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

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1	Displacement-dependent microstructural and petrophysical properties
2	of deformation bands and gouges in poorly lithified sandstone
3	deformed at shallow burlal depth (Crotone Basin, Italy)
4	
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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

supplementary file additional SEM photomicrographs, porosity, permeability data and grain
 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 Crotone Basin, Southern Italy. The investigated extensional fault zone 31 has a total displacement of ~ 90 m and juxtaposes marine clayish sediments in the hanging wall against arkosic to lithic arkosic sandstone in the footwall. In the footwall 32 damage zone, deformation is achieved by a network of conjugate deformation bands. 33 whereas the foliated fault core hosts cm-thick gouges. Deformation bands and black 34 gouges accommodated displacement between 0.2 to 20 cm. Microstructural observations 35 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 controlled grain-scale deformation mechanism: following this, feldspar experienced 38 39 extensive intragranular crushing, while guartz grains were deformed mainly by splitting and abrasion. Permeability of pristine sandstone spans from 5.4×10^4 to 1.4×10^5 mD, while 40 inside deformation bands is reduced by 1-2 orders of magnitude, reaching 3-4 orders of 41 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 such as deformation bands and gouge layers in damage zones and fault cores, 49 50 respectively (Antonellini and Aydin, 1994; Balsamo and Storti, 2010; Bense et al., 2013; Rotevatn et al., 2013; Ballas et al., 2015). Deformation bands can develop both as single 51 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 Johnson, 1978; Mair et al., 2000; Soliva et al., 2016; Fossen et al., 2017; Philit et al., 54 2018). Although strain-hardening is usually invoked as the main process leading to 55 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., 2013). Deformation bands often show a limited lateral continuity with maximum length 58 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 matrix. In the present contribution, we are referring to more specific fault rock types, 65 namely black gouges, which are discrete elements showing extreme comminution and 66 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).

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

2010; Cilona et al., 2012; Kristensen et al., 2013; Antonellini et al., 2014; Griffiths et al., 73 74 2016; Tavani et al., 2016; Cavailhes and Rotevatn, 2018), deformation mechanisms (Aydin, 1978; Aydin and Johnson, 1983; Bense et al., 2003; Rawling and Goodwin, 2003; 75 76 Fossen et al., 2017), stress-strain conditions (Friedman and Logan, 1973; Olsson, 2000; Baud et al., 2012; Ballas et al., 2013; Robert et al., 2018) and microstructural features 77 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 granularparticulate flow) may cause a significant variability of permeability drops, from 1 up to 6 80 orders of magnitude with respect to the undeformed high-porosity protoliths (Ogilvie and 81 82 Glover, 2001; Balsamo and Storti, 2010; Ballas et al., 2015; Fossen et al., 2017). Permeability diminishing in siliciclastic rocks is typically achieved through processes 83 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 and related deformation mechanisms is critical to assess the hydrological role of fault 86 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).

Despite the significant amount of work that has been done on the genesis and evolution of deformation bands (e.g., Antonellini et al., 1994; Cashman and Cashman, 2000; Mair et al., 2002a; Balsamo and Storti, 2010; Kaproth et al., 2010; Charalampidou et al., 2011; Fossen et al., 2017), basic scaling-laws such as the relationships between displacement and petrophysical properties are still a matter of debate (Torabi and Fossen, 2009; Ballas et al., 2012; Rotevatn et al., 2013, 2017). Previous studies mainly focused on the 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 was analyzed. For this purpose, we investigated in detail the microstructural and 103 104 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 Crotone Basin, Southern Italy. The footwall damage zone of the Rocca di Neto fault zone is characterized by widespread occurrence of deformation bands, both as single elements 107 108 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

The study area is located in the Crotone forearc basin, in Southern Italy (Fig. 1a), which developed as a consequence of subduction of the Adria plate below the European plate (e.g., Van Dijk et al., 2000; Zecchin et al., 2004; Reitz and Seeber, 2012). Basin infill began in Middle Miocene times, resulting in a stratigraphic succession as thick as 2500 m, overlying the metamorphic basement of the Sila Massif (Zecchin et al., 2004, 2012). Basin
evolution includes five subsidence-uplift events during a dominant extensional and subtle
transpressional tectonic history (Van Dijk and Scheepers, 1995; Van Dijk et al., 2000;
Ferranti et al., 2009). Eventually, the onset of regional uplift since Middle Pleistocene
times, led to the cessation of sedimentation and at the same time to the exhumation and
surface exposure of the sedimentary succession (Knott and Turco, 1991; Antonioli et al.,
2006; Zecchin et al., 2012; Massari and Prosser, 2013).

The present-day tectonic architecture of the onshore portion of the basin is defined by two 131 132 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 fault zone juxtaposes clayish sediments (Cutro Clay) in the hanging wall against silty 137 138 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 fault zone displays extensive occurrence of deformation features affecting high-porosity 143 144 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 high-porosity sandstones crop out. Conversely, the hanging wall block is almost 146 completely covered by vegetation due to the presence of clayish sediments (Fig. 2a). 147 Deformation bands are thin and well-localized tabular features that, when arranged in 148 conjugate sets, typically have displacement between 1 and 5 cm. Deformation bands with 149

displacement < 1 cm are found far from subsidiary faults and deformation band clusters.
Fault-parallel deformation bands located closer to the master fault can display higher
offsets, from 5 to 10 cm. Subsidiary faults accommodate larger amounts of displacement
(> 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 lowdisplacement (Fig. 2b, c); (2) the damage zone, characterized by abundant conjugate 157 deformation bands, together with subsidiary faults showing antithetic and synthetic shear 158 159 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 accommodated along the mixed zone and fault core, deformation bands and gouges 163 164 significantly contribute to the offset partitioning along the entire fault zone.

Inside the low-deformation zone, and to lesser extent in the outer part of the footwall 165 166 damage zone, deformation bands are arranged in conjugate sets and have offsets typically lower than ~ 1 cm (Fig. 3a). In the footwall damage zone, deformation bands are arranged 167 in three sets; two of them form an inclined conjugate system (hereafter DB₁ and DB₂), 168 while the third one (DB_{//}) is parallel to subsidiary faults (Fig. 3b). Within the mixed zone, 169 170 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.

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

Inside the fault zone deformation bands and subsidiary faults often display evidence for selective cementation in the form of carbonate concretions made of calcite. Carbonate concretions develop tabular-to lens-shaped cemented bodies with thickness ranging from a few cm to 10-20 cm, paralleling the surface of the structural elements they encase (Fig. 3c, d). Cementation affects only deformation bands and subsidiary faults, while the host sandstone is completely non-cemented, except for rare, thin, bedding-parallel concretions 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 throughout the fault zone, according to the sediment type, position with respect to the 191 192 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 used the Hydro EV wet dispersion unit, with distilled water as dispersant fluid. Different 197 198 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 and final grain size distributions are provided in the online Supplementary Material. Based on the grain size distribution curves, mean grain size, mode, span (sorting), and fractal dimension (D-value) were calculated. Span is defined as the width of the grain size distribution, while the D-value is calculated as the slope of the best-fit power-law distribution between grain size and cumulative frequency of particles per each grain size class in a log-log graph (Blenkinsop, 1991; Rawling and Goodwin, 2003; Balsamo and Storti, 2011).

207 3.2. In situ air permeability

A total of 652 *in situ* permeability measurements were performed across the fault zone using a portable Tiny Perm II air-permeameter (New England Research), which provides accurate data between 10⁻¹ and 10⁵ mD, according to the methodology described by Balsamo et al. (2013). Permeability measurements were performed in the same sites where grain size samples were collected (see Fig. 2a and Figs. A2 and A3 in the online Supplementary Material), after careful brushing the target sediment to remove any alteration crust.

215 3.3. Image analysis technique

Fifty-five polished thin sections impregnated with blue-dyed resin were scanned at high 216 resolution with a Nikon SuperCoolScan 5000 and studied with a Zeiss Axioplan 2 217 218 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 12.5x 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 12.5× magnification, from 35 to 95 µm with 25× magnification (2352×1764 µm), from 25 to 225 226 $35 \,\mu\text{m}$ with $50 \times$ magnification (1242×932 μ m) and those between 10 and 25 μ m with 100× 227 magnification (614×461 µm). Particles finer than 10 µm were not taken into account because of their size below the resolution limit of the 100x optical microscope 228 magnification. Particles with equivalent diameter greater than 500 µm are rare due to the 229 230 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.

Three shape descriptors were used, namely aspect ratio, circularity and solidity. Aspect
ratio (AR) is defined as:

$$237 AR = \frac{Major \ axis}{Minor \ axis} aga{1}$$

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

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

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

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

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

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

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4. Petrographic and microstructural characterization

4.1. Petrography of undeformed sandstone

The composition of the undeformed sandstone was constrained by modal analysis on 35 255 256 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) (Fig. 4a). In particular, quartz percentage spans from 50.3 to 67.7%, while feldspar ranges 260 261 from 19.6 to 36.9% and lithics from 5.3 to 18.2%. Lithics mainly include gneiss and granitic rock fragments, but sedimentary detrital grains also occur in the form of calcite grains and 262 263 fossil shells. Other less frequent lithics are biotite mica, iron oxides-hydroxides, rare muscovite, chlorite and glauconite. 264

265 4.2. Microstructures

Deformed sandstone shows a variety of microstructures, according to the total displacement. In the low-deformation zone, deformation bands are tabular structures with a minimum thickness of 1-5 mm and sharp boundaries with the surrounding pristine sandstone (Fig. 4b). Grain size reduction is negligible and depositional fabric re270 organization results in significant porosity loss. Deformation bands having few cm of 271 displacement show grain size reduction, mainly produced by fragmentation of coarser feldspar grains and quartz abrasion (Fig. 4c). In particular, feldspar grains are deformed by 272 273 several intragranular fractures, leading to the formation of tens of clasts, while guartz grains show mostly splitting and flaking of asperities (Fig. 5a, b). When displacement 274 275 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 grain size reduction is more intense (Fig. 4d). The abundant dark brown matrix is 277 dominantly composed of crushed feldspar and lithic grains, together with fine-grained 278 279 quartz chips and to lesser extent fragments of detrital calcite. Locally, feldspar and guartz oversized survivor grains are present within the core of deformation bands and are 280 281 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 commonly display a more pronounced grain size reduction on the footwall side. 293 294 Conversely, deformation bands inside the fault core and mixed zone are characterized by asymmetric grain size reduction on the hanging wall side. Black gouges show the same 295

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

299

5. Grain size data

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

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

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

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

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

The fault core hosts foliated and stretched coarse sand pods characterized by a mean grain size of 428 µm and mean span of 4.3 (table 1). Foliated very fine sand displays a 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.

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

While the comparison of samples in Figure 7 provides a summary of grain size data 331 332 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 Figure 8 (Storti et al., 2003). To this end, representative samples of deformation bands 334 335 and gouges characterized by different displacement magnitudes were compared with the 336 adjacent host sediments (undeformed in the low-deformation domain, and tectonically compacted foliated sand within mixed zone and fault core). In particular, a low-337 338 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 medium-fine sand has a mean grain size of 280 µm and a modal peak at 320 µm (Fig. 8a). 340 341 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 faulted vs undeformed particles points out a relative increase of particles between the 344 range from 0.4 to 240 µm in the deformation band and a decrease of coarse particles from 345 240 to 500 µm (Fig. 8c). The medium-displacement deformation band collected inside the 346

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 with modal value of 200 µm (Fig. 8d). The D-value shows marked differences between the 349 350 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 (Fig. 8f). High-displacement deformation band in the footwall damage zone has a mean 354 grain size of 95 µm having slightly pronounced trimodal distribution with relative maxima at 355 356 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 of particle number with respect to the undeformed host sand (Fig. 8i). Moving to the mixed 362 363 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 formed by foliated sand with mean grain size of 72 µm, having similar distribution to the 365 previous sample with relative maxima at 0.7, 26 and 153 µm (Fig. 8j). Span of the two 366 367 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. 8I). Eventually, a 371 black gouge sample inside the fault core is characterized by a mean grain size of 32 µm, with trimodal distribution having maxima at 0.6, 8 and 81 µm (Fig. 8m). The adjacent 372 15

373 sediment is composed of foliated very fine sand with a mean grain size of 78 μ m and a 374 bimodal distribution with relative peaks at 0.7 and 62 μ m. 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 μ m and from 516 to 586 μ m, and by a relative decrease from 378 14.5 to 516 μ m with respect to the foliated host sand (Fig. 8o).

379

380 6. Petrophysical properties

381 6.1. Permeability measurements

Along the footwall of the fault, in situ air-permeability shows a progressive decrease from 382 383 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, with mean values of 5.4×10^4 and 1.4×10^5 mD, respectively (Fig. 7c). Deformation bands 385 386 with displacement < 1 cm, have almost half of the permeability shown by undeformed 387 sandstone (3.1 \times 10⁴ mD). In the footwall damage zone, relatively undeformed mediumfine and coarse sandstones in the interband domain are characterized by mean 388 permeability of 1.2×10^4 and 5.3×10^4 mD, respectively. Permeability in these interband 389 390 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 have permeability spanning from 2.6 \times 10³ to 7.4 \times 10³ mD, thus causing a drop from 1 to 392 393 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

Primary porosity was calculated from acquired images neglecting any secondary porosity 403 404 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 deformation bands, both in the low-deformation and in the damage zone domains 407 408 (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 deformation bands have a mean porosity of 2.2%, while thin black gouges reach 1% (Fig. 413 414 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).

At the micro-scale, porosity calculation performed along transects through deformation bands provides more details relative to porosity distribution (Fig. 9). In particular, a strand of low-displacement deformation bands has an almost symmetrical decrease of porosity (porosity decrement is almost the same on both sides of the deformation band) (Fig. 9a). On the contrary, a high-displacement deformation band has more pronounced asymmetry 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 distribution along the deformation band due to the development of a preferential slip 425 426 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). These deformation features are formed by several preferential slip zones contributing to 430 the major internal complexity with respect to deformation bands. However, also in black 431 432 gouges a major preferential slip zone can be identified and corresponds to the sharp porosity contrast between undeformed and deformed sand (Fig. 9c). Differently to 433 434 deformation bands, black gouges localize strain solely along their hanging wall side.

435

436 **7. Grain shape data**

437 7.1. Cumulative data

In Figure 10 are shown the grain shape descriptors (aspect ratio, circularity and solidity) 438 439 versus grain size classes for deformation bands (low, medium and high-displacement), black gouges and subsidiary faults. All grain shape data are reported as ratio between 440 441 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 composing the deformed domains is lower than the reference undeformed sample 446 447 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 increase approaching the undeformed reference sand. Only in the 200-250 µm interval, 450 451 two deformation band samples show aspect ratio values above the undeformed reference, featuring an increase of particle elongation. Circularity of deformed particles is higher than 452 453 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 circle-like shape than grains composing the undeformed control sample. The highest 455 circularity values are recorded in the finest grain size interval (0-50 µm), with a progressive 456 457 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 the 200-250 µm grain size class (Fig. 10c). According to this, faulted particles display a 459 460 smoother outer surface, with less asperities than the reference sample. Highest solidity values are shown in the finest grain size range (0-50 µm), while they progressively 461 462 diminish with increasing grain size (Fig. 10c).

More details are provided by the comparison of grain shape data of the representative five 463 464 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, medium, high-displacement deformation bands and the black gouge. The difference 466 between each dataset is more pronounced at finer grain size, while values converge in 467 468 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 low-circularity interval partially overlapping with low-to-medium-displacement bands (Fig. 473

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. Eventually solidity between the five structural features displays trends similar to circularity. 476 477 In particular, a progressive increase of particle smoothness from low-displacement deformation band to black gouge is observed, with medium-to-high-displacement bands 478 479 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 one (Fig. 10c). In summary, (i) aspect ratio of deformed particles is generally lower (more 482 483 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.

For statistical analysis of the entire grain shape dataset the reader is referred to the on-line
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 size classes for deformation bands (low, medium and high-displacement), black gouges 492 and subsidiary faults, subdivided according to grain mineralogy (quartz, feldspar and lithic 493 494 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, guartz, 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 entire grain size range. Conversely, feldspar has the highest value in the 0-50 µm grain 507 508 size class, while at coarser grain size is exceeded by lithic fragments (Fig. 11b). Solidity 509 graph indicates an increase of grain smoothness for guartz, 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 guartz 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 guartz, 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 guartz, feldspar and lithics along 523 the same deformation structure. This difference is particularly marked in the finer grain size classes (0-100 µm), while it becomes faint and less easily distinguishable in the 524

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

To summarize, (i) quartz grains are generally the more elongated and angular particles; (ii) feldspar grains are less elongated and more rounded than quartz; (iii) lithic fragments have highly varying shape descriptors; (iv) grain shape differences between quartz, feldspar and lithics generally increase with increasing displacement of deformation structures and are more marked at finer grain size range. The statistical analysis of grain shape dataset is 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.

Low-displacement deformation band displays a weak grain preferential alignment parallel to the band direction, as highlighted by the high angular deviation from the direction of the band (Fig. 12a). In medium-displacement deformation band, grains have a marked preferred orientation, both parallel and at 50-60° clockwise from the direction of deformation band (Fig. 12b). Grains in high-displacement deformation band are strongly 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 properties of deformation features documented in the Rocca di Neto fault zone. The 561 562 studied fault developed at very shallow-burial depth as indicated by stratigraphic constraints (Zecchin et al., 2012) and by the very weak compaction shown by the 563 undeformed high-porosity sandstone, collectively suggesting a maximum burial depth 564 565 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 reduction, are interpreted to develop by particulate flow in highly porous sandstone (e.g., 567 568 Rawling and Goodwin, 2003; Balsamo and Storti, 2010; Rodrigues and Alves da Silva, 2018) (Figs. 4b and 13a). Particulate flow does not obliterate the original texture of pristine 569 570 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 between the shape descriptors of deformed and undeformed domains is less pronounced 574

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 fragmentation throughout all the investigated size classes. Moving toward the master fault, 577 578 deformation bands in the footwall damage zone show a more severe reduction of grain size, even for bands with few cm of displacement (Fig. 4c, d). Grains are internally 579 580 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 13b, c). Grain breakage leads to a pronounced reduction of interparticle porosity (Fig. 7d), 582 due to the presence of small grain fragments filling pores (Antonellini et al., 1994; Kaproth 583 584 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. 11a, b, c). The difference of the shape descriptors is related to the development of grain-588 589 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 < 1 cm, whereas cataclasis settled for displacement > 1 cm and after a porosity loss to 5-598 599 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).

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

606 The fragmentation of grains via cataclasis, promotes the development of more equant, smoother and regular shaped grains compared to the undeformed sandstone (Blenkinsop, 607 1991; Heilbronner and Keulen, 2006; Storti et al., 2007; Balsamo and Storti, 2011) (Fig. 608 609 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 subordinately by intragranular fractures, forming highly elongated finer, and more equant 622 smoothed coarse grains (cf. Balsamo and Storti, 2011) (Fig. 14d). Lithic fragments deform 623 624 both via intragranular, trans-granular fracturing as well as by abrasion (Fig. 14b, c).

However, the deformation mechanism affecting lithics vary according to grain mineralogy(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 deforming structures display a different maturity of cataclastic fabric with increasing 630 631 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 subsidiary faults accommodating higher offset are characterized by a more mature 634 cataclastic fabric as indicated by the pronounced grain size reduction and widening of 635 636 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 parameters of grains, in particular by evaluating the difference between quartz and 640 641 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.

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

or gouge (Fig. 6b, c). The greater is the displacement, the stronger is the grain size reduction and the asymmetry of comminution within the deformation band, up to the development of a 100-200 µm-thick slip surface (Figs. 4d). We suggest that the strainlocalization on one side of the deformation bands could be caused by the kinematic stress field active in the vicinity of the master fault (Pizzati et al., 2019). This is further confirmed by the occurrence of microstructural asymmetry only inside deformation features close to 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 (Figs. 4 and 6), and also with the progressive increase of sorting-span and D-value with 660 higher displacement magnitudes (Figs. 7 and 8). Inside the mixed zone and fault core, the 661 662 presence of high-displacement structures (with offset exceeding bedding thickness) favored also the grain-scale mixing of layers with different grain size. Tectonic mixing is a 663 664 common process in thinly-bedded siliciclastic successions (Heynekamp et al., 1999; Rawling and Goodwin, 2006; Balsamo and Storti, 2011). In the studied fault zone, tectonic 665 666 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 by the shape descriptor values that do not follow the increasing displacement trend 668 identified by the other deforming structures. This would suggest a mixing of sediment 669 670 volumes with different grain size concealing the real effect of the high-displacement 671 magnitude (Figs. 10 and 11).

In the studied fault zone, we documented deformation features showing severe cataclasis even if the host sandstone was buried at very shallow depth (< 400-500 m) (Zecchin et al., 2012). Following this, although typically favored by significant overburden, we suggest that 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

The deformation mechanism previously described causes a strong deterioration of 682 petrophysical properties of faulted sandstone, as underlined by the permeability drop 683 684 characterizing the most deformed domains (exceeding four orders of magnitude diminishing) (Figs. 7c and 15). From cross-correlation graphs between permeability and 685 686 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. grain size is best fitted by a power-law function, with finer grain size (higher displacement) 691 692 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

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

The influence of grain shape (aspect ratio, circularity and solidity) in determining the 705 706 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 deformation bands with low-displacement (< 1 cm), accommodated dominantly via 720 721 particulate flow, may show a permeability drop of at least half an order of magnitude (Fig. 16a). Deformation bands with higher displacement (1 cm < d < 5 cm), developing an 722 723 immature cataclastic fabric, may induce a permeability decrease up to 1.5 orders of 724 magnitude (Fig. 16b). High-displacement bands (5 cm < d < 10 cm) feature an effective 725 permeability drop from 2 to 3 orders of magnitude, due to the pronounced cataclastic fabric

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

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

The presence of deformed whitish sand within deformation bands, surrounded by orangebrown stained undeformed sandstone due to iron oxide precipitation, suggests an effective sealing behavior even for a few cm displacement (Fig. 3a). Even tough, the barrier-conduit role within deformed high-porosity sandstone is not straightforward as it is in the case of fully lithified rocks (Caine et al., 1996; Evans et al., 1997; Fisher et al., 2018). Whereas in 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., 2012). In water-saturated conditions deformation bands and gouges display a barrier role, 754 755 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 by the presence of selective cementation along deformation bands and faults (Balsamo et 759 760 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.

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

769

770 **10. Conclusions**

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

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

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

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

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

grain shape played a minor role in determining the magnitude of permeability dropassociated with deformed domains.

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

807

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1116 **Figure captions**

1117 Fig. 1. (a) Geographic position of the Crotone Basin in the framework of the Southern 1118 Apennine orogenic belt and Calabrian Arc. The thinly dotted line marks the landward limit of the on-shore portion of the Crotone Basin. (b) Simplified geological map of the Crotone 1119 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 black and white star in Fig. 1b. ATB, Apennine thrust belt; CA, Calabrian Arc; CAW, 1124 1125 Calabrian accretionary wedge; CB, Crotone 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 hanging wall is almost completely covered by vegetation and debris and hosts the Middle 1129 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 from the contour of poles to deformation bands. Stereonets were realized with 1135 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, synthetic high-angle deformation band; DB₂, antithetic low-angle deformation band; DB_{//}, 1138 1139 fault-parallel deformation band; SF, subsidiary fault; MF, master fault; FMZ, footwall mixed

zone; FC, fault core; c.i., contouring interval; n, number of measured faults and
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 (DB₁) and antithetic low-angle (DB₂) 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 cement (CC) (see the coin for scale). (d) Black gouges inside the fault core encased by 1152 1153 mixed coarse and fine foliated sand (pencil for scale). DB1, synthetic high-angle 1154 deformation band; DB₂, antithetic low-angle deformation band; DB₁, 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 pronounced grain size reduction. Coarse grains are surrounded by a fine-grained light-1163 brown matrix formed by highly comminute fragments. (d) High-displacement fault-parallel 1164

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 following higher displacement magnitude. (b) Details of intragranular fractures affecting 1177 1178 feldspar, developed along crystal twinning planes, and flaking of asperities characterizing 1179 guartz grains. Pores are partially filled by a fine-grained matrix formed by guartz chips and 1180 feldspar fragments. (c) Oversized survivor feldspar grain in a medium-displacement band. The brown matrix is composed of fine-grained quartz, feldspar and calcite flakes. (d) 1181 1182 Survivor grains of quartz inside a high-displacement deformation band, are not affected by 1183 fracturing or flaking. Qz, guartz; K-f, K-feldspar; L, lithic fragment; P, pore space.

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

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

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

Fig. 9. Plane-polarized photo-mosaics reporting the porosity variation across lowdisplacement band (a), medium-displacement band (b) and black gouge (c). Twodimensional porosity is reported on profile crossing the entire length of the structural element as mean percentage calculated from the areas delimited by white dotted lines 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, aspect ratio (a), circularity (b) and solidity (c). Symbols represent mean values of the 1228 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.

Fig. 11. Grain shape analysis performed on the three most recurred minerals (quartz, feldspar and lithic fragments) in low, medium, high-displacement deformation bands, fault core of subsidiary fault and black gouge. Grains are described using three shape 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.

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

1254 Fig. 13. Microstructural features according to the identified deformation mechanism. (a) Inside the low-deformation zone and the outer damage zone, deformation bands 1255 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 fragmentation via intragranular fracturing and deforms mainly by flaking and chipping of 1262 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 deformation bands may develop an inner core with severe grain size reduction, leading to 1266 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 of grain size reduction moving away from it. Within the fault core, black gouges (f) display 1271 extreme grain crushing leading to the formation of ultra-comminute thin layers, encased by 1272 1273 less deformed sand arranged in S-C arrays. The deformation mechanism described above is able to reduce the permeability up to 3.5-4 orders of magnitude with respect to the 1274 pristine high-porosity sandstone. Kav, average permeability; SS, slip surface; d, 1275 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.

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

diffraction. (c) Permeability ratio vs mean sorting-span gained from laser diffraction analysis. (d) Permeability ratio vs grain aspect ratio from cumulative data. (e) Permeability ratio vs grain circularity from cumulative data. (f) Permeability ratio vs grain solidity from cumulative data. The reference permeability was assumed as a mean of all permeability measurements on the undeformed sandstone outside the fault zone. Error bars represent the standard deviation associated with datasets. d, displacement; n, number of 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 rolling of grains results in an immature cataclastic fabric, responsible for the reduction of 1301 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 asymmetrical drop of porosity (~ 1%) and permeability (3 orders of magnitude less than 1305 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.

Table 1. Structural position, deforming element, distance from the master fault, mean diameter, mode, sorting-span (with associated standard deviation), D-value and R² of the analyzed grain size samples. LDZ, low-deformation zone; FDZ, footwall damage zone;

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





















FC: Fault Core

