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

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Abstract

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

1. Introduction

Fractures in the damage zone (Chester and Logan, 1986; Chester et al., 1993) constitute the main pathway for fluids within faults hosted in low-porosity rocks (Caine et al., 1996; Aydin, 2000; Gudmundsson et al., 2001; Bense et al., 2013; Bigi et al., 2013). Fracture frequency and the variation of geometrical and topological properties of fracturing in space are an important control on permeability, and hence on fluid flow and fault mechanics. For example, these variations in these attributes may control traps and leakage points within hydrocarbon reservoirs affected by the presence of faults and promote or prevent local fluid overpressures. A poorly connected fracture system might lead to the development of high fluid pressures, which can in turn influence the evolution of the stress state (Sibson, 1994) with profound implications for earthquake triggering (e.g., Nur and Booker, 1972; Miller et al., 2004). Conversely, a well-connected fracture system prevents the development of fluid overpressures and this leads to the maintenance of a strong but critically stressed crust (Townend and Zoback, 2000). Furthermore, fracture distribution can have a direct effect on fault mechanics: a change of elastic properties of host rock promoted by fracturing may lead to a stress field rotation within damage zone, allowing reactivation of unfavourably orientated faults (Faulkner et al., 2006). Characterization of fracture distribution and its controlling factors is therefore fundamental to better understand fluid circulation and mechanics of fault zones, with obvious consequences for hydrogeology and hydrocarbon exploration. Assessing fracture distribution is particularly relevant for relay ramps (and generally, for zones of faults interaction) as they are commonly characterized by stronger damage than isolated fault segments (Kim et al., 2004; Peacock et al., 2017) and by high structural complexity (Kattenhorn et al., 2000; Peacock et al., 2000; Peacock and Parfitt, 2002; Fossen et al., 2005; Ciftci & Bozkurt, 2007; Bastesen and Rotevatn, 2012; Peacock et al., 2017), with important consequences for fluid flow (Sibson, 1996; Rotevatn et al., 2007; Fossen and Rotevatn, 2016 and references therein).

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

1.1. Factors controlling fracture distribution within fault zones.

Many field and laboratory studies have been carried out to investigate factors controlling fracture distribution within fault zones. A first factor is represented by distance from the main fault: both microfracture and fracture density generally increase moving toward fault core (Brock and Engelder, 1977; Wilson et al., 2003; Faulkner et al., 2006; Mitchell and Faulkner, 2009). However, fracture intensity does not scale with displacement accommodated by the main fault (Anders and Wiltschko, 1994; Shipton and Cowie, 2003). This has been attributed to the existence of a critical value of deformation intensity marking the transition from a strain hardening to a strain softening behaviour induced by the development of slip surfaces (Shipton and Cowie, 2003). Instead, higher displacements accommodated by faults lead to an increase in the damage zone thickness until a critical width is reached (Shipton and Cowie, 2001, 2003; Mitchell and Faulkner, 2009; Savage and Brodsky, 2011). This can be attributed to a continuous development of subsidiary faults producing their own damage zone (Shipton and Cowie, 2003). Other fault-related factors that influence distribution and the geometrical/topological properties of fractures are related to the stress field. For example, the asymmetric pattern of the stress field occurring during the long-term propagation of a fault (Berg and Skar, 2005), and rupture directivity during earthquakes (Dor et al., 2006a, 2006b; Mitchell et al., 2011) may produce an asymmetric damage distribution between hangingwall and footwall, whilst development of local stresses may promote a deflection of fractures (Gudmundsson et al., 2010).

Lithology plays another important role in fracture frequency distribution. A stratigraphic or tectonic juxtaposition of different lithologies leads to contrasts in mechanical properties (e.g., brittleness; Peacock and Xing, 1994) causing a mechanical layering that influences deformation pattern (Tavani et al., 2008), and fracture spacing, propagation and arrest (Odling et al., 1999; McGinnis et al., 2017). In general, fractures tend to form in more brittle layers and they often arrest at interfaces where mechanical contrasts are present (e.g., bedding). For carbonate lithologies, even a variation in carbonate facies at metric to decametric scale can affect fracturing (Wennberg et al., 2006; De Paola et al., 2008; Larsen et al., 2010a, 2010b; Michie et al., 2014; Rustichelli et al., 2016; Volatili et al., 2019). For example, Rustichelli et al. (2016) observed higher fracture intensity, trace length and connectivity in platform compared to ramp carbonates, whilst Larsen and co-authors (2010a, b) found that fractures forming in the subtidal facies tend to arrest in proximity to intertidal laminated limestones. Finally, thickness of sedimentary beds can influence fracturing: a widely observed relationship is that, for strata-bound fractures, fracture intensity is inversely proportional to bed thickness (Ladeira and Price, 1981; Pollard and Aydin, 1988; Huang and Angelier, 1989; Narr and Suppe, 1991; Wu and Pollard, 1995; Bai and Pollard, 2000).

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

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

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

2. Geological setting

2.1. The central Apennines tectonic framework

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

2.2. The Tre Monti fault

Tre Monti fault has been exhumed from a depth < 3 km (Smeraglia et al., 2016) and crops out as a series of right-stepping, SE dipping fault scarps for a length of ~ 7 km (Fig. 1b). The fault accommodates a throw that varies from ~ 0.7 km in the SW to ~ 2 km towards the NE (Smeraglia et al., 2016). The fault scarps juxtapose Early Cretaceous to Miocene carbonates in the footwall with Pliocene to Holocene continental deposits in the hangingwall (Fig. 1a, b). The predominance of dip slip slickenlines on the main fault scarps (Fig. 1b; See also Morewood and Roberts, 2000; Smeraglia et al., 2016; Mercuri et al., 2020) and paleoseismological investigations (Benedetti et al., 2013; Cowie et al., 2017) indicate that the Tre Monti fault has been active as a normal fault since the Pliocene, probably acting as a release fault (sensu Destro, 1995) for the San Potito – Celano fault (SPCF; Fig. 1a). Finally, the Tre Monti fault has experienced past earthquakes, as suggested by microstructural studies of the fault core (Smith et al., 2011; Smeraglia et al., 2016, 2017).

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

The fault damage zone is exposed in almost 360° perspective on the quarry walls (Fig. 1c) and is hosted by Lower Cretaceous limestones pertaining to the “*Calcari Ciclotemici a Gasteropodi e ooliti*” Formation (Centamore et al., 2006). They were deposited at the transition between tidal flat and lagoon carbonate platform environments (Fig. 2a) and are organized in metric-scale peritidal cycles (Fig. 2b), reflecting the variation of accommodation space (c.f., Osleger 1991; D’Argenio et al., 1997). The supratidal facies comprises light-gray to havana-brown poorly sorted grainstones with radial ooids and pisoids (Fig. 2e, h). The intertidal facies is defined by laminated, white coloured microbial bindstones with birdseyes and fenestrae (Fig. 2f, i). Finally, the subtidal facies is mainly composed of white packstones with peloids and oncoids (Fig. 2g, j), although some sporadic floatstones with gastropods and some oncoidal rudstones are present.

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

3. Methods

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

3.1. Scan-lines

We performed 26 scan-line surveys (Priest and Hudson, 1981; see the example in Fig. 3) in the quarry area (see Section S1.1 for their location). Length, position, and orientation of the scan-lines were chosen in order to maximise their length and to maintain a sub-horizontal direction in irregular outcrops. The effective length and the orientation of each scanline is reported in Table S4.1. The effective length of the scan-line surveys was calculated by subtracting portions of outcrop hidden by vegetation from their total length. For each scanline survey we collected trace lengths and orientations of all the fractures (mostly joints, minor shear fractures, and rare veins) intersecting the measuring tape. For trace length analysis we considered only fractures having both the terminations visible (~94% of all collected fractures). Fracture orientation was investigated by producing contour plots with the software Stereonet (Allmendinger et al., 2012; Cardozo & Allmendinger, 2013). The contours account for the inhomogeneous sampling of fractures along a scanline depending on their orientation (Terzaghi, 1965). The Terzaghi correction (Terzaghi, 1965) was applied by inserting the trend and plunge of each scanline in the Stereonet software (Allmendinger et al., 2012; Cardozo & Allmendinger, 2013). When data from scanlines with similar orientations (coming from the same sector of the quarry) were plotted in a single stereoplot, we applied the Terzaghi correction by using the mean direction of the scanlines (e.g., Figure 6). We calculated the mean fracture spacing by dividing the effective length of the scanline for (N-1), where N is the number of fractures intercepted by the scan-line. The linear fracture frequency, or P10 (Sanderson and Nixon, 2015), was calculated as the reciprocal of the mean spacing (Fig. 3). Finally, we assigned a carbonate facies to each scanline through a visual inspection in the field (Table S4.1). Due to the nature of the quarry this was limited to the intertidal facies and supratidal facies only.

3.2. Samples

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

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

3.3. Fracture analysis on the virtual outcrop

The photos used for the structure-from-motion algorithm were captured by an Unmanned Aerial Vehicle survey performed with an Aeromax X4 quadcopter equipped with a Sony Alpha 5000 camera (Fig. 5a). We collected 650 photos with an overlap of ~ 70% between adjacent pictures. The workflow we adopted to build the 3D model is very similar to that described by other authors (e.g., Tavani et al., 2014; Bistacchi et al., 2015; Bonali et al., 2019): photos were aligned through a semi-automatic identification of common points in adjacent pictures in order to create a point cloud. The point cloud is subsequently used to build a mesh and, finally, a textured mesh, that is the virtual outcrop (Fig. 5b). The virtual outcrop was scaled and georeferenced with respect to a previous terrestrial laser-scanner survey (Mercuri et al. 2020). We constructed 6 ortho-mosaics (such as the one represented in Fig. 5c), with a resolution of 1 pixel per 1 cm, from the virtual outcrop, one for each quarry wall (labelled with capital letters in the inset in Fig. 6a). We subdivided each ortho-mosaic into several squares with 5 m side length, to form virtual scan-areas (Fig. 5c, d). The dimension of virtual scan-areas was established in order to have the side length bigger than most of the fracture trace lengths observed in scanlines (Fig. S2.1a). The location of all the virtual scan-areas is shown in Section S1.3. All the processing for the virtual outcrop and ortho-mosaic were executed within the 3DFlow Zephyr Aerial software. Each scan-area was manually interpreted in Adobe Illustrator® by drawing polylines, representing the traces of fractures, minor faults, and bedding (Fig. 5e), and polygons to map the supratidal and the intertidal facies (Fig. 5f). The supratidal and intertidal facies were recognized by the visible cm to dm thick beds. The fracture analysis was performed in FracPaQ, using the same parameters as described in the previous section, to evaluate the areal fracture frequency (P20), fracture intensity (P21), and trace length. We also evaluated the minimum content of supratidal and intertidal facies in each scan-area by calculating their area in pixel^2 and dividing it by 250,000 px^2 (the scan-area). The fracture analysis results for each scan-area are reported in Section S4.3. Finally, we captured 420 aerial photos using a Phantom 4 Pro quadcopter. The photos were processed using the same procedure described above to produce an aerial orthophoto of the quarry. This orthophoto was used as base map to check the position of all the georeferenced data we collected.

4. Results

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

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

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

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

5. Discussion

5.1 Classical field techniques vs. virtual outcrop models

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

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

5.2 Fracture density distribution

The employment of scanlines allowed us to collect more than 1800 fracture attitudes (stereoplot in Fig. 6) that were used as a control on the fracture frequency distribution obtained from the virtual scan-areas. Fractures are mostly subvertical and strike in an E-W direction (± 20°). The pole to such an orientation is coherent with the orientation of the T axis obtained by inverting the kinematic indicators on the front segment of the relay ramp (stereoplot in Fig. 1c). The other fracture sets striking NE-SW and NNW-SSE (Fig. 6) are likely to be related to the evolution of the fault structure. In particular, the NE-SW striking set is coherent with the orientation of the T axis obtained by inverting the kinematic indicators collected on the entire Tre Monti fault (stereoplot in Fig. 1b). The NNW-SSE striking fracture set can be interpreted as related to the development of the relay ramp: bending of strata around an axis orthogonal to the main fault segments may lead to ENE-WSW extension, consistent with the NNW-SSE striking joint set. The data on the widespread population of fractures, i.e. those E-W striking, may be influenced by the direction of the scanlines, most of them performed on NW-SE oriented quarry walls (Fig. 6; see also Fig. S1 and Table S4). However, E-W striking fractures constitute the main set independently on the quarry wall orientation (Figure 6), and therefore, if present, the bias induced by scanlines orientation is limited.

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

We interpret this unusual trend of fracture frequency to be the result of two main factors. The first control is structural and related to the higher density of minor faults away from the front segment of the relay ramp (i.e., in the north-western sector of the quarry; Figs. 6, 10, 11a). In this scenario, due to the direct relationship between the number of fractures and faults, relatively higher fracture frequencies reflect the development of fractures pertaining to the damage zones of the subsidiary faults (e.g., Shipton and Cowie, 2003). The second important control on fracture distribution is played by lithology and, in particular, by the carbonate facies. Approaching the centre of the relay zone we document an increase in supratidal/intertidal facies (Fig. 11) that are characterized by a higher fracture frequency (Fig. 9).

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

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

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

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

6. Conclusions

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

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

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

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

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Figure captions

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

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

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

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

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

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

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

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

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

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

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

Figure 12 – Damage evolution versus supratidal and intertidal facies content. (A) The alternation of supratidal/intertidal and subtidal carbonate facies promotes a mechanical stratigraphy. The higher fracture intensity observed in the supratidal and intertidal facies can be related to smaller thickness of the beds (cm- to dm-thick, whilst the subtidal facies is characterized by m-thick beds) and to the

development of compartmentalized fractures. The supratidal portions can contain small amount of clay minerals. (B) The average fracture intensity increases with increasing supratidal/intertidal content for a fixed sampling area (C) Foliated breccias can eventually develop in portions of the quarry dominated by the supratidal facies.

Figure 13 – Hypotheses for the role of carbonate facies on fracture intensity distribution. (A) Carbonate facies define a mechanical stratigraphy at metre scale, with highly damaged supratidal intervals but has no effect on fracture intensity distribution at hundreds of meters scale. (B) Supratidal facies distribution guides the intensity of subsidiary faults and fractures at hundreds of meters scale. Pleistocene continental breccias (see Fig. 1b) cropping out in the relay zone are not represented in the cartoon.

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