

1 **Lithological and structural control on fracture frequency distribution within a carbonate-**  
2 **hosted relay ramp**

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24

## 25 **Abstract**

26 Understanding the factors controlling fracture frequency distribution can greatly improve the  
27 assessment of fluid circulation in fault damage zones, with evident implications for fault mechanics,  
28 hydrogeology and hydrocarbon exploration. This is particularly important for relay zones that are  
29 usually characterized by strong damage and structural complexity. We investigated the fracture  
30 frequency within an outcrop adjacent to the front fault segment of a relay ramp, hosted within peritidal  
31 carbonates that forms part of the Tre Monti fault (Central Italy). We analysed the distribution of  
32 fracture frequency in the outcrop through (1) scanlines measured in the field, (2) oriented rock  
33 samples, and (3) scan-areas performed on a virtual outcrop model. Fracture frequency increases with  
34 distance from the front segment of the relay ramp. Moreover, supratidal and intertidal carbonate facies  
35 exhibit higher fracture frequency than subtidal limestones. This trend of increased fracture frequency  
36 has two main explanations. (1) The number of subsidiary faults and their associated damage zones  
37 increases moving away from the front segment. (2) the supratidal and intertidal carbonate facies  
38 content increases toward the centre of the relay ramp. Our results indicate that the fracture frequency  
39 pattern is very complex in relay ramps hosted in shallow-water limestones and that its prediction  
40 necessitates a good control on structures and sedimentary facies distribution.

41

## 42 **1. Introduction**

43 Fractures in the damage zone (Chester and Logan, 1986; Chester et al., 1993) constitute the main  
44 pathway for fluids within faults hosted in low-porosity rocks (Caine et al., 1996; Aydin, 2000;  
45 Gudmundsson et al., 2001; Bense et al., 2013; Bigi et al., 2013). Fracture frequency and the variation  
46 of geometrical and topological properties of fracturing in space are an important control on  
47 permeability, and hence on fluid flow and fault mechanics. For example, these variations in these  
48 attributes may control traps and leakage points within hydrocarbon reservoirs affected by the presence  
49 of faults and promote or prevent local fluid overpressures. A poorly connected fracture system might  
50 lead to the development of high fluid pressures, which can in turn influence the evolution of the stress

51 state (Sibson, 1994) with profound implications for earthquake triggering (e.g., Nur and Booker,  
52 1972; Miller et al., 2004). Conversely, a well-connected fracture system prevents the development of  
53 fluid overpressures and this leads to the maintenance of a strong but critically stressed crust (Townend  
54 and Zoback, 2000). Furthermore, fracture distribution can have a direct effect on fault mechanics: a  
55 change of elastic properties of host rock promoted by fracturing may lead to a stress field rotation  
56 within damage zone, allowing reactivation of unfavourably orientated faults (Faulkner et al., 2006).  
57 Characterization of fracture distribution and its controlling factors is therefore fundamental to better  
58 understand fluid circulation and mechanics of fault zones, with obvious consequences for  
59 hydrogeology and hydrocarbon exploration. Assessing fracture distribution is particularly relevant  
60 for relay ramps (and generally, for zones of faults interaction) as they are commonly characterized  
61 by stronger damage than isolated fault segments (Kim et al., 2004; Peacock et al., 2017) and by high  
62 structural complexity (Kattenhorn et al., 2000; Peacock et al., 2000; Peacock and Parfitt, 2002; Fossen  
63 et al., 2005; Ciftci & Bozkurt, 2007; Bastesen and Rotevatn, 2012; Peacock et al., 2017), with  
64 important consequences for fluid flow (Sibson, 1996; Rotevatn et al., 2007; Fossen and Rotevatn,  
65 2016 and references therein).

66 Here we integrate classical and modern structural geology techniques to investigate the fracture  
67 frequency distribution and its controlling factors within a well-exposed portion of a carbonate-hosted  
68 relay ramp damage zone that is part of the Tre Monti fault, a normal fault in the Central Apennines  
69 of Italy. We observe that lithology (carbonate facies) and the distribution of secondary faults  
70 accompanying relay ramp development play an important role in the fracture density.

71

### 72 *1.1. Factors controlling fracture distribution within fault zones.*

73 Many field and laboratory studies have been carried out to investigate factors controlling fracture  
74 distribution within fault zones. A first factor is represented by distance from the main fault: both  
75 microfracture and fracture density generally increase moving toward fault core (Brock and Engelder,  
76 1977; Wilson et al., 2003; Faulkner et al., 2006; Mitchell and Faulkner, 2009). However, fracture

77 intensity does not scale with displacement accommodated by the main fault (Anders and Wiltschko,  
78 1994; Shipton and Cowie, 2003). This has been attributed to the existence of a critical value of  
79 deformation intensity marking the transition from a strain hardening to a strain softening behaviour  
80 induced by the development of slip surfaces (Shipton and Cowie, 2003). Instead, higher  
81 displacements accommodated by faults lead to an increase in the damage zone thickness until a  
82 critical width is reached (Shipton and Cowie, 2001, 2003; Mitchell and Faulkner, 2009; Savage and  
83 Brodsky, 2011). This can be attributed to a continuous development of subsidiary faults producing  
84 their own damage zone (Shipton and Cowie, 2003). Other fault-related factors that influence  
85 distribution and the geometrical/topological properties of fractures are related to the stress field. For  
86 example, the asymmetric pattern of the stress field occurring during the long-term propagation of a  
87 fault (Berg and Skar, 2005), and rupture directivity during earthquakes (Dor et al., 2006a, 2006b;  
88 Mitchell et al., 2011) may produce an asymmetric damage distribution between hangingwall and  
89 footwall, whilst development of local stresses may promote a deflection of fractures (Gudmundsson  
90 et al., 2010).

91 Lithology plays another important role in fracture frequency distribution. A stratigraphic or tectonic  
92 juxtaposition of different lithologies leads to contrasts in mechanical properties (e.g., brittleness;  
93 Peacock and Xing, 1994) causing a mechanical layering that influences deformation pattern (Tavani  
94 et al., 2008), and fracture spacing, propagation and arrest (Odling et al., 1999; McGinnis et al., 2017).

95 In general, fractures tend to form in more brittle layers and they often arrest at interfaces where  
96 mechanical contrasts are present (e.g., bedding). For carbonate lithologies, even a variation in  
97 carbonate facies at metric to decametric scale can affect fracturing (Wennberg et al., 2006; De Paola  
98 et al., 2008; Larsen et al., 2010a, 2010b; Michie et al., 2014; Rustichelli et al., 2016; Volatili et al.,  
99 2019). For example, Rustichelli et al. (2016) observed higher fracture intensity, trace length and  
100 connectivity in platform compared to ramp carbonates, whilst Larsen and co-authors (2010a, b) found  
101 that fractures forming in the subtidal facies tend to arrest in proximity to intertidal laminated  
102 limestones. Finally, thickness of sedimentary beds can influence fracturing: a widely observed

103 relationship is that, for strata-bound fractures, fracture intensity is inversely proportional to bed  
104 thickness (Ladeira and Price, 1981; Pollard and Aydin, 1988; Huang and Angelier, 1989; Narr and  
105 Suppe, 1991; Wu and Pollard, 1995; Bai and Pollard, 2000).

106

### 107 *1.2. The structure-from-motion algorithm to build virtual outcrops*

108 In this study we integrate classical field techniques (i.e., scanlines; Wu and Pollard, 1995) and a  
109 virtual outcrop (Bellian et al., 2005; McCaffrey et al., 2005a, 2005b) to investigate fracture frequency  
110 distribution and its controlling factors in a relay ramp system formed in carbonate host rocks.

111 In the last decade, virtual outcrops have been extensively used in structural geology (Bemis et al.,  
112 2014; Telling et al., 2017 for a review), and in particular for studies dealing with fractures (Olariu et  
113 al., 2008; Vasuki et al., 2014; Pless et al., 2015; Casini et al., 2016; Seers and Hodgetts, 2016;  
114 Corradetti et al., 2017; Bonali et al., 2019 and many others). The employment of virtual outcrops in  
115 geology has increased our ability and efficiency to collect data, allowing the collection of high-  
116 precision georeferenced datasets, also from inaccessible portions of the outcrop (Bellian et al., 2005;  
117 McCaffrey et al., 2005a, 2005b). An increasingly adopted methodology to build virtual outcrops is  
118 represented by the structure-from-motion technique (Westoby et al., 2012; Bemis et al., 2014;  
119 Colomina and Molina, 2014; Tavani et al., 2014; Vasuki et al., 2014; Bistacchi et al., 2015; Bonali et  
120 al., 2019), because it has a higher efficiency to cost ratio than other techniques such as laser scanning  
121 (LiDAR) (Wilkinson et al., 2016; Cawood et al., 2017). The structure-from-motion algorithm exploits  
122 a series of overlapping photos taken from various positions by a person or a drone (UAV, Unmanned  
123 Aerial Vehicle) to build a 3D model of the scene (Bemis et al., 2014). The model can be sized and  
124 georeferenced using the knowledge of the geographic position of some objects (i.e., ground control  
125 points) in the scene (Bemis et al., 2014). For this study, the employment of a virtual outcrop allowed  
126 us to accurately map the fracture distribution in our study outcrop.

127

## 128 **2. Geological setting**

129 *2.1. The central Apennines tectonic framework*

130 The central Apennines are an active NE to ENE verging fold-and-thrust belt that started to form in  
131 the late-Oligocene in response to the westward directed subduction of the Adria plate beneath the  
132 European plate (Doglioni, 1991; Carminati et al., 2010). Thrusting scraped-off and piled up the  
133 sedimentary sequence overlying the continental basement of Adria, including a shallow- to deep-  
134 water Upper Triassic to Middle Miocene carbonate succession (Cosentino et al., 2010 and references  
135 therein). Since the Early Pliocene, NE-SW oriented extension started to act in the Central Apennines  
136 to the west of the compressive front, in response to the opening of the Tyhrrenian back-arc basin  
137 (Doglioni, 1991). The compressive-extensional couple has continuously migrated to the northeast  
138 (Cavinato and De Celles, 1999). Extension is currently active in the Central Apennines (D'Agostino  
139 et al., 2001a; Devoti et al., 2010) and is accommodated by normal faults striking mainly NW-SE,  
140 although rare SW-NE trending fault, such as the Tre Monti fault are present (Fig. 1a). These faults  
141 cut through both the pre-orogenic carbonates and the syn-orogenic flysch deposits (Fig. 1a), and their  
142 activity is manifest in the numerous earthquakes that have affected Italy in the recent past, such as  
143 the L'Aquila 2009 (Chiaraluce, 2012 and references therein), and the 2016-17 central Italy seismic  
144 sequences (Chiaraluce et al., 2017; Scognamiglio et al., 2018). The exhumation associated with the  
145 uplift that accompanies the extensional tectonic regime (D'Agostino et al., 2001b; Devoti et al., 2010)  
146 has exposed formerly buried active normal faults that now usually constitute the borders of the  
147 intermountain basins. The Tre Monti fault forms the north-west borders of the Fucino intermontane  
148 basin (Fig. 1a). In the Fucino basin, thrusting occurred from the Late Miocene to Early Pliocene,  
149 whilst the extensional tectonics started in the Late Pliocene and is still ongoing, as testified by the  
150 1915 Avezzano earthquake (e.g., Galadini and Galli, 1999).

151

152 *2.2. The Tre Monti fault*

153 Tre Monti fault has been exhumed from a depth < 3 km (Smeraglia et al., 2016) and crops out as a  
154 series of right-stepping, SE dipping fault scarps for a length of ~ 7 km (Fig. 1b). The fault

155 accommodates a throw that varies from  $\sim 0.7$  km in the SW to  $\sim 2$  km towards the NE (Smeraglia et  
156 al., 2016). The fault scarps juxtapose Early Cretaceous to Miocene carbonates in the footwall with  
157 Pliocene to Holocene continental deposits in the hangingwall (Fig. 1a, b). The predominance of dip  
158 slip slickenlines on the main fault scarps (Fig. 1b; See also Morewood and Roberts, 2000; Smeraglia  
159 et al., 2016; Mercuri et al., 2020) and paleoseismological investigations (Benedetti et al., 2013; Cowie  
160 et al., 2017) indicate that the Tre Monti fault has been active as a normal fault since the Pliocene,  
161 probably acting as a release fault (*sensu* Destro, 1995) for the San Potito – Celano fault (SPCF; Fig.  
162 1a). Finally, the Tre Monti fault has experienced past earthquakes, as suggested by microstructural  
163 studies of the fault core (Smith et al., 2011; Smeraglia et al., 2016, 2017).

164 A key outcrop for the Tre Monti fault zone structure is provided by an abandoned quarry located  $\sim 2$   
165 km WSW of Celano village ( $42^{\circ}04'35''$ N  $13^{\circ}30'00''$ E; see also Fig. 1a, b). The quarry is located  
166 within a portion of a relay zone delimited by two right-stepping segments on the main fault (zoom  
167 in Fig. 1b) and has been named “La Forchetta quarry” in previous studies (Smeraglia et al., 2016,  
168 2017, Mercuri et al., 2020). The quarry extends for  $\sim 200$  m in a NE-SW direction and for  $\sim 100$  m  
169 in the NW-SE direction (inset of Fig. 1b). The south-eastern limit of the quarry is marked by the front  
170 segment of the relay ramp (Fig. 1b-c), which dips ( $\sim 55^{\circ}$ ) to the southeast ( $156^{\circ}$  mean dip azimuth)  
171 (Smeraglia et al., 2016, Mercuri et al. 2020; see also the stereoplot in Fig. 1c). The slickenlines on  
172 the front segment indicate a right-transtensional to right-lateral kinematics (mean rake  $155^{\circ}$ ; see  
173 stereoplot in Fig. 1c). The kinematics observed here may be due to a stress field rotation promoted  
174 by the interaction of the segments that border the relay zone (Mercuri et al., 2020).

175 The fault damage zone is exposed in almost  $360^{\circ}$  perspective on the quarry walls (Fig. 1c) and is  
176 hosted by Lower Cretaceous limestones pertaining to the “*Calcarei Ciclotemici a Gasteropodi e ooliti*”  
177 Formation (Centamore et al., 2006). They were deposited at the transition between tidal flat and  
178 lagoon carbonate platform environments (Fig. 2a) and are organized in metric-scale peritidal cycles  
179 (Fig. 2b), reflecting the variation of accommodation space (c.f., Osleger 1991; D’Argenio et al.,  
180 1997). The supratidal facies comprises light-gray to havana-brown poorly sorted grainstones with

181 radial ooids and pisoids (Fig. 2e, h). The intertidal facies is defined by laminated, white coloured  
182 microbial bindstones with birdseyes and fenestrae (Fig. 2f, i). Finally, the subtidal facies is mainly  
183 composed of white packstones with peloids and oncoids (Fig. 2g, j), although some sporadic  
184 floatstones with gastropods and some oncoidal rudstones are present.

185 The bedding organization is strongly controlled by the relative abundance of the carbonate facies  
186 mentioned above. Where the supratidal and the intertidal are the most abundant facies, the limestones  
187 are arranged in cm- to dm- scale tabular beds (Fig. 2c). Conversely, a predominance of the subtidal  
188 facies has beds that are more than 1 m thick (Fig. 2d).

189

### 190 **3. Methods**

191 In this section, we present the methodology employed to extract fracture properties from scanlines  
192 (section 3.1), samples (section 3.2), and the virtual outcrop (section 3.3).

193

#### 194 *3.1. Scan-lines*

195 We performed 26 scan-line surveys (Priest and Hudson, 1981; see the example in Fig. 3) in the quarry  
196 area (see Section S1.1 for their location). Length, position, and orientation of the scan-lines were  
197 chosen in order to maximise their length and to maintain a sub-horizontal direction in irregular  
198 outcrops. The effective length and the orientation of each scanline is reported in Table S4.1. The  
199 effective length of the scan-line surveys was calculated by subtracting portions of outcrop hidden by  
200 vegetation from their total length. For each scanline survey we collected trace lengths and orientations  
201 of all the fractures (mostly joints, minor shear fractures, and rare veins) intersecting the measuring  
202 tape. For trace length analysis we considered only fractures having both the terminations visible  
203 (~94% of all collected fractures). Fracture orientation was investigated by producing contour plots  
204 with the software Stereonet (Allmendinger et al., 2012; Cardozo & Allmendinger, 2013). The  
205 contours account for the inhomogeneous sampling of fractures along a scanline depending on their  
206 orientation (Terzaghi, 1965). The Terzaghi correction (Terzaghi, 1965) was applied by inserting the



207 trend and plunge of each scanline in the Stereonet software (Allmendinger et al., 2012; Cardozo &  
208 Allmendinger, 2013). When data from scanlines with similar orientations (coming from the same  
209 sector of the quarry) were plotted in a single stereoplot, we applied the Terzaghi correction by using  
210 the mean direction of the scanlines (e.g., Figure 6). We calculated the mean fracture spacing by  
211 dividing the effective length of the scanline for  $(N-1)$ , where  $N$  is the number of fractures intercepted  
212 by the scan-line. The linear fracture frequency, or P10 (Sanderson and Nixon, 2015), was calculated  
213 as the reciprocal of the mean spacing (Fig. 3). Finally, we assigned a carbonate facies to each scanline  
214 through a visual inspection in the field (Table S4.1). Due to the nature of the quarry this was limited  
215 to the intertidal facies and supratidal facies only.

216

### 217 3.2. Samples

218 27 oriented hand-samples (Fig. 4a) were collected, mostly in the same locations as the scanlines  
219 (section S1.2). Oriented samples were cut along vertical sections striking  $\sim 155^\circ$  N (i.e., parallel to  
220 the front fault segment dip), polished, and scanned at a 1200 dpi resolution. Fracture traces were  
221 digitized using a commercial vector graphic software (Fig. 4b). For each sample, we evaluated the  
222 fracture spacing, the linear and areal fracture frequency (P10 and P20 respectively; Sanderson and  
223 Nixon, 2015), and fracture intensity (P21; Sanderson and Nixon, 2015). The spacing and the linear  
224 fracture frequency (P10), were calculated by tracing a series of sub-parallel scanlines on each sample  
225 (Fig. 4c), and following the same procedure adopted for the “regular” scan-lines (section 3.1). The  
226 others fracture properties were extracted using the FracPaQ (v. 2.4) Matlab tool (Fig. 4d; Healy et al.,  
227 2017). This software takes a .svg file containing the polylines of fracture traces as input, and,  
228 according to the parameters inserted by the user, calculates the fracturing properties mentioned above.  
229 We refer the reader to the paper of (Healy et al., 2017) for a complete description of the algorithms  
230 used by the FracPaQ software. For each sample, we inserted the appropriate pixel/m ratio, in order to  
231 obtain the outputs in unit length (Healy et al., 2017). Furthermore, a carbonate facies was assigned to

232 each sample by visual inspection. The lists of fracture parameters obtained are summarised in section  
233 S4.2.

234

### 235 *3.3. Fracture analysis on the virtual outcrop*

236 The photos used for the structure-from-motion algorithm were captured by an Unmanned Aerial  
237 Vehicle survey performed with an Aeromax X4 quadcopter equipped with a Sony Alpha 5000 camera  
238 (Fig. 5a). We collected 650 photos with an overlap of ~ 70% between adjacent pictures. The workflow  
239 we adopted to build the 3D model is very similar to that described by other authors (e.g., Tavani et  
240 al., 2014; Bistacchi et al., 2015; Bonali et al., 2019): photos were aligned through a semi-automatic  
241 identification of common points in adjacent pictures in order to create a point cloud. The point cloud  
242 is subsequently used to build a mesh and, finally, a textured mesh, that is the virtual outcrop (Fig.  
243 5b). The virtual outcrop was scaled and georeferenced with respect to a previous terrestrial laser-  
244 scanner survey (Mercuri et al. 2020). We constructed 6 ortho-mosaics (such as the one represented  
245 in Fig. 5c), with a resolution of 1 pixel per 1 cm, from the virtual outcrop, one for each quarry wall  
246 (labelled with capital letters in the inset in Fig. 6a). We subdivided each ortho-mosaic into several  
247 squares with 5 m side length, to form virtual scan-areas (Fig. 5c, d). The dimension of virtual scan-  
248 areas was established in order to have the side length bigger than most of the fracture trace lengths  
249 observed in scanlines (Fig. S2.1a). The location of all the virtual scan-areas is shown in Section S1.3.  
250 All the processing for the virtual outcrop and ortho-mosaic were executed within the 3DFlow Zephyr  
251 Aerial software. Each scan-area was manually interpreted in Adobe Illustrator® by drawing  
252 polylines, representing the traces of fractures, minor faults, and bedding (Fig. 5e), and polygons to  
253 map the supratidal and the intertidal facies (Fig. 5f). The supratidal and intertidal facies were  
254 recognized by the visible cm to dm thick beds. The fracture analysis was performed in FracPaQ, using  
255 the same parameters as described in the previous section, to evaluate the areal fracture frequency  
256 (P20), fracture intensity (P21), and trace length. We also evaluated the minimum content of supratidal

257 and intertidal facies in each scan-area by calculating their area in  $\text{pixel}^2$  and dividing it by 250,000  
258  $\text{px}^2$  (the scan-area). The fracture analysis results for each scan-area are reported in Section S4.3.  
259 Finally, we captured 420 aerial photos using a Phantom 4 Pro quadcopter. The photos were processed  
260 using the same procedure described above to produce an aerial orthophoto of the quarry. This  
261 orthophoto was used as base map to check the position of all the georeferenced data we collected.

262

#### 263 **4. Results**

264 Fractures in the quarry are mainly joints and shear fractures. Calcite-filled veins are quite rare and, if  
265 present, can be appreciated only at the hand sample scale. Fractures are accompanied by at least 80  
266 minor faults with various orientations and kinematics (Fig. 6; see Mercuri et al., 2020 for further  
267 details). In the present study we distinguish the minor faults from the shear fractures by the presence  
268 of a fault core. Fractures exhibit a centimetre- to a meter-scale trace-length, with modal values  
269 between 10 and 50 cm (Section S2.1). The mean trace length calculated for each scanline is quite  
270 homogeneous throughout the whole quarry and generally smaller than 0.25 m (section S2.2). Virtual  
271 scan-areas suggest that the mean trace length is heterogeneous, with longer fractures located in the  
272 northern (trace lengths  $> 0.58$  m) and in the western ( $0.46$  m  $<$  trace length  $< 0.58$  m) sectors of the  
273 quarry (S2.3). Most of the fractures are sub-vertical and E-W striking, while two minor clusters  
274 indicate the occurrence of sub-vertical fractures striking approximately NE-SW and NNW-SSE (Fig.  
275 6). We do not observe any systematic cross-cutting relationship between the different fracture sets.  
276 Although the entire quarry is characterized by high fracture frequency values, both scanlines and  
277 virtual scan-area show similar fracture frequency distribution patterns (Fig. 6). The portions of the  
278 quarry located immediately at the footwall of the front segment of the relay ramp are characterized  
279 by relatively low fracture frequency values (Fig. 6). On the SW side of the quarry (sectors E and F;  
280 see Fig. 6) the linear fracture frequency (P10) is lower than  $25 \text{ m}^{-1}$ , reaching a value of  $10 \text{ m}^{-1}$  close  
281 to front segment (for the scanline SL13; see S1.2 and S4.1), whilst the areal fracture frequency values  
282 (P20) are lower than  $27 \text{ m}^{-2}$ . The whole NE side of the quarry is characterized by relatively low

283 fracture frequency values (Sector A in Fig. 6); in this sector the linear fracture frequency is generally  
284 lower than  $28 \text{ m}^{-1}$ , although it locally reaches values higher than  $38 \text{ m}^{-1}$  near the front segment (for  
285 the scanline SL12; see S1.2 and S4.1). High linear fracture frequency values ( $P10 \geq 39 \text{ m}^{-1}$ ) are also  
286 located far from the front segment (for scanlines SL21 and 22; see S1.2 and S4.1). The areal fracture  
287 frequency is always smaller than  $34 \text{ m}^{-2}$  in the NE sector of the quarry. The portions of the quarry  
288 located far from the front segment of the relay ramp (sectors B, C, D; see Fig. 6) are characterized by  
289 the highest fracture frequencies. In detail the sectors B and D show areal fracture frequencies reaching  
290 values larger than  $48 \text{ m}^{-2}$ , up to  $60 \text{ m}^{-2}$  (Fig. 6, S4.3). Furthermore, the northern sector shows the  
291 highest concentration of minor faults, that are often associated with foliated breccias (Fig. 6). Breccias  
292 are characterized by anastomosing foliations, consisting of closely spaced undulated, striated slip  
293 surfaces, which are roughly parallel to the associated subsidiary faults (Fig. 7; see also Smeraglia et  
294 al., 2016). At hand-sample scale, the clasts are characterized by chaotic to crackle breccia textures  
295 (Woodcock and Mort, 2008; Smeraglia et al., 2016). The scan-area derived fracture intensity (P21)  
296 distribution mimics the distribution mentioned above (section S3.2).

297 In Figure 8 we show the variation in fracture frequency with distance from the principal fault in the  
298 quarry (i.e., the front segment of the relay ramp). Despite the high variability in fracture frequency  
299 for each fixed distance from the front segment, we recognize a general trend of fracture frequency  
300 increase moving away from the front segment (Fig. 8). The linear fracture frequency measured from  
301 scanlines increases from a median value of  $23 \text{ m}^{-1}$  at distances  $< 60 \text{ m}$  from the front segment to  $32$   
302  $\text{m}^{-1}$  at distances  $> 60 \text{ m}$  (Fig. 8). Analogously, the areal fracture frequency measured from virtual  
303 scan-areas increases with distance from the front fault segment from a median value of  $18 \text{ m}^{-2}$   
304 (distances  $< 60 \text{ m}$ ) to  $29 \text{ m}^{-2}$  (distances  $> 60 \text{ m}$ ) (Fig. 8). Conversely, we do not observe any particular  
305 relationship between fracture frequency/intensity distribution and distance from the front segment  
306 from data retrieved from the oriented samples (section S3.1.4).

307 We observe that supratidal and intertidal carbonates are more fractured than subtidal carbonates both  
308 in scanlines and oriented samples (Fig. 9a,b). The median of the linear fracture frequency retrieved

309 from scanlines measured in supratidal and intertidal facies ( $28 \text{ m}^{-1}$ ) is  $\sim 40\%$  larger than that measured  
310 in subtidal facies ( $20 \text{ m}^{-1}$ ) (Fig. 9a). Intertidal and supratidal oriented samples show median areal  
311 fracture frequencies (P20) that are respectively 170% ( $5.4 \times 10^4 \text{ m}^{-2}$ ) and 100% ( $4.0 \times 10^4 \text{ m}^{-2}$ )  
312 higher than the subtidal samples ( $2.0 \times 10^4 \text{ m}^{-2}$ ) (Fig. 9b). The relationship between fracture  
313 frequency and carbonate facies is clearer in virtual scan-areas (Fig. 9c), where the areal fracture  
314 frequency increases with the supratidal and intertidal content (Fig. 9c). In detail, fracture frequency  
315 ranges between  $10 \text{ m}^{-2}$  and  $30 \text{ m}^{-2}$  for supratidal and intertidal content  $< 50\%$ , whilst it reaches  $\sim 60$   
316  $\text{m}^{-2}$  where the percentage is  $\sim 80 \%$ .

317

## 318 **5. Discussion**

### 319 *5.1 Classical field techniques vs. virtual outcrop models*

320 Our data show a consistent fracture distribution in the fault damage zone in both data retrieved from  
321 the scanlines and from the virtual scan areas (Figs. 6, 8). The strong similarity of results produced by  
322 classical field techniques such as scanlines (Priest and Hudson, 1981; Wu and Pollard, 1995) and by  
323 the virtual scan areas, further demonstrates the high potential of virtual outcrops in structural geology  
324 (e.g., McCaffrey et al., 2005a, 2005b; Tavani et al., 2014; Bistacchi et al., 2015; Cawood et al., 2017).  
325 However, we do observe a small difference between the fracture trace length distribution computed  
326 from scanlines and virtual scan areas (S2.1). This small discrepancy can be only partially attributed  
327 to the employment of a virtual outcrop. We believe that such a difference is due to two main biases.  
328 Firstly, scanlines are subjected to higher censoring effects (e.g., Priest and Hudson, 1981 among  
329 others) than virtual scan-areas. In fact, due to the vertical cliffs of the quarry, the sampling of vertical  
330 fractures longer than  $\sim 2 \text{ m} - 3 \text{ m}$  was impossible during most of the scanlines, whilst all the  $5 \text{ m} \times 5$   
331  $\text{m}$  virtual scan-areas allowed the collection of trace lengths smaller than  $5 \text{ m}$ . Secondly, scanlines  
332 allowed the collection of very small ( $< 10 \text{ cm}$ ) fractures that were quite impossible to identify in  
333 virtual scan-areas. The biases mentioned above produce a censoring of long fractures and

334 oversampling of small fractures during scanlines, and this is evident when the histograms of trace  
335 lengths measured through the two methods are compared (S2.1).

336 The main advantage of using a virtual outcrop is the ability to collect fracture data on inaccessible or  
337 dangerous portions of the quarry. In this way we exploited most of the quarry wall surfaces for data  
338 collection (section S1.3), whilst only the base of the cliffs was analysed with scanlines for safety  
339 reasons (section S1.1). Since we manually interpreted the fractures, the employment of a virtual  
340 outcrop has not provided a consistent advantage in a matter of time efficiency. In fact, in addition to  
341 the generation of virtual outcrop model (photo acquisition and processing), which took about a week  
342 of work, the interpretation of each scan-area took approximately 2 hours, whilst the time needed for  
343 the data collection along a scanline in the field was ~2-3 hours. Despite the time requirements, the  
344 manual interpretation of fractures enabled us to preserve the interpretation ability of the user. In  
345 addition, the virtual scan-areas method enabled us to use the FracPaQ software (Healy et al., 2017)  
346 on the virtual outcrop models (Vinci et al., 2018; Giuffrida et al., 2019), which means that once the  
347 interpretation is complete it is easy to extract in a very short time (few minutes) a large number of  
348 fracture parameters. We believe that an important improvement in time-efficiency for the fracture  
349 analysis from virtual outcrops would be provided by the development of algorithms and workflows  
350 for the semi-automatic identification of fractures (e.g. Vasuki et al., 2014).

351

## 352 *5.2 Fracture density distribution*

353 The employment of scanlines allowed us to collect more than 1800 fracture attitudes (stereoplot in  
354 Fig. 6) that were used as a control on the fracture frequency distribution obtained from the virtual  
355 scan-areas. Fractures are mostly subvertical and strike in an E-W direction ( $\pm 20^\circ$ ). The pole to  
356 such an orientation is coherent with the orientation of the T axis obtained by inverting the kinematic  
357 indicators on the front segment of the relay ramp (stereoplot in Fig. 1c). The other fracture sets  
358 striking NE-SW and NNW-SSE (Fig. 6) are likely to be related to the evolution of the fault structure.  
359 In particular, the NE-SW striking set is coherent with the orientation of the T axis obtained by

360 inverting the kinematic indicators collected on the entire Tre Monti fault (stereoplot in Fig. 1b). The  
361 NNW-SSE striking fracture set can be interpreted as related to the development of the relay ramp:  
362 bending of strata around an axis orthogonal to the main fault segments may lead to ENE-WSW  
363 extension, consistent with the NNW-SSE striking joint set. The data on the widespread population of  
364 fractures, i.e. those E-W striking, may be influenced by the direction of the scanlines, most of them  
365 performed on NW-SE oriented quarry walls (Fig. 6; see also Fig. S1 and Table S4). However, E-W  
366 striking fractures constitute the main set independently on the quarry wall orientation (Figure 6), and  
367 therefore, if present, the bias induced by scanlines orientation is limited.

368 Although many studies have demonstrated that the fracture frequency in fault damage zones increases  
369 moving toward the main fault segment (Brock and Engelder, 1977; Wilson et al., 2003; Faulkner et  
370 al., 2006; Mitchell and Faulkner, 2009; Savage & Brodsky, 2011), in our case study both scanlines  
371 and virtual scan-areas show that fracture frequency increases with distance away from the most  
372 important fault in the outcrop, represented by the front segment of the relay ramp (i.e., moving from  
373 SE to NW; Figs. 6, 8). The observed trend is not due to a geometric bias. Since the most abundant set  
374 is E-W oriented, this has the biggest impact on the fracture density calculation and we would expect  
375 the highest fracture density in the quarry sectors that have an orientation close to N-S (e.g., sectors  
376 A, C, and E; see Fig. 6). Conversely, we observe the highest fracture frequency in sectors B, C and  
377 D (Fig. 6). Therefore, if any geometric bias affects the absolute values of fracture frequency, it would  
378 lead to an underestimation of the rate of fracture frequency increase with distance from the front  
379 segment of the relay ramp.

380 We interpret this unusual trend of fracture frequency to be the result of two main factors. The first  
381 control is structural and related to the higher density of minor faults away from the front segment of  
382 the relay ramp (i.e., in the north-western sector of the quarry; Figs. 6, 10, 11a). In this scenario, due  
383 to the direct relationship between the number of fractures and faults, relatively higher fracture  
384 frequencies reflect the development of fractures pertaining to the damage zones of the subsidiary  
385 faults (e.g., Shipton and Cowie, 2003). The second important control on fracture distribution is played

386 by lithology and, in particular, by the carbonate facies. Approaching the centre of the relay zone we  
387 document an increase in supratidal/intertidal facies (Fig. 11) that are characterized by a higher  
388 fracture frequency (Fig. 9).

389 The role of different carbonate facies in fracture density is further testified by fracture frequency  
390 measured on oriented samples showing that supratidal and intertidal rock samples are more fractured  
391 than the subtidal samples (Fig. 9b). Other authors have shown that carbonate facies can control  
392 fracture spacing in shallow-water limestones because of different Dunham's textures (Wennberg et  
393 al., 2006; Larsen et al., 2010b) or different mechanical properties (e.g., Giorgetti et al., 2016;  
394 Rustichelli et al., 2016). In particular, Wennberg et al. (2006) show that carbonate facies can be even  
395 more important than the mechanical layer thickness if the interbeds are strong (e.g., absence of a well-  
396 developed bedding). In our case study, the effect of carbonate facies on fracture frequency is related  
397 to the supratidal/intertidal facies being characterized by thinner bedding (cm- to dm- scale)  
398 facilitating a larger fracture frequency (Ladeira and Price, 1981; Pollard and Aydin, 1988; Huang and  
399 Angelier, 1989; Narr and Suppe, 1991; Wu and Pollard, 1995; Bai and Pollard, 2000).

400 Independently of the cause, the alternation of subtidal and intertidal/supratidal lithofacies at the  
401 outcrop scale is responsible for the formation of a mechanical stratigraphy, with strongly fractured  
402 intervals confined in the supratidal/intertidal facies beds (Fig. 12a,b; see also Fig. 5e-f). The relative  
403 content of supratidal/intertidal facies plays an important role also in the deformation style developed  
404 in the northern sector of the study outcrop, which is characterized by the presence of foliated breccias  
405 (Fig. 11a). We suggest that during the fault activity, the high fracturing within the supratidal/intertidal  
406 facies increased permeability, favouring the influx of fluids into these portions of the relay zone.  
407 Fluids reacted with the fine grains within the fractured rocks promoting fluid-assisted dissolution and  
408 precipitation mass transfer processes (i.e., pressure-solution; Rutter, 1983; Gratier et al., 1999;  
409 Collettini et al., 2019). In addition, small amounts of clay minerals present in the supratidal facies  
410 (Strasser et al 1999; Fig. 12c) may further enhance pressure-solution (Gratier et al., 1999; Renard et  
411 al., 2001).



412 Since the quarry intercepts only a portion of the relay ramp (see Fig. 10), no constraints allow us to  
413 evaluate whether the fracture intensity distribution was prevalently structurally or lithologically  
414 controlled. We provide two end-member scenario depending on the main controlling factor on  
415 fracture distribution. In a first more conservative scenario, it is assumed that the distribution of  
416 carbonate facies is homogeneous and facies variations control fracture frequency only at metric to  
417 decametric scale (Fig. 13a). As a consequence, the increase of fracture frequency away from the front  
418 segment of the relay ramp is related to tectonic factors, such as the presence of an incipient breaching  
419 zone between the front and rear segment of the relay ramp that is not directly observable in map view  
420 because it is hidden by the presence of Pleistocene breccias (Fig. 13a; see also Fig. 1b). A clue for  
421 the presence of a breaching zone may be represented by the numerous subsidiary faults in the northern  
422 sector of the quarry. In this case, the increase in fracture frequency with distance from the front  
423 segment would be explained by the abandoned quarry intercepting the damage caused by the incipient  
424 breaching zone (Fig. 13a). In a second scenario, the distribution of carbonate facies is assumed as  
425 heterogeneous (Fig. 13b). As a consequence, the damage is heterogeneously distributed, and  
426 relatively higher fracture frequency is expected to follow the primary distribution of supratidal  
427 carbonate facies (Fig. 13b). According to this hypothesis, the increase of fracture frequency moving  
428 away from the fault segment of the relay ramp would be explained by the presence in the northern  
429 sector of the study outcrop, of a stratigraphic interval characterized by a high supratidal facies content  
430 (Fig. 13b).

431 Our results indicate that fracture frequency pattern is very complex in relay ramps hosted in shallow-  
432 water limestones and that its prediction necessitates a good control on structures and sedimentary  
433 facies distribution. We suggest that both of these factors should be considered during fluid flow  
434 modelling within relay ramps hosted in shallow water limestones.

435

## 436 **6. Conclusions**

437 We evaluated the fracture distribution and its controlling factors within a relay ramp damage zone  
438 hosted in shallow water limestones. Combining classical (i.e., scanlines) and modern (i.e., virtual  
439 scan-areas) techniques, we have shown that fracture frequency increases moving toward the centre  
440 of the relay zone. Two main factors can explain this trend:

441 1) The number of subsidiary faults and their associated damage zones accommodating the  
442 development of the relay ramp increases moving toward the centre of the relay zone.

443 2) The supratidal and intertidal carbonate facies abundance increases toward the centre of the relay  
444 zone. All the employed techniques show that supratidal and intertidal carbonate facies are  
445 characterized by higher fracture frequencies than the subtidal carbonates.

446 To conclude, our results highlight that fracture distribution patterns with respect to the main faults  
447 are not easily predictable within a relay ramp, because they can be modulated by subsidiary faults  
448 formation and slip during the relay ramp development. Moreover, carbonate facies may play a non-  
449 negligible role in fracture distribution within fault zones hosted in shallow water carbonates. Our  
450 results therefore provide important suggestions for factors controlling fracture distribution and fluid  
451 flow within relay ramps hosted by shallow water limestones.

452

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886

887 **Figure captions**

888 Figure 1 – Geological setting of the analysed outcrop. (A) Simplified geological map of the Fucino  
889 basin in the central Apennines, Italy (the black arrow in the upper right inset indicates the location).  
890 SPCF: San Potito – Celano Fault. (B) Simplified geological map of the Tre Monti fault area and  
891 zoom of the studied area. (C) Panoramic view of the study outcrop. Stereoplots with Linked  
892 Bingham solution in (B) and (C) show the overall kinematics of the Tre Monti fault and of the front  
893 fault segment in the relay ramp respectively. P: pressure axis; T: tension axis. Blue and red dots are  
894 P and T axis calculated individually for each slickenside data. Kinematic inversions have been  
895 performed using FaultKin (Marrett and Allmendinger, 1990; Allmendinger et al., 2012).

896

897 Figure 2 -Lithological characterization of the damage zone host rock. (A) Cartoon representing the  
898 hypothesized depositional environment of the limestones in the quarry: the transition between a  
899 tidal flat and a lagoon carbonate platform environment. The subtidal facies content increases  
900 moving toward the lagoon environment. (B) Representation of an ideal peritidal cycle with the  
901 associated carbonate facies. (C) Example of an outcrop where supratidal and intertidal facies,  
902 characterized by centimetric to decimetric thick beds, predominate. (D) Outcrop characterized by  
903 the predominance of subtidal facies and characterized by > 1 m thick beds. (E-J): scans (E-G) and  
904 optical micrographs at plane polarized light (H-I) of samples pertaining to the supratidal (E, H),  
905 intertidal (F, I), and subtidal (G, J) carbonate facies.

906

907 Figure 3 – Scanlines. Example of a scanline survey (SL13, see Section S1 for the location) and  
908 linear fracture frequency calculation. L: scanline length; N: number of fractures intercepted by the  
909 scanline; P10: linear fracture frequency.

910

911 Figure 4 – Fracture analysis on the oriented samples. (A) Collected rock sample with marked  
912 orientation. (B) Fracture traces digitized on a high-resolution scan of the sample (dark blue lines).  
913 (C) The linear fracture frequency has been calculated by counting the fracture traces sampled by  
914 sub-horizontal scanlines (yellow lines). (D) Other fracturing parameters such as areal fracture  
915 frequency and fracture intensity have been calculated by using the FracPaQ software (Healy et al.,  
916 2017).

917

918 Figure 5 – Fracture analysis on the virtual outcrop. (A) Unmanned Aerial Vehicle survey in the  
919 study outcrop. (B) Virtual outcrop model of the quarry obtained by a structure-from-motion  
920 processing. (C) Example of an orthorectified panels with 1 mm per pixel resolution extracted from  
921 the virtual outcrop model. A1-12 indicate the label of the virtual scan-areas (D) Example of a  
922 virtual scan-area (A3). (E, F) The orthorectified squares were interpreted by drawing fractures  
923 (yellow lines in panel E), bedding (green lines in panel E), and supratidal/intertidal carbonate facies  
924 (F). The fracture analysis was performed using FracPaQ software (Healy et al., 2017).

925

926 Figure 6 – Fracture frequency and geometry. (A) Space distribution of the linear (diamonds, P10)  
927 and areal (circles, P20) fracture frequencies respectively measured along scanlines and obtained  
928 from virtual scan-areas. The minor faults traces are retrieved from Mercuri et al. (2020). The  
929 stereoplots (Schmidt's net, low hemisphere) show the density contour of the poles to fractures in  
930 different sectors of the quarry (see inset in the upper left). The label of the scanlines used as input  
931 are reported in brackets (B) Density contour plot of the poles to the fractures collected along the  
932 scanlines.

933

934 Figure 7 – Foliated breccias. Photo (A) and interpretation (B) of an exposure of foliated breccias. B:  
935 bedding, F: foliation, J: joints, SS: slip surfaces. The location of the photo is reported in Figure 6.

936

937 Figure 8 – Evolution of the linear and areal fracture frequency with distance from the front segment  
938 of the relay ramp respectively measured through scanlines (blue) and virtual scan-areas (red).

939

940 Figure 9 – Relationship between fracture frequency and carbonate facies. (A) Box plot showing  
941 fracture frequency for different carbonate facies in scanlines (B) Box plot showing fracture  
942 frequency for different carbonate facies in oriented samples (C) Fracture frequency vs. supratidal  
943 and intertidal facies content in virtual scan-areas.

944

945 Figure 10 – Structural control on the fracture frequency. The fracture frequency increases with  
946 density of subsidiary faults that increases moving from SE to NW in the quarry, i.e., approaching  
947 the centre of the relay ramp.

948

949 Figure 11 – Facies distribution in the quarry. (A) Map of the quarry showing the percentage of  
950 supratidal and intertidal carbonate facies measured in the virtual-scan areas. The supratidal and  
951 intertidal content is higher in the north-western sector of the quarry. High supratidal/intertidal facies  
952 contents are often accompanied by the development of foliated breccias. (B) Supratidal and  
953 intertidal carbonate facies content with distance from front segment (i.e. moving toward NW).

954

955 Figure 12 – Damage evolution versus supratidal and intertidal facies content. (A) The alternation of  
956 supratidal/intertidal and subtidal carbonate facies promotes a mechanical stratigraphy. The higher  
957 fracture intensity observed in the supratidal and intertidal facies can be related to smaller thickness  
958 of the beds (cm- to dm-thick, whilst the subtidal facies is characterized by m-thick beds) and to the  
959 development of compartmentalized fractures. The supratidal portions can contain small amount of  
960 clay minerals. (B) The average fracture intensity increases with increasing supratidal/intertidal

961 content for a fixed sampling area (C) Foliated breccias can eventually develop in portions of the  
962 quarry dominated by the supratidal facies.

963

964 Figure 13 – Hypotheses for the role of carbonate facies on fracture intensity distribution. (A)

965 Carbonate facies define a mechanical stratigraphy at metre scale, with highly damaged supratidal  
966 intervals but has no effect on fracture intensity distribution at hundreds of meters scale. (B)

967 Supratidal facies distribution guides the intensity of subsidiary faults and fractures at hundreds of  
968 meters scale. Pleistocene continental breccias (see Fig. 1b) cropping out in the relay zone are not  
969 represented in the cartoon.

970