



UNIVERSITÀ DI PARMA

ARCHIVIO DELLA RICERCA

University of Parma Research Repository

Displacement-dependent microstructural and petrophysical properties of deformation bands and gouges in poorly lithified sandstone deformed at shallow burial depth (Crotone Basin, Italy)

This is the peer reviewed version of the following article:

Original

Displacement-dependent microstructural and petrophysical properties of deformation bands and gouges in poorly lithified sandstone deformed at shallow burial depth (Crotone Basin, Italy) / Pizzati, M.; Balsamo, F.; Storti, F.. - In: JOURNAL OF STRUCTURAL GEOLOGY. - ISSN 0191-8141. - 137:(2020). [10.1016/j.jsg.2020.104069]

Availability:

This version is available at: 11381/2882567 since: 2024-12-12T08:46:54Z

Publisher:

Elsevier

Published

DOI:10.1016/j.jsg.2020.104069

Terms of use:

Anyone can freely access the full text of works made available as "Open Access". Works made available

Publisher copyright

note finali coverpage

(Article begins on next page)

02 May 2026

1 **Displacement-dependent microstructural and petrophysical properties**
2 **of deformation bands and gouges in poorly lithified sandstone**
3 **deformed at shallow burial depth (Crotone Basin, Italy)**

4
5 Mattia Pizzati*, Fabrizio Balsamo, Fabrizio Storti

6 *NEXT, Natural and Experimental Tectonics Research Group, Department of Chemistry, Life Sciences, and
7 Environmental Sustainability, University of Parma, 43124 Parma, Italy.

8 Corresponding author's E-mail address: mattia.pizzati@studenti.unipr.it

9 Corresponding author's phone number: +39 0521 905202

10

11 **Keywords**

12 Cataclastic deformation bands; sub-seismic deformation features; petrophysical
13 properties; particulate flow-cataclasis; shallow-burial depth; high-porosity sandstone.

14 **Highlights**

- 15 - Fault zone characterized by sub-seismic scale deformation features.
- 16 - Permeability drops up to 3-4 orders of magnitude with respect to pristine sandstone.
- 17 - Particulate flow operates until porosity is > 5-6%, while below cataclasis settles.
- 18 - Deformation mechanism depends upon mineralogy of grains.
- 19 - Permeability and microstructures are strictly related to the total displacement.

20 **Supplementary material**

21 Detailed description of standard operating procedures adopted during grain size analysis
22 and all the grain size distribution curves are provided with detailed permeability, grain size
23 data and sampling sites along the studied fault zone. Moreover, inside the online

24 supplementary file additional SEM photomicrographs, porosity, permeability data and grain
25 shape analysis are provided with related statistical tests.

26

27 **ABSTRACT**

28 We present the results of meso- and micro-structural analyses performed on fault-related
29 soft-sediment deformation structures affecting poorly lithified, high-porosity siliciclastic
30 sediments in the Crotona Basin, Southern Italy. The investigated extensional fault zone
31 has a total displacement of ~ 90 m and juxtaposes marine clayish sediments in the
32 hanging wall against arkosic to lithic arkosic sandstone in the footwall. In the footwall
33 damage zone, deformation is achieved by a network of conjugate deformation bands,
34 whereas the foliated fault core hosts cm-thick gouges. Deformation bands and black
35 gouges accommodated displacement between 0.2 to 20 cm. Microstructural observations
36 and quantitative image analysis pointed out that particulate flow operated during the early
37 stages of faulting, followed by cataclasis after significant porosity loss. Mineralogy of clasts
38 controlled grain-scale deformation mechanism: following this, feldspar experienced
39 extensive intragranular crushing, while quartz grains were deformed mainly by splitting and
40 abrasion. Permeability of pristine sandstone spans from 5.4×10^4 to 1.4×10^5 mD, while
41 inside deformation bands is reduced by 1-2 orders of magnitude, reaching 3-4 orders of
42 magnitude within fault gouges. Permeability drop inside the fault zone is related to the
43 accommodated displacement along each deformation structure, potentially leading to
44 hydraulic compartmentalization of high-porosity sandstone reservoir.

45

46 **1. Introduction**

47 Fault zones in poorly lithified sediments and high-porosity rocks typically behave as
48 barriers toward subsurface fluid flow, due to the development of deformation structures
49 such as deformation bands and gouge layers in damage zones and fault cores,
50 respectively (Antonellini and Aydin, 1994; Balsamo and Storti, 2010; Bense et al., 2013;
51 Rotevatn et al., 2013; Ballas et al., 2015). Deformation bands can develop both as single
52 structures or as clusters formed by tens to hundreds discrete elements, within which slip
53 localizes along few discrete surfaces during progressive strain-hardening (Aydin and
54 Johnson, 1978; Mair et al., 2000; Soliva et al., 2016; Fossen et al., 2017; Philit et al.,
55 2018). Although strain-hardening is usually invoked as the main process leading to
56 deformation band development, recent studies have pointed out that strain-softening may
57 occur as well especially after reaching the yield point of the deformed material (Nicol et al.,
58 2013). Deformation bands often show a limited lateral continuity with maximum length
59 typically below 100 m, which is proportional to the accommodated displacement along
60 each structure (Schultz and Fossen, 2002; Schultz et al., 2008). Fault gouges are usually
61 found in high-strain domains and result by extreme grain size reduction and strain-
62 localization processes (Engelder, 1974; Sibson, 1977; Balsamo and Storti, 2010).
63 According to the classification of Sibson, (1977) the term gouge is used to identify
64 incohesive fault rocks with less than 30% of visible clasts with respect to the fine-grained
65 matrix. In the present contribution, we are referring to more specific fault rock types,
66 namely black gouges, which are discrete elements showing extreme comminution and
67 occur as isolated, or as an intricate network of deforming structures. Black gouges
68 developing inside high-porosity sandstones were associated to a combination of grain size
69 reduction and frictional heating produced during coseismic slip events related to shallow-
70 depth (< 1 Km) earthquakes (Balsamo and Storti, 2011; Balsamo et al., 2014).

71 Petrophysical properties of deformation bands and fault gouges depend on several factors
72 including lithological composition of host rock (Wilson et al., 2003; Exner and Grasemann,

73 2010; Cilona et al., 2012; Kristensen et al., 2013; Antonellini et al., 2014; Griffiths et al.,
74 2016; Tavani et al., 2016; Cavailhes and Rotevatn, 2018), deformation mechanisms
75 (Aydin, 1978; Aydin and Johnson, 1983; Bense et al., 2003; Rawling and Goodwin, 2003;
76 Fossen et al., 2017), stress-strain conditions (Friedman and Logan, 1973; Olsson, 2000;
77 Baud et al., 2012; Ballas et al., 2013; Robert et al., 2018) and microstructural features
78 (Antonellini and Aydin, 1994; Main et al., 2000; Taylor and Pollard, 2000; Balsamo and
79 Storti, 2011). In particular, different deformation mechanisms (cataclasis and granular-
80 particulate flow) may cause a significant variability of permeability drops, from 1 up to 6
81 orders of magnitude with respect to the undeformed high-porosity protoliths (Ogilvie and
82 Glover, 2001; Balsamo and Storti, 2010; Ballas et al., 2015; Fossen et al., 2017).
83 Permeability diminishing in siliciclastic rocks is typically achieved through processes
84 involving grain size reduction, sorting decrease and pore space collapse (Main et al.,
85 2000; Balsamo and Storti, 2010; Kaproth et al., 2010). The recognition of fault structure
86 and related deformation mechanisms is critical to assess the hydrological role of fault
87 zones in sediments or high-porosity rocks hosting aquifers or hydrocarbon reservoirs
88 (Bense et al., 2003; Parnell et al., 2004; Sternlof et al., 2006; Fossen and Bale, 2007;
89 Kolyukhin et al., 2010). Further, burial depth during deformation is a key parameter that
90 may influence the permeability drop associated with deformation band development
91 (Ballas et al., 2015).

92 Despite the significant amount of work that has been done on the genesis and evolution of
93 deformation bands (e.g., Antonellini et al., 1994; Cashman and Cashman, 2000; Mair et
94 al., 2002a; Balsamo and Storti, 2010; Kaproth et al., 2010; Charalampidou et al., 2011;
95 Fossen et al., 2017), basic scaling-laws such as the relationships between displacement
96 and petrophysical properties are still a matter of debate (Torabi and Fossen, 2009; Ballas
97 et al., 2012; Rotevatn et al., 2013, 2017). Previous studies mainly focused on the
98 permeability ratio between faulted and undeformed rocks (Ballas et al., 2015; Fossen et

99 al., 2017). With the present contribution, we attempt to provide additional details
100 concerning the effect of total accommodated displacement on the microstructural features
101 of deformation bands and gouges formed at shallow-burial conditions. Furthermore, the
102 influence of microstructural-textural and petrophysical properties upon overall permeability
103 was analyzed. For this purpose, we investigated in detail the microstructural and
104 petrophysical properties of sub-seismic scale deformation structures occurring along the
105 Rocca di Neto extensional fault zone affecting Pleistocene high-porosity sandstones in the
106 Croton Basin, Southern Italy. The footwall damage zone of the Rocca di Neto fault zone
107 is characterized by widespread occurrence of deformation bands, both as single elements
108 as well as clusters, and subsidiary faults with different amounts of displacement and grain
109 size comminution. Black gouge layers are abundant in the foliated fault core, adjacent to
110 the master slip zone. In this study, such sub-seismic scale structural elements were
111 studied both at the meso and at the micro-scale. Petrophysical properties of deformed and
112 undeformed sediments (permeability, grain size and porosity) were measured both by *in*
113 *situ* and laboratory analyses. Complementary image analysis was used to quantify the
114 grain shape and their preferred orientation. This multidisciplinary approach allowed us to
115 constrain the evolution of deformation mechanism during faulting, which progressed from
116 particulate flow to cataclasis, and to quantify the role of displacement in determining the
117 petrophysical properties of faulted sandstones.

118

119 **2. Geological setting and fault zone structure**

120 The study area is located in the Croton forearc basin, in Southern Italy (Fig. 1a), which
121 developed as a consequence of subduction of the Adria plate below the European plate
122 (e.g., Van Dijk et al., 2000; Zecchin et al., 2004; Reitz and Seeber, 2012). Basin infill
123 began in Middle Miocene times, resulting in a stratigraphic succession as thick as 2500 m,

124 overlying the metamorphic basement of the Sila Massif (Zecchin et al., 2004, 2012). Basin
125 evolution includes five subsidence-uplift events during a dominant extensional and subtle
126 transpressional tectonic history (Van Dijk and Scheepers, 1995; Van Dijk et al., 2000;
127 Ferranti et al., 2009). Eventually, the onset of regional uplift since Middle Pleistocene
128 times, led to the cessation of sedimentation and at the same time to the exhumation and
129 surface exposure of the sedimentary succession (Knott and Turco, 1991; Antonioli et al.,
130 2006; Zecchin et al., 2012; Massari and Prosser, 2013).

131 The present-day tectonic architecture of the onshore portion of the basin is defined by two
132 major left-lateral shear zones bounding the basin to the NE and to the SW. A set of NE-
133 SW-striking extensional fault zones accommodates displacement of several tens to
134 hundreds meters in the centre of the basin (Van Dijk, 1994; Zecchin et al., 2004) (Fig. 1b).
135 The Rocca di Neto fault zone belongs to the latter extensional fault system and affects
136 Pleistocene sediments pertaining to the late-stage basin infill (Fig. 1c). In particular, the
137 fault zone juxtaposes clayish sediments (Cutro Clay) in the hanging wall against silty
138 sands, sandstones and conglomerates (Scandale Sandstone) in the footwall block
139 (Zecchin et al., 2012) (Figs. 1c and 2a). The Cutro Clay was deposited in an offshore,
140 shallow-marine environment, while the deposition of the Scandale Sandstone occurred in
141 a shoreface setting where the majority of sediment supply was provided by a nearby river
142 delta (Zecchin et al., 2012). Due to the unconsolidated nature of faulted sediments, the
143 fault zone displays extensive occurrence of deformation features affecting high-porosity
144 rocks (Balsamo and Storti, 2010; Pizzati et al., 2019), namely deformation bands and fault
145 gouges. These structures are exclusively present in the footwall block of the fault, where
146 high-porosity sandstones crop out. Conversely, the hanging wall block is almost
147 completely covered by vegetation due to the presence of clayish sediments (Fig. 2a).
148 Deformation bands are thin and well-localized tabular features that, when arranged in
149 conjugate sets, typically have displacement between 1 and 5 cm. Deformation bands with

150 displacement < 1 cm are found far from subsidiary faults and deformation band clusters.
151 Fault-parallel deformation bands located closer to the master fault can display higher
152 offsets, from 5 to 10 cm. Subsidiary faults accommodate larger amounts of displacement
153 (> 15-20 cm) and are characterized by several cm-thick slip surfaces.

154 The overall structural architecture of the exposed footwall of the Rocca di Neto fault zone
155 consists of four structural domains (Pizzati et al., 2019) (Fig. 2a, b): (1) a low-deformation
156 zone, with widely spaced deformation bands and few subsidiary faults having low-
157 displacement (Fig. 2b, c); (2) the damage zone, characterized by abundant conjugate
158 deformation bands, together with subsidiary faults showing antithetic and synthetic shear
159 sense with respect to the master fault (Fig. 2b, c); (3) the mixed zone, with a dense
160 network of conjugate and high-strain fault-parallel deformation bands (Fig. 2b, c); (4) the
161 fault core formed by foliated coarse to very fine sand cut by slip surfaces decorated by
162 mm-to cm-thick black gouges (Fig. 2b, c). Although the majority of the total displacement is
163 accommodated along the mixed zone and fault core, deformation bands and gouges
164 significantly contribute to the offset partitioning along the entire fault zone.

165 Inside the low-deformation zone, and to lesser extent in the outer part of the footwall
166 damage zone, deformation bands are arranged in conjugate sets and have offsets typically
167 lower than ~ 1 cm (Fig. 3a). In the footwall damage zone, deformation bands are arranged
168 in three sets; two of them form an inclined conjugate system (hereafter DB₁ and DB₂),
169 while the third one (DB₃) is parallel to subsidiary faults (Fig. 3b). Within the mixed zone,
170 deformation bands are organized in dense arrays, mostly trending parallel to subsidiary
171 synthetic faults and to lesser extent arranged in conjugate arrays similar to the adjacent
172 damage zone (Fig. 3c). Several 5-20 cm-thick clusters of fault-parallel deformation bands
173 developed both in the damage zone and mixed zone, have cumulative offset typically
174 exceeding 10 cm.

175 The studied cross-sectional exposure includes also the fault core, where most of the
176 displacement is accommodated. This structural domain hosts several anastomosing slip
177 surfaces decorated by black gouges (Fig. 2a, c) with thickness of ~ 1 cm, locally
178 developing a gently folded pattern (Fig. 3d). Foliated sand encasing black gouges is highly
179 deformed and tectonically compacted (Pizzati et al., 2019).

180 Inside the fault zone deformation bands and subsidiary faults often display evidence for
181 selective cementation in the form of carbonate concretions made of calcite. Carbonate
182 concretions develop tabular-to lens-shaped cemented bodies with thickness ranging from
183 a few cm to 10-20 cm, paralleling the surface of the structural elements they encase (Fig.
184 3c, d). Cementation affects only deformation bands and subsidiary faults, while the host
185 sandstone is completely non-cemented, except for rare, thin, bedding-parallel concretions
186 displaying limited lateral continuity.

187

188 **3. Analytical methods**

189 *3.1. Grain size analysis by laser diffraction*

190 Sediment grain size was measured on 68 samples collected from different positions
191 throughout the fault zone, according to the sediment type, position with respect to the
192 master fault, and displacement (sampling sites are reported in Fig. 2a and Fig. A3 in the
193 Supplementary Material). Samples were first dried at a constant temperature of 45°C for
194 48 hours, and then sieved with a 2000 µm mesh to remove impurities. Grain size analysis
195 was performed with a Mastersizer 3000 (Malvern Instruments) laser diffraction particle size
196 analyzer having an operating size range spanning from 0.01 to 3500 µm. In particular, we
197 used the Hydro EV wet dispersion unit, with distilled water as dispersant fluid. Different
198 analytical procedures were specifically developed for each sample type in order to
199 minimize the alteration during the analysis (e.g. Storti and Balsamo, 2010). Details of tests

200 and final grain size distributions are provided in the online Supplementary Material. Based
201 on the grain size distribution curves, mean grain size, mode, span (sorting), and fractal
202 dimension (D-value) were calculated. Span is defined as the width of the grain size
203 distribution, while the D-value is calculated as the slope of the best-fit power-law
204 distribution between grain size and cumulative frequency of particles per each grain size
205 class in a log-log graph (Blenkinsop, 1991; Rawling and Goodwin, 2003; Balsamo and
206 Storti, 2011).

207 *3.2. In situ air permeability*

208 A total of 652 *in situ* permeability measurements were performed across the fault zone
209 using a portable Tiny Perm II air-permeameter (New England Research), which provides
210 accurate data between 10^{-1} and 10^5 mD, according to the methodology described by
211 Balsamo et al. (2013). Permeability measurements were performed in the same sites
212 where grain size samples were collected (see Fig. 2a and Figs. A2 and A3 in the online
213 Supplementary Material), after careful brushing the target sediment to remove any
214 alteration crust.

215 *3.3. Image analysis technique*

216 Fifty-five polished thin sections impregnated with blue-dyed resin were scanned at high
217 resolution with a Nikon SuperCoolScan 5000 and studied with a Zeiss Axioplan 2
218 petrography microscope and a JEOL JSM 6400 scanning electron microscope (SEM),
219 operating at 240 nA and 20 kV beam current. Two-dimensional porosity calculations were
220 performed on 273 selected images acquired with the petrographic microscope at 12.5×
221 magnification (thin section area 4747×3560 μm), both for the undeformed and faulted
222 sandstone, using ImageJ open-source image analysis software (Schneider et al., 2012). A
223 multi-scale image analysis technique was used to quantitatively describe particle shape. In

224 particular, grains with equivalent diameter between 95 and 500 μm were investigated with
225 12.5 \times magnification, from 35 to 95 μm with 25 \times magnification (2352 \times 1764 μm), from 25 to
226 35 μm with 50 \times magnification (1242 \times 932 μm) and those between 10 and 25 μm with 100 \times
227 magnification (614 \times 461 μm). Particles finer than 10 μm were not taken into account
228 because of their size below the resolution limit of the 100 \times optical microscope
229 magnification. Particles with equivalent diameter greater than 500 μm are rare due to the
230 medium-fine grain size of the analyzed samples. Grains were manually digitized at each
231 magnification to prevent any bias and inaccuracy induced by the auto-tracing methods.
232 Particle shape data were plotted against five grain size classes from 0 to 250 μm , with 50
233 μm bin size. Typically, more than 30 data were collected and averaged for each grain size
234 class to grant statistical significance of the shape descriptors.
235 Three shape descriptors were used, namely aspect ratio, circularity and solidity. Aspect
236 ratio (AR) is defined as:

$$237 \quad AR = \frac{\text{Major axis}}{\text{Minor axis}} \quad (1)$$

238 where *Major axis* indicates the segment connecting the two farthest points along the
239 perimeter of the grain, while *Minor axis* is the segment having as tips the nearest points on
240 the perimeter. Values span from 1 (equant particle) to infinity (very elongated particle).

241 Circularity (C) is given by:

$$242 \quad C = \frac{4\pi A}{p^2} \quad (2)$$

243 where A is the total area of the grain and p is the perimeter. Circularity spans from 0
244 (extremely elongated and irregular shape) to 1 (perfect circle). Solidity (S) is defined as:

$$245 \quad S = \frac{A}{A_{conv}} \quad (3)$$

246 where A_{conv} is the convex area delimited by the convex hull. Solidity varies from 0 (grain
247 with extremely rough surface) to 1 (grain with very smooth surface).

248 Grain preferred orientation was also analyzed by measuring the angle between grain
249 major axis and a horizontal reference plane. Half-rose diagrams were produced, using
250 dotted lines to represent orientations of the investigated deformation structures in the thin
251 sections.

252

253 **4. Petrographic and microstructural characterization**

254 *4.1. Petrography of undeformed sandstone*

255 The composition of the undeformed sandstone was constrained by modal analysis on 35
256 selected photomicrographs acquired at 12.5× magnification (thin section area 4747×3560
257 μm), via image analysis extracting the area percentage of the most recurrent mineralogical
258 species. According to the results, 23 pristine sandstone samples lay in the lithic arkose
259 field, while 12 of them plot in the arkose field in the Q-F-L ternary diagram of Folk (1974)
260 (Fig. 4a). In particular, quartz percentage spans from 50.3 to 67.7%, while feldspar ranges
261 from 19.6 to 36.9% and lithics from 5.3 to 18.2%. Lithics mainly include gneiss and granitic
262 rock fragments, but sedimentary detrital grains also occur in the form of calcite grains and
263 fossil shells. Other less frequent lithics are biotite mica, iron oxides-hydroxides, rare
264 muscovite, chlorite and glauconite.

265 *4.2. Microstructures*

266 Deformed sandstone shows a variety of microstructures, according to the total
267 displacement. In the low-deformation zone, deformation bands are tabular structures with
268 a minimum thickness of 1-5 mm and sharp boundaries with the surrounding pristine
269 sandstone (Fig. 4b). Grain size reduction is negligible and depositional fabric re-

270 organization results in significant porosity loss. Deformation bands having few cm of
271 displacement show grain size reduction, mainly produced by fragmentation of coarser
272 feldspar grains and quartz abrasion (Fig. 4c). In particular, feldspar grains are deformed by
273 several intragranular fractures, leading to the formation of tens of clasts, while quartz
274 grains show mostly splitting and flaking of asperities (Fig. 5a, b). When displacement
275 approaches or overcomes 10 cm, deformation bands are up to 5-6 mm-thick and display
276 outer sectors made of comminute and crushed grains, and ~ 300 μm -thick cores where
277 grain size reduction is more intense (Fig. 4d). The abundant dark brown matrix is
278 dominantly composed of crushed feldspar and lithic grains, together with fine-grained
279 quartz chips and to lesser extent fragments of detrital calcite. Locally, feldspar and quartz
280 oversized survivor grains are present within the core of deformation bands and are
281 cushioned by finer particles, which prevented their fracturing (Fig. 5c, d).

282 Black gouges have complex microstructural features, characterized by the presence of
283 ultra-comminute 500-1000 μm -thick slip zones encased by less comminute sand volumes
284 where subtle S-C structures are imparted by preferential orientation of mica flakes and
285 coarse survivor grains (Fig. 4e). Fault cores of subsidiary faults show intense grain size
286 comminution with several oversized survivor grains surrounded by a fine-grained matrix
287 (Fig. 4f). Along deformation bands and gouges grain fracturing markedly occurs in their
288 outer portion, whereas in the interior clasts are rarely affected by fractures (Fig. 6a). A
289 gradient of comminution intensity is frequently observed in deformation band cores,
290 resulting in the progressive increase of grain size from one boundary to the other (in Fig.
291 6b the left (footwall side) boundary of the deformation band is more comminute than the
292 right side). High-displacement deformation bands sampled in the footwall damage zone
293 commonly display a more pronounced grain size reduction on the footwall side.
294 Conversely, deformation bands inside the fault core and mixed zone are characterized by
295 asymmetric grain size reduction on the hanging wall side. Black gouges show the same

296 gradient of grain size reduction as the one observed in deformation bands, but typically it
297 is more intense along the hanging wall rather than on the footwall side (right side in Fig.
298 6c); thus these deformation elements display an asymmetric structure at the micro-scale.

299

300 **5. Grain size data**

301 Undeformed protoliths in the low-deformation zone are mainly composed of well-sorted,
302 medium-to fine-grained sand with a mean size of 334 μm and, subordinately, medium-
303 coarse sand with a mean size of 501 μm (Fig. 7a and table 1). Span values are very low
304 for both sediment types (1.7 and 1.2, respectively; Fig. 7b). In the low-displacement zone,
305 deformation bands have mean grain size of 236 μm , a mean span of 3.3 (Fig. 7a, b).

306 Moving to the footwall damage zone, the mean grain size of medium-fine sand layers
307 composing the interband domain (i.e., the sand volume in between two adjacent
308 deformation bands) decreases to 249 μm , whereas interband coarse sand has mean grain
309 size of 614 μm (Fig. 7a), with mean span values of 1.9 and 3.1, respectively (Fig. 7b).

310 Conjugate deformation bands with different displacement magnitude inside the footwall
311 damage zone display a range of grain size from 127 to 339 μm , while span varies from 4.6
312 to 8.1 (Fig. 7a, b).

313 Subsidiary faults and thick clusters of deformation bands have a mean grain size of 123
314 μm and a mean span of 5.8 (Fig. 7a, b).

315 Inside the footwall mixed zone, foliated sand is characterized by a mean grain size of 54
316 μm and a mean span of 9.2. Along the same structural domain, thin black gouges display
317 mean grain size of 57 μm , with a mean span of 12.8 (Fig. 7a, b).

318 The fault core hosts foliated and stretched coarse sand pods characterized by a mean
319 grain size of 428 μm and mean span of 4.3 (table 1). Foliated very fine sand displays a
320 mean grain size of 84 μm , with mean span of 5.4. Eventually, black gouges in the fault

321 core are characterized by mean grain size of 49 μm and a mean span of 11.2 (Fig. 7a, b).
322 Details on granulometric curves of undeformed and deformed sediment samples are
323 provided in the online Supplementary Material and in table 1.

324 Overall, low-displacement deformation bands induce an almost 2 times decrease of mean
325 grain size, while medium-to high-displacement bands may reach mean grain size 3 times
326 finer than the undeformed medium-fine sand. Black gouges and foliated very fine sand
327 inside the fault core are characterized by mean grain size 7 and 5 times finer than the
328 corresponding pristine medium-fine sand, respectively. Deformed sediment samples show
329 a progressive increase in span, with the highest values characterizing deformation
330 features inside the mixed zone and fault core (Fig. 7a, b).

331 While the comparison of samples in Figure 7 provides a summary of grain size data
332 through the entire fault zone, accurate analysis of grain size variability induced by
333 deformation is possible by evaluating granulometric curves of adjacent sample pairs as in
334 Figure 8 (Storti et al., 2003). To this end, representative samples of deformation bands
335 and gouges characterized by different displacement magnitudes were compared with the
336 adjacent host sediments (undeformed in the low-deformation domain, and tectonically
337 compacted foliated sand within mixed zone and fault core). In particular, a low-
338 displacement deformation band collected inside the low-deformation zone is characterized
339 by a mean grain size of 185 μm with a modal peak at 225 μm , while the undeformed
340 medium-fine sand has a mean grain size of 280 μm and a modal peak at 320 μm (Fig. 8a).
341 The shape and span of the grain size distribution curves are almost the same. Although
342 similar, the D-value of the deformation band is slightly higher compared to the undeformed
343 host sand (2.307 and 2.242, respectively) (Fig. 8b). The ratio between the number of
344 faulted vs undeformed particles points out a relative increase of particles between the
345 range from 0.4 to 240 μm in the deformation band and a decrease of coarse particles from
346 240 to 500 μm (Fig. 8c). The medium-displacement deformation band collected inside the

347 footwall damage zone is characterized by a mean grain size of 155 μm , having a modal
348 value of 225 μm , whereas the undeformed counterpart has a mean grain size of 248 μm
349 with modal value of 200 μm (Fig. 8d). The D-value shows marked differences between the
350 two samples, with the medium-displacement deformation band attesting at 2.634, while the
351 adjacent interband domain has 2.3 (Fig. 8e). The deformed domain is characterized by an
352 increase in fine particles in the range between 0.4 and 86 μm , with respect to the
353 undeformed sample, while displays a decrease of coarse particles from 86 to 1630 μm
354 (Fig. 8f). High-displacement deformation band in the footwall damage zone has a mean
355 grain size of 95 μm having slightly pronounced trimodal distribution with relative maxima at
356 0.7, 30 and 230 μm (Fig. 8g). The interband domain is characterized by mean grain size of
357 248 μm with a modal value of 200 μm . The span of the grain size distributions is different
358 with the deformation band showing a wider curve with respect to the undeformed control
359 sample. D-value of the high-displacement deformation band is 2.769, much higher than
360 the one characterizing the undeformed sand in the interband domain (2.3) (Fig. 8h). Below
361 the 65 μm threshold, the high-displacement deformation bands shows a relative increase
362 of particle number with respect to the undeformed host sand (Fig. 8i). Moving to the mixed
363 zone, the fault core of a subsidiary fault displays mean grain size of 98 μm , with a trimodal
364 distribution having relative maxima at 0.7, 29 and 160 μm . The adjacent sediment is
365 formed by foliated sand with mean grain size of 72 μm , having similar distribution to the
366 previous sample with relative maxima at 0.7, 26 and 153 μm (Fig. 8j). Span of the two
367 granulometric distributions is almost the same. The fault core of the subsidiary fault has a
368 D-value of 2.866 while for the foliated host sand is 2.776 (Fig. 8k). Inside the fault core of
369 subsidiary fault the number of particles increases in the interval between 0.3 and 6.5 μm ,
370 and from 240 to 350 μm , while it decreases from 6.5 to 240 μm (Fig. 8l). Eventually, a
371 black gouge sample inside the fault core is characterized by a mean grain size of 32 μm ,
372 with trimodal distribution having maxima at 0.6, 8 and 81 μm (Fig. 8m). The adjacent

373 sediment is composed of foliated very fine sand with a mean grain size of 78 μm and a
374 bimodal distribution with relative peaks at 0.7 and 62 μm . The D-value of black gouge is
375 substantially higher than the one calculated for the foliated very fine sand (3.191 and
376 2.747, respectively) (Fig. 8n). Black gouge is characterized by an increase in the number
377 of particles from 0.5 to 14.5 μm and from 516 to 586 μm , and by a relative decrease from
378 14.5 to 516 μm with respect to the foliated host sand (Fig. 8o).

379

380 **6. Petrophysical properties**

381 *6.1. Permeability measurements*

382 Along the footwall of the fault, *in situ* air-permeability shows a progressive decrease from
383 the low-deformation zone toward the fault core (Fig. 7c). The highest permeability is
384 recorded by medium-to fine-grained and coarse sandstone in the low-deformation domain,
385 with mean values of 5.4×10^4 and 1.4×10^5 mD, respectively (Fig. 7c). Deformation bands
386 with displacement < 1 cm, have almost half of the permeability shown by undeformed
387 sandstone (3.1×10^4 mD). In the footwall damage zone, relatively undeformed medium-
388 fine and coarse sandstones in the interband domain are characterized by mean
389 permeability of 1.2×10^4 and 5.3×10^4 mD, respectively. Permeability in these interband
390 sandstones shows a drop of at least half order of magnitude with respect to the
391 undeformed sediments. Conjugate DB₁ and DB₂ sets inside the footwall damage zone
392 have permeability spanning from 2.6×10^3 to 7.4×10^3 mD, thus causing a drop from 1 to
393 1.5 orders of magnitude (Fig. 7c). Fault core of subsidiary faults and thick clusters of
394 deformation bands are characterized by a permeability drop up to 2 orders of magnitude
395 (Fig. 7c). From the inner damage zone to the mixed zone, permeability shows an abrupt
396 decrease in foliated sand layers and in thin black gouges (mean permeability of 193 and
397 201 mD, respectively) (Fig. 7c). Black gouges in fault core have mean permeability of 245

398 mD, with 7 mD as the lowest recorded value, thus featuring an overall permeability drop of
399 3 to 4 orders of magnitude with respect to the undeformed sandstone. In the same
400 domain, foliated very fine sand and stretched very coarse sandstone recorded mean
401 permeability of 496 and 4026 mD, respectively (Fig. 7c).

402 *6.2. Two-dimensional porosity calculation*

403 Primary porosity was calculated from acquired images neglecting any secondary porosity
404 related to rare tensile micro-fractures and dissolution of fossil shells. Undeformed
405 sandstone samples, from fine-to coarse-grained, have a mean 2-D porosity of 37.6% with
406 a wide range of variation between 27.5 and 50.6% (Fig. 7d). Sediment volumes between
407 deformation bands, both in the low-deformation and in the damage zone domains
408 (interband domain), show a mean 2-D porosity of 29.7%. In the footwall damage zone,
409 deformation bands with different displacement magnitude display a wide range of porosity
410 values from 0.3 to 31.9% with a mean of 3.9% (Fig. 7d). Subsidiary faults and thick
411 clusters of deformation bands inside the inner part of the damage zone are characterized
412 by a mean porosity of 1.1%. In the footwall mixed zone, foliated sand volumes outside
413 deformation bands have a mean porosity of 2.2%, while thin black gouges reach 1% (Fig.
414 7d). Eventually, foliated coarse sand pods in the fault core display a mean porosity of
415 2.9%, while foliated very fine sand reaches 0.8%. Black gouges encompassing the master
416 fault are again characterized by very low porosity values below 1% (Fig. 7d).

417 At the micro-scale, porosity calculation performed along transects through deformation
418 bands provides more details relative to porosity distribution (Fig. 9). In particular, a strand
419 of low-displacement deformation bands has an almost symmetrical decrease of porosity
420 (porosity decrement is almost the same on both sides of the deformation band) (Fig. 9a).
421 On the contrary, a high-displacement deformation band has more pronounced asymmetry
422 of porosity decrease from side to side (Fig. 9b). In this sample, porosity shows a more

423 gradual diminishing from left to right, while on the right side the decrease is more abrupt at
424 the sharp contact with undeformed sand. Porosity values reflect the different grain size
425 distribution along the deformation band due to the development of a preferential slip
426 surface. The vast majority of deformation bands tend to localize the shear along the
427 hanging wall side, but also a few samples with localization along the footwall side were
428 documented. Eventually, the black gouge has a marked asymmetric porosity diminishing
429 approaching the preferential slip surface localized on the right side of the figure (Fig. 9c).
430 These deformation features are formed by several preferential slip zones contributing to
431 the major internal complexity with respect to deformation bands. However, also in black
432 gouges a major preferential slip zone can be identified and corresponds to the sharp
433 porosity contrast between undeformed and deformed sand (Fig. 9c). Differently to
434 deformation bands, black gouges localize strain solely along their hanging wall side.

435

436 **7. Grain shape data**

437 *7.1. Cumulative data*

438 In Figure 10 are shown the grain shape descriptors (aspect ratio, circularity and solidity)
439 versus grain size classes for deformation bands (low, medium and high-displacement),
440 black gouges and subsidiary faults. All grain shape data are reported as ratio between
441 faulted and undeformed particles, so that the following graphs show the relative increase-
442 decrease of shape parameters in comparison with the reference sandstone. The
443 undeformed reference sample used is a medium-to fine-grained sand belonging to the low-
444 deformation zone (detailed shape data of the undeformed reference sample are reported
445 in the online Supplementary Material Fig. A8). Overall, the aspect ratio of grains
446 composing the deformed domains is lower than the reference undeformed sample
447 throughout almost the entire investigated grain size interval. Thus, deformed grains tend to

448 be more equant than undeformed ones (Fig. 10a). The lowest aspect ratio values are
449 recorded in the grain size interval between 0 and 100 μm , while at coarser grain size they
450 increase approaching the undeformed reference sand. Only in the 200-250 μm interval,
451 two deformation band samples show aspect ratio values above the undeformed reference,
452 featuring an increase of particle elongation. Circularity of deformed particles is higher than
453 undeformed medium-fine sand, with only two mean values lying below the reference in the
454 200-250 μm range (Fig. 10b). Following this, deformed particles have more regular and
455 circle-like shape than grains composing the undeformed control sample. The highest
456 circularity values are recorded in the finest grain size interval (0-50 μm), with a progressive
457 decrease at coarse grain size classes (Fig. 10b). Eventually, solidity of deformed domains
458 is higher compared to the undeformed sand except for one deformation band sample in
459 the 200-250 μm grain size class (Fig. 10c). According to this, faulted particles display a
460 smoother outer surface, with less asperities than the reference sample. Highest solidity
461 values are shown in the finest grain size range (0-50 μm), while they progressively
462 diminish with increasing grain size (Fig. 10c).

463 More details are provided by the comparison of grain shape data of the representative five
464 structural deformation features taken into account. In particular, the aspect ratio values
465 show a progressive diminishing through the entire grain size range considering low,
466 medium, high-displacement deformation bands and the black gouge. The difference
467 between each dataset is more pronounced at finer grain size, while values converge in
468 coarser grain size classes (Fig. 10a). The subsidiary fault displays aspect ratio between
469 the low and medium-displacement deformation bands. Comparison of circularity between
470 single structures points out low-displacement deformation band having the lowest values,
471 while black gouge has the highest ones (Fig. 10b). Medium and high-displacement bands
472 lay in between the previously mentioned structures, with the subsidiary fault covering the
473 low-circularity interval partially overlapping with low-to-medium-displacement bands (Fig.

474 10b). As seen before for the aspect ratio, also differences in circularity are more evident in
475 the finer grain size classes, while they are less emphasized in the coarser range.
476 Eventually solidity between the five structural features displays trends similar to circularity.
477 In particular, a progressive increase of particle smoothness from low-displacement
478 deformation band to black gouge is observed, with medium-to-high-displacement bands
479 lying in between (Fig. 10c). The subsidiary fault sample is characterized by values
480 overlapping with low-and medium-displacement deformation bands. Differences between
481 each dataset are more pronounced in the fine grain size range rather than in the coarse
482 one (Fig. 10c). In summary, (i) aspect ratio of deformed particles is generally lower (more
483 equant shape) than the undeformed sample; (ii) circularity of faulted grains is higher (more
484 rounded shape) than undeformed ones; (iii) solidity is higher (smoother grains) in faulted
485 domains; (iv) the difference of shape descriptors from deformed to undeformed domains is
486 more evident with increasing displacement, except for the subsidiary fault, which seems
487 not to follow this trend.

488 For statistical analysis of the entire grain shape dataset the reader is referred to the on-line
489 Supplementary Material tables A2, A3 and A4.

490 *7.2. Quartz, Feldspar, and Lithic grain shape data*

491 Figure 11 displays the shape descriptors (aspect ratio, circularity and solidity) versus grain
492 size classes for deformation bands (low, medium and high-displacement), black gouges
493 and subsidiary faults, subdivided according to grain mineralogy (quartz, feldspar and lithic
494 fragments). All grain shape data are reported as ratio between faulted and undeformed
495 particles; the undeformed reference sample is the same medium-to fine-grained sand used
496 in Figure 10 (detailed shape data of the undeformed reference are reported in the online
497 Supplementary Material Fig. A10). As a general observation, aspect ratio of the three
498 dominant mineralogical phases is below the undeformed sandstone adopted as reference.

499 Thus, quartz, feldspar and lithic deformed grains are more equant than the undeformed
500 ones (Fig. 11a). Quartz grains have higher aspect ratio values than feldspar and lithics
501 especially in the finer (0-100 μm) and coarser (150-200 μm) grain size ranges, while the
502 difference is less evident from 100 to 150 μm (Fig. 11a). The circularity graph shows that
503 almost all plotted mean data are above the reference sample except for the quartz data
504 belonging to subsidiary fault in the 150-200 μm range. This suggests that all three
505 mineralogical species are characterized by higher circularity values than the undeformed
506 sand (Fig. 11b). Quartz has lower values compared to feldspar and lithics throughout the
507 entire grain size range. Conversely, feldspar has the highest value in the 0-50 μm grain
508 size class, while at coarser grain size is exceeded by lithic fragments (Fig. 11b). Solidity
509 graph indicates an increase of grain smoothness for quartz, feldspar and lithics in the
510 entire investigated grain size interval, except for the quartz data characterizing the
511 subsidiary fault in the 150-200 μm interval (Fig. 11c). Similarly to trends identified for
512 circularity, also solidity shows quartz having lower mean values compared to feldspar and
513 lithics. Through the observation of trends from every deformation structures it stems that
514 the decrease of aspect ratio for quartz, feldspar and lithics with respect to undeformed
515 sand is more pronounced at finer grain size. Conversely, in the coarse size range aspect
516 ratio diminishing is less marked (Fig. 11a). Increasing offset from low-displacement band
517 to black gouge is reflected by an overall wider aspect ratio difference with the undeformed
518 control sample and by a more evident difference between quartz, feldspar and lithics in the
519 fine-grained interval. Despite having the highest displacement, the subsidiary fault has
520 aspect ratio values similar to the low-displacement deformation band (Fig. 11a). Also for
521 circularity the increase of displacement is reflected in a wider difference between
522 undeformed and deformed domains and also between quartz, feldspar and lithics along
523 the same deformation structure. This difference is particularly marked in the finer grain
524 size classes (0-100 μm), while it becomes faint and less easily distinguishable in the

525 coarser interval (Fig. 11b). As pointed out before for the aspect ratio, also circularity of
526 subsidiary fault has values comparable to deformation bands with limited offset. Solidity
527 suggests trends between the three mineralogical species very similar to what described for
528 circularity, with a marked difference with respect to the undeformed sample in the fine
529 grain size classes (0-100 μm) and less pronounced in coarse interval (100-200 μm) (Fig.
530 11c). Also in this case, the subsidiary fault shows relatively low solidity values comparable
531 to low-displacement deformation bands.

532 To summarize, (i) quartz grains are generally the more elongated and angular particles; (ii)
533 feldspar grains are less elongated and more rounded than quartz; (iii) lithic fragments have
534 highly varying shape descriptors; (iv) grain shape differences between quartz, feldspar and
535 lithics generally increase with increasing displacement of deformation structures and are
536 more marked at finer grain size range. The statistical analysis of grain shape dataset is
537 provided in tables A4-A13 in the online Supplementary Material.

538

539 **8. Grain preferential orientation**

540 Grain preferential orientation was performed by calculating the angle between grain major
541 axis and a reference horizontal plane. Data presented are not differentiated according to
542 the mineralogy of grains (quartz, feldspar and lithics), so that they report the bulk
543 preferential orientation of deformed and undeformed sand.

544 Low-displacement deformation band displays a weak grain preferential alignment parallel
545 to the band direction, as highlighted by the high angular deviation from the direction of the
546 band (Fig. 12a). In medium-displacement deformation band, grains have a marked
547 preferred orientation, both parallel and at 50-60° clockwise from the direction of
548 deformation band (Fig. 12b). Grains in high-displacement deformation band are strongly
549 aligned along the band direction and the most frequent angular classes fall within 40°

550 counter-clockwise and 10° clockwise direction to the reference deformation band plane
551 (Fig. 12c). Grain preferential orientation in black gouge is well evident, with the majority of
552 grain major axes falling within a 35° counter-clockwise angular fan from the gouge layer
553 direction (Fig. 12d). Subsidiary fault has most of the grains preferentially oriented at 30-35°
554 clockwise from the fault (Fig. 12e). Increasing displacement magnitude produces a more
555 evident grain preferential orientation, with particles paralleling the direction of the
556 deformation element.

557

558 **9. Discussion**

559 *9.1. Deformation mechanisms (particulate flow followed by cataclasis)*

560 In Figure 13, are summarized the main structural, microstructural and petrophysical
561 properties of deformation features documented in the Rocca di Neto fault zone. The
562 studied fault developed at very shallow-burial depth as indicated by stratigraphic
563 constraints (Zecchin et al., 2012) and by the very weak compaction shown by the
564 undeformed high-porosity sandstone, collectively suggesting a maximum burial depth
565 below 400-500 m (Paxton et al., 2002). In this framework, deformation bands with
566 displacement < 1 cm (Fig. 3a), characterized by grain re-organization and little grain size
567 reduction, are interpreted to develop by particulate flow in highly porous sandstone (e.g.,
568 Rawling and Goodwin, 2003; Balsamo and Storti, 2010; Rodrigues and Alves da Silva,
569 2018) (Figs. 4b and 13a). Particulate flow does not obliterate the original texture of pristine
570 sandstone, but rather operates a re-organization of fabric leading to a closer packing of
571 grains and to porosity reduction, increasing contacts between particles (Antonellini et al.,
572 1994; Kaproth et al., 2010; Soliva et al., 2013; Griffiths et al., 2016) (Figs. 7d and 13a). In
573 low-displacement deformation bands within the low-deformation domain, the difference
574 between the shape descriptors of deformed and undeformed domains is less pronounced

575 compared to the other deformation structures (Fig. 10a, b, c). This line of evidence
576 supports particulate flow as the main deformation mechanism, causing very limited grain
577 fragmentation throughout all the investigated size classes. Moving toward the master fault,
578 deformation bands in the footwall damage zone show a more severe reduction of grain
579 size, even for bands with few cm of displacement (Fig. 4c, d). Grains are internally
580 fractured, indicating that cataclasis was the main deformation mechanism (Engelder, 1974;
581 Aydin and Johnson, 1978; Blenkinsop, 1991; Balsamo and Storti, 2010) (Figs. 5a, b and
582 13b, c). Grain breakage leads to a pronounced reduction of interparticle porosity (Fig. 7d),
583 due to the presence of small grain fragments filling pores (Antonellini et al., 1994; Kaproth
584 et al., 2010; Skurtveit et al., 2013; Torabi, 2014). The interpretation of a cataclastic
585 deformation mechanism is also supported by the significant difference of the shape
586 parameters of the three main mineralogical phases involved in the deformation, with quartz
587 grains resulting more elongated and angular with respect to feldspar and lithic grains (Fig.
588 11a, b, c). The difference of the shape descriptors is related to the development of grain-
589 scale fractures produced by cataclastic processes involving the high-porosity sandstone
590 (grain crushing, translation and rotation) (Balsamo and Storti, 2011; Skurtveit et al., 2013).
591 Cataclasis is even more severe in high-displacement deformation bands inside the mixed
592 zone and fault core, leading to the formation of a thin core with strongly comminute grain
593 size and an ultra fine-grained matrix (Figs. 4d and 13d). The strongest degree of cataclasis
594 is found in black gouges and in the fault core of subsidiary faults, where strain-localization
595 is testified by the occurrence of ultra-comminute layers (Engelder, 1974; Mair et al., 2002b;
596 Balsamo et al., 2014) (Figs. 4e, f and 13e, f). Microstructural observations, in conjunction
597 with grain size and porosity data, suggest that particulate flow was active for displacement
598 < 1 cm, whereas cataclasis settled for displacement > 1 cm and after a porosity loss to 5-
599 6%. As highlighted by other authors, porosity exerts a strong control upon the deformation

600 mechanism affecting porous granular materials (Flodin et al., 2003; Shipton et al., 2005;
601 Schultz et al., 2010).

602 In the investigated high-porosity sandstone, a porosity value of 5-6% can be assumed as
603 the critical threshold to switch from particulate flow to cataclasis. Below this threshold,
604 grains are forced to deform mostly via intragranular fracturing and then by abrasion during
605 rolling (Fig. 5a, b).

606 The fragmentation of grains via cataclasis, promotes the development of more equant,
607 smoother and regular shaped grains compared to the undeformed sandstone (Blenkinsop,
608 1991; Heilbronner and Keulen, 2006; Storti et al., 2007; Balsamo and Storti, 2011) (Fig.
609 11a, b, c). Grain shape data indicate that cataclasis acted selectively according to the
610 mineralogy of grains. This is evident considering the systematically higher aspect ratio and
611 lower circularity and solidity values shown by quartz with respect to feldspar, especially in
612 the finer grain size range (Fig. 11). This difference in deformation mechanism can be
613 linked to the presence of cleavages and twinning planes along the crystal structure of
614 feldspar, acting as preferential breakage surfaces (Exner and Tschegg, 2012; Nicchio et
615 al., 2018; Del Sole and Antonellini, 2019) (Figs. 5b and 14). The presence of the
616 aforementioned reticular weaknesses, promotes the development of intragranular fractures
617 during incipient cataclasis, leading to the formation of several equant small-sized clasts
618 (Antonellini et al., 1994; Kaproth et al., 2010; Balsamo and Storti, 2011) (Fig. 14b, c).
619 Quartz grains are less sensitive to the development of intragranular fractures due to the
620 lack of twinning planes and to a higher hardness compared to feldspar. This results in
621 deformation achieved mainly by grain splitting and abrasion of the asperities, and
622 subordinately by intragranular fractures, forming highly elongated finer, and more equant
623 smoothed coarse grains (cf. Balsamo and Storti, 2011) (Fig. 14d). Lithic fragments deform
624 both via intragranular, trans-granular fracturing as well as by abrasion (Fig. 14b, c).

625 However, the deformation mechanism affecting lithics vary according to grain mineralogy
626 (micas, gneiss-granitic fragments, bioclasts).

627 *9.2. Displacement-dependent cataclasis*

628 The deformation intensity in studied sub-seismic scale structures is related to the total
629 amount of displacement accommodated by each deformation element. The investigated
630 deforming structures display a different maturity of cataclastic fabric with increasing
631 displacement (Figs. 4 and 6). In particular, in low-to medium-displacement deformation
632 bands cataclasis is rather immature as testified by the slight decrease of mean grain size
633 and sorting (Figs. 7a, b and 8a-f). High-displacement deformation bands and fault core of
634 subsidiary faults accommodating higher offset are characterized by a more mature
635 cataclastic fabric as indicated by the pronounced grain size reduction and widening of
636 granulometric curves (i.e., sorting decrease) (Figs. 4d, f and 7a, b). Black gouges inside
637 the fault core are interpreted as the products of extreme cataclasis caused by strain-
638 localization, leading to the formation of thin, ultra-comminute layers (Fig. 4e). The
639 increasing cataclastic intensity with displacement can be inferred also from the shape
640 parameters of grains, in particular by evaluating the difference between quartz and
641 feldspar (Fig. 11). Pronounced cataclasis is also responsible for the development of a
642 weak foliation, imparted by the preferential alignment of grains parallel or at low-angle to
643 the orientation of the deformation bands and gouges (Cladouhos, 1999; Cashman and
644 Cashman, 2000) (Fig. 12). In summary, the higher is the accommodated displacement, the
645 strongest is the foliation with major axis of grains paralleling the direction of the
646 deformation element.

647 At the micro-scale, grain comminution is not uniform within the deformation band, but it is
648 commonly more intense near one of the boundaries. This asymmetry of grain size
649 comminution is caused by progressive localization of deformation on one side of the band

650 or gouge (Fig. 6b, c). The greater is the displacement, the stronger is the grain size
651 reduction and the asymmetry of comminution within the deformation band, up to the
652 development of a 100-200 μm -thick slip surface (Figs. 4d). We suggest that the strain-
653 localization on one side of the deformation bands could be caused by the kinematic stress
654 field active in the vicinity of the master fault (Pizzati et al., 2019). This is further confirmed
655 by the occurrence of microstructural asymmetry only inside deformation features close to
656 the master fault, where the additional stress field was stronger.

657 Field observations indicate that deformation bands, subsidiary faults and gouges in the
658 studied fault zone tend to increase their displacement approaching the master fault surface
659 (Figs. 2 and 3). This is in accordance with the increase of the maturity of cataclastic fabric
660 (Figs. 4 and 6), and also with the progressive increase of sorting-span and D-value with
661 higher displacement magnitudes (Figs. 7 and 8). Inside the mixed zone and fault core, the
662 presence of high-displacement structures (with offset exceeding bedding thickness)
663 favored also the grain-scale mixing of layers with different grain size. Tectonic mixing is a
664 common process in thinly-bedded siliciclastic successions (Heynekamp et al., 1999;
665 Rawling and Goodwin, 2006; Balsamo and Storti, 2011). In the studied fault zone, tectonic
666 mixing is testified by the anomalous coarser grain size in cores of subsidiary faults with
667 respect to the surrounding foliated very fine sand (Fig. 8j-l). A further evidence is provided
668 by the shape descriptor values that do not follow the increasing displacement trend
669 identified by the other deforming structures. This would suggest a mixing of sediment
670 volumes with different grain size concealing the real effect of the high-displacement
671 magnitude (Figs. 10 and 11).

672 In the studied fault zone, we documented deformation features showing severe cataclasis
673 even if the host sandstone was buried at very shallow depth ($< 400\text{-}500\text{ m}$) (Zecchin et al.,
674 2012). Following this, although typically favored by significant overburden, we suggest that
675 cataclastic processes in high-porosity sandstones, may occur not only in deep-burial

676 settings (2-3 Km) (Ballas et al., 2015; Fossen et al., 2017), but also at shallower depth.
677 Our data show that the onset of cataclasis depends mainly on the total displacement
678 magnitude and upon the evolution of petrophysical-textural properties of the sandstone in
679 the early stages of deformation. Following this, deep burial conditions are not strictly
680 necessary for the onset of cataclasis in high-porosity arkosic to lithic arkosic sandstones.

681 *9.3. Displacement-dependent petrophysical properties*

682 The deformation mechanism previously described causes a strong deterioration of
683 petrophysical properties of faulted sandstone, as underlined by the permeability drop
684 characterizing the most deformed domains (exceeding four orders of magnitude
685 diminishing) (Figs. 7c and 15). From cross-correlation graphs between permeability and
686 petrophysical-textural properties it is possible to verify the role of each parameter in
687 causing overall permeability decrement (Fig. 15). In particular, permeability shows a
688 progressive decrease with increasing displacement from deformation bands to black
689 gouges and subsidiary faults. Permeability vs 2-D porosity relationship describes a linear
690 decreasing trend with increasing displacement (Fig. 15a). Conversely, permeability vs
691 grain size is best fitted by a power-law function, with finer grain size (higher displacement)
692 correlating with lowest permeability values (Fig. 15b). Permeability vs sorting-span is again
693 fitted by a power-law distribution, but with negative exponent. Grain size distribution curves
694 with high span (wide curves) are related with the lowest permeability values (Fig. 15c).
695 Thus, a decrease of 2-D porosity and grain size and at the same time span increase
696 (sorting decrease) due to cataclasis in response to incremental displacement, strongly
697 affect the permeability drop of faulted sandstone. From the three graphs is evident the
698 anomalous values reported for the subsidiary fault, not following the displacement
699 relationship described by the other structural elements (Fig. 15a, b, c). This discrepancy
700 can be interpreted as a further evidence for tectonic mixing affecting deformation features

701 with displacement exceeding sedimentary bed thickness (Heynekamp et al., 1999;
702 Rawling and Goodwin, 2006). This implies that porosity as well as grain size and span
703 data are the results of deformation mechanism (cataclasis) and mixing of sediments with
704 different textural and petrophysical properties.

705 The influence of grain shape (aspect ratio, circularity and solidity) in determining the
706 permeability drop was also checked (Fig. 15d, e, f). Cumulative data indicate that lower
707 permeability values are associated with slightly lower aspect ratio (equant grains)
708 characterizing deformed particles (Fig. 15d). Deformed domains with lower permeability
709 show also higher circularity (circle-shaped grains) (Fig. 15e). Significant permeability drop
710 is associated with higher particle solidity (smoother grains) (Fig. 15f). Although shape
711 descriptors of undeformed and deformed sandstone display different values, differences
712 are not so pronounced. This can be translated in a minor role played by the development
713 of more equant, regular and smoothed particles via cataclasis to the overall permeability
714 decrease (Fig. 15d, e, f). Following this, from the shown datasets we interpret 2-D porosity,
715 grain size and sorting-span as the main drivers for permeability drop occurring with
716 increasing displacement.

717 *9.4. Implications for fluid flow*

718 The deformation mechanism previously described causes a deterioration of petrophysical
719 properties of the faulted sandstone following the increase of displacement. Even
720 deformation bands with low-displacement (< 1 cm), accommodated dominantly via
721 particulate flow, may show a permeability drop of at least half an order of magnitude (Fig.
722 16a). Deformation bands with higher displacement ($1 \text{ cm} < d < 5 \text{ cm}$), developing an
723 immature cataclastic fabric, may induce a permeability decrease up to 1.5 orders of
724 magnitude (Fig. 16b). High-displacement bands ($5 \text{ cm} < d < 10 \text{ cm}$) feature an effective
725 permeability drop from 2 to 3 orders of magnitude, due to the pronounced cataclastic fabric

726 formed via intense fragmentation followed by abrasion of grains during rolling and
727 translation (Fig. 16c). In these bands, strain-localization may occur along the boundary
728 between band and undeformed sand thus leading to a gradient of porosity and
729 permeability drop approaching the preferential slip surface (Figs. 9 and 16c). Mature
730 cataclasis affecting the core of subsidiary faults ($d > 20$ cm) and gouges ($d \sim 15$ cm)
731 causes a drop of mean permeability up to 4 orders of magnitude due to extreme grain size
732 reduction and to the highest measured span of the granulometric curves (Fig. 16d).
733 Therefore, early stage particulate flow followed by cataclasis affecting poorly lithified
734 sandstone can reduce the effective permeability up to 4 orders of magnitude even with
735 moderate displacement (10-20 cm). Following this, displacement is a key factor in
736 controlling the permeability of sub-seismic deformation structures developed in high-
737 porosity rocks, in conjunction with burial depth and stress-strain conditions (Ballas et al.,
738 2012, 2015).

739 The studied deformation features are likely to have played a barrier role toward fluids
740 orthogonal to the strike of the structural elements (Fig. 7). However, the real influence
741 upon fluid flow has to be related to the lateral continuity and three-dimensional
742 arrangement of deformation bands and gouges (Shipton et al., 2005; Sternlof et al., 2006;
743 Kolyukhin et al., 2010; Ballas et al., 2015). Moreover, lateral variations concerning
744 thickness of deformation bands can be a critical parameter in decreasing the sealing
745 potential at the scale of the single band (Rotevatn et al., 2013, 2017).

746 The presence of deformed whitish sand within deformation bands, surrounded by orange-
747 brown stained undeformed sandstone due to iron oxide precipitation, suggests an effective
748 sealing behavior even for a few cm displacement (Fig. 3a). Even though, the barrier-conduit
749 role within deformed high-porosity sandstone is not straightforward as it is in the case of
750 fully lithified rocks (Caine et al., 1996; Evans et al., 1997; Fisher et al., 2018). Whereas in
751 lithified rocks the fault core acts as an effective barrier and the damage zone as a

752 preferential conduit, in granular materials the sealing behavior may depend on the
753 hydrological conditions (Sigda and Wilson, 2003; Wilson et al., 2003; Balsamo et al.,
754 2012). In water-saturated conditions deformation bands and gouges display a barrier role,
755 while in unsaturated ones, they may act as partial conduits due to high retention time of
756 fluids within the deformed sediments (Sigda and Wilson, 2003). The Rocca di Neto fault
757 zone has a present-day barrier role (as testified by *in situ* permeability measurement) (Fig.
758 7c), while during the early stages of deformation, the partial conduit behavior is witnessed
759 by the presence of selective cementation along deformation bands and faults (Balsamo et
760 al., 2012; Pizzati et al., 2019). This change in hydrological behavior is likely related to the
761 different diagenetic environments and water-saturation conditions experienced by the fault
762 during the deformation history and basin-scale tectonic exhumation occurred since Middle
763 Pleistocene.

764 Our results could be useful to evaluate the possible compartmentalization of high-porosity
765 sandstone reservoirs deformed at shallow-burial depth, through development of sub-
766 seismic deformation structures (deformation bands and gouges). Such deformation
767 features may represent major hydraulic discontinuities even after few cm of
768 accommodated displacement.

769

770 **10. Conclusions**

771 We described the meso-scale structural features, microstructural characteristics and
772 petrophysical properties of the extensional Rocca di Neto fault zone, deforming lithic
773 arkosic to arkosic poorly lithified shoreface sandstones. Deformation occurred at shallow-
774 burial conditions (< 400-500 m) and the pristine sandstone was characterized by high
775 primary porosity. On the basis of our observations we came to the following main
776 conclusions:

777 1- The deformation mechanisms responsible for the development of deformation bands
778 are non-destructive particulate flow followed by cataclasis. Cataclasis becomes dominant
779 after porosity decrease to 5-6%, and is more intense with increasing displacement
780 eventually forming black gouges in the fault core, characterized by extreme grain size
781 reduction, poor sorting and high D-value.

782 2- Cataclasis acts differently according to the mineralogy of the deformed grains: feldspar
783 grains deform mainly by intragranular fractures leading to several equant sub-grains with
784 circular and more regular shape, while quartz grains are less affected by intragranular
785 fractures and deform by flaking of asperities producing more elongated chips. Thus, the
786 resulting quartz clasts are more elongated, less circular and less smooth with respect to
787 feldspar ones at finer grain size, while the difference is less pronounced at coarser grain
788 size range.

789 3- The intensity of cataclasis is more pronounced along deformation bands, subsidiary
790 faults and black gouges accommodating high offset. At the scale of the whole fault zone,
791 deforming structures are characterized by an increasing displacement gradient
792 approaching the master fault surface. In high-strain structural domains (mixed zone and
793 fault core) cataclasis along high-displacement structures is accompanied by tectonic
794 mixing of sediments having different grain size.

795 4- In deformation bands and gouges, the grain size is drastically reduced (7-8 times) with
796 respect to the pristine sandstone, and permeability shows drops up to 3-4 orders of
797 magnitude, in agreement with the total displacement accommodated along single
798 structures. Permeability decreases as a function of displacement, coupled with grain size
799 and porosity diminishing and span increase (sorting decrease). Conversely, evolution of

800 grain shape played a minor role in determining the magnitude of permeability drop
801 associated with deformed domains.

802 5- Cataclasis-related sub-seismic deformation structures (deformation bands and gouges)
803 developing in high-porosity sandstones are capable of locally compartmentalize reservoirs
804 deformed at shallow-burial depth. The occurrence of cataclastic processes at very shallow-
805 burial conditions is related to major extent to the evolution of petrophysical and textural
806 properties of deformed sandstone following increasing displacement magnitude.

807

808 **Acknowledgements**

809 The reviewers Eric Salomon and Conrad Childs are deeply acknowledged for the precise
810 and thorough revisions of the early version of the manuscript. The Editor Cess Passchier
811 is thanked for the careful editorial work.

812 The authors would like to thank Andrea Comelli for thin section preparation and Luca
813 Barchi (University of Parma) for support during SEM image acquisition. Cristian CavoZZi
814 (University of Parma) is thanked for technical support. Federica Pessina (University of
815 Parma) is also acknowledged for assistance during field work on the Rocca di Neto fault
816 zone and in the Crotona Basin. This work has benefited from the equipments and
817 framework of the COMP-HUB Initiative, funded by the 'Departments of Excellence'
818 program of the Italian Ministry for Education, University and Research (MIUR, 2018-2022).
819 Author contributions: Mattia Pizzati carried out field and laboratory work, data
820 interpretation, and wrote the manuscript; Fabrizio Balsamo participated to field work and
821 data interpretation, and critically revised the manuscript; Fabrizio Storti participated to data
822 interpretation, and critically revised the manuscript.

823

824 **References**

- 825 Antonellini, M., Aydin, A., 1994. Effect of faulting on fluid flow in porous sandstones:
826 petrophysical properties. *American Association of Petroleum Geologists Bulletin* 78,
827 355–377. <https://doi.org/10.1306/8D2B1B60-171E-11D7-8645000102C1865D>
- 828 Antonellini, M., Aydin, A., Pollard, D.D., 1994. Microstructure of deformation bands in
829 porous sandstones at Arches National park, Utah. *Journal of Structural Geology* 16,
830 941–959.
- 831 Antonellini, M., Petracchini, L., Billi, A., Scrocca, D., 2014. First reported occurrence of
832 deformation bands in a platform limestone, the Jurassic Calcare Massiccio Fm.,
833 northern Apennines, Italy. *Tectonophysics* 628, 85–104.
834 <https://doi.org/10.1016/j.tecto.2014.04.034>
- 835 Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006. Late
836 Pleistocene to Holocene record of changing uplift rates in southern Calabria and
837 northeastern Sicily (southern Italy, Central Mediterranean Sea). *Tectonophysics* 422,
838 23–40. <https://doi.org/10.1016/j.tecto.2006.05.003>
- 839 Aydin, A., 1978. Small faults formed as deformation bands in sandstone. *Pageoph* 116,
840 913–930.
- 841 Aydin, A., Johnson, A.M., 1983. Analysis of faulting in porous sandstones. *Journal of*
842 *Structural Geology* 5, 19–31. [https://doi.org/10.1016/0191-8141\(83\)90004-4](https://doi.org/10.1016/0191-8141(83)90004-4)
- 843 Aydin, A., Johnson, A.M., 1978. Development of faults as zones of deformation bands and
844 as slip surfaces in sandstone. *Pageoph* 116, 931–942.
- 845 Ballas, G., Fossen, H., Soliva, R., 2015. Factors controlling permeability of cataclastic
846 deformation bands and faults in porous sandstone reservoirs. *Journal of Structural*
847 *Geology* 76, 1–21. <https://doi.org/10.1016/j.jsg.2015.03.013>
- 848 Ballas, G., Soliva, R., Sizun, J., Fossen, H., Benedicto, A., 2013. Shear-enhanced
849 compaction bands formed at shallow burial conditions; implications for fluid flow
850 (Provence, France). *Journal of Structural Geology* 47, 3–15.
851 <https://doi.org/10.1016/j.jsg.2012.11.008>
- 852 Ballas, G., Soliva, R., Sizun, J.P., Benedicto, A., Cavailhes, T., Raynaud, S., 2012. The
853 importance of the degree of cataclasis in shear bands for fluid flow in porous
854 sandstone Provence, France. *AAPG Bulletin* 96, 2167–2186.
855 <https://doi.org/10.1306/04051211097>
- 856 Balsamo, F., Aldega, L., De Paola, N., Faoro, I., Storti, F., 2014. The signature and
857 mechanics of earthquake ruptures along shallow creeping faults in poorly lithified
858 sediments. *Geology* 42, 435–438. <https://doi.org/10.1130/G35272.1>
- 859 Balsamo, F., Bezerra, F.H.R., Vieira, M.M., Storti, F., 2013. Structural control on the
860 formation of iron-oxide concretions and Liesegang bands in faulted, poorly lithified
861 Cenozoic sandstones of the Paraíba Basin, Brazil. *Bulletin of the Geological Society*
862 *of America* 125, 913–931. <https://doi.org/10.1130/B30686.1>
- 863 Balsamo, F., Storti, F., 2011. Size dependent comminution, tectonic mixing and sealing
864 behavior of a “structurally oversimplified” fault zone in poorly lithified sands: Evidence
865 for a coseismic rupture? *Bulletin of the Geological Society of America* 123, 651–668.
866 <https://doi.org/10.1130/B30099.1>

- 867 Balsamo, F., Storti, F., 2010. Grain size and permeability evolution of soft-sediment
868 extensional sub-seismic and seismic fault zones in high-porosity sediments from the
869 Crotone basin, southern Apennines, Italy. *Marine and Petroleum Geology* 27, 822–
870 837. <https://doi.org/10.1016/j.marpetgeo.2009.10.016>
- 871 Balsamo, F., Storti, F., Gröcke, D., 2012. Fault-related fluid flow history in shallow marine
872 sediments from carbonate concretions, Crotone basin, south Italy. *Journal of the*
873 *Geological Society, London* 169, 613–626. <https://doi.org/10.1144/0016-76492011-109>.
874
- 875 Baud, P., Meredith, P., Townend, E., 2012. Permeability evolution during triaxial
876 compaction of an anisotropic porous sandstone. *Journal of Geophysical Research:*
877 *Solid Earth* 117, 1–23. <https://doi.org/10.1029/2012JB009176>
- 878 Bense, V.F., Gleeson, T., Loveless, S.E., Bour, O., Scibek, J., 2013. Fault zone
879 hydrogeology. *Earth-Science Reviews* 127, 171–192.
880 <https://doi.org/10.1016/j.earscirev.2013.09.008>
- 881 Bense, V.F., Van den Berg, E.H., Van Balen, R.T., 2003. Deformation mechanisms and
882 hydraulic properties of fault zones in unconsolidated sediments; the Roer Valley Rift
883 System, The Netherlands. *Hydrogeology Journal* 11, 319–332.
884 <https://doi.org/10.1007/s10040-003-0262-8>
- 885 Blenkinsop, T.G., 1991. Cataclasis and Processes of Particle Size Reduction. *Pageoph*
886 136, 59–86.
- 887 Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability
888 structure. *Geology* 24, 1025–1028. [https://doi.org/10.1130/0091-7613\(1996\)024<1025](https://doi.org/10.1130/0091-7613(1996)024<1025)
- 889 Cardozo, N., Allmendinger, R.W., 2013. Spherical projections with OXS Stereonet.
890 *Computers & Geosciences* 51, 193–205.
891 <https://doi.org/doi:10.1016/j.cageo.2012.07.021>.
- 892 Cashman, S., Cashman, K., 2000. Cataclasis and deformation-band formation in
893 unconsolidated marine terrace sand, Humboldt County, California. *Geology* 28, 111–
894 114. [https://doi.org/10.1130/0091-7613\(2000\)28<111:CADFIU>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<111:CADFIU>2.0.CO;2)
- 895 Cavailhes, T., Rotevatn, A., 2018. Deformation bands in volcanoclastic rocks – Insights
896 from the Shihtiping tuffs, Coastal Range of Taiwan. *Journal of Structural Geology* 113,
897 155–175. <https://doi.org/10.1016/j.jsg.2018.06.004>
- 898 Charalampidou, E.M., Hall, S.A., Stanchits, S., Lewis, H., Viggiani, G., 2011.
899 Characterization of shear and compaction bands in a porous sandstone deformed
900 under triaxial compression. *Tectonophysics* 503, 8–17.
901 <https://doi.org/10.1016/j.tecto.2010.09.032>
- 902 Cilona, A., Baud, P., Tondi, E., Agosta, F., Vinciguerra, S., Rustichelli, A., Spiers, C.J.,
903 2012. Deformation bands in porous carbonate grainstones: Field and laboratory
904 observations. *Journal of Structural Geology* 45, 137–157.
905 <https://doi.org/10.1016/j.jsg.2012.04.012>
- 906 Cladouhos, T.T., 1999. Shape preferred orientations of survivor grains in fault gouge.
907 *Journal of Structural Geology* 21, 419–436. [https://doi.org/10.1016/S0191-8141\(98\)00123-0](https://doi.org/10.1016/S0191-8141(98)00123-0)
908

- 909 Del Sole, L., Antonellini, M., 2019. Microstructural, petrophysical, and mechanical
 910 properties of compactive shear bands associated to calcite cement concretions in
 911 arkose sandstone. *Journal of Structural Geology* 126, 51–68.
 912 <https://doi.org/10.1016/j.jsg.2019.05.007>
- 913 Engelder, J.-T., 1974. Cataclasis and the generation of Fault Gouge. *Geological Society of
 914 America Bulletin* 85, 1515–1522. [https://doi.org/10.1130/0016-
 915 7606\(1974\)85<1515:catgof>2.0.co;2](https://doi.org/10.1130/0016-7606(1974)85<1515:catgof>2.0.co;2)
- 916 Evans, J.P., Forster, C.B., Goddard, J. V, 1997. Permeability of fault-related rocks, and
 917 implications for hydraulic structure of fault zones. *Journal of Structural Geology* 19,
 918 1393–1404.
- 919 Exner, U., Grasemann, B., 2010. Deformation bands in gravels: displacement gradients
 920 and heterogeneous strain. *Journal of the Geological Society* 167, 905–913.
 921 <https://doi.org/10.1144/0016-76492009-076>
- 922 Exner, U., Tschegg, C., 2012. Preferential cataclastic grain size reduction of feldspar in
 923 deformation bands in poorly consolidated arkosic sands. *Journal of Structural Geology*
 924 43, 63–72. <https://doi.org/10.1016/j.jsg.2012.08.005>
- 925 Ferranti, L., Santoro, E., Mazzella, M.E., Monaco, C., Morelli, D., 2009. Active
 926 transpression in the northern Calabria Apennines, southern Italy. *Tectonophysics* 476,
 927 226–251. <https://doi.org/10.1016/j.tecto.2008.11.010>
- 928 Fisher, Q.J., Haneef, J., Grattoni, C.A., Allshorn, S., Lorinczi, P., 2018. Permeability of
 929 fault rocks in siliciclastic reservoirs: Recent advances. *Marine and Petroleum Geology*
 930 91, 29–42. <https://doi.org/10.1016/j.marpetgeo.2017.12.019>
- 931 Flodin, E., Prasad, M., Aydin, A., 2003. Petrophysical constraints on deformation styles in
 932 Aztec sandstone, Southern Nevada, USA. *Pure and Applied Geophysics* 160, 1589–
 933 1610. <https://doi.org/10.1007/s00024-003-2377-1>
- 934 Folk, R.L., 1974. *Petrology of sedimentary rocks*, Hemphill Publishing Company, Austin,
 935 pp. 190. <https://doi.org/10.1017/CBO9781107415324.004>
- 936 Fossen, H., Bale, A., 2007. Deformation bands and their influence on fluid flow. *AAPG
 937 Bulletin* 91, 1685–1700. <https://doi.org/10.1306/07300706146>
- 938 Fossen, H., Soliva, R., Ballas, G., Trzaskos, B., Cavalcante, C., Schultz, R.A., 2017. A
 939 review of deformation bands in reservoir sandstones: geometries, mechanisms and
 940 distribution. *Geological Society, London, Special Publications* 459, 9–33.
 941 <https://doi.org/10.1144/SP459.4>
- 942 Friedman, M., Logan, J.M., 1973. Lüders' bands in experimentally deformed sandstone
 943 and limestone. *Bulletin of the Geological Society of America* 84, 1465–1476.
 944 [https://doi.org/10.1130/0016-7606\(1973\)84<1465:LBIEDS>2.0.CO;2](https://doi.org/10.1130/0016-7606(1973)84<1465:LBIEDS>2.0.CO;2)
- 945 Griffiths, J., Faulkner, D.R., Edwards, A.P., Worden, R.H., 2016. Deformation band
 946 development as a function of intrinsic host-rock properties in Triassic Sherwood
 947 Sandstone. *Geological Society, London, Special Publications* 435.
 948 <https://doi.org/10.1144/SP435.11>
- 949 Heilbronner, R., Keulen, N., 2006. Grain size and grain shape analysis of fault rocks.

- 950 Tectonophysics 427, 199–216. <https://doi.org/10.1016/j.tecto.2006.05.020>
- 951 Heynekamp, M.R., Goodwin, L.B., Mozley, P.S., Haneberg, W.C., 1999. Controls on Fault-
952 Zone Architecture in Poorly Lithified Sediment, Rio Grande Rift, New Mexico:
953 Implications for Fault-Zone Permeability and Fluid Flow. Haneberg, W.C., Mozley,
954 P.S., Moore, J.C., and Goodwin, L.B., Eds., *Faults and Subsurface Fluid Flow in the*
955 *Shallow Crust: Washington D.C., USA, Geophysical Monograph 113, American*
956 *Geophysical Union. 27–49.*
- 957 Kaproth, B.M., Cashman, S.M., Marone, C., 2010. Deformation band formation and
958 strength evolution in unlithified sand: The role of grain breakage. *Journal of*
959 *Geophysical Research: Solid Earth* 115, 1–11. <https://doi.org/10.1029/2010JB007406>
- 960 Knott, S.D., Turco, E., 1991. Late Cenozoic kinematics of the Calabrian Arc, southern Italy.
961 *Tectonics* 10, 1164–1172. <https://doi.org/10.1029/91TC01535>
- 962 Kolyukhin, D., Schueller, S., Espedal, M.S., Fossen, H., 2010. Deformation band
963 populations in fault damage zone-impact on fluid flow. *Computational Geosciences*
964 14, 231–248. <https://doi.org/10.1007/s10596-009-9148-8>
- 965 Kristensen, M.B., Childs, C., Olesen, N., Korstgård, J.A., 2013. The microstructure and
966 internal architecture of shear bands in sand-clay sequences. *Journal of Structural*
967 *Geology* 46, 129–141. <https://doi.org/10.1016/j.jsg.2012.09.015>
- 968 Main, I., Kwon, O., Ngwenya, B., Elphick, S., 2000. Fault sealing during deformation band
969 growth in porous sandstone. *Geology* 28, 1131–1134.
- 970 Mair, K., Elphick, S., Main, I., 2002a. Influence of confining pressure on the mechanical
971 and structural evolution of laboratory deformation bands. *Geophysical Research*
972 *Letters* 29, 49-1-49–4. <https://doi.org/10.1029/2001GL013964>
- 973 Mair, K., Frye, K.M., Marone, C., 2002b. Influence of grain characteristics on the friction of
974 granular shear zones. *Journal of Geophysical Research: Solid Earth* 107, 1–9.
975 <https://doi.org/10.1029/2001JB000516>
- 976 Mair, K., Main, I., Elphick, S., 2000. Sequential growth of deformation bands in the
977 laboratory. *Journal of Structural Geology* 22, 25–42. [https://doi.org/10.1016/S0191-8141\(99\)00124-8](https://doi.org/10.1016/S0191-8141(99)00124-8)
- 979 Massari, F., Prosser, G., 2013. Late Cenozoic tectono-stratigraphic sequences of the
980 Croton Basin: Insights on the geodynamic history of the Calabrian arc and
981 Tyrrhenian Sea. *Basin Research* 25, 26–51. <https://doi.org/10.1111/j.1365-2117.2012.00549.x>
- 983 Nicchio, M.A., Nogueira, F.C.C., Balsamo, F., Souza, J.A.B., Carvalho, B.R.B.M., Bezerra,
984 F.H.R., 2018. Development of cataclastic foliation in deformation bands in feldspar-
985 rich conglomerates of the Rio do Peixe Basin, NE Brazil. *Journal of Structural*
986 *Geology* 107, 132–141. <https://doi.org/10.1016/j.jsg.2017.12.013>
- 987 Nicol, A., Childs, C., Walsh, J.J., Schafer, K.W., 2013. A geometric model for the formation
988 of deformation band clusters. *Journal of Structural Geology* 55, 21–33.
989 <https://doi.org/10.1016/j.jsg.2013.07.004>
- 990 Ogilvie, S.R., Glover, P.W.J., 2001. The petrophysical properties of deformation bands in

- 991 relation to their microstructure. *Earth and Planetary Science Letters* 193, 129–142.
992 [https://doi.org/10.1016/S0012-821X\(01\)00492-7](https://doi.org/10.1016/S0012-821X(01)00492-7)
- 993 Olsson, W.A., 2000. Origin of Lüders' bands in deformed rock. *Journal of Geophysical*
994 *Research* 105, 5931–5938. <https://doi.org/10.3109/17453674.2010.492765>
- 995 Parnell, J., Watt, G.R., Middleton, D., Kelly, J., Baron, M., 2004. Deformation Band Control
996 on Hydrocarbon Migration. *Journal of Sedimentary Research* 74, 552–560.
997 <https://doi.org/10.1306/121703740552>
- 998 Paxton, S.T., Szabo, J.O., Ajdukiewicz, J.M., Klimentidis, R.E., 2002. Construction of an
999 intergranular volume compaction curve for evaluating and predicting compaction and
1000 porosity loss in rigid-grain sandstone reservoirs. *AAPG Bulletin* 86, 2047–2067.
1001 <https://doi.org/10.1306/61eeddfa-173e-11d7-8645000102c1865d>
- 1002 Philit, S., Soliva, R., Castilla, R., Ballas, G., Taillefer, A., 2018. Clusters of cataclastic
1003 deformation bands in porous sandstones. *Journal of Structural Geology* 114, 235–
1004 250. <https://doi.org/10.1016/j.jsg.2018.04.013>
- 1005 Pizzati, M., Balsamo, F., Storti, F., Iacumin, P., 2019. Physical and chemical strain-
1006 hardening during faulting in poorly lithified sandstone: The role of kinematic stress
1007 field and selective cementation. *GSA Bulletin* 1–18. <https://doi.org/10.1130/b35296.1>
- 1008 Rawling, G.C., Goodwin, L.B., 2006. Structural record of the mechanical evolution of
1009 mixed zones in faulted poorly lithified sediments, Rio Grande rift, New Mexico, USA.
1010 *Journal of Structural Geology* 28, 1623–1639.
1011 <https://doi.org/10.1016/j.jsg.2006.06.008>
- 1012 Rawling, G.C., Goodwin, L.B., 2003. Cataclasis and particulate flow in faulted, poorly
1013 lithified sediments. *Journal of Structural Geology* 25, 317–331.
1014 [https://doi.org/10.1016/S0191-8141\(02\)00041-X](https://doi.org/10.1016/S0191-8141(02)00041-X)
- 1015 Reitz, M.A., Seeber, L., 2012. Arc-parallel strain in a short rollback-subduction system:
1016 The structural evolution of the Crotone basin (northeastern Calabria, southern Italy).
1017 *Tectonics* 31, 1–23. <https://doi.org/10.1029/2011TC003031>
- 1018 Robert, R., Robion, P., Souloumiac, P., David, C., Sallet, E., 2018. Deformation bands,
1019 early markers of tectonic activity in front of a fold-and-thrust belt: Example from the
1020 Tremp-Graus basin, southern Pyrenees, Spain. *Journal of Structural Geology* 110,
1021 65–85. <https://doi.org/10.1016/j.jsg.2018.02.012>
- 1022 Rodrigues, R. de S., Alves da Silva, F.C., 2018. Deformation bands and associated
1023 structures in the Tucano Basin, NE Brazil: A multiscale analysis. *Marine and*
1024 *Petroleum Geology* 96, 202–213. <https://doi.org/10.1016/j.marpetgeo.2018.05.035>
- 1025 Rotevatn, A., Fossmark, H.S., Bastesen, E., Thorsheim, E., Torabi, A., 2017. Do
1026 deformation bands matter for flow? Insights from permeability measurements and flow
1027 simulations in porous carbonate rocks. *Petroleum Geoscience* 23, 104–119.
1028 <https://doi.org/10.1144/petgeo2016-038>
- 1029 Rotevatn, A., Sandve, T.H., Keilegavlen, E., Kolyukhin, D., Fossen, H., 2013. Deformation
1030 bands and their impact on fluid flow in sandstone reservoirs: The role of natural
1031 thickness variations. *Geofluids* 13, 359–371. <https://doi.org/10.1111/gfl.12030>

- 1032 Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of
1033 image analysis. *Nature Methods* 9, 671–675. <https://doi.org/10.1038/nmeth.2089>
- 1034 Schultz, R.A., Fossen, H., 2002. Displacement-length scaling in three dimensions: The
1035 importance of aspect ratio and application to deformation bands. *Journal of Structural*
1036 *Geology* 24, 1389–1411. [https://doi.org/10.1016/S0191-8141\(01\)00146-8](https://doi.org/10.1016/S0191-8141(01)00146-8)
- 1037 Schultz, R.A., Okubo, C.H., Fossen, H., 2010. Porosity and grain size controls on
1038 compaction band formation in Jurassic Navajo Sandstone. *Geophysical Research*
1039 *Letters* 37, 1–5. <https://doi.org/10.1029/2010GL044909>
- 1040 Schultz, R.A., Soliva, R., Fossen, H., Okubo, C.H., Reeves, D.M., 2008. Dependence of
1041 displacement-length scaling relations for fractures and deformation bands on the
1042 volumetric changes across them. *Journal of Structural Geology* 30, 1405–1411.
1043 <https://doi.org/10.1016/j.jsg.2008.08.001>
- 1044 Shipton, Z.K., Evans, J.P., Thompson, L.B., 2005. The geometry and thickness of
1045 deformation-band fault core and its influence on sealing characteristics of
1046 deformation-band fault zones. *Aapg Memoir* 85, 181–195.
1047 <https://doi.org/10.1306/1033723M853135>
- 1048 Sibson, R.H., 1977. Fault rocks and fault mechanisms. *Journal of the Geological Society of*
1049 *London* 133, 191–213.
- 1050 Sigda, J.M., Wilson, J.L., 2003. Are faults preferential flow paths through semiarid and arid
1051 vadose zones? *Water Resources Research* 39, 1–14.
1052 <https://doi.org/10.1029/2002WR001406>
- 1053 Skurtveit, E., Torabi, A., Gabrielsen, R.H., Zoback, M.D., 2013. Experimental investigation
1054 of deformation mechanisms during shear-enhanced compaction in poorly lithified
1055 sandstone and sand. *Journal of Geophysical Research: Solid Earth* 118, 4083–4100.
1056 <https://doi.org/10.1002/jgrb.50342>
- 1057 Soliva, R., Ballas, G., Fossen, H., Philit, S., 2016. Tectonic regime controls clustering of
1058 deformation bands in porous sandstone. *Geology* 44, 423–426.
1059 <https://doi.org/10.1130/G37585.1>
- 1060 Soliva, R., Schultz, R.A., Ballas, G., Taboada, A., Wibberley, C., Sallet, E., Benedicto, A.,
1061 2013. A model of strain localization in porous sandstone as a function of tectonic
1062 setting, burial and material properties; new insight from Provence (southern France).
1063 *Journal of Structural Geology* 49, 50–63. <https://doi.org/10.1016/j.jsg.2012.11.011>
- 1064 Sternlof, K.R., Karimi-Fard, M., Pollard, D.D., Durlofsky, L.J., 2006. Flow and transport
1065 effects of compaction bands in sandstone at scales relevant to aquifer and reservoir
1066 management. *Water Resources Research* 42, 1–16.
1067 <https://doi.org/10.1029/2005WR004664>
- 1068 Storti, F., Balsamo, F., 2010. Particle size distributions by laser diffraction: sensitivity of
1069 granular matter strength to analytical operating procedures. *Solid Earth* 1, 25–48.
1070 <https://doi.org/10.5194/se-1-25-2010>
- 1071 Storti, F., Balsamo, F., Salvini, F., 2007. Particle shape evolution in natural carbonate
1072 granular wear material. *Terra Nova* 19, 344–352. <https://doi.org/10.1111/j.1365-3121.2007.00758.x>

- 1074 Storti, F., Billi, A., Salvini, F., 2003. Particle size distributions in natural carbonate fault
1075 rocks: Insights for non-self-similar cataclasis. *Earth and Planetary Science Letters*
1076 206, 173–186. [https://doi.org/10.1016/S0012-821X\(02\)01077-4](https://doi.org/10.1016/S0012-821X(02)01077-4)
- 1077 Tavani, S., Vitale, S., Grifa, C., Iannace, A., Parente, M., Mazzoli, S., 2016. Introducing
1078 dolomite seams: Hybrid compaction-solution bands in dolomitic limestones. *Terra*
1079 *Nova* 28, 195–201. <https://doi.org/10.1111/ter.12210>
- 1080 Taylor, L.W., Pollard, D.D., 2000. Estimation of in situ permeability of deformation bands in
1081 porous sandstone, Valley of Fire, Nevada. *Water Resources Research* 36, 2595–
1082 2606.
- 1083 Torabi, A., 2014. Cataclastic bands in immature and poorly lithified sandstone, examples
1084 from Corsica, France. *Tectonophysics* 630, 91–102.
1085 <https://doi.org/10.1016/j.tecto.2014.05.014>
- 1086 Torabi, A., Fossen, H., 2009. Spatial variation of microstructure and petrophysical
1087 properties along deformation bands in reservoir sandstones. *AAPG Bulletin* 93, 919–
1088 938. <https://doi.org/10.1306/03270908161>
- 1089 Van Dijk, J.P., 1994. Late Neogene kinematics of intra-arc oblique shear zones: The
1090 Petilia-Rizzuto Fault Zone (Calabrian Arc, Central Mediterranean). *Tectonics* 13,
1091 1201–1230. <https://doi.org/10.1029/93TC03551>
- 1092 Van Dijk, J.P., Bello, M., Brancaleoni, G.P., Cantarella, G., Costa, V., Frixia, A., Golfetto,
1093 F., Merlini, S., Riva, M., Torricelli, S., Toscano, C., Zerilli, A., 2000. A regional
1094 structural model for the northern sector of the Calabrian Arc (southern Italy).
1095 *Tectonophysics* 324, 267–320. [https://doi.org/10.1016/S0040-1951\(00\)00139-6](https://doi.org/10.1016/S0040-1951(00)00139-6)
- 1096 Van Dijk, J.P., Scheepers, P.J.J., 1995. Neotectonic rotations in the Calabrian Arc;
1097 implications for a Pliocene-Recent geodynamic scenario for the Central
1098 Mediterranean. *Earth Science Reviews* 39, 207–246. [https://doi.org/10.1016/0012-8252\(95\)00009-7](https://doi.org/10.1016/0012-8252(95)00009-7)
- 1100 Wilson, J.E., Goodwin, L.B., Lewis, C.J., 2003. Deformation bands in nonwelded
1101 ignimbrites: Petrophysical controls on fault-zone deformation and evidence of
1102 preferential fluid flow. *Geology* 31, 837–840. <https://doi.org/10.1130/G19667R.1>
- 1103 Zecchin, M., Caffau, M., Civile, D., Critelli, S., Di Stefano, A., Maniscalco, R., Muto, F.,
1104 Sturiale, G., Roda, C., 2012. The Plio-Pleistocene evolution of the Crotona Basin
1105 (southern Italy): Interplay between sedimentation, tectonics and eustasy in the frame
1106 of Calabrian Arc migration. *Earth-Science Reviews* 115, 273–303.
1107 <https://doi.org/10.1016/j.earscirev.2012.10.005>
- 1108 Zecchin, M., Massari, F., Mellere, D., Prosser, G., 2004. Anatomy and evolution of a
1109 Mediterranean-type fault bounded basin: The Lower Pliocene of the northern Crotona
1110 Basin (Southern Italy). *Basin Research* 16, 117–143. <https://doi.org/10.1111/j.1365-2117.2004.00225.x>
- 1112 Zecchin, M., Massari, F., Mellere, D., Prosser, G., 2003. Architectural styles of prograding
1113 wedges in a tectonically active setting, Crotona Basin, Southern Italy. *Journal of the*
1114 *Geological Society* 160, 863–880. <https://doi.org/10.1144/0016-764902-099>
- 1115

1116 **Figure captions**

1117 **Fig. 1.** (a) Geographic position of the Crotona Basin in the framework of the Southern
1118 Apennine orogenic belt and Calabrian Arc. The thinly dotted line marks the landward limit
1119 of the on-shore portion of the Crotona Basin. (b) Simplified geological map of the Crotona
1120 Basin with the position of the study area along the extensional fault system affecting the
1121 middle sector of the basin (modified after Zecchin et al., 2003). (c) Detailed geological
1122 cross-section of the study area reporting the position of the Rocca di Neto fault zone
1123 (redrawn after Balsamo et al., 2012). The trace of the cross-section is indicated by the
1124 black and white star in Fig. 1b. ATB, Apennine thrust belt; CA, Calabrian Arc; CAW,
1125 Calabrian accretionary wedge; CB, Crotona Basin.

1126 **Fig. 2.** Architecture and structural data of the studied fault zone (adapted from Pizzati et
1127 al., 2019). (a) Detailed geological cross-section through the footwall of the Rocca di Neto
1128 fault, developing inside the Early Pleistocene Scandale poorly lithified sandstone. The
1129 hanging wall is almost completely covered by vegetation and debris and hosts the Middle
1130 Pleistocene Cutro Clay. The blue dots along the fault zone represent the 68 permeability
1131 and grain size sampling-measuring sites. Dotted rectangles report the exact position of the
1132 photographs shown in Fig. 3. (b) Cumulative structural data of faults and deformation
1133 bands also reporting the extensional slickenlines (Schmidt equal area, lower hemisphere
1134 projection). The three mean planes of the identified deformation band sets are calculated
1135 from the contour of poles to deformation bands. Stereonets were realized with
1136 Allmendinger's "*Stereonet 10.0 software*" (Cardozo and Allmendinger, 2013). (c) Sketch
1137 illustrating the most recurrent deformation structures along the studied fault zone. DB₁,
1138 synthetic high-angle deformation band; DB₂, antithetic low-angle deformation band; DB_{//},
1139 fault-parallel deformation band; SF, subsidiary fault; MF, master fault; FMZ, footwall mixed

1140 zone; FC, fault core; c.i., contouring interval; n, number of measured faults and
1141 deformation bands

1142 **Fig. 3.** Outcrop details of the main deformation elements. (a) Low-displacement
1143 deformation band ($d < 1$ cm), inside the low-deformation domain. See the whitish color of
1144 deformed sandstone within the band contrasting with the marked orange-colored oxidation
1145 front abutting at the contact with the outer part of the band (black arrows). (b) Conjugate
1146 deformation bands characterizing the footwall damage zone of the fault, organized in two
1147 distinct sets, synthetic high-angle (DB_1) and antithetic low-angle (DB_2) with respect to the
1148 master fault. A third set is composed of deformation bands parallel to subsidiary faults
1149 ($DB_{//}$). See the coin in the top left corner of the image for scale. (c) High-strain deformation
1150 band surrounding a subsidiary fault hosted at the boundary between the footwall damage
1151 zone and the mixed zone. The fault is selectively cemented via precipitation of calcite
1152 cement (CC) (see the coin for scale). (d) Black gouges inside the fault core encased by
1153 mixed coarse and fine foliated sand (pencil for scale). DB_1 , synthetic high-angle
1154 deformation band; DB_2 , antithetic low-angle deformation band; $DB_{//}$, fault-parallel
1155 deformation band; CC, carbonate concretion.

1156 **Fig. 4.** (a) Ternary Quartz-Feldspar-Lithics diagram showing the modal composition of the
1157 pristine sandstone, following the classification of Folk (1974). Sediment composition was
1158 measured on 35 different petrographic images evaluating the percentage of the dominant
1159 mineralogical phases. Plane-polarized photomicrographs of microstructural features of
1160 deformation bands and gouges. (b) Low-displacement fault-parallel deformation band
1161 within the low-deformation zone showing grain re-orientation and limited fragmentation. (c)
1162 Fault-parallel deformation band ($DB_{//}$) within the footwall damage zone displaying
1163 pronounced grain size reduction. Coarse grains are surrounded by a fine-grained light-
1164 brown matrix formed by highly comminute fragments. (d) High-displacement fault-parallel

1165 deformation band close to the master fault, with a well developed ultra-comminute central
1166 core showing brownish matrix and an outer part with less pronounced grain size reduction.
1167 Tiny tensile fractures may develop both parallel and inclined to the band direction (white
1168 arrows). (e) Thin black gouge with severe comminution of grains in localized shear zone
1169 and S-C type structures imparted by the alignment of survivor grains and clay minerals. (f)
1170 Fault core of a subsidiary fault with cataclastic fabric, given by highly heterogeneous grain
1171 size distribution and poor sorting. DB, deformation band; Q, quartz; F, K-feldspar; L, lithic
1172 fragment.

1173 **Fig. 5.** Detailed plane-polarized photomicrographs of the grain-scale deformation features.
1174 (a) Pervasive crushing of lithic fragments and feldspar grains by intragranular and trans-
1175 granular fractures, in the outer part of a low-displacement band. Porosity of this sample is
1176 still high due to the lack of fine-grained matrix produced after severe grain crushing
1177 following higher displacement magnitude. (b) Details of intragranular fractures affecting
1178 feldspar, developed along crystal twinning planes, and flaking of asperities characterizing
1179 quartz grains. Pores are partially filled by a fine-grained matrix formed by quartz chips and
1180 feldspar fragments. (c) Oversized survivor feldspar grain in a medium-displacement band.
1181 The brown matrix is composed of fine-grained quartz, feldspar and calcite flakes. (d)
1182 Survivor grains of quartz inside a high-displacement deformation band, are not affected by
1183 fracturing or flaking. Qz, quartz; K-f, K-feldspar; L, lithic fragment; P, pore space.

1184 **Fig. 6.** Back-scattered SEM photomicrographs of deformation bands and gouges. (a)
1185 Medium-displacement deformation band with grains, especially feldspar, affected by
1186 intragranular fractures in its outer part (white arrows). Conversely, inside the deformation
1187 band itself grains rarely display fractures. (b) High-displacement deformation band close to
1188 the fault core, displaying a central core with pronounced grain size reduction, developing a
1189 slip surface on one side of the core. Grain size reduction has a decreasing gradient from

1190 the slip surface toward the other side of the band. This sample was selectively cemented
1191 by calcite precipitation during progressive deformation. (c) Black gouge characterized by
1192 extreme comminution along the slip zone and by a gradient of grain size reduction moving
1193 away from it. Black gouge samples are often characterized by slip localization along the
1194 hanging wall side. Qz, quartz; K-f, K-feldspar; L, lithic fragment; P, pore space; C, calcite
1195 cement; M, biotite mica; SS, slip surface.

1196 **Fig. 7.** Inter-quartile box-whisker plots of petrophysical properties of the most recurrent
1197 lithologies and deformation elements throughout the fault zone. (a) Mean grain size
1198 obtained from the analyses performed with the laser granulometer. (b) Sorting-span of the
1199 grain size distribution curves. (c) *In situ* air-permeability values measured with the Tiny
1200 Perm II permeameter. (d) Two-dimensional porosity calculation from image analysis of thin
1201 section photomicrographs. LDZ, low-deformation zone; FDZ, footwall damage zone; FMZ,
1202 footwall mixed zone; FC, fault core; DB₁, synthetic high-angle deformation band; DB₂,
1203 antithetic low-angle deformation band; n, number of measurements or analyses.

1204 **Fig. 8.** Comparison of grain size distribution curves, D-value (fractal dimension) and ratio
1205 of faulted vs undeformed particles between sample pairs representative of the most
1206 recurrent deformation features. Sample pairs were selected to directly compare deformed
1207 structures with the surrounding host sediments. D-value provides details concerning the
1208 cumulative particle number, indicating the number of fine vs coarse grains through a factor
1209 describing the slope of the power-law function fitting data distribution. Ratio of particle
1210 number between faulted and undeformed domains is useful to evaluate the relative
1211 increase or decrease of particles in a specific grain size range. Red color is used to
1212 distinguish deformed domains, while undeformed ones are reported in blue. (a, b, c) Low-
1213 displacement deformation band vs undeformed medium-fine sand inside the low-
1214 deformation zone. (d, e, f) Medium-displacement deformation band vs undeformed

1215 medium-fine sand inside the footwall damage zone. (g, h, i) High-displacement
1216 deformation band vs undeformed medium-fine sand inside the footwall damage zone. (j, k,
1217 l) Fault core of subsidiary fault vs foliated very fine sand inside the footwall mixed zone.
1218 (m, n, o) Black gouge vs foliated very fine sand inside the fault core; GSD, grain size
1219 distribution; DB, deformation band; Φ , mean grain size; d, displacement.

1220 **Fig. 9.** Plane-polarized photo-mosaics reporting the porosity variation across low-
1221 displacement band (a), medium-displacement band (b) and black gouge (c). Two-
1222 dimensional porosity is reported on profile crossing the entire length of the structural
1223 element as mean percentage calculated from the areas delimited by white dotted lines
1224 throughout the deformation structures.

1225 **Fig. 10.** Grain shape analysis performed on cumulative data of the most representative
1226 deformation features: low, medium, high-displacement deformation bands, fault core of
1227 subsidiary fault and black gouge. Grains are described using three shape descriptors,
1228 aspect ratio (a), circularity (b) and solidity (c). Symbols represent mean values of the
1229 shape parameters plotted as ratio between the faulted and undeformed samples, to ease
1230 the recognition of differences and similarities between the five datasets. All data are
1231 subdivided in five distinct grain size classes, 50 μm each. Complete datasets are provided
1232 in the online Supplementary material Figs. A7 and A8, together with data regarding the
1233 undeformed medium-fine sand adopted as reference and statistical analysis. d,
1234 displacement; n, number of grains traced and analyzed via image analysis.

1235 **Fig. 11.** Grain shape analysis performed on the three most recurred minerals (quartz,
1236 feldspar and lithic fragments) in low, medium, high-displacement deformation bands, fault
1237 core of subsidiary fault and black gouge. Grains are described using three shape
1238 descriptors, aspect ratio (a), circularity (b) and solidity (c). Symbols represent mean values

1239 of the shape parameters plotted as ratio between the faulted and undeformed samples, to
1240 ease the recognition of differences and similarities between the five datasets. All data are
1241 subdivided in four distinct grain size classes, 50 μm each; the coarser grain size class from
1242 200 to 250 μm was omitted because of the limited number of data unable to provide
1243 statistical robustness. Complete datasets are provided in the online Supplementary
1244 material Figs. A9 and A10, together with data regarding the undeformed medium-fine sand
1245 adopted as reference and statistical analysis. Qz, quartz; K-f, feldspar; L, lithic fragment; d,
1246 displacement; n, number of grains traced and analyzed via image analysis.

1247 **Fig. 12.** Half-rose plots of the preferential orientation of grains according to the angle
1248 between the major axis and a horizontal reference plane. Undeformed control samples are
1249 on the left side (green diagrams), while deformed counterparts are on the right side of the
1250 figure (red diagrams). Preferential orientation for low-displacement (a), medium-
1251 displacement (b), high-displacement deformation band (c), black gouge (d) and subsidiary
1252 fault (e). Black dotted lines indicate the orientation of the deformation band, gouge or fault
1253 on thin section. d, displacement; n, number of grains.

1254 **Fig. 13.** Microstructural features according to the identified deformation mechanism. (a)
1255 Inside the low-deformation zone and the outer damage zone, deformation bands
1256 accommodated small-scale displacement (typically < 5 cm). Along these structures
1257 deformation is mainly achieved via particulate flow with fabric re-organization and
1258 negligible grain fragmentation. This causes a decrease of porosity from 37% of the pristine
1259 sandstone to 5-7% within deformation bands. (b) In the outer footwall damage zone,
1260 higher displacement along deformation bands forced grains, especially feldspar, to break
1261 along crystal weaknesses such as twinning planes. Quartz is less affected by
1262 fragmentation via intragranular fracturing and deforms mainly by flaking and chipping of
1263 the asperities along the outer surface. (c) Inside the footwall damage zone, fault-parallel

1264 deformation bands with displacement above 5 cm, are characterized by an immature
1265 cataclastic fabric, with grain size reduction and sorting diminishing. (d) High-displacement
1266 deformation bands may develop an inner core with severe grain size reduction, leading to
1267 the formation of a brownish matrix composed of crushed feldspar and calcite grains. To
1268 the outer part of the band grain size reduction is less pronounced. Eventually, within the
1269 mixed zone and fault core the most deformed end-members are located, with subsidiary
1270 faults (e) displaying an asymmetric structure with a slip surface and a decreasing gradient
1271 of grain size reduction moving away from it. Within the fault core, black gouges (f) display
1272 extreme grain crushing leading to the formation of ultra-comminute thin layers, encased by
1273 less deformed sand arranged in S-C arrays. The deformation mechanism described above
1274 is able to reduce the permeability up to 3.5-4 orders of magnitude with respect to the
1275 pristine high-porosity sandstone. K_{av} , average permeability; SS, slip surface; d,
1276 displacement.

1277 **Fig. 14.** Grain-scale deformation mechanism. (a) Undeformed high-porosity sand. (b) Early
1278 deformation with compaction leading to intragranular crushing of feldspar and flaking of
1279 coarser quartz grains. Lithic fragments are affected by trans-granular as well as
1280 intragranular fractures. (c) With progressive deformation, crushing of feldspar produces
1281 sub-equant particles, while flakes of quartz grains display highly elongated shape with
1282 angular borders. (d) In the final stage of deformation, cataclasis forms angular fine-grained
1283 quartz flakes and equant-smooth fine-grained feldspar clasts. The oversized-survivor
1284 quartz and feldspar clasts are more equant and display smooth shape. Qz, quartz; K-f,
1285 feldspar; L, lithic grain; P, pore space.

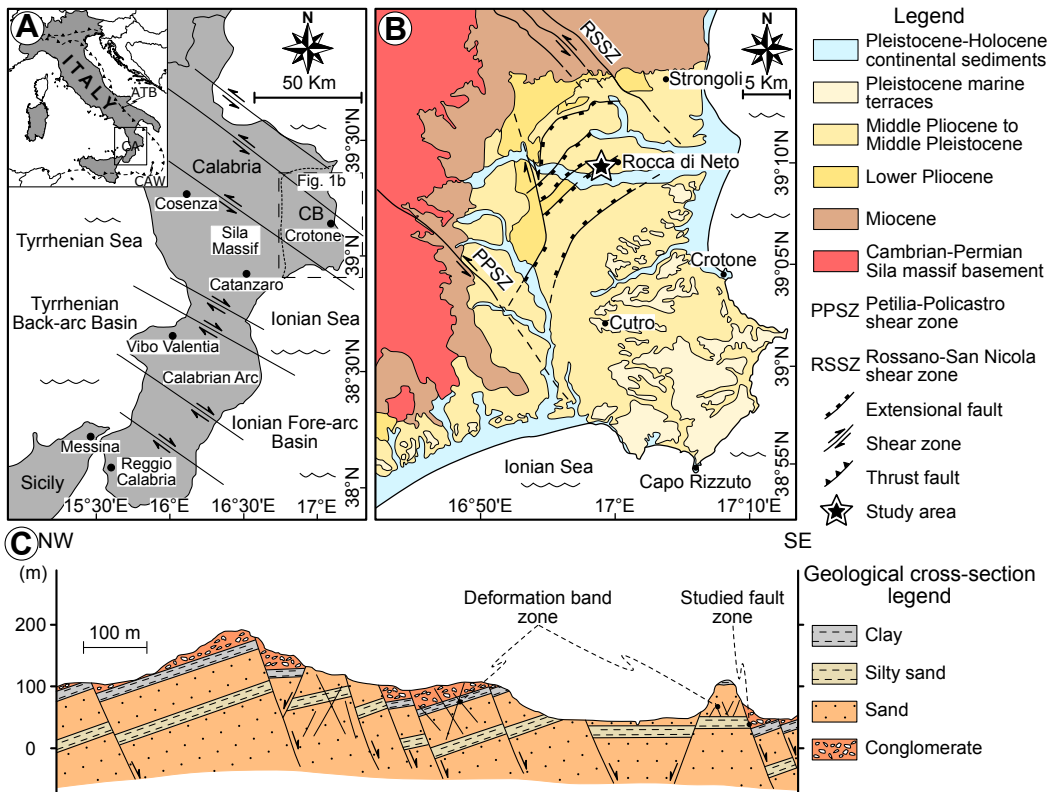
1286 **Fig. 15.** Relationships between permeability ratio of faulted and undeformed sediments
1287 with petrophysical properties and shape descriptors. (a) Permeability ratio vs 2-D porosity
1288 calculated on thin section. (b) Permeability ratio vs mean grain size measured by laser

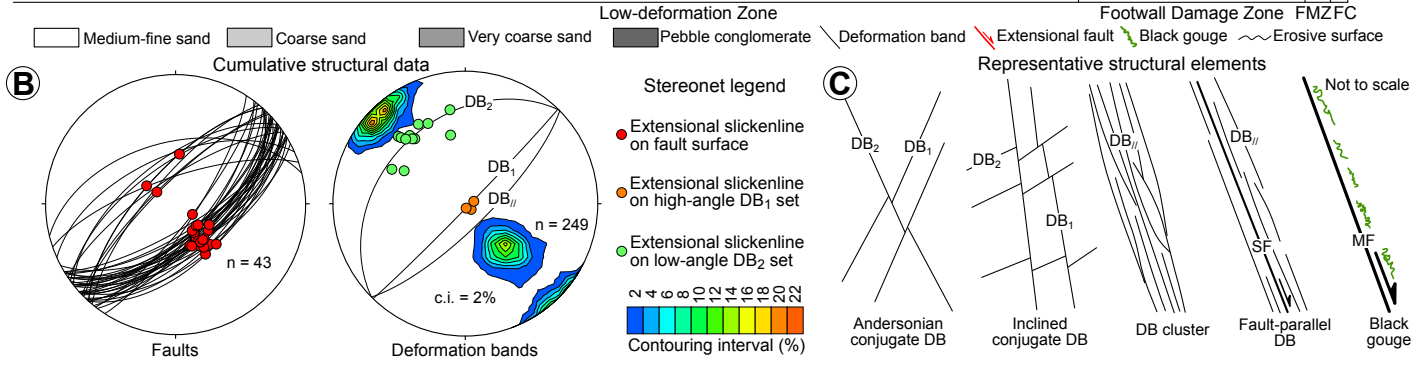
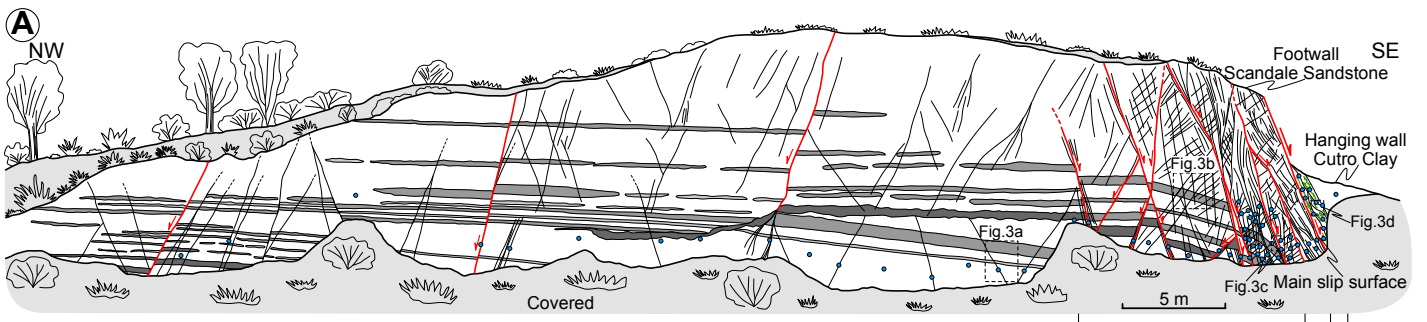
1289 diffraction. (c) Permeability ratio vs mean sorting-span gained from laser diffraction
1290 analysis. (d) Permeability ratio vs grain aspect ratio from cumulative data. (e) Permeability
1291 ratio vs grain circularity from cumulative data. (f) Permeability ratio vs grain solidity from
1292 cumulative data. The reference permeability was assumed as a mean of all permeability
1293 measurements on the undeformed sandstone outside the fault zone. Error bars represent
1294 the standard deviation associated with datasets. d, displacement; n, number of
1295 measurements, analysis and grains traced on thin section.

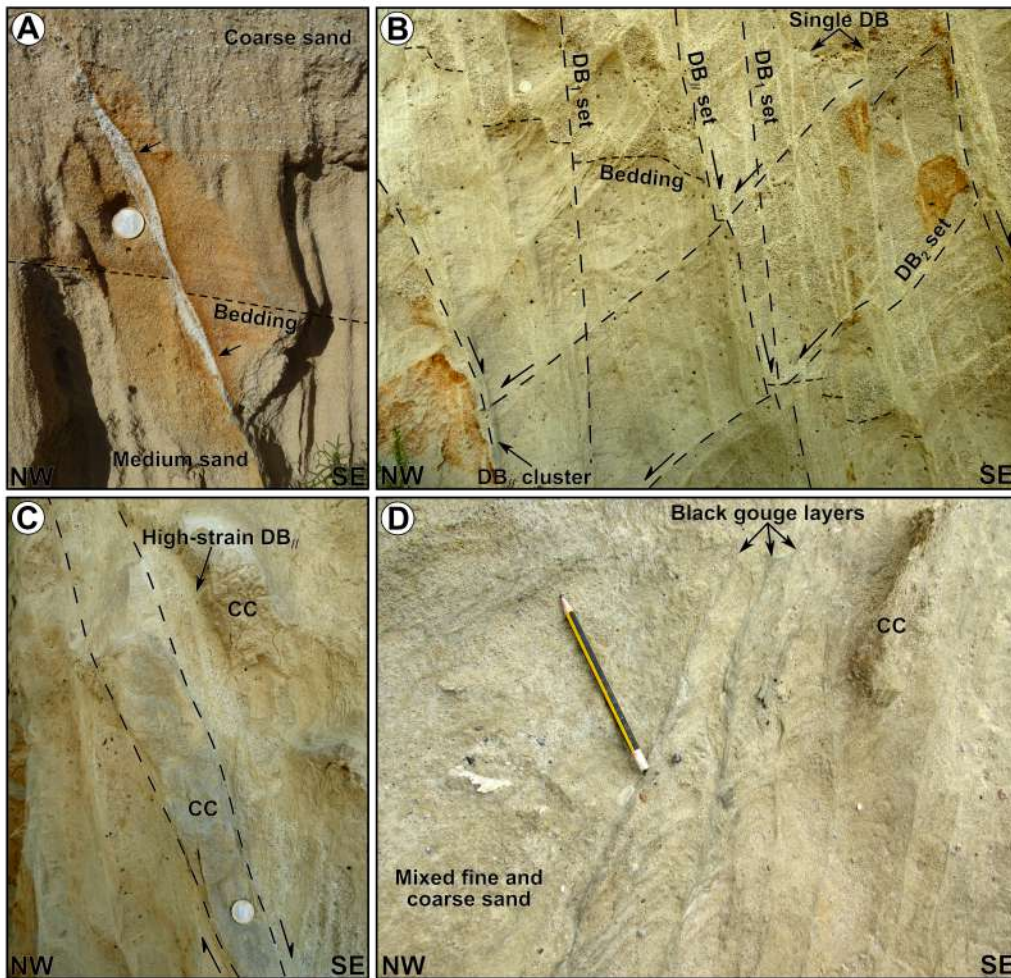
1296 **Fig. 16.** Evolutionary model of deforming structures from low-offset deformation bands to
1297 faults. (a) Particulate flow affecting low-displacement deformation bands causes a weak
1298 grain size reduction and a closer packing of grains, leading to mean porosity of 5-6%. The
1299 reduction of porosity features a decrease of permeability of less than one order of
1300 magnitude. (b) In medium-displacement deformation bands the onset of fragmentation and
1301 rolling of grains results in an immature cataclastic fabric, responsible for the reduction of
1302 grain size and sorting. Porosity is further reduced (2-3%) as well as permeability (1.5
1303 orders of magnitude less than undeformed sand). (c) High-displacement deformation
1304 bands are affected by pronounced cataclasis and strain-localization processes inducing an
1305 asymmetrical drop of porosity (~ 1%) and permeability (3 orders of magnitude less than
1306 the undeformed sandstone). (d) Eventually, along subsidiary faults with offset > 20 cm,
1307 cataclasis is extreme and severe grain size reduction leads to low values of porosity (<
1308 1%) and to a permeability contrast up to 4 orders of magnitude with respect to the pristine
1309 sandstone. K_{fault} , average permeability of faulted sandstone; K_{und} , average permeability of
1310 pristine sandstone; d, displacement.

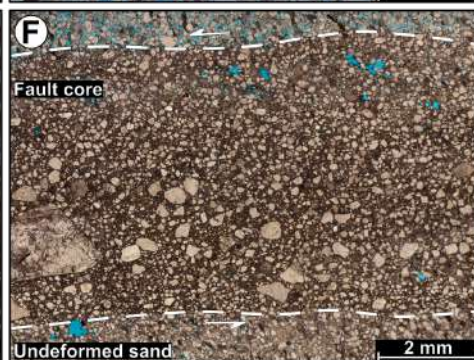
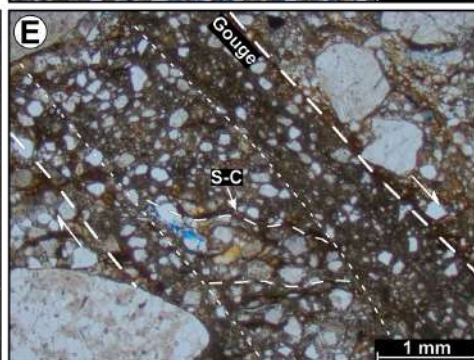
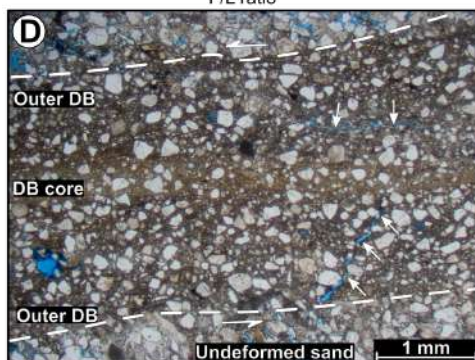
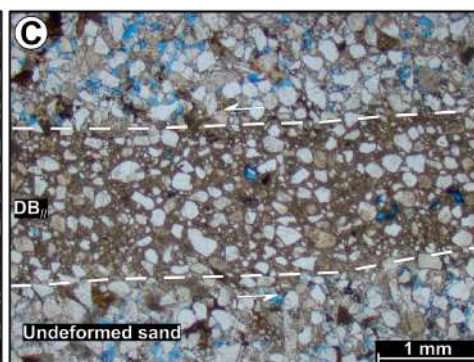
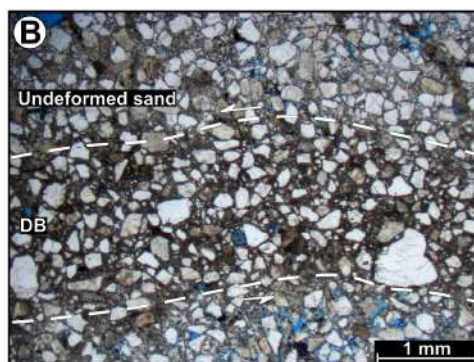
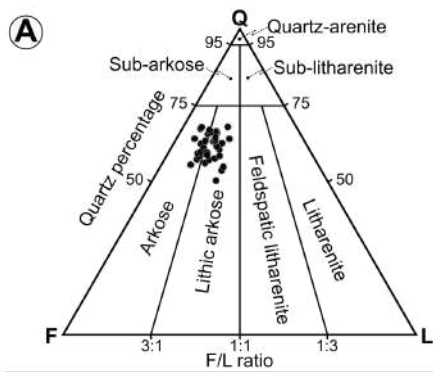
1311 **Table 1.** Structural position, deforming element, distance from the master fault, mean
1312 diameter, mode, sorting-span (with associated standard deviation), D-value and R^2 of the
1313 analyzed grain size samples. LDZ, low-deformation zone; FDZ, footwall damage zone;

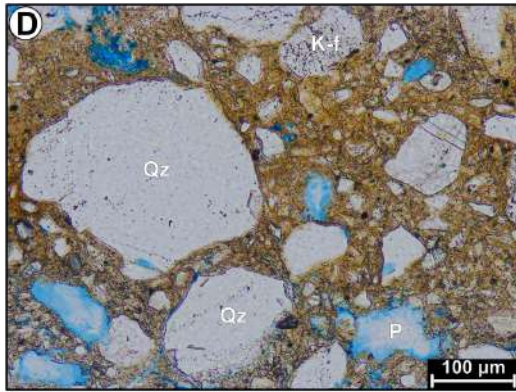
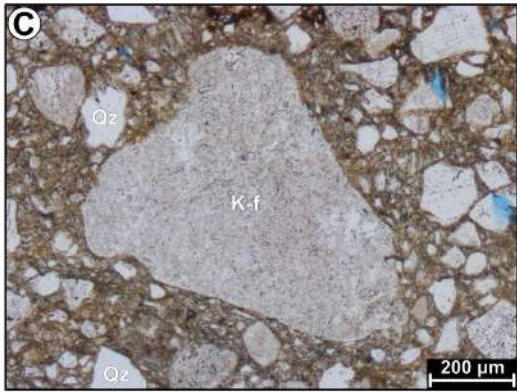
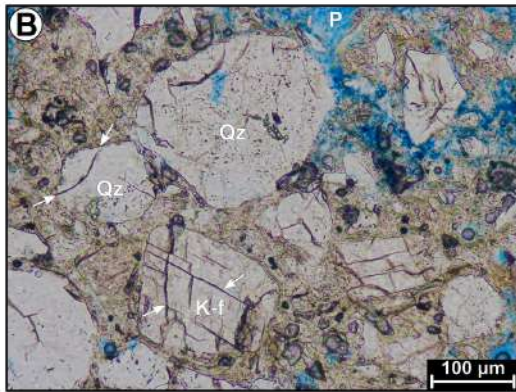
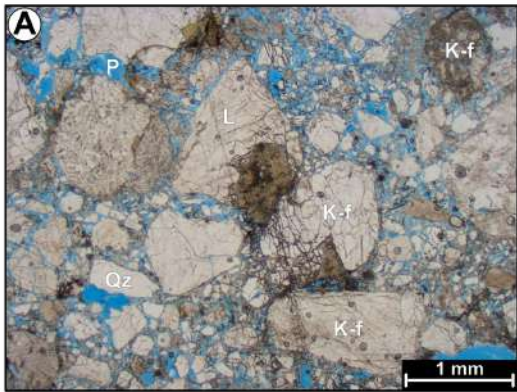
1314 FMZ, footwall mixed zone; FC, fault core; MF, master fault; DB₁, synthetic high-angle
1315 deformation band; DB₂, antithetic low-angle deformation band.

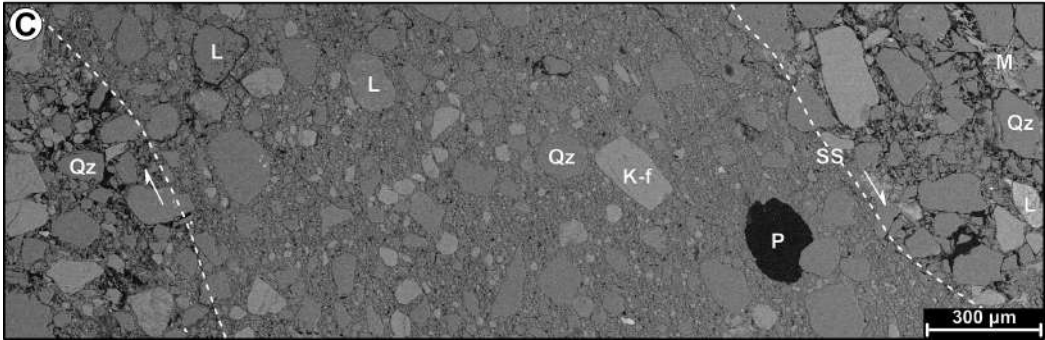
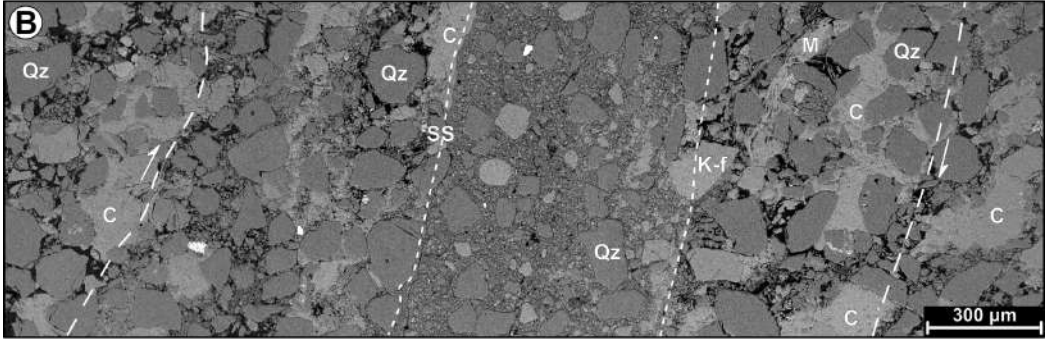
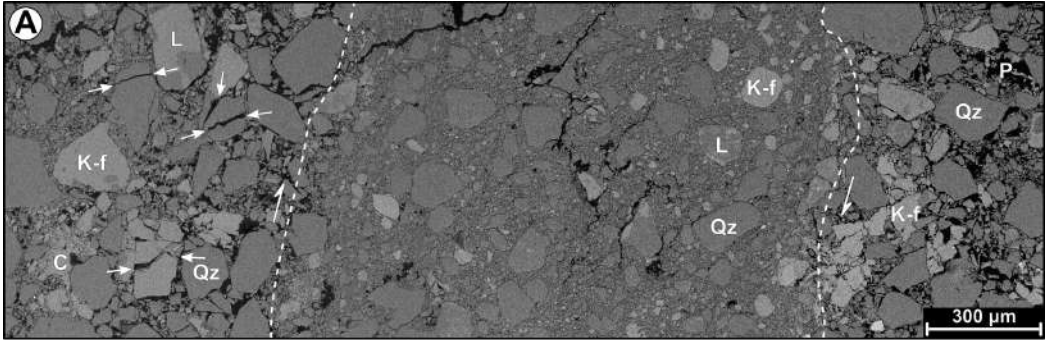


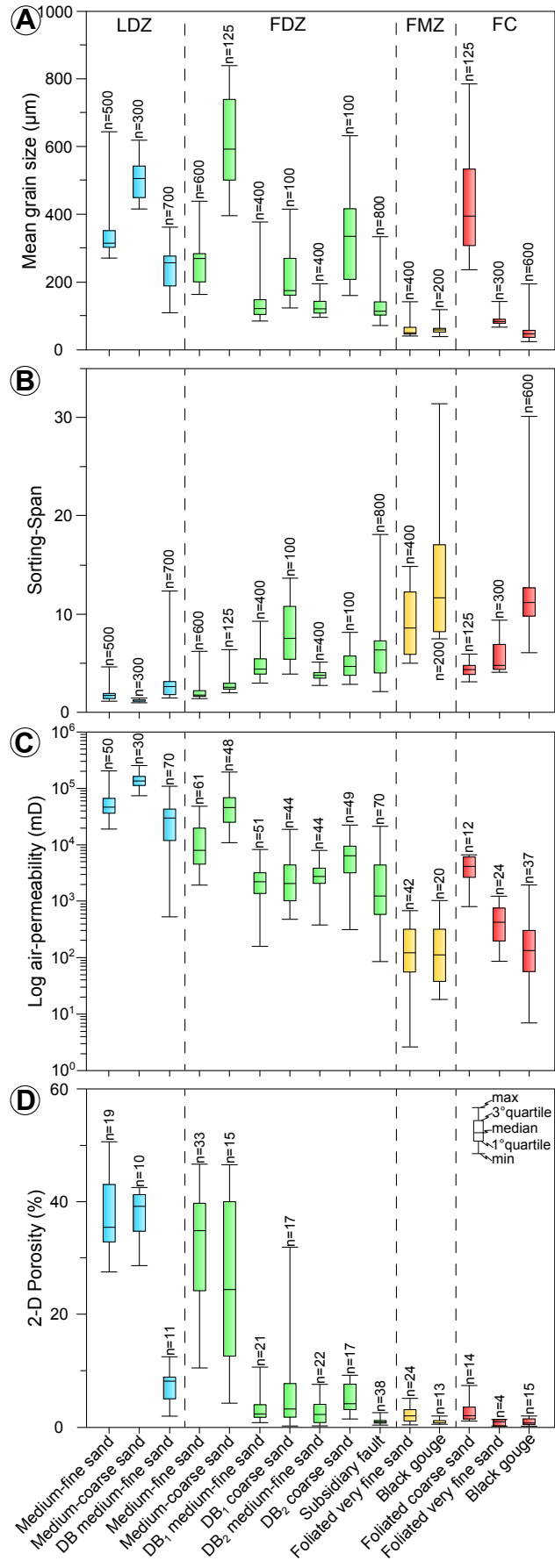


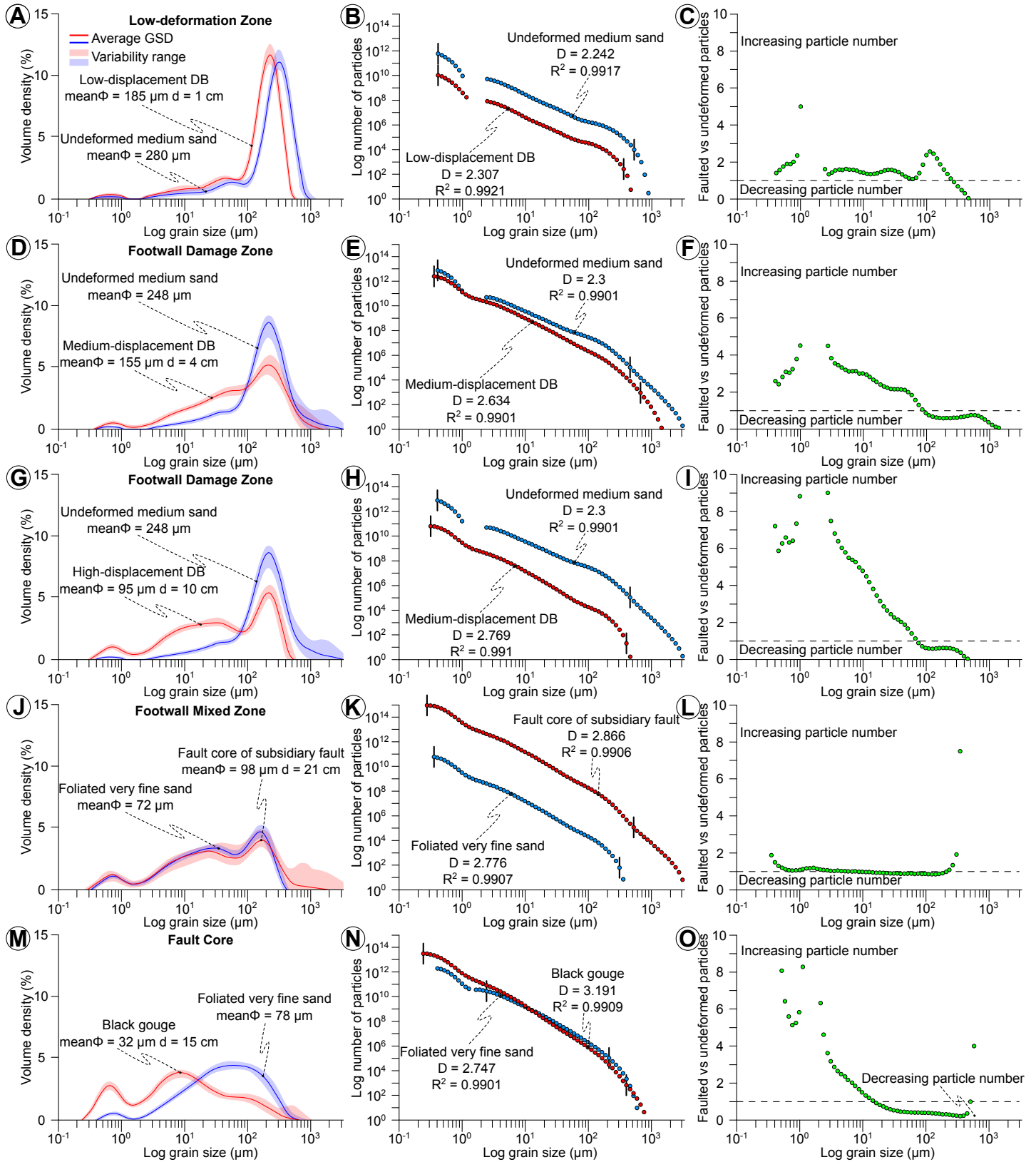


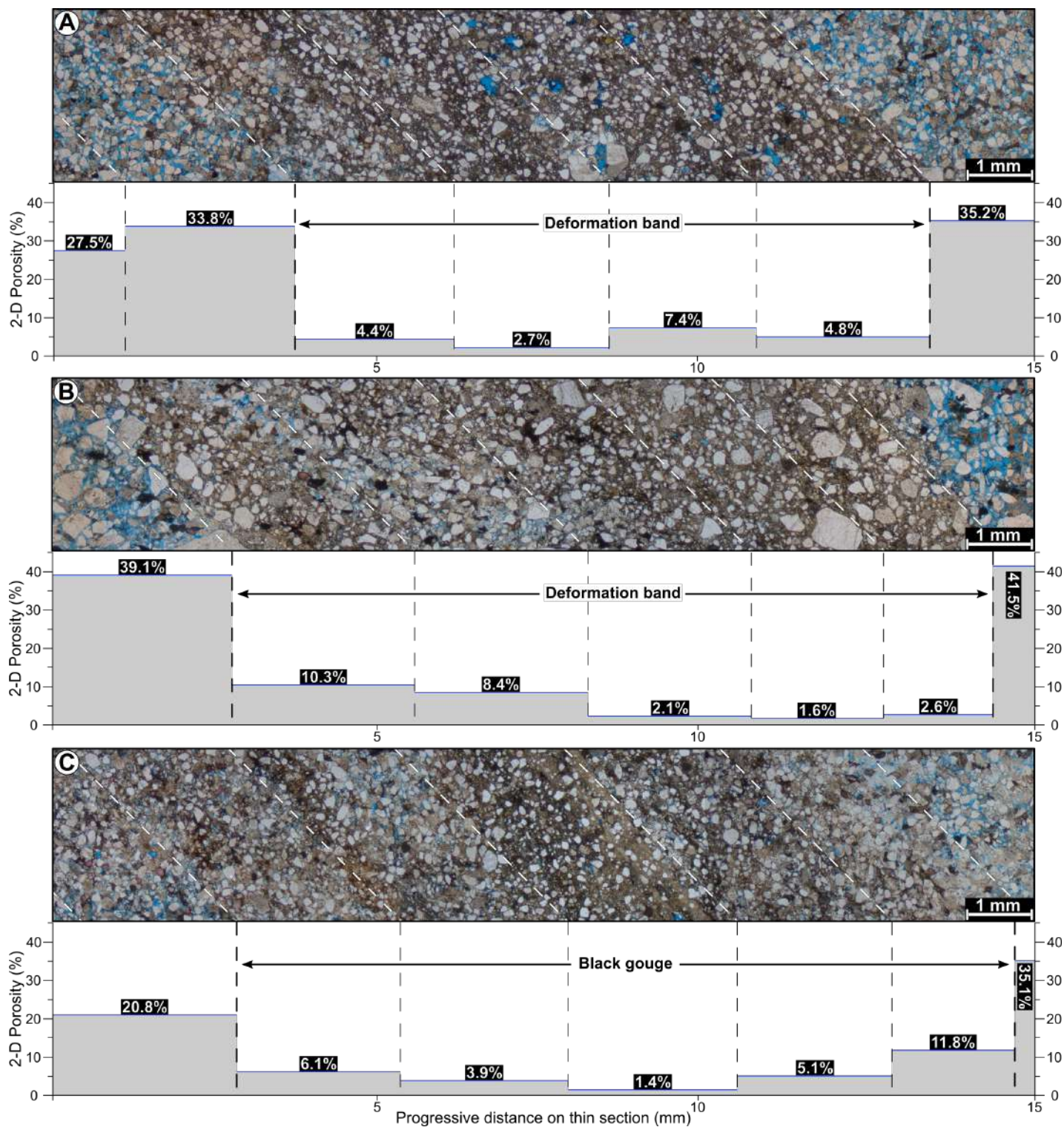


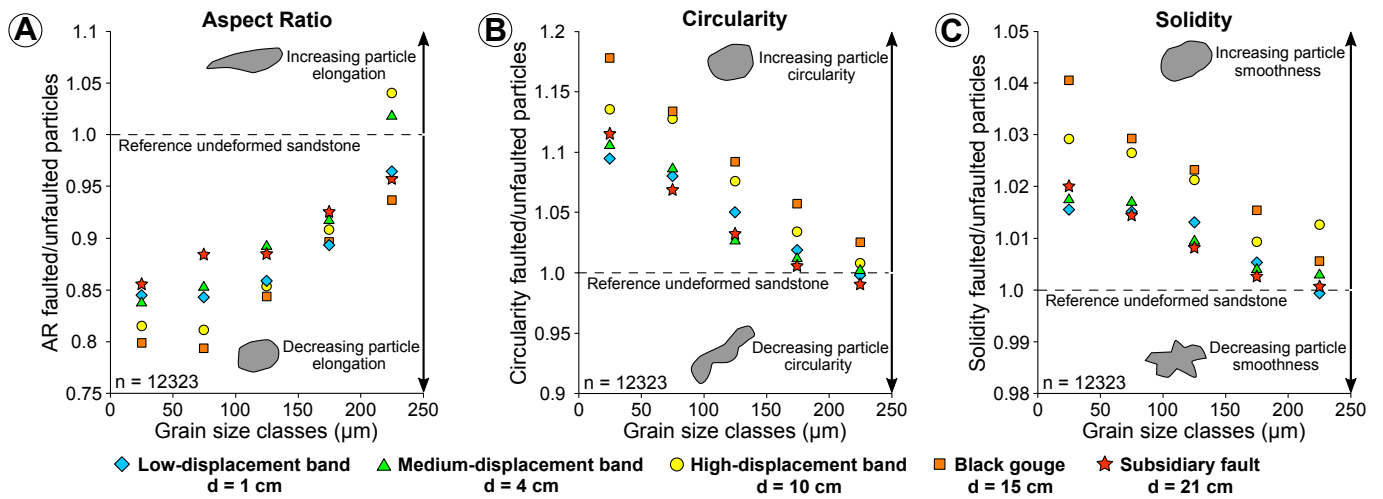


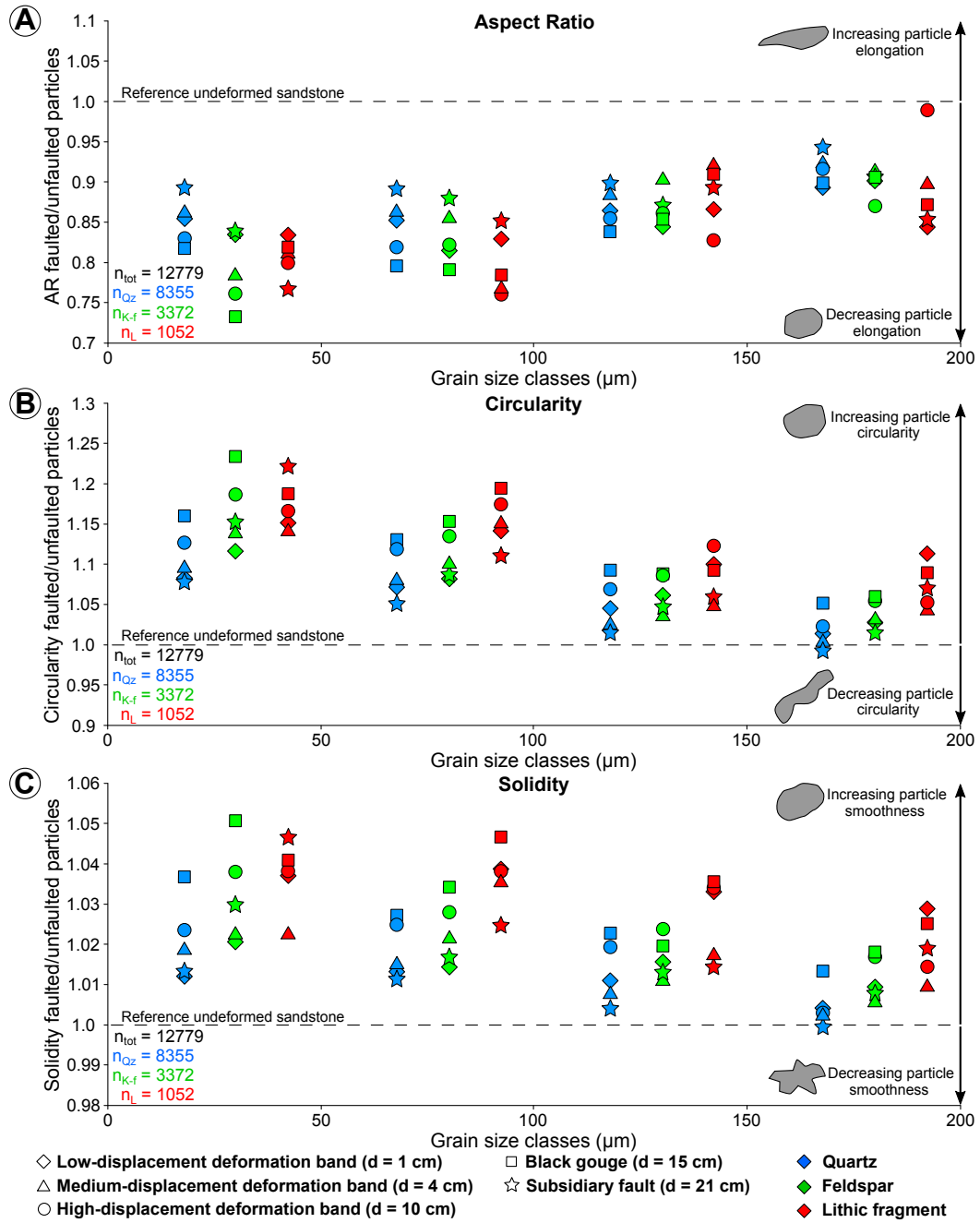


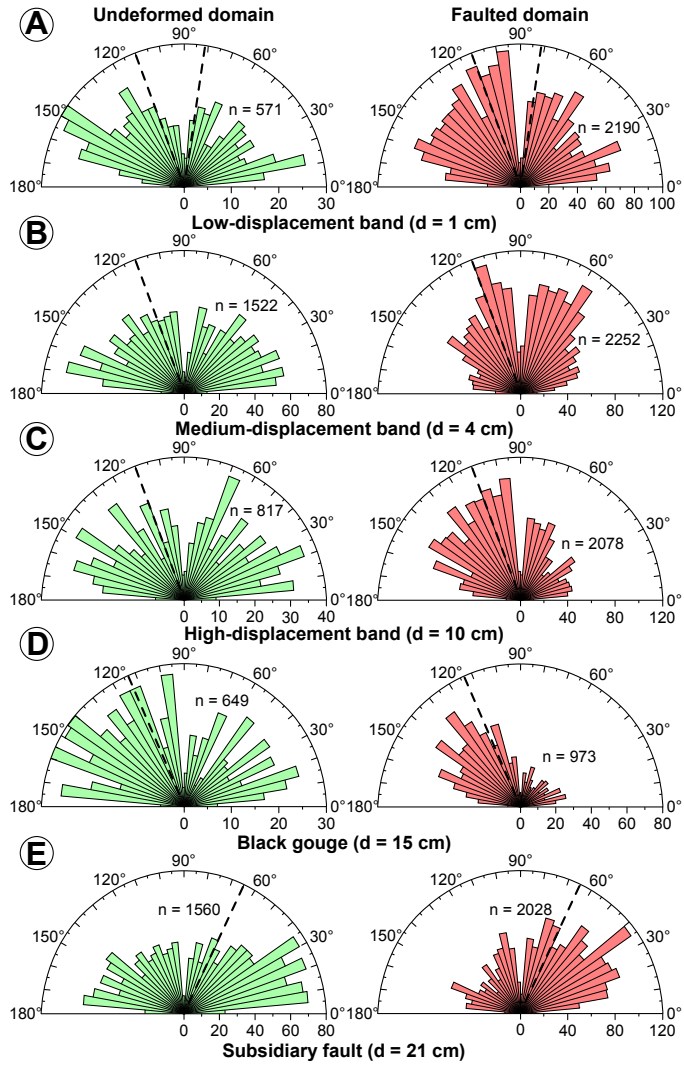


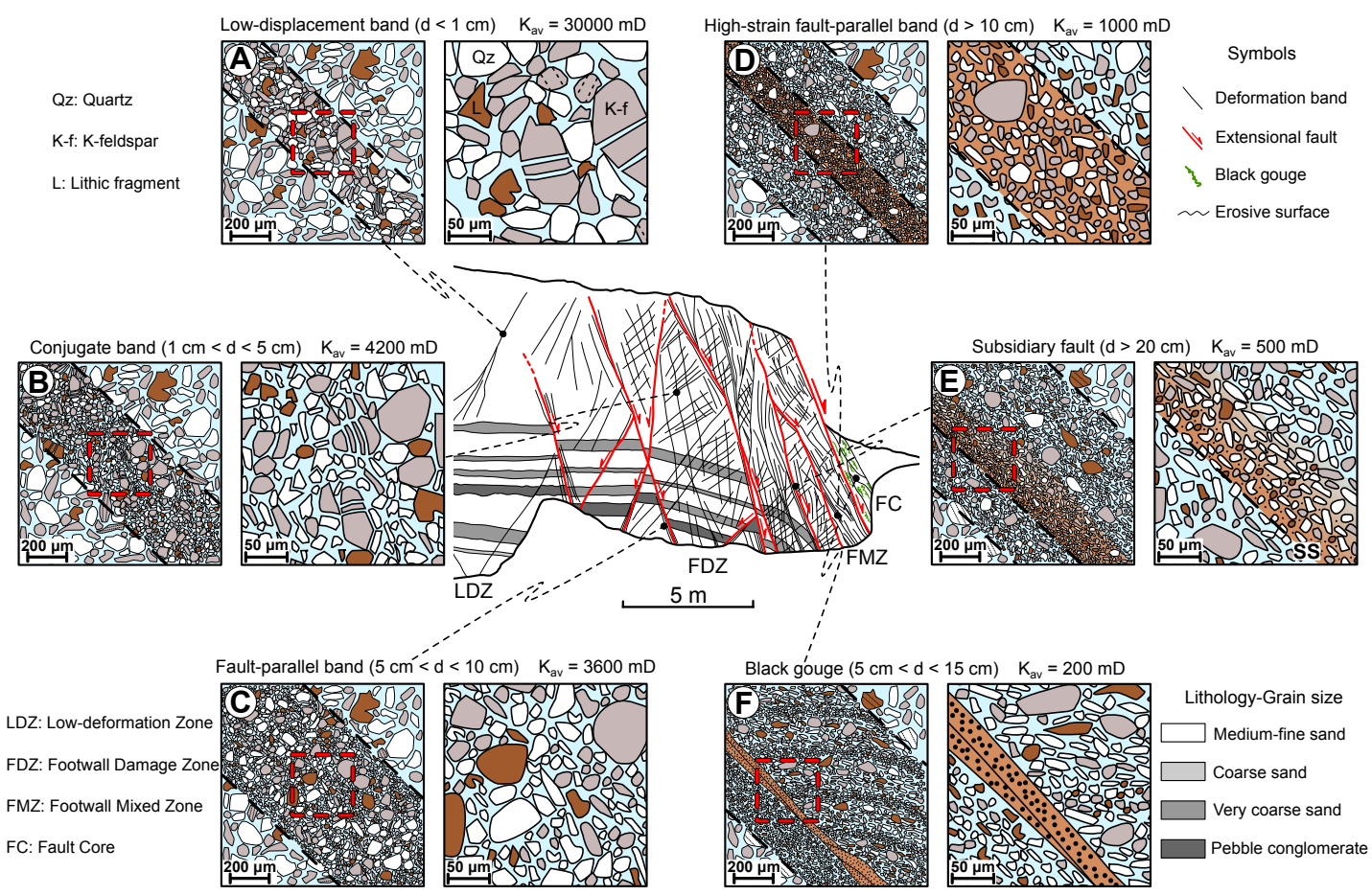


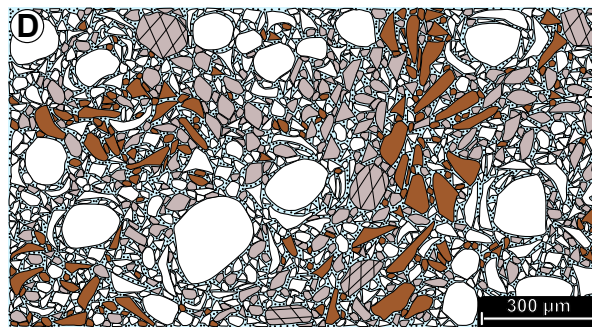
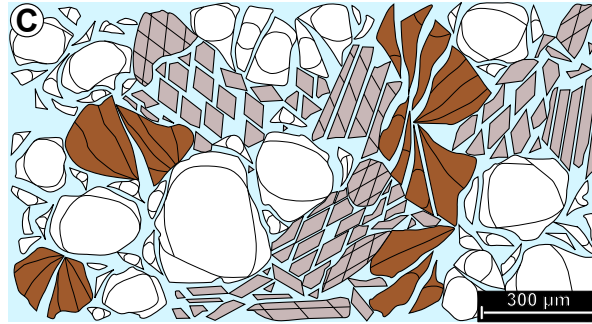
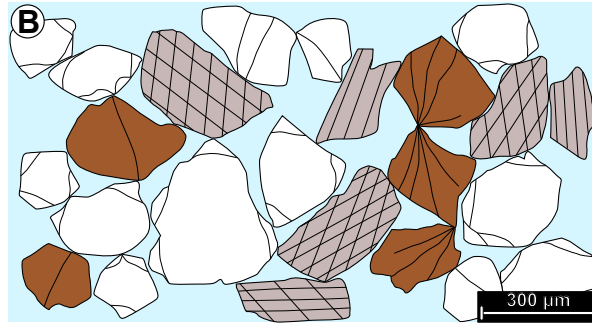
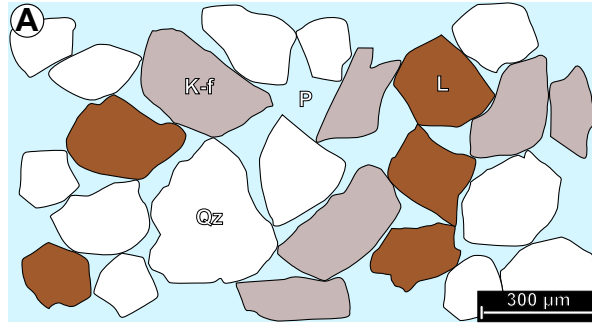




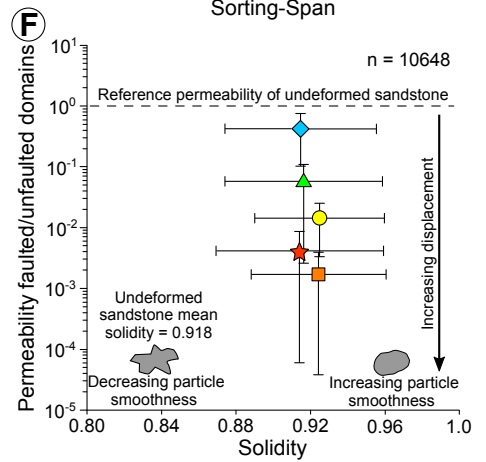
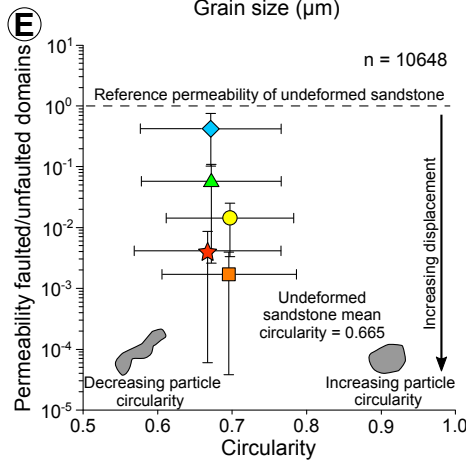
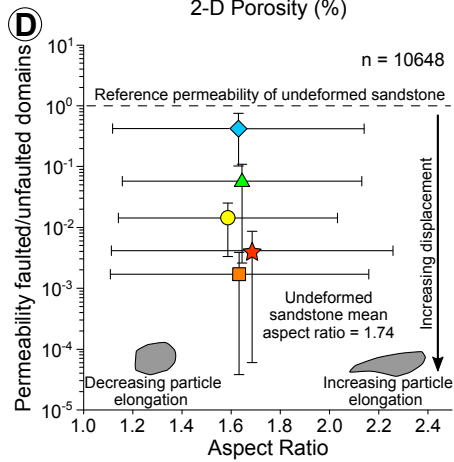
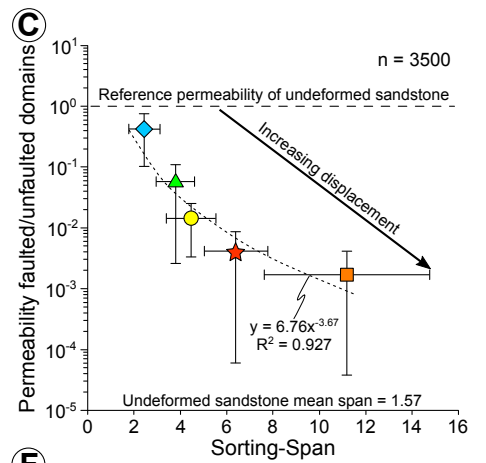
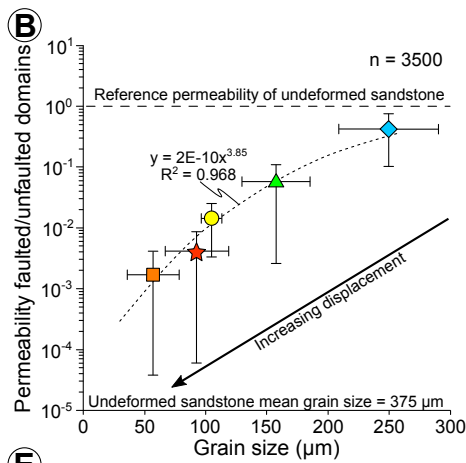
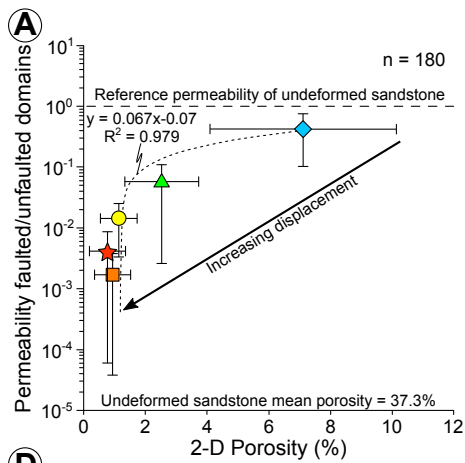




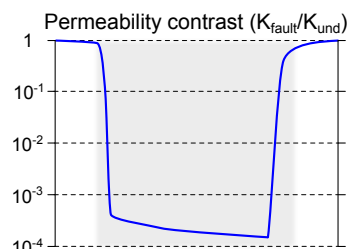
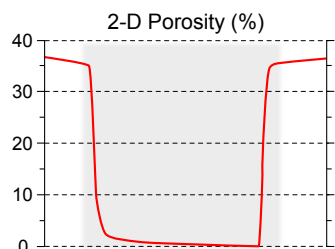
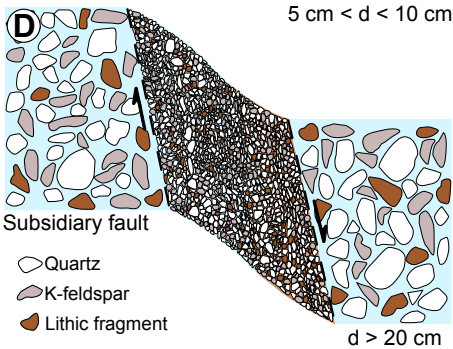
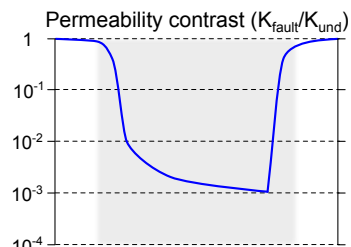
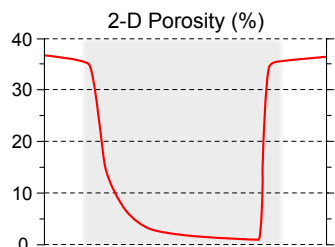
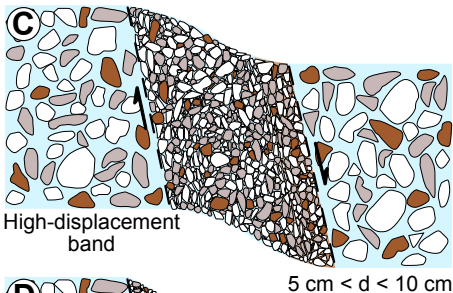
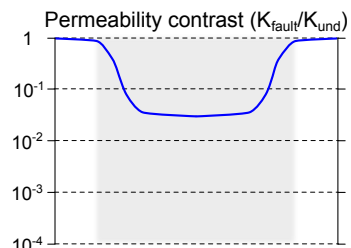
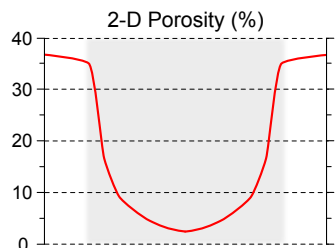
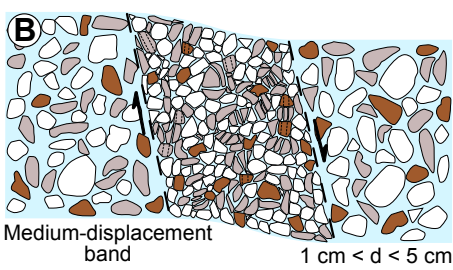
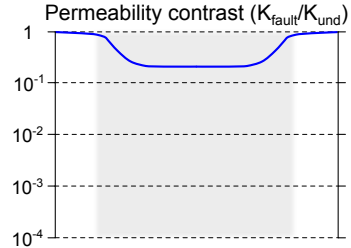
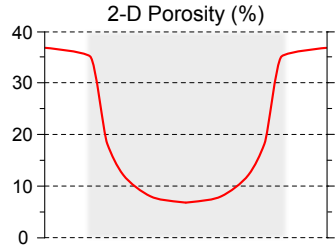
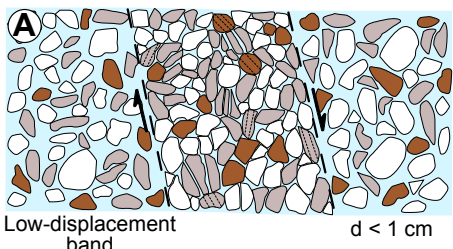




Increasing displacement and strain



◆ Low-displacement band $d = 1$ cm ▲ Medium-displacement band $d = 4$ cm ● High-displacement band $d = 10$ cm ■ Black gouge $d = 15$ cm ★ Subsidiary fault $d = 21$ cm



Increasing displacement and strain