and kinematically consistent thrust faults.
120 A second N145E oriented contraction is marked by N055E stylolites and N145E joints. A last
121 N-S contractional stage is visible with N-S joints and E-W stylolites. This last contraction
122 allows activation of the N020E joints and N055E stylolites in sinistral strike-slip (Petit et al.,
123 1999; Soliva et al., 2010). These faults have also been reactivated during the Oligocene
124 extension phase as normal faults (e.g. Arthaud and Mattauer, 1969).

125 Depending on the different accessibilities and outcrop quality in Languedoc area, this
126 study focuses on the St Clement normal fault, the Taurac reverse fault and two other minor
127 faults in the St Clement area. Like the crustal-scale Cevennes and Nimes faults, the St
128 Clement fault was probably active during 3 tectonic phases. (1) NW-SE middle Cretaceous
129 extension showing a normal phase of slip; (2) during the Paleocene to Eocene Pyrenean
130 shortening, a sinistral strike-slip phase; and (3) a main phase during Oligocene NW-SE Gulf
131 Lion rifting with around 550 m displacement on the fault (Arthaud and Mattauer, 1969; Steer
132 et al., 2011). The brittle structures are mainly consistent with normal faulting, but a minority
133 can be related to strike-slip events (Auzende et al., 1973; Séranne et al., 1995; Benedicto et
134 al., 1999; Steer et al., 2011). The Taurac fault is a reverse strike-slip fault connected to the
135 Cevennes fault. Striations on the main fault slip surface show reverse strike-slip and dip-slip
136 reverse displacement.

137

138 2.2 *Maestrat*

139 The second study area is located at the eastern border of the Maestrat basin (Fig. 1b). The
140 Maestrat is a part of the Iberian Range, which contains several kilometres of Mesozoic and
141 Cenozoic sediments (Nebot Miralles and Guimerà i Rosso, 2016). This region was affected by
142 two phases of extensional rifting with NW-SE trending normal faulting, from the Triassic to
143 the mid-Cretaceous (Albian), during which time were deposited the Jurassic shallow
144 carbonate platform, Cretaceous carbonates and different layers of marls (Salas and Casas,
145 1993; Salas et al., 2001, 2011; Martín-Martín et al., 2013). During the Middle Eocene to Early
146 Miocene, the Alpine orogeny affected the basin with a contractional deformation (González,
147 1989).

148 A general tectonic extensional event followed the Alpine inversion, and caused the Catalan
149 and Valencian coastal rifts. During Late Oligocene to Early Miocene this extensional stage
150 generated multiple NE-SE minor normal faults through the Mesozoic carbonates (Roca and
151 Guimerà, 1992; Salas and Casas, 1993; Salas et al., 2001). In the Sant Mateu area (Fig. 1b),
152 the Mesozoic rocks are tilted 30° to the NE and the lithologies are consistent with Languedoc
153 carbonates. In the Aliaga area the N-S Alpine inversion, during late Oligocene and early
154 Miocene, generate strike slip fault and reverse faults with south and north vergence (Fig. 1b).
155 Mesozoic cover rises to over 1,000 m altitude, being tilted and folded (Nebot Miralles and
156 Guimerà i Rosso, 2016). In this area, there is no evidence of Neogene extensional
157 reactivation.

158 In summary, the Languedoc and Maestrat study areas show carbonate rocks that were
159 deposited during the Tethys ocean opening and were deformed both during the Alpine
160 contractional events, and the extensional rifting during the Late Oligocene to Early Miocene.
161 In the Sant Mateu and St Clement areas, folding is gentle and there is no evidence of thrust
162 faults in the vicinity of the area.

163

164

165 **3. Methods**

166 3.1 *Terminology of brittle damage structures*

167 In this study, discontinuous deformation of the carbonate rocks observed in the field are
168 qualified by 4 different terms, joints, veins, stylolites, and faults, and are identified in the field
169 depending on their geometric and kinematic properties (Fig. 2). The term joint refers to a
170 Mode I fracture, from metric to decametric length, for millimetre to centimetre opening, not
171 sealed or filled with druse calcite. Veins are defined as centimetric to metric Mode I fractures
172 and always cemented with sparitic calcite. They can also be described as “tension gashes”.
173 Veins and joints are generally oriented perpendicular to the minor-principal stress axis
174 (Fossen, 2016). A generic usage of the term “fracture” refers to both joints and veins. Veins
175 and joints that affect carbonates are frequently preferential surfaces for dissolution, depending
176 on cementation. In this study, three scanlines were made to sample structures on an outcrop
177 that has suffered significant dissolution. In these cases dissolution patterns on the rock surface
178 have been counted as fractures. Stylolites are dissolution surfaces also known as solution
179 seams or Mode –I structures in carbonate rocks (Toussaint et al., 2018). They are
180 perpendicular to the major-principal stress axis and also to veins or a set of joints.

181 Faults are slip planes of mode II or III tips of metric to kilometric length, generally
182 showing one or multiple slickensides with slickenlines. DZ can include secondary minor
183 faults and slickensides with a certain width of fault rocks in their individual CZs. Secondary
184 faults in DZs are always indicated on the scanline histograms.

185

186 3.2 *Scanline measurements*

187 Measurement of fracture damage was performed along scanlines across the damage zones.
188 A scanline consists of the fracture frequency measurement per linear metre along a sampling
189 line. This frequency is also referred to as the fracture density (P10) as the number of fracture
190 intersections along a 1D scanline (Dershowitz, 1984; Bisdorn et al., 2014). The sampling step
191 (W_s), the distance over which the number of fractures is counted, is adapted to the total
192 scanline length (L_s). For $L_s < 5$ m, $W_s = 10$ cm; for $5 \leq L_s \leq 20$ m, $W_s = 50$ cm; for $L_s >$
193 20 m, $W_s = 1$ m. When $W_s < 1$ m, the frequency is normalized to be comparable with others
194 dataset.

195 The scanline is oriented nearly perpendicular to the fault trace and starting at the boundary
196 between the main CZ and the DZ. Moreover all the scanlines satisfy several other criteria
197 including (1) the position of the outcrop far from the observed fault tips at the map scale (2)
198 the outcrop must be large enough to reach the background fracturing, (3) the lithology must
199 be similar through the entire scanline, and (4) the fault net displacement must be measurable.
200 We selected 12 fault outcrops meeting all these criteria allowing measurement of fracture
201 frequency along 12 scanlines noted S1 to S12. Two of these scanlines (S5 and S6) actually
202 come from the same fault but were measured at different places and along different carbonate
203 layers.

204 The fractures counted on the outcrops were those visible to the naked eye along scanlines,
205 and several effects can generate “gaps” in the outcrop. The vegetation and outcrop
206 degradation are the major sources of gaps. For the reverse Taurac fault, the scanline is
207 positioned along the wall of an artificial tunnel and exposed to calcite precipitation and
208 speleothems. These gaps are reported in the histograms of the scanlines as shaded areas,
209 which represent a proportion of the scanline length ranging between 0% for the smallest faults
210 (S1, S3, S7 and S10) up to 48% for the largest scanline (S2).

211 On the studied outcrops, dissolved fractures were counted separately from the sealed veins
212 on the histograms. The number of dissolved fractures thus brings together different types of
213 fractures, veins, joints, and sub-vertical stylolitic surfaces.

214

215 3.3 *Damage zone thickness*

216 The DZ thickness is estimated using the cumulative frequency curve (Berg and Skar, 2005;
217 Choi et al., 2016). The gaps in frequency value are corrected by adding an average value of
218 the two measurements before and after the gap. According to Berg and Skar (2005) and Choi
219 et al. (2016), the DZ thickness is defined by the distance to the fault core corresponding to the
220 inflection of the cumulative frequency curve. This inflection shows a stabilization of fracture
221 density away from the fault defined as the background fracturing. Most of the scanlines have
222 two inflections of the cumulative frequency curve. In this study, it is the farthest inflection
223 from the fault that is retained as the DZ thickness. This inflection corresponds to the value
224 where the cumulative frequency curve reaches the lowest slope gradient, which means a lower
225 and homogenous fracture density. The distance between the first and the second inflection is
226 considered as the half of the DZ thickness uncertainty.

227 The cumulative frequency curve used to define DZ thickness has several advantages (Choi
228 et al., 2016), including (1) a better detection of outer boundaries of the DZ based on the
229 intersection point of the cumulative frequency trends, (2) less influence of structural effects
230 like secondary faults on the general decay, and (3) a correction of the gaps based on adjacent
231 cumulative frequency gradient.

232 The apparent thickness defined along the scanlines is corrected as the real damage zone
233 thickness (T) using the angle between the scanlines and fault dip (Fig. 3). For the scanlines
234 acquired only on the footwall or the hangingwall, the DZ thickness value is doubled, as
235 proposed by Savage and Brodsky (2011). This value is very close to the “Total fault zone

236 thickness” used in literature, which actually includes the CZ thickness. The core zone
237 thickness could not be measured for all the faults, but its thickness generally correspond to
238 values lower than one order of magnitude of the DZ thickness (e.g. Childs et al., 2009;
239 Fossen, 2016), and is therefore smaller than the estimated error.

240

241 3.4 *Fault displacement*

242 The scanlines are always acquired on faults whose displacement is quantifiable.
243 Displacement (or net slip, D , Fig. 3) is determined using both fault surface dip, slickenline
244 orientation, layer dip and the offset between fault cutoff lines. In cases where slickenlines or
245 fault surfaces were not observed in the field (4 faults, referred to S7, S9, S10 and S11), we
246 used the average of fault dip and slickenline data measured in the considered studied fault
247 system. To define the error bars, we consider a minimum and maximum value of
248 displacement using $\pm 30^\circ$ for the pitch of the value measured on the outcrop, or the mean
249 value used for faults without slickenlines.

250

251 3.5 *Fracture orientations*

252 On all the scanlines, fracture orientations were systematically recorded along the profile to
253 characterize the fault damage fracture trends with respect to background fracturing. These
254 measurements have been made to identify the orientation of each type of deformation
255 structure exposed in Section 3.1, and to verify that fracture orientations are sub-parallel and
256 consistent with the orientation of the main fault. Field measurements were conducted using
257 mini-tablets and FieldMove Clino ©Copyright Midland Valley Exploration Ltd 2014. The
258 data were regularly double-checked with a classical compass and clinometer to check the
259 potential deviation of the mini-tablet measurements (Allmendinger et al., 2017; Novakova and
260 Pavlis, 2017). The treatment of fault and fracture plane orientations and their representation

261 on a stereogram has been done with the software Stereonet, R. W. Allmendinger © 2006-
262 2016. Because of the large amount of fracture data, and their planes often being vertical, we
263 represent them as “rose diagrams”. The orientations have also been measured for the
264 background fracturing between faults, along outcrops distributed between faults at map scale.
265

266 3.6 *Map scale analysis*

267 Brittle damage at the map scale was characterized from geological maps, orthophotos of
268 0.5 m pixel size (PNAO from Centro Nacional de Information Geografica, ORTHO HR®
269 from IGN), measured in the field, and synthetized into the QGIS 2.18 software for precise
270 interpretation of the structures in the study area (Fig. 4 and A1). The main brittle faults being
271 characterized by Earth surface objects (reliefs, shadows, layer and rock discontinuities, limits
272 and lineaments in the vegetal cover), fault mapping is mainly derived from orthophoto
273 lineaments (Clark and Wilson, 1994). A manual lineament interpretation approach allowed
274 geological and anthropic lineaments to be distinguished. In many cases, vegetation,
275 Quaternary sediments and anthropic cover provide significant censoring biases for more than
276 50% of the studied areas. This particularly affects the detection of small lineaments lower
277 than 100 m in length, such as small faults and all Mode I fractures, that cannot be detected
278 with such a method. To characterize Mode I and stylolite background fracturing at this map
279 scale, we measured their orientation and density along 47 outcropping stations between faults.

280

281

282 **4. Damage Zone analysis**

283 4.1 *Map scale analysis*

284 The St Clement and Sant Mateu study areas allow the map-scale analysis of master fault
285 geometry and the spatial distribution of secondary faults only (Fig. 4 and A1). The master
286 fault observed on the West side of the Sant Mateu area is shown in Fig.4a. This master fault is
287 formed of fault segments, with variable degrees of interaction (open relays, e.g. at Salzadella,
288 Fig. 4b, or linked relays). The uplifted eastern side of this master fault exhibits many
289 unlinked, adjacent secondary-fault segments. These secondary fault segments define a zone of
290 brittle faulting adjacent to the master fault, which increases towards the northern fault tip.
291 This type of secondary fault tip damage pattern at a smaller scale is also observed with small
292 lineaments (Fig.4b). Note however that truncation and censoring biases are too large at this
293 scale to correctly analyse fault damage patterns close to the secondary faults. In the St
294 Clement area, the master fault is also composed of more or less linked fault segments (Fig.
295 A1). Secondary fault patterns are observed close to the master fault tips, but also at its centre
296 around a linked relay composed of two master fault segments.

297 Outcrop data show Mode I fracture mainly trending N030E to N060E, which is consistent
298 with the main lineament orientations, secondary faults and the master fault (Fig. 4c). In St
299 Clement, both fracture and lineament orientations are more scattered, between N030E and
300 N090E, and that fracture orientations are more perturbed in relay zones at both sites. Fracture
301 densities counted in these outcrops between faults allows a characterization of background
302 fracturing, giving a P10 density ranging between 15 and 17 Mode I fracture/m.

303

304 4.2 *Scanline analysis*

305 In this section, we present the data of 12 scanlines (S1 to S12, Fig. 5), taken from 11
306 different faults. A total of more than 14,800 fractures were counted on all the scanlines. The

307 S1, S2, S3 and S4 scanlines (Fig. 5a, b, c and d) were acquired in the Languedoc region
308 (France); the S5, S6, S7, S8 and S9 (Fig. 5e, f, g, h and i) scanlines were acquired in the Sant
309 Mateu area (Spain) and S10, S11, S12 (Fig. 5j, k, l) were acquired in the Aliaga area (Spain).

310 Scanline S8 illustrates the decrease of damage decay with distance from a normal fault
311 oriented N097E 67°S, with a slickenline of 70°SW pitch (Fig. 6). Its displacement is
312 estimated at 27 m. The number of sealed fractures clearly shows a decrease along the profile
313 away from the main fault. As for scanline S8 (Fig. 5h and Fig. 6), all the scanlines show a
314 decrease in the frequency of sealed veins with increasing distance (Fig. 5). This decay can
315 have different shapes and can be distributed along the entire scanline, or localised close to the
316 main fault. The decay of fractures in S8 is not continuous, with a polymodal shape marked by
317 fracture frequency peaks present in both the inner and the outer damage zone. These peaks
318 systematically correspond to secondary faults observed at the outcrop. When the displacement
319 is greater than 50 m, the faults are often accompanied by minor faults in the damage zone of
320 the main fault (S2, S4, S6, S9, and S12 see Fig. 5b, d, f, g, and l). These minor faults have
321 small displacements, i.e. centimetric to metric. These secondary faults are always
322 accompanied by fractures frequency peaks, and can be the maximum of fracture density of the
323 entire scanline. Furthermore, when the displacement is lower than 50 m, several fractures
324 frequency peaks are present on the scanline. These peaks mark secondary fault initiation or tip
325 damage of another segment as in Fig. 2d. These secondary faults are observed at different
326 scales and dimensions, on scanlines (Fig. 5), in the field (Fig. 2d) or in map view (Fig. 4).

327 The stereograms representing fracture orientations by typology (Fig. 6c) show that the
328 veins and joints have on average the same orientation (N160E and N090E). In these
329 stereograms, as in each stereogram representing fractures without distinction of typology (Fig.
330 6), the most represented orientation is sub-parallel to the main fault, except close to the main
331 fault. The dip of these fractures is from 50 to 80° NW, also sub-parallel to the main fault.

332 On all the scanlines, stylolites do not show clear frequency decay, being of generally
333 constant frequency overall along the scanline (except on S1 and S3). Along the S8 profile,
334 two sets of stylolites are measured, (1) a sub-vertical set between 80° and 90° dip and nearly
335 perpendicular to the fractures, and (2) a nearly horizontal set dipping 20° to 30° to the East,
336 nearly parallel to the stratification. In the damage zones, we also observe fracture sets and
337 stylolites with trends inconsistent with the Oligocene extension, revealing that a small
338 proportion of the fractures, consistent with the absolute background fracture density, are
339 present into the damage zones.

340

341 4.3 *D-T scaling law in carbonate rocks*

342 Fig. 7 shows *Damage zone thickness* and *Displacement* values estimated from the faults
343 shown as scanlines in Fig. 5. The data acquired in the studied carbonate rocks clearly show a
344 normal correlation between *T* and *D* on a log/log diagram (Fig. 7). They are continuous over
345 three orders of magnitude of displacement and show little dispersion (Fig. 7).

346 The data fit to a power law of the type function in the form of:

$$347 \quad y = Cx^\alpha$$

348

349 *C* being a constant and α the exponent, which is a real between 0 and 1 (Fig. 7a). The least
350 square coefficient of the trend is $R^2 = 0.93$, in which α equals to 0.82, then very close to an
351 affine relation, and *C* equals 1.6.

352 The function shows a good fit with the data from faults where $D < 100$ m. The *D-T* data
353 follow a near-linear *D-T* law with a correlation coefficient of 0.97 (Fig. 7c and d). In contrast,
354 in this part of the graph, literatures data are scattered over more than two orders magnitude
355 (Fig. 8). Total damage zone thickness of St Clement (S4) and Taurac (S2) faults are clearly
356 under the linear *D-T* scaling law. As these faults have displacements of 556 m and 516 m

357 respectively, this finding is coherent with the literature data and the D - T scaling law for
358 displacements over 150 m.

359

360

361 **5. Discussion**

362 The determination of the displacement and the DZ thickness based on 12 scanlines reveals
363 a well-defined D - T scaling relationship, characterised by a nearly-linear scaling over three
364 orders of magnitude of displacement and for displacement below 100 m. Over the value of
365 100 m displacement, the only two faults that can be measured define a bend in the scaling
366 relationship suggesting that DZ thickness may saturate around 150 m.

367

368 *5.1 Scattering in the D - T scaling*

369 Damage zone scaling relationships for faults with displacement lower than 100 m shows a
370 least square coefficient of $R^2 = 0.97$ with an exponent $\alpha = 0.95$, i.e. very close to a linear
371 scaling relationship. The accuracy of this data set contrasts with the scattering observed in the
372 Savage & Brodsky (2011) data compilation from various studies Fig. 8. Compared to this data
373 compilation, the data presented in Fig. 7 were acquired exclusively in non-porous carbonate
374 rocks, far from the fault tips and with the same methodology to estimate the DZ thickness. In
375 particular, the fact that scanlines have been acquired far from the fault tips, probably
376 contributes to reducing the scattering (Kim et al., 2004, Perrin et al., 2016). This suggests that
377 the spread of data observed in Savage & Brodsky (2011) can be due to several geological
378 factors and processes, including the rheology of the host rocks and the fault zone (Berg and
379 Skar, 2005; Fossen and Rotevatn, 2016; Philit et al., 2018), modalities of slip accumulation
380 (incremental ruptures, characteristic rupture size, creep; Hadizadeh and Law, 1991; Robert et

381 al., 1995; Gratier et al., 1999), but also to the method of determination of the damage
382 thickness (Choi et al., 2016) and fault net slip.

383 In our approach, the method for determining fault displacement depends on both the offset
384 of the layer and slickenline orientations measured in the field. The main source of error
385 concerns the slip vector, and a quite large uncertainty has been considered in the error
386 calculation (see Section 3.5). However that error bar for the displacement values is still
387 generally lower than the error bars obtained for damage zone thicknesses (see Figs. 7 and 8).
388 Although the error bar is quite large on damage zone thickness, the D - T values are much less
389 scattered than the data provided by previous studies (Fig. 8). This is probably due to an
390 improved consistency in the criteria chosen to measure fault damage and (Section 3.2), and a
391 more restricted set of geological variables (e.g. same lithology).

392 Despite working in the same lithology and the same methodology, damage thickness
393 values include some errors and uncertainties related to outcrop quality and therefore damage
394 zone thickness determination. In some of the scanlines, outcrop comprises gaps due to
395 weathering and vegetal cover, potentially affecting the trend in frequency decay. The
396 determination of the damage zone thickness is less robust for large faults where the gaps can
397 represent, in the worst case, 48% of the scan-line. In our study, for large faults such as S2 and
398 S6, the DZ thickness might be underestimated due to the lack of outcrop continuity, or
399 especially for S4 and S2, due to the scanline size which appears insufficient in length. Faults
400 S4 and S2 are actually within the scale range of fault displacement at which the linearity of D -
401 T scaling is generally considered lost and critically discussed in terms of data scattering
402 (Savage and Brodsky, 2011; Mitchell and Faulkner, 2012) (Fig. 8). For these two faults, the
403 mean fracture density observed at the end of the scanline is around 20 and 23 fractures/m,
404 which close to the background fracture density measured far from the faults (15 fractures/m)

405 from the map scale fracture analysis (see section 4.1, Fig. A1). This suggests that the
406 scanlines for these two faults are actually large enough to reach the background fracturing.

407

408 *5.2 Damage zone growth model*

409 *5.2.1 Segmentation and linear D-T scaling*

410 Several conceptual and numerical models have been proposed to account for the growth of
411 damage zones around faults, including processes of fault propagation, fault slip accumulation,
412 and subsequent fault and fracture coalescence (e.g. Shipton and Cowie, 2001; Manighetti et
413 al., 2004; Micarelli et al., 2006; Childs et al., 2009; Faulkner et al., 2011; Schueller et al.,
414 2013). With the exception of Shipton and Cowie (2003), these models fail to explain a normal
415 correlation between displacement and DZ thickness. The slip-patch model of Shipton and
416 Cowie (2003) relates fault damage growth to the quasi-static stress distributed around the
417 incremental ruptures (also possible for dynamic ruptures, Griffith et al., 2009), and to the way
418 the fault ruptures in different places during its growth history. Although very interesting, and
419 probably accounting for the damage zone growth of an isolated fault, this model does not
420 clearly account for the major and well-known process of fault growth by segment linkage
421 inherent to most, fault systems (e.g. Peacock and Sanderson, 1991; Mansfield and Cartwright,
422 1996; Cowie, 1998; Soliva and Benedicto, 2004).

423 Segment linkage appears to be a prominent process of fault growth within the development
424 of fault populations (e.g. Peacock, 2003, and references therein), including the fault systems
425 studied here, and the concept has also been used to explain the step-wise development of fault
426 core zones and overall fault zone thickness development in general (Wibberley et al., 2008;
427 Childs et al., 2009). It therefore has significant impact on fracture frequency decay around
428 fault and damage zone growth. In most of the scanlines Fig. 5, the logarithmic decay of
429 fracture frequency is actually formed through addition of smaller secondary peaks of fracture

430 frequency. These fracture clusters have modal values decreasing toward the outside edges of
431 the fault damage zone and are generally related to the presence of secondary faults. In other
432 words, fault damage zones are actually formed of secondary faults with their own damage,
433 and in this way the entire topic of the damage zone thickness definition is a multi-scale
434 phenomenon. Complementary observations of the fault architecture in the field (Fig. 2d) or at
435 the map scale (Fig. 4 and A1) show that these faults are always composed of multiple partially
436 or fully linked segments at different scales, for both out-of-plane and in-plane observations
437 (also see section 4.1). These faults, as many others in fault systems, are formed of linked
438 faults segments, with abandoned tips (e.g. Peacock and Sanderson, 1991) or aborted small
439 faults in the stress drop zone of the master through-going fault (e.g. Gupta and Scholz, 2000),
440 with their own small damage zones. Such geometries are commonly observed in fault systems
441 and are inherent to scale invariant 3D fault patterns having linear *Displacement – Length*
442 scaling and fractal fault size distribution (e.g. Scholz and Cowie, 1990; Dawers et al., 1993;
443 Cowie et al., 1995; Cladouhos and Marrett, 1996; Schlische et al., 1996; Cowie and Shipton,
444 1998).

445 Fault segment linkage has also been identified as a self-similar process in terms of fault
446 displacement and spacing at relay zones (Peacock, 2003; Soliva and Benedicto, 2004;
447 Acocella and Neri, 2005; Fig. 9b). On a broad range of scales (i.e. displacement ranging
448 between 10^{-3} m and 10^3 m), two fault segments are generally linked for a value of
449 displacement close to the value of spacing between them (Soliva and Benedicto, 2004). This
450 process of linkage therefore allows both the accumulation of displacement and fault damage
451 thickness by incorporating (1) the secondary damages of the former segments, (2) abandoned
452 tips and (3) small faults (Fig. 9a and d). In other words, fault linkage allows the creation of a
453 master fault and incorporation of both types of damages, i.e. wall, tip and link damages of

454 former segments at its vicinity. If this process is scale invariant the thickness of fault damage
455 must increase proportionally with displacement as proposed in Fig. 9c.

456

457 5.2.2 *Non-linear D-T scaling*

458 Although debatable, the *D-T* data obtained on the two largest faults (Fig. 7 and 8) define a
459 trend consistent with those observed by Savage and Brodsky (2011) and Mitchell and
460 Faulkner (2012). In both of those studies, a *D-T* linear scaling is observed up to a scale of
461 displacement of 100 – 150 m whereas lower or no increase of DZ thickness is observed for
462 larger fault displacement (Fig. 8). This however contrasts with what Perrin et al. (2016) show
463 from map scale analysis of damage only formed of secondary faults, especially close to fault
464 tip, such as the “tip damage” in the terms of Kim et al. (2004), or “parent fault” in the terms of
465 Marchal et al. (1998). This might be because at a certain scale, fault damage defined by Mode
466 I fractures (or deformation bands) is limited and that fault damage might still be present in the
467 form of secondary faults, far enough from the master fault and therefore not considered in
468 scanline analyses. We tested this hypothesis by reporting a DZ thickness obtained from map
469 analysis of secondary faults around the main faults in the Sant Mateu and St Clément study
470 areas (see section 4.1, Fig. 4 and Fig. A1). We also added data from the Têt fault zone cutting
471 crystalline rocks in the Pyrenees (Taillefer et al., 2017), which was also examined using
472 scanline and map analysis. These new data obtained at this scale suggest that fault damage
473 due to Mode I fractures might scale very differently to fault damage derived from secondary
474 faults only. This might be particularly expressed close to the tip of master faults, where Mode
475 I fracture damage should decrease in thickness towards the tip of the master fault as
476 displacement decreases to zero, whereas tip damage observed for secondary faults increases
477 towards the master fault tip, and scales with fault length (Perrin et al., 2016; Fig. 9d and Fig.
478 10). The scanline method is however fully efficient to define and understand the scaling of

479 Mode I fracture damage and to plot together enough data. Mapping of Mode I fracture or
480 deformation band damage around faults is rarely possible (e.g. Flodin, 2003; Davatzes et al.,
481 2005; Shipton and Cowie, 2003) and generally biased.

482 Several solutions might be envisaged to explain a non-linear scaling of Mode I fracture
483 damage. The first one was proposed by Ampuero and Mao (2017), on the basis that fracture
484 damage mainly results from co-seismic events (Griffith, 2009 and Aben et al, 2016) and
485 which extent is limited by the thickness of the brittle crust hosting earthquakes. Fault ruptures
486 restricted to the brittle crust and related stress perturbations do not increase proportionally in
487 length and height (also see Soliva et al., 2006) and therefore imply scale-dependent rupture
488 and damage properties, or at least that the thickness of the brittle crust is an upper limit to
489 scale independence. An additional model proposed here is based on the segmentation model
490 exposed in Section 5.2.1. Faults with displacements larger than 100 m might have a lower
491 fault tip reaching the brittle-ductile transition (Schlische et al., 1996; Nicol et al. 1996;
492 Manighetti et al., 2001), and will not be able to link with new fault segments down dip (Fig.
493 10). This change in crustal rock behaviour prevents fault linkage, link damage processes and
494 the accumulation of fault damage from former faults segments. This process must also favour
495 normal and reverse fault weakening by asperity removal such as proposed by Childs et al.
496 (2009), and therefore inhibits asperity damage processes for such faults (e.g. Mitchell and
497 Faulkner, 2009). Other types of scale dependent behaviour were documented in fault system
498 scaling laws (size distribution, *Displacement – Length*) where faults are restricted at the base
499 of the crust or major layer discontinuities within the brittle crust, and where few or no faults
500 are able to cut the underlying units due to (1) its specific behaviour, or (2) a limited amount of
501 remote strain (Ackermann et al., 2001; Bohnenstiehl and Carbotte, 2001; Soliva and Schultz,
502 2008). In some cases, this process can happen at the scale of stratigraphic units (Soliva et al.,
503 2006), at which non-linear damage scaling has also been observed (Micarelli et al., 2006).

504 Finally, an additional model of scale dependent fault damage could be considered given
505 that a significant part of the fractures might form during the interseismic periods such as
506 described by Robert et al. (1995). Carbonate rocks in particular express pressure solution
507 processes, which generally form during these interseismic periods or during fault creep.
508 Although the scanlines of Fig. 5 are not correctly oriented to count stylolites, they generally
509 show their presence in the damage zones, with kinematically coherent orientations in relation
510 to Mode I fractures. Their specific localisation close to fault cores documented by Benedicto
511 and Schultz (2010) in carbonate rocks, suggests that a part of fault damage strain is due to
512 slow deformation, although the proportion remains unclear. It is worth noting that, for strike
513 slip fault, slow interseismic strain is distributed around faults following an arctangent
514 function, with wavelength being related to the fault locking depth and therefore the brittle-
515 ductile transition depth (Savage and Burford, 1973). This potentially provides an additional
516 process to explain non-linear scaling of fracture damage, especially for strike-slip faults
517 documented by Savage and Brodsky (2011) at large scale. Such a hypothesis currently suffers
518 from lack of field data on interseismic fracture damage and definitions of the fault locking
519 depth, if any. Other potential processes generating fault damage, such as Mode I fractures due
520 to fault-related folding, are also hard to demonstrate from these field data due to the lack of
521 layer dip variations in the examples studied.

522

523

524 **6. Conclusions**

525 We present new results about fault damage in carbonate rocks combining fault system
526 analysis at map scale and D - T scaling, implying the following main results:

- 527 1) The scanlines obtained from field data show a clear logarithmic decrease of
528 fracture frequency as distance increases from the main fault, with local frequency
529 peaks in the damage zone corresponding to secondary faults.
- 530 2) Faults are formed of linked segments and abandoned tips in the fault damage zones
531 thickness.
- 532 3) *D-T* data comprised between 0 and 100 m fault displacement show a nearly linear
533 *D-T* scaling (power law with exponent of 0.95, with a least square coefficient $R^2 =$
534 0.97).
- 535 4) Including two additional data with $D > 100$ m, the best fit is a power law with an
536 exponent of 0.82 and $R^2 = 0.93$. As suggested by previous studies on fault damage
537 zones, damage thickness tends to saturate with increasing displacement larger than
538 100 m, and such an upper bound may be related to mechanical unit thickness.
- 539 5) These new data are discussed with respect to fault segmentation observed in the
540 field. We propose a new model which explains *D-T* scaling by fault growth
541 through segment linkage and damage zone thickness accumulation.
- 542 6) *D-T* scaling data of the largest faults, as well as data from the literature for
543 different rock types, suggest that Mode I fracture damage might be scale dependent
544 for $D > 100$ m. This is discussed in terms of inhibition of the down-dip
545 segmentation process and asperity weakening for crustal scale faults able to cut the
546 entire brittle crust.

547

548

549

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555

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838

839 **Figures Captions**

840

841 **Fig. 1** Locations and geological schemes of the studied areas. a) Cenozoic cover map in
842 Languedoc area. Red box 1 is the St Clement fault study area. Red box 2 is the Taurac fault
843 study area. The regional stratigraphic column shows, in red, layers where damage
844 measurements are made in this study. Stereogram shows the average fracture and fault
845 orientations in these areas. Cross section according to the profile A-A'. b) Cenozoic cover
846 map in Maestrat study area. Red box 3 is the Sant Mateu study area and red box 4 is the
847 Aliaga study area. Similarly to a), the regional stratigraphic column, stereogram and cross
848 section according to profile B-B' are also represented for this area.

849

850

851 **Fig. 2** Brittle structures in carbonate rocks measured in the field. a) Joint sealed by sparite
852 mineralization. b) Tension crack Mode I opening sealed by sparite mineralization. c)
853 Horizontal stylolite associated with vertical fracture. d) Normal fault with 1.5 m displacement.
854 This fault has been selected for scanline measurement (Fig. 5a).

855

856

857 **Fig. 3** Scheme for the damage zone thickness correction using the angle between the
858 scanline and the normal to the fault plane.

859

860

861 **Fig. 4** Geological and mapping data in Sant mateu area. a) Sant Mateu master fault trace.
862 b) Geological map of the Sant Mateu area. Stereograms correspond to field fracture

863 measurements on one outcrop. c) Average orientation of the 1358 lineaments traces on map.
864 d) Colour chart for stereogram.

865

866

867 **Fig. 5** Total scanlines sampled in the four study areas. a), c), d) have been sampled in St
868 Clement, b) Taurac fault, e), f), g), h), i) at Sant Mateu and j), k), l) in Aliaga area. Yellow
869 dashed line marked the DZ boundary estimated with cumulative frequency curve. Faults with
870 0.5 m and 1 m displacement have only one inflection due to the small DZ thickness. Grey
871 boxes represent all the gaps where the outcrop quality prevents measurement.

872

873

874 **Fig. 6** Detail S8 scanline and average fractures orientations on normal fault in Sant Mateu.
875 a) Picture of the fault and the outcrop where the scanline was done (blue line). d) Scanline
876 histogram with fracture frequency as a function of the distance to the fault. The DZ thickness
877 (yellow dashed line) is determined by the inflection of the cumulative frequency curve (grey
878 dot). c) (up) Rose diagram of the fracture orientations classified in function of their types. The
879 length of each segment represents the proportional orientation for each fracture types. (down)
880 Rose diagram of unclassified fracture orientations, proportions of orientations are represented
881 independently to the fracture types.

882

883

884 **Fig. 7** Damage zone thickness data for this study as a function of displacement. Data show
885 an accurate linear law mainly define by normal faults, in carbonate rocks. a) log-log diagram
886 for all 12 scanlines, b) Same as a) with linear axis. The two faults with displacements over

887 100 m show significant deviation of the linear correlation. c) and d) Same as a) and b) without
888 outliers (S2 and S4).

889

890

891 **Fig. 8** Total fault zone thickness as a function of displacement modified from Savage and
892 Brodsky, 2011. Linear scaling is well defined for faults displacement between 1 m and 100 m
893 in carbonate rocks. Two faults over 100 m displacement seem to start the bending of the
894 scaling law trend. Têt fault is a normal fault in Eastern Pyrénées, affecting granit and
895 mylonite. Point with dot contour represent fault DZ evaluated in map view with secondary
896 fault damage, for St Clement fault, Sant Mateu master faults and Têt fault (from Taillefer et
897 al., 2017).

898

899

900 **Fig. 9** Model of fault segmentation and damage zone growth. a) 3D model of segmented
901 master fault with secondary faults and associated Mode I fracture damage zone. b) Spacing
902 (S) between linking master faults as function of the displacement. c) Mode I damage zone
903 increasing as function of the displacement and segment linkage show in d). d) Model of Mode
904 I fracturing damage increased by fault segment linkage and tip secondary fault incorporation.

905

906

907 **Fig. 10** a) Diagram for Mode I and secondary fault damage zone. b) Mode I damage zone
908 growth by fault segments interaction. c) Fault segment linkage model inhibited by brittle
909 ductile transition.

910

911 **Appendices**

912

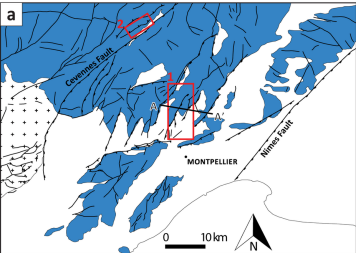
913 **Fig. A1** Geological and mapping data in St Clement area. a) Geological map of the St
914 Clement area. Stereograms correspond to field fracture measurements on one outcrop. b)
915 Colour chart for stereogram. c) Average orientation of the 532 lineaments traces on map.

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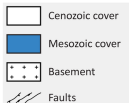
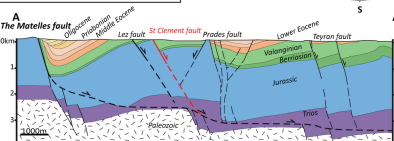
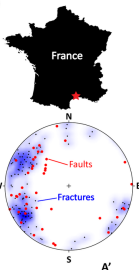
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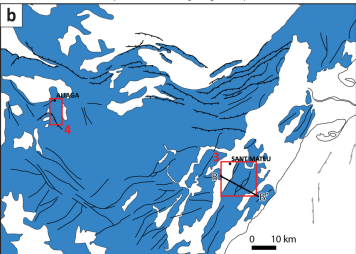
Synthetic Languedoc geological map



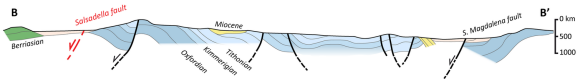
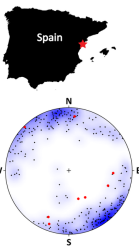
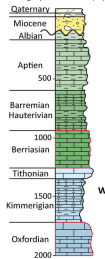
Stratigraphic column (m)

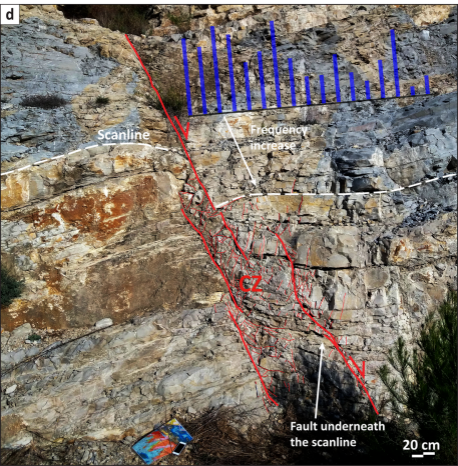
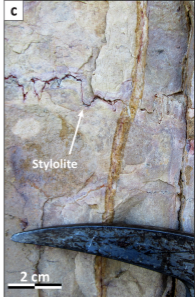
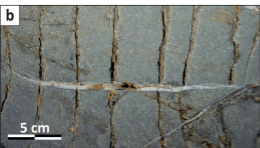
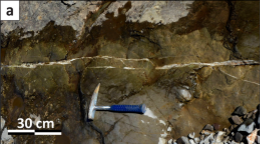


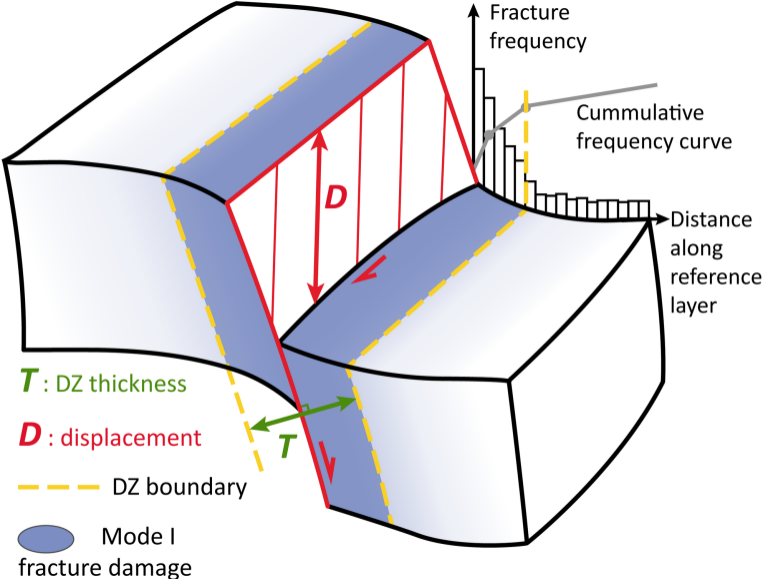
Synthetic Maestrat geological map

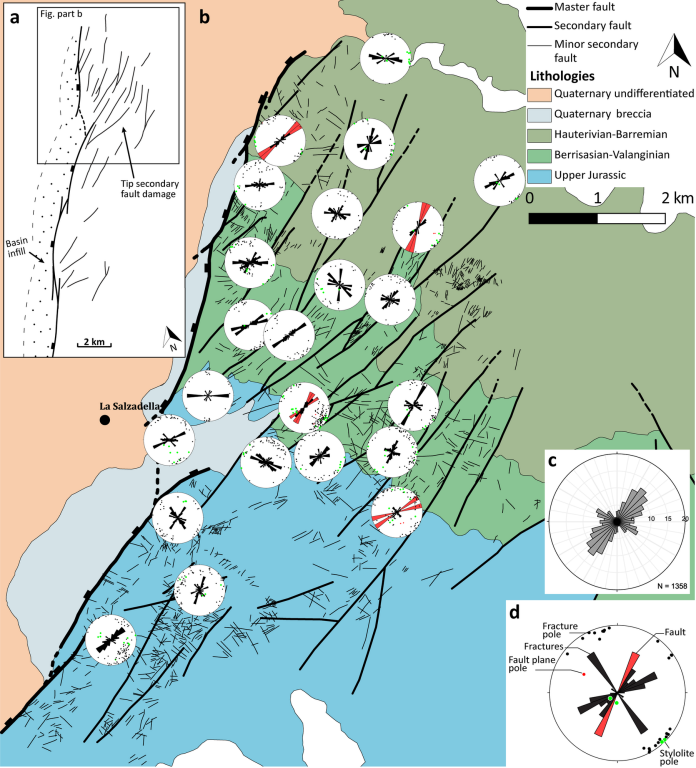


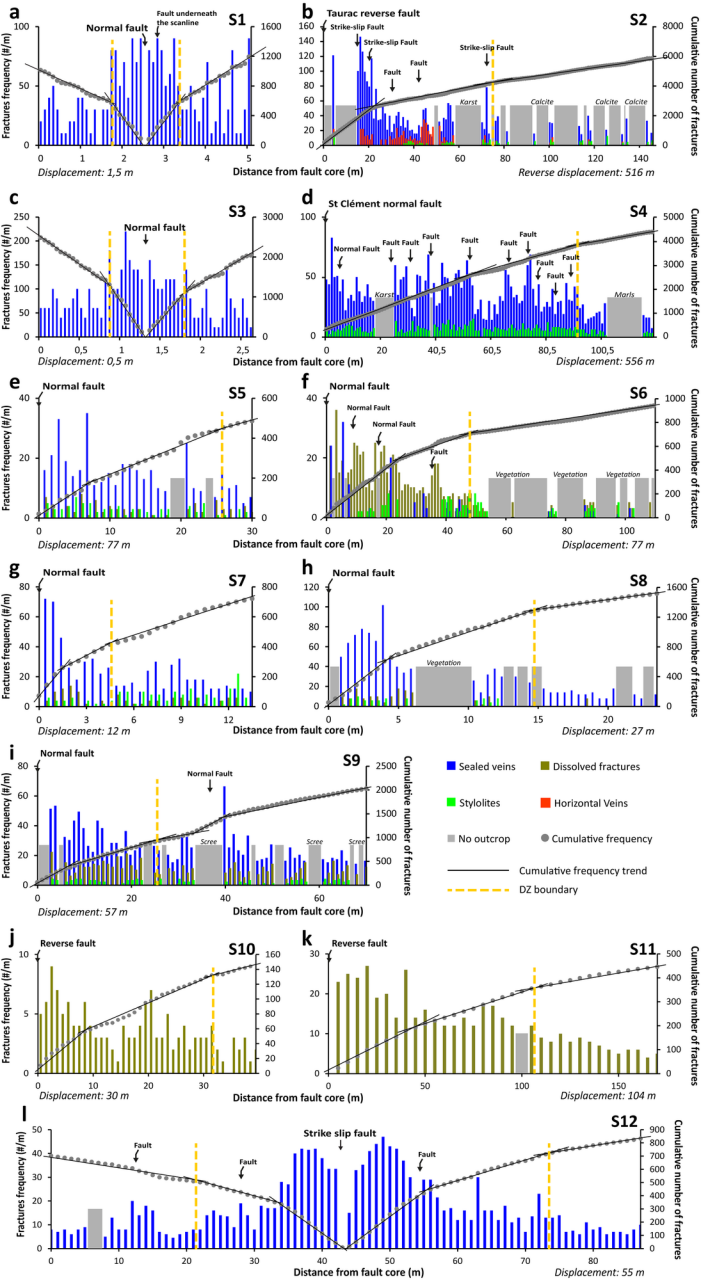
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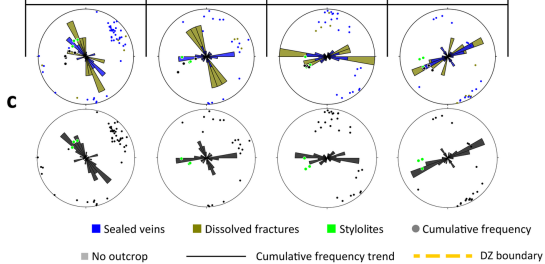
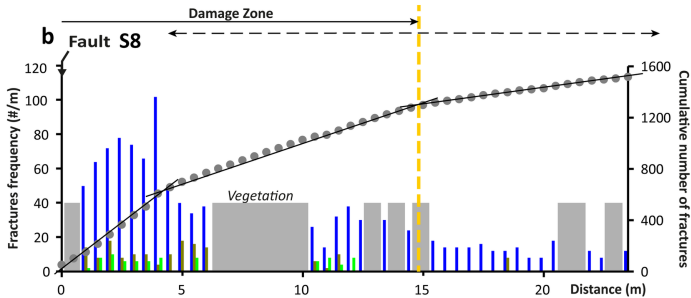
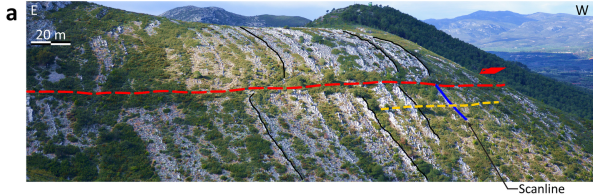


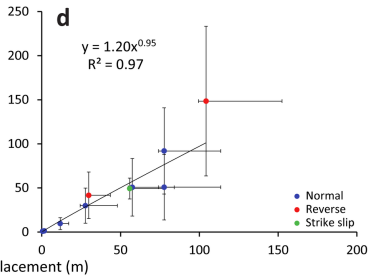
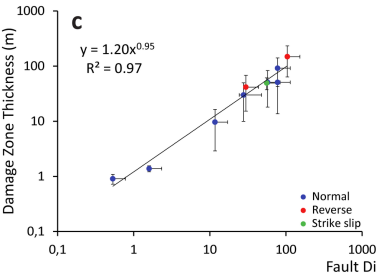
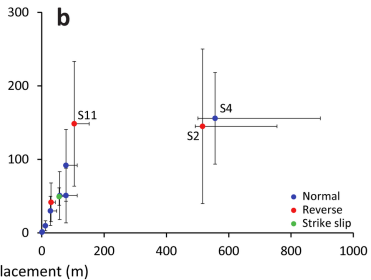
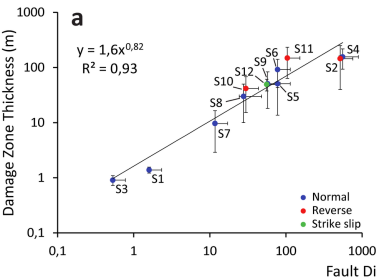


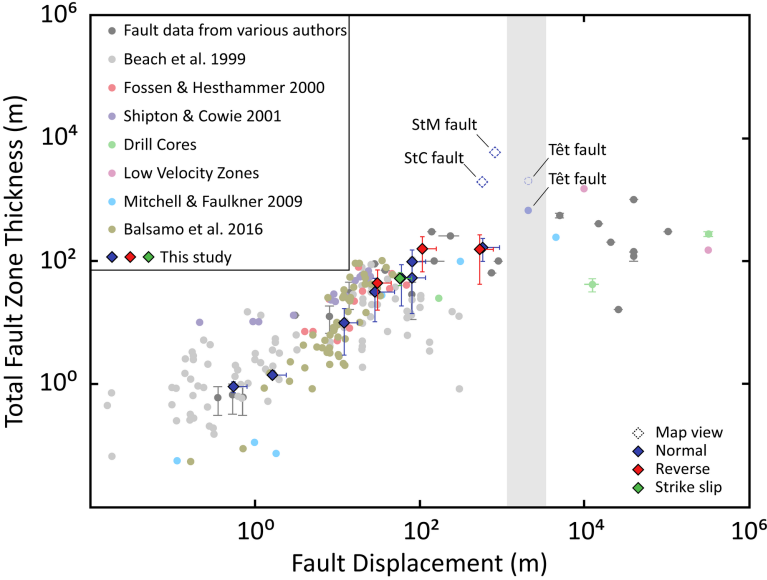


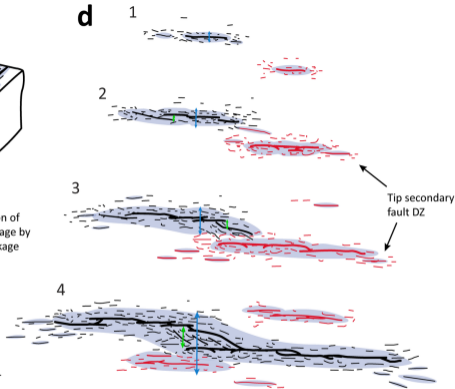
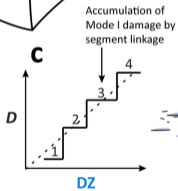
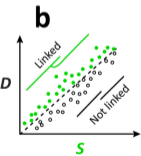
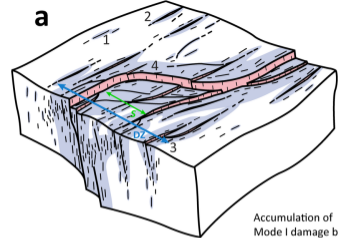












Mode I fracture damage

Master fault considered in figure part c

Master fault not considered in figure part c

Spacing between linking master faults

Mode I damage thickness

Minor secondary faults

