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Structure of a normal seismogenic fault zone in carbonates: the Vado di Corno Fault,
Campo Imperatore, Central Apennines (Italy)

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Keywords: earthquake; Central Apennines; carbonate; fault zone; fault rock;

Abstract

The Vado di Corno Fault Zone (VCFZ) is an active extensional fault cutting through carbonates in the Italian Central Apennines. The fault zone was exhumed from ~2 km depth and accommodated a normal throw of ~2 km since Early-Pleistocene. In the studied area, the master fault of the VCFZ dips N210/54° and juxtaposes Quaternary colluvial deposits in the hangingwall with cataclastic dolostones in the footwall. Detailed mapping of the fault zone rocks within the ~300 m thick footwall-block evidenced the presence of five main structural units (Low Strain Damage Zone, High Strain Damage Zone, Breccia Unit, Cataclastic Unit 1 and Cataclastic Unit 2). The Breccia Unit results from the Pleistocene extensional reactivation of a pre-existing Pliocene thrust. The Cataclastic Unit 1 forms a ~40 m thick band lining the master fault and recording *in-situ* shattering due to the propagation of multiple seismic ruptures. Seismic faulting is suggested also by the occurrence of mirror-like slip surfaces, highly localized sheared calcite-bearing veins and fluidized cataclasites. The VCFZ architecture compares well with seismological studies of the L'Aquila 2009 seismic sequence (mainshock M_w 6.1), which imaged the reactivation of shallow-seated low-angle normal faults (Breccia Unit) cut by major high-angle normal faults (Cataclastic Units).

1. Introduction

Thick carbonate sedimentary sequences (4-10 km) are common within the shallow crust of many seismically active areas worldwide, including the circum-Mediterranean mountain belts. In most of these belts (e.g., the Apennines, Italy; the Hellenides-Dinarides, Balkan Peninsula; the Maghrebides, Algeria–Tunisia) moderate to large earthquakes nucleate and propagate within carbonate host rocks (i.e., limestones and dolostones) (e.g., Di Bucci and Mazzoli, 2003; Burchfiel et al., 2008). Modern advanced geophysical and seismological techniques (e.g., tomographic studies, trapped waves, double-difference method; Waldhauser and Ellsworth, 2000; Di Stefano et al., 2011; Allam and Ben-Zion, 2012) allow to image the geometrical complexity of active buried fault zones with high spatial resolution (i.e., tens of meters) (e.g., Schaff et al., 2002; Chiaraluce et al., 2011; Valoroso et al., 2013, 2014) comparable to the resolution of geological field observations (e.g., Collettini et al., 2014). Therefore, the characterization of the internal structure of exhumed fault zones in the field is even more necessary both for the validation of the remotely acquired geophysical/seismological observations and for the investigation of the deformation processes active at smaller scale during the seismic cycle (e.g., Alvarez et al., 1978; Lavecchia, 1985; Wojtal and Mitra, 1986; Gratier and Gamond, 1990; Willemse et al., 1997; Faulkner et al., 2003; Agosta and Aydin, 2006; Mitchell and Faulkner, 2009; Bistacchi et al., 2010; Mitchell et al., 2011; Fondriest et al., 2012; Tesei et al., 2013; Bullock et al., 2014; Collettini et al., 2014). Regarding the deformation processes, clues can arise from laboratory experiments conducted both on cohesive and non-cohesive rocks (e.g., Paterson, 1958; Rutter, 1983; Verberne et al., 2010; De Paola et al., 2011; Di Toro et al., 2011; Smith et al., 2013) and from detailed microstructural investigations of both natural and experimental fault rocks through different techniques, such as cathodoluminescence (e.g., Clemenzi et al., 2015), electron back scatter diffraction (e.g., Smith et al., 2013), optical-, electron- and atomic force- microscopy (e.g., Siman-Tov et al., 2013; Tesei et al., 2013; Viti et al., 2014), water- and laser-granulometry (e.g., Billi and Storti, 2004; Storti et al., 2007;).

Based on these studies, simplified models of fault zones have been developed to describe the architecture and permeability of fault zones. In particular, they consist of a fault core, where most of the strain is accommodated, surrounded by an intensely deformed damage zone, which grades into a host rock with background deformation level (Chester and Logan, 1986; Caine et al., 1996; Shipton et al., 2006; Childs et al., 2009; Faulkner et al., 2010). The fault core is characterized by intense faulting and includes fault products like gouges, ultracataclasites, cataclasites and breccias (Sibson, 1977). The damage zone generally comprises most of the fault zone volume (up to hundreds of meters in thickness) and includes rocks that underwent fault-related fracturing, veining and subsidiary faulting, but maintain their primary features (Caine et al., 1996; Wibberley et al., 2008). Though this model describes fairly well a number of fault zones in different tectonic settings and lithologies (Faulkner et al., 2003; Wibberley and Shimamoto, 2003; Agosta and Aydin, 2006; Micarelli et al., 2006), it may result oversimplified when the presence of inherited structures developed through different times and kinematics results in complex spatial relationships between high- and low-strain compartments (e.g., Fagereng and Sibson, 2010). This point is of paramount importance in carbonates, which are frequently affected by the presence of joints, pressure solution seams, veins and faults derived from sequential deformation events (e.g., Agosta and Aydin, 2006; Aydin et al., 2010). Moreover, carbonates rocks are frequently characterized by compositional and facies heterogeneities (e.g., bedding thickness variation, laminations, grain size, presence of marl layers) that have a strong influence on rock mechanical and transport properties (Billi et al., 2003; Bonson et al., 2007; Tesei et al., 2013; Bullock et al., 2014; Michie et al., 2014; Tesei et al., 2014).

The carbonate-dominated sequences of the Apennines have experienced the alternation of extensional and compressional deformation regimes since Jurassic times, resulting in a complex structural setting on which the Quaternary extension is superposed (Elter et al., 1975). In particular, the Apennines expose the sedimentary sequences of the passive margin associated with the opening of the Alpine Tethys, subsequently involved in the westward subduction of the African plate underneath Eurasia (Boccaletti et al., 1971; Patacca et al., 1990) starting from the Eocene and the

build-up of the collisional chain (fold-and-thrust belt) from Pliocene onwards (Malinverno and Ryan, 1986; Buiter et al., 1998; Jolivet and Faccenna, 2000; Vezzani et al., 2010; Molli and Malavieille, 2011; Carminati et al., 2012; Cardello and Doglioni, 2014;). Since late Tortonian-Messinian times, the eastward rollback of the subducting plate (Malinverno and Ryan, 1986) resulted in a progressive eastward migration of the fold-and-thrust belt and backarc extension started affecting the upper plate. As a consequence, the former compressional domains in the hinterland of the Apennine belt have been progressively subjected to extension coaxial with compression (Elter et al., 1975; Ghisetti and Vezzani, 1981; Patacca et al., 1990; Jolivet et al., 1998; Rosenbaum and Lister, 2004).

In the Central Apennines, the main topographic divide is located within the Gran Sasso Massif (GSM, the Corno Grande, 2912 m a.s.l. is the highest peak of the Apennines), which marks the eastern limit where active extension occurs (D'Agostino et al., 1998). The GSM is located at the transition between the Mesozoic Latium-Abruzzi carbonate platform and the Umbria-Marche pelagic domain (e.g. Parotto and Praturlon, 1975). The inherited paleogeography influenced both the construction of the thrust belt and the subsequent extension, leading to the formation of a complex array of non-cylindrical thrusts, folds and normal faults whose interpretation is still largely debated (D'Agostino et al., 1998; Calamita et al., 2003a; Speranza, 2003; Speranza et al., 2003; Vezzani et al., 2010; Santantonio and Carminati, 2011; Cardello and Doglioni, 2014). Indeed different authors described the same structural framework as the result of (i) out-of-sequence thrusting with the formation of duplex structures eventually cut by normal faults due to eastward migration of extensional domains (Ghisetti and Vezzani, 1991; Sani et al., 2004; Vezzani et al., 2010), (ii) postorogenic normal faulting due to gravitational collapse of the orogen (D'Agostino et al., 1998), or (iii) alternation of positive and negative stress inversions and subsequent rotation and folding of preexisting faults during the evolution of the belt (Calamita et al., 2003a; Calamita et al., 2003b; Calamita et al., 2008; Cardello and Doglioni, 2014).

Extension in the GSM and surrounding areas occurred since late Pliocene-Early Pleistocene and led to the formation of a series of seismically active extensional fault zones striking NW-SE, which are responsible for major earthquakes in the Central Apennines. A major recent seismic sequence that hit the area was associated with the L'Aquila earthquake ($M_w = 6.1$, April 6th 2009, Chiarabba et al., 2009; Chiaraluce, 2012). There are still uncertainties whether the main shock of the seismic sequence was localized within the crystalline basement or in the overlying ultra-thick (up to 8 km) carbonate succession (Chiaraluce, 2012; Speranza and Minelli, 2014), but it is certain that the mainshock rupture propagated through the carbonate sequence, and that some of the foreshocks and most aftershocks nucleated within and propagated through it (Chiaraluce, 2012). Focal mechanism solutions of the seismic events were mostly normal dip-slip, consistent with the mainshock (strike = $140^\circ \pm 5^\circ$, dip angle = $52^\circ \pm 5^\circ$; rake = $97^\circ \pm 10^\circ$; Chiaraluce, 2012), and just a few focal mechanism solutions showed strike-slip kinematics (Valoroso et al., 2013; 2014).

In this paper we describe the architecture of the Vado di Corno Fault Zone (VCFZ), an extensional fault cutting through a dolomitized carbonate platform sequence in the GSM area, which is a segment of the Campo Imperatore Fault System (CIFS) (Vezzani et al., 2010). Field surveys were performed in the fault footwall block, which is excellently exposed due to the occurrence of a well-developed badland morphology. Several structural units were recognized within the fault zone. The mapped structural units allowed us to document the evidence for a Pliocene dolomitized thrust zone and determine its crosscutting relationships with the Quaternary extensional structures of the VCFZ. Microstructural and field observations suggest that most of the slip surfaces within the VCFZ experienced coseismic deformation. Therefore the VCFZ can be considered as an exhumed analogue of seismogenic sources active in the Central Apennines. Based on this assumption we finally compare the overall geometry and kinematics of the exposed section of the VCFZ (footwall block) with the geophysically imaged structures of the L'Aquila fault system activated during the April 2009 seismic sequence.

2. Geological setting

2.1 The Gran Sasso Massif

The GSM is one of the principal structural features of the Central Apennines and formed during Late Messinian, Early-Middle Pliocene orogenic contraction (Ghisetti and Vezzani, 1991). The main thrust and related anticline display an arcuate geometry that consists of two main segments striking ~ E-W and N-S, respectively (Fig. 1a). The E-W striking segment is characterized by an overturned anticline in the hangingwall, cut by out-of-sequence dip-slip thrusts (e.g., Ghisetti and Vezzani, 1991). The N-S striking segment shows both dip-slip and right-lateral strike-slip components (Speranza et al., 2003; Vezzani et al., 2010). The GSM consists of an array of six major thrust faults crosscutting each other in an out-of-sequence geometry (Ghisetti and Vezzani, 1991) with the uppermost thrust faults outcropping in the Vado di Corno area (i.e., the Omo Morto thrust fault; Ghisetti and Vezzani, 1991; Fig. 1b). Early Pleistocene to Present extension within the GSM is testified by the presence of a well-developed system of active extensional fault zones including the VCFZ described in this manuscript (e.g., D'Agostino et al., 1998; Galadini, 1999).

In the study area, the VCFZ is developed mostly within the same lithostratigraphic unit, namely the *Calcare Massiccio Fm.* (Lower Jurassic; e.g. Adamoli et al., 2012; Fig. 1b-c), which consists of an up to 600 m thick sequence of whitish to brownish limestones with beds (5-50 cm thick) and intervals (1-5 m thick) organized in cyclothems. The cyclothems comprise grainstones, packstones and wackestones with oolites, oncolites, intraclasts, peloids and trails of birdseyes and *fenestrae* (Adamoli et al., 2003). The occurrence of dolostones is frequent. This is the case of the studied outcrops, which are located within a wide band (up to 300 m thick) of intensely deformed dolostones. Exposures of undeformed dolostones are not observed within the study area. Nevertheless, the primary sedimentary and diagenetic features of the dolostones are preserved within low-strain domains embedded within the fault footwall damage zone (see section 5.1 and

Fig. 4). At least two dolostone facies were distinguished: (i) dolomicrite to dolomitic packstone-wackestones with stromatolitic laminations and preserved original microfabric (i.e., allochems of limestone precursor) and (ii) crystalline dolostones with coarser average crystal/grain size, which locally are nodular and porous (*fenestrae*, etc.). The two facies are in stratigraphic continuity or are separated by irregular boundaries (e.g., rock lenses), and are interpreted as the product of different diagenesis (i.e., timing and intensity of dolomitization).

Other lithologies outcropping along the fault zone adjacent to the study area consist of the slope and basinal deposits of the *Corniola* (mudstone, Lower Jurassic), *Verde Ammonitico e Calcari e Marne a Posidonia* (micritic limestone, Lower-Middle Jurassic), *Calcari Bioclastici Inferiori* (breccias and megabreccias Middle-Upper Jurassic) and *Maiolica Detritica* (micritic limestone, Upper Jurassic-Lower Cretaceous) formations (Adamoli et al., 2012). The *Verde Ammonitico e Calcari e Marne a Posidonia Fm.*, hereby simply indicated as *Verde Ammonitico Fm.*, consists of green to dark grey micrite, locally intercalated with marly layers and levels rich in dark chert. To the east of the study area, the *Verde Ammonitico Fm.* is overthrust by the *Calcare Massiccio Fm.* (e.g., Ghisetti and Vezzani, 1991; Adamoli et al., 2012; Fig. 1b-d). In the footwall of the VCFZ, we found local occurrences of strongly dolomitized *Verde Ammonitico Fm.* and associated dark chert remnants, typically underlying the dolomitized *Calcare Massiccio Fm.* This indicates that the stacking exposed to the east, actually occurs also in the footwall of the VCFZ, in the study area, where both units underwent severe dolomitization preceding Quaternary extensional faulting. Small outcrops of the *Maiolica Detritica Fm.* occur in the hangingwall of the fault zone near Mt. Brancastello (Fig. 1d).

The Campo Imperatore intramontane basin, in the hanging wall of the VCFZ, is characterized by glacial, alluvial and colluvial deposits. The former are related to Late Pleistocene glacial events (Giraudi and Frezzotti, 1995, 1997; Adamoli et al., 2012); the latter are Holocene in age and derived from weathering of the exposed carbonate rocks. These loose deposits feed well-

developed alluvial fan systems (Adamoli et al., 2012 and references therein). In this study all these deposits will be comprehensively referred to as *Quaternary deposits*.

2.2. The Vado di Corno Fault Zone

The VCFZ outcrops continuously for ca. 5 km bordering the northern part of the Campo Imperatore intramontane basin (Fig. 1b). The VCFZ belongs to a larger fault system (the so called Campo Imperatore Fault System – CIFS) which runs for ~ 20 km in the Gran Sasso Massif and is thought to have accommodated a cumulative throw of 2000-3000 m (Ghisetti and Vezzani, 1991; D'Agostino et al., 1998; Ghisetti and Vezzani, 1999). The exposed fault zone was exhumed from ca. 1-2 km depth starting from Early-Pleistocene (Agosta and Kirschner, 2003).

Between Vado di Corno and Mt. Brancastello, the VCFZ outcrops almost continuously along about 20 sub-parallel creeks oriented orthogonal to the average strike of the fault zone. The creeks are affected to fast erosion and the resulting badland topography offers a unique three-dimensional view into the fault zone footwall block. With the aim of describing the internal structure of the VCFZ, we performed a detailed survey along the strike of the fault zone and selected a creek (UTM coordinates, zone 33N WGS84, 385611 E, 4700440 N, white arrow in Fig. 1b) that provided a representative cross-section of the fault. Measurements of bedding surfaces (dip azimuth/dip angle N270/20°, Fig. 1e) in the fault zone show a gently W-dipping monocline at the hangingwall block of the GSM thrust.

The seismic activity of the CIFS is documented both by paleoseismological studies and instrumental seismicity (Giraudi and Frezzotti, 1995; Galli et al., 2002; Galadini et al., 2003; ISIDE Working Group, 2010). Trenches dug in the Campo Imperatore basin highlighted at least three main surface ruptures since Late Pleistocene; an earthquake with magnitude up to $M_w = 6.95$ was estimated to be produced in case of activation of the entire extensional Campo Imperatore Fault System (Galli et al., 2002; Galadini et al., 2003). Current seismicity is documented in the GSM; in

particular, the CIFS is characterized by relatively continuous microseismicity with $M_L < 2.5$ (ISIDe Working Group, 2010).

3. Methods

The footwall block of the VCFZ was mapped at 1:500 scale in a selected creek and the adjacent areas (mapped area c. $0.2 \times 0.4 \text{ km}^2$; Fig. 2a) using, as a topographic basis, orthorectified aerial photographs (spatial resolution 0.2 m, courtesy of the Regione Abruzzo: www.regione.abruzzo.it/xcartografia). The resulting structural map of the exposed fault zone is shown in Fig. 2a. The map shows (i) the principal fault strands and (ii) the spatial distribution of fault zone structural units, i.e. rock volumes affected by distinct bulk deformation intensity and, likely, deformation processes. Fault zone structural units were defined on the base of a series of mesoscale observations such as:

- spacing of fractures and subsidiary faults (i.e., faults with outcrop continuity less than 5 m);
- relative abundance and geometry of veins and sealed fractures;
- clast/matrix proportion in the fault rocks;
- color of non-weathered rocks;
- preservation of primary sedimentary features.

In particular, we identified five main structural units within the VCFZ (Fig. 2a): (i) the Low Strain Damage Zone (LSDZ), (ii) the High Strain Damage Zone (HSDZ), (iii) the Breccia Unit (BU), (iv) the Cataclastic Unit 1 (CU1) and (v) the Cataclastic Unit 2 (CU2). In the exposed footwall, the CU1 and CU2 represent the fault core, while the LSDZ, HSDZ and BU represent the damage zone. These data were digitized using ArcGIS© and Move© software.

Structural data, such as attitude of bedding, joints, and veins, orientation and kinematics of faults, and fracture frequency in damage zones, were collected at sites evenly distributed across the

outcrops and located using a handheld GPS (accuracy typically ± 2 m) and along scan-lines oriented perpendicular to the master fault.

Fracture abundance (i.e., areal fracture density and intensity, P_{20} and P_{21} respectively, *sensu* Dershowitz and Herda, 1992) was computed in both the LSDZ and the HSDZ to quantify fault-related damage at increasing distance from the master fault of the VCFZ. The areal fracture density (P_{20}) is defined as number of trace centers per unit sampling area [m^{-2}], while the areal fracture intensity (P_{21}) is defined as length of fracture traces per unit sampling area [m^{-1}]. Since both P_{20} and P_{21} are orientation-dependent, they were measured perpendicular to the principal fracture/fault systems of the structural domain. To prevent bias due to the resolution of the techniques (i.e., data truncation) and the finite size of the sampled domain (i.e., data censoring), measurements were performed on a selected range of fracture length. The upper and lower cutoff were specifically chosen to consider only the linear interval of the trace length distribution in a logarithmic plot (i.e., 0.407-1.125 m and 0.01-0.1 m for the LSDZ and HSDZ respectively). Truncation and censoring take place since the lower cutoff usually exceeds the resolution of the images (typically ≤ 1 cm) and the upper cutoff is smaller than the dimension of the sampled domain. Since the selected range for computing fracture abundance was limited up to two orders of magnitude, we used this data only for comparison between the damage intensity in the LSDZ and HSDZ. For the LSDZ, fracture traces were digitized in Move© on a vertical section oriented perpendicular to the master fault (strike N30°) obtained from a georeferenced photogrammetric model. Traces were then exported in GoCAD© to compute trace properties (centroid distance from the master fault, trace length, trend and plunge). Finally, fracture statistics were computed with an *ad-hoc* Matlab© script. For the HSDZ, traces were mapped in ArcGIS© on smaller image frames oriented both parallel and perpendicular to the master fault (window sampling dimension 60 x 40 cm, photo resolution < 1 mm). Fracture statistics were then calculated using the same Matlab© script as for the LSDZ.

The acquisition of structural data ($n = 965$) was coupled with the collection of oriented fault rock samples ($n = 87$) to characterize the microstructures and mineralogy of the host rock, veins and

slipping zones. Microstructural observations were conducted on polished thin sections ($n = 40$) cut perpendicular to the veins and the slip surfaces and oriented either parallel or perpendicular to fault lineations, using transmitted-light optical microscopy (OM), field emission scanning electron microscopy (FE-SEM), and optical microscopy cathodoluminescence (OM-CL). Mineral phase identification and elemental analysis were performed through energy dispersive spectroscopy (EDS) at the FE-SEM, while bulk mineralogy was derived from X-ray powder diffraction (XRPD) analyses. Analyses were conducted at the Department of Geoscience in Padua (Italy) and at HT-HP laboratories at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome (Italy).

4. Cross-sectional structural architecture

The VCFZ in the mapped creek consists of an array of $\sim$ NW-SE striking, mostly SW dipping, fault surfaces. The major ones can be easily followed in the field for distances of 20-30 m and are characterized by strong shear strain localization within layers of cataclasite with thickness up to 30 cm. They bound different structural units both in the fault core and in the damage zone (Fig. 2a-b). At the base of the badlands, the contact between the cataclastic rocks and the hangingwall Quaternary deposits is marked by a polished fault slip surface with average dip azimuth/dip of N209/54° and average pitch of 80° to the E (Fig. 3a). The fault is assumed to be the master fault because (i) it marks the major discontinuity between the Quaternary alluvial deposits of the Campo Imperatore intramontane basin in the hangingwall block and the Jurassic carbonates in the footwall block (Fig. 3b) and, (ii) it is associated with a $\sim$ 40 m thick cataclastic fault core (CU1) in the footwall block. The master fault principal slip zone consists of a $\sim$ 20 cm thick cataclastic layer with mixed hangingwall and footwall materials, characterized by up to two-centimeter-thick, cohesive injections of reddish and whitish ultracataclasites (Fig. 3c). The boundaries of the injected ultracataclasites are wavy and resemble fluidization features (e.g., Brodsky et al., 2009). Moreover, they are truncated by sharp slip surfaces (Fig. 3c) (e.g., Siman-Tov et al., 2013).

A representative cross-section of the VCFZ footwall is provided in figure 2b. The CU1 lines the master fault forming a continuous ~ 40 m thick band. Moving to the NE, the CU1 grades into the CU2, which crosscuts the BU along a SW dipping major synthetic normal fault. The BU is the lowermost structural unit, which outcrops along the bottom of the creek, with the mean attitude of a gently SW dipping flat (Fig. 2a). The BU is embedded within the damage zone units (LSDZ and HSDZ) (Fig. 2a-b), which show a sharp fault contact with the cataclastic rocks (CU1 and CU2). Most of the damage zone volume consists of HSDZ, while the LSDZ represents a ca. 20 m thick isolated block (in direction orthogonal to the Vado di Corno master fault) embedded within the HSDZ. Bands of cataclastic rocks (mostly CU1) up to few meters thick were also documented along major fault strands in the outer part of the VCFZ up to distances of hundreds of meters from the master fault. Smaller volumes of LSDZ occur also in the northernmost outer portion of the creek towards the mountain ridge.

The faults in the footwall damage zone typically show high dip angles ($> 70^\circ$) and are organized in two main sets synthetic and antithetic with respect to the master fault. A third set striking NE-SW is also present (Fig. 3d). Synthetic faults include two subsets with attitude (dip azimuth/dip angle) N195/75° and N225/80°, while the average orientation of antithetic faults is N50/85°. NE-SW striking faults control the topography in the upper part of the creek (usually at distance greater than 100 m from the master fault) and dip both towards SE and NW. Grooves and fault lineations are generally dip-slip for synthetic faults, while antithetic- and NE-SW striking faults exhibit both dip-slip and left- (rarely right-) lateral slip kinematics. The absence of clear markers makes difficult to estimate the amount of offset accommodated by individual faults. Poles to joints (opening mode fractures) are at high angle and show different orientations with clustering around the orientations of the faults (Fig. 3d).

5. Structural units

5.1. Low Strain Damage Zone

The *Low Strain Damage Zone (LSDZ)* consists of relatively poorly deformed rock volumes, where sedimentary features of the host rocks such as bedding surfaces, stromatolitic lamination, planar trails of *fenestrae* and “burial” stylolites/pressure solution seams are well recognizable (Fig. 4a-b). In the selected creek, the LSDZ outcrops as a ca. 20 m thick block (measured orthogonal to the master fault, Fig. 2a). Smaller volumes of LSDZ, less than 15 m thick, are found in the upper part of the mountain ridge (i.e., upper right part in Fig. 2a). Faults within LSDZ are spaced 1 to 15 m apart and dislocate strata with normal separation (i.e., displacement) < 1 m. Joints are the most abundant deformation features, with minor strata-bound calcite and dolomite veins, and subsidiary faults (Fig. 4a-b). Since most faults and fractures in this area are synthetic and antithetic to the master fault (Fig. 4c), areal fracture density and intensity were calculated on a continuously exposed outcrop oriented at high angle to the master fault that have been projected in Move© on a vertical cross section perpendicular to the master fault (Fig. 4d). Fracture abundance was computed for fracture traces with length in the range 0.407 – 1.125 m and resulted in $P_{20} = 3.3 \text{ m}^{-2}$ and $P_{21} = 1.96 \text{ m}^{-1}$. Veins are typically arranged perpendicular to pressure solution seams and have aperture up to 0.2 mm for calcite and 2-3 mm for dolomite veins. Calcite veins have a lateral continuity typically < 10 cm, while dolomite veins have lateral continuity usually 10-15 cm and are spaced up to few centimeters apart. Systematic cross-cutting relationships suggest that calcite-filled veins are younger than the dolomite-filled ones (Fig. 4e).

5.2. High Strain Damage Zone

The *High Strain Damage Zone (HSDZ)* consists of fractured rock volumes with significantly higher fracture density/intensity with respect to the LSDZ. The HSDZ is the structural unit that occupies the largest volume within the VCFZ (thickness of 150 – 300 m measured orthogonal to the master fault). Faults are few and spaced 5-15 m apart. Fracturing is pervasive and typically results from the intersection of three to five sets of joints isolating rock fragments down to 1-2 cm in size

(Fig. 5b). In this structural unit, fracture attitude is scattered and is associated to synthetic, antithetic and NE-SW striking faults (Fig. 5a). Veins are less frequent. Here, the higher fracture intensity makes the recognition of primary sedimentary features much more difficult compared to LSDZ. Quantitative scan-areas were performed on image frames oriented both parallel and perpendicular to the master fault (frame attitudes were N204/74° and N292/66°, respectively). For sampling windows oriented perpendicular to the master fault, $P_{20} = 5170 \text{ m}^{-2}$ and $P_{21} = 124.454 \text{ m}^{-1}$ (fracture trace length range 0.01 – 0.1 m, Fig. 5c). For sampling windows oriented parallel to the master fault, $P_{20} = 5107 \text{ m}^{-2}$ and $P_{21} = 118.377 \text{ m}^{-1}$ (fracture trace length range 0.01 – 0.1 m, Fig. 5d).

5.3. Breccia Unit

The BU consists of rocks that show evidence of pervasive secondary dolomitization of the host rock and dolomite veining. This structural unit is strictly related to areas where the *Verde Ammonitico* Fm. is exposed and at the outcrop scale it mainly consists of grey, green to brownish in color fault rocks (Fig. 6a), which can be classified mostly as cohesive crush breccias (Sibson, 1977). Following the classification proposed by Mort and Woodcock (2008) the breccias should furthermore be classified as “mosaic-crackle breccias” (i.e., clast concentration > 60%, clast rotation < 20 %). The BU typically outcrops (i) at the bottom of the creeks, (ii) associated with NNE-SSW striking low-angle (dip angle 20-40°) oblique faults with contractional S-C cleavages and R-shear fractures (Riedel fractures) or (iii) related with low-angle normal faults characterized by an older-on-younger “stratigraphy” (Fig. 6b-c). The transition to the less deformed structural units of the damage zones is typically gradational, i.e. characterized by progressively decreasing vein intensity, while the transition to the cataclastic rock is generally sharp and fault-bounded (e.g., Fig. 6b). Faults inside the BU are few and have polished to mirror-like slip surfaces associated with very localized cataclastic to ultracataclastic brownish slipping zones with thickness up to 5-10 cm. Major faults (i.e., fault that can be followed in the field for more than 10 m) within the BU are usually lined by < 50 cm thick fault cores.

Dolomite veins in less brecciated areas have large lateral continuity (up to few meters), planar geometries and large aperture (2-3 cm at maximum, 5-6 mm on average). They are typically found in conjugate sets dipping perpendicular (NW-SE and NE-SW striking with dip angle 75-85°) and parallel to low-angle bedding surfaces (Fig. 6d-e); however, when approaching subsidiary faults, veins are arranged in chaotic networks that overprint tectonic brecciation. Breccia clasts (up to tens of centimeters in size) are generally angular but locally show irregular cusped-lobate boundaries related to a diffuse presence of dolomite veins (Fig. 6f).

5.4. Cataclastic Units

The cataclastic structural units include mainly fault rocks of the “cataclasite series” according to the definition by Sibson (1977) (i.e., volumetric matrix content of 10-50% for a protocataclasite, 50-90% for a cataclasite and 90-100% for an ultracataclasite); therefore we called it “cataclastic unit” (CU). At the outcrop scale, depending of the grade of cataclasis and preservation of the protolith, two subunits of the CU, called *cataclastic unit 1* (CU1) and *cataclastic unit 2* (CU2) respectively, were identified. The contact between CU1 and CU2 can be both sharp (i.e., marked by faults) or transitional (i.e., gradual change in fabric from CU1 to CU2). In the latter case, the contact between the CU1 and CU2 is usually mapped where one subunit becomes dominant in terms of volume with respect to the other one.

5.4.1. Cataclastic Unit 2

The CU2 comprises brownish proto-cataclasites and cataclasites where the original fabric of the protolith is still recognizable (Fig. 7a). Clasts (cm- to tens of cm in size) are pervasively fractured *in-situ* down to the millimeter scale (*in-situ* shattering *sensu* Brune, 2001). At the outcrop scale, the CU2 exhibits great variability in the fabric depending on the source rock (e.g. *Calcare Massiccio* rather than *Verde Ammonitico*). In particular, the occurrence of heterogeneities in the protolith, such as the alternation of facies in the *Calcare Massiccio Fm.* or chert nodules in the

Verde Ammonitico Fm., typically result in a lower intensity of deformation of these features and their preservation within the CU2.

At the outcrop scale, the CU2 is cut by a relatively dense network of dolomite- and calcite-bearing veins and veinlets (maximum aperture 1 cm), which contribute to seal the entire fragmented rock volume (Fig. 7b). Most of the veins have scarce lateral continuity (up to few 10s cm for dolomite veins and < 10 cm for calcite veins) and irregular shape possibly due to subsequent shearing/rotation and complex cross-cutting/abutting relationships among the different sets of veins and faults. Their attitude distribution is scattered though veins have often high dip angles (i.e., > 70°, Fig. 7c). Pockets of “microbreccias” (clasts size less < 1 mm) are observed within the CU2 as consequence of the complex intersection of branching of larger veins (Fig. 7d). The “microbreccia” clasts are typically separated by microcrystalline calcite-filled veins (crystal size 5-10 µm) and often seem to be not in contact.

5.4.2. Cataclastic Unit 1

The CU1 consists of a white in color, fine-grained (average grain size <1-2 mm) and calcite cemented ultracataclasite (Fig. 8a). Well-rounded “survivor” clasts in the cataclasite are few and usually small in size (usually <1-2 cm). Locally, the CU1 includes lithons of the CU2 up to tens of meters in size (Fig. 8b), which are bounded or cross-cut by minor faults, or are in contact with the surrounding cataclasite through irregular wavy contacts.

At the microscale, calcite veins have sharp boundaries, are arranged in en-echelon or branching arrays and are often cross-cut and displaced by shear fractures with an offset typically < 1 mm (Fig. 8c). Small calcite veins with fuzzy boundaries, irregular geometries and lateral continuity of few millimeters are also frequent. Veins are filled by blocky calcite crystals with average size of 10-50 µm. The CU1 typically contains polished (i.e., mirror-like) slip surfaces (Fig. 8d) associated with cataclastic and ultracataclastic bands with foliated and non-foliated fabric (see section 6 for an extensive description of the slipping zones). The mirror-like slip surfaces sharply

truncate dolostone and small calcite clasts (grain size $< 10 \mu\text{m}$) (Fig. 8d) and are often decorated by iron oxides and hydroxides. Fault spacing is usually less than 10 cm. In places, mm- to cm thick deformation bands (i.e., narrow tabular structures with limited shear offset, Fossen et al., 2007) were found in the granular cataclastic unit (Fig. 8e).

6. Microstructures of the slipping zones

The five structural units of the VCFZ are cut by faults with different types of slipping zones including: (1) highly localized sheared calcite veins, (2) non-foliated cataclasites to ultracataclasites, (3) foliated ultracataclasites with flow structures, and 4) deformation bands. Slipping zones (1), (2) and (3) are often bounded by mirror-like principal slip surfaces. Here we define the slip surface as the fault surface itself, sometimes containing slip direction indicators such as slickenlines and surface grooves (Smith et al., 2011). The slipping zone, up to several centimeters thick, develops beneath the slip surface and consists of variously developed fault rocks described following the classification of Sibson (1977). Together, the slip surface and the slipping zone are thought to accommodate the bulk of displacement during seismic faulting (Sibson, 2003). In addition, we define the principal slip surface (PSS) as the slip surface on which the majority of the displacement is thought to be accommodated.

6.1. Highly localized sheared calcite veins

Locally within the CU1 shear deformation is accommodated within up to $200 \mu\text{m}$ thick slipping zones exploiting preexisting calcite veins. The latter are up to $300\text{-}500 \mu\text{m}$ thick and sealed by undeformed polygonal calcite crystals with an average size of ca. $50\text{-}100 \mu\text{m}$ (Fig. 9a). Instead, slipping zones contain fine-grained calcite crystals 50 nm to $1 \mu\text{m}$ in size rimming sub-angular to rounded micrometer in size dolomite grains (Fig. 9b). The calcite grains are often euhedral and with straight boundaries terminating in triple junctions decorated by nanometric in size pores (foam

texture, Fig. 9c). The sheared calcite veins are cut by sharp, ultra-smooth slip surfaces truncating larger dolostone grains ($>100\ \mu\text{m}$ in size) (Fig. 9d). The sheared veins record multiple cycles of fracture opening – calcite deposition – shearing, as suggested by the occurrence, within the same slipping zone, of multiple slip surfaces and deformed veins (Fig. 9e). Both undeformed veins and sheared veins sub-parallel and at high angle to the principal slip surface are observed, with the high angle sheared veins frequently dislocating the subparallel ones (Fig. 9a-e).

6.2. *Non-foliated cataclasites*

Most slipping zones of the CU1 and CU2 – and few of the BU – are 5 cm to 30 cm thick and consist of dolomite-built cataclasites grading into ultracataclasites (Sibson, 1977) (Fig. 10a). The non-foliated cataclasites consist of angular to sub-rounded dolostone clasts (size $< 1\ \text{cm}$) immersed in a matrix of sub-angular dolostones grains (size below $50\ \mu\text{m}$ down to $1\ \mu\text{m}$). Extended areas and bands of calcite cement with $10\text{-}20\ \mu\text{m}$ in size polygonal crystals occur locally as infilling of pores in the dolomite matrix (Fig. 10b). Moving towards the principal slip surface, the volume of matrix increases and the cataclasite grades into ultracataclasites. Both cataclasites and ultracataclasites contain reworked clasts derived from fragments of older slipping zones or from the fragmentation of the calcite cement. Both synthetic and antithetic Riedel shear fractures and stylolites are occasionally found within the ultracataclasites.

Some of the cataclasites include up to 1 cm in size radially fragmented dolostone clasts immersed in a matrix made of angular dolostone clasts with evidence of splitting down to the micrometer scale (Fig. 10c-d). These fault rocks lack clear evidence of shear strain accommodation and are interpreted as the result of *in-situ* shattering (Fondriest et al., 2015; Schröckenfuchs et al., 2015). Minor faults cutting the LSDZ and HSDZ are usually associated with slipping zones with a proto-cataclastic fabric (volumetric matrix content $< 20\%$). Most of the slipping zones described above and in particular those associated to cataclasites, ultracataclasites and *in-situ* shattered fault rocks, are cut by polished and ultra-smooth mirror-like slip surfaces truncating large dolostones

clasts (Fig. 10e).

6.3. Foliated cataclasites

Some of the dolomite-rich cataclasites with the highest content ($> 30\%$ in volume) of calcite as cement-rich areas or bands display a peculiar “foliated” fabric. These “foliated cataclasites” consist of bands of fragmented dolomite clasts (grey in BSE-SEM images) alternating with either patchy or more continuous layers of sheared calcite matrix (white in BSE-SEM images) (Fig. 11a). The calcite layers contain clasts from few to hundreds of micrometers in size arranged in a S- or C-type foliation consistent with the shear sense of the slipping zone (Fig. 11a). Elongated “tails” of fine-grained dolomite and calcite matrix (down to few micrometers in size) wrap larger dolomite and calcite clasts. Similar microstructures have been documented by Smith et al. (2016) in rotary shear experiments performed at seismic slip velocity in mixed calcite/dolomite gouges and resemble porphyroclastic systems in mylonites (e.g., Passchier and Trouw, 2005) or rigid grains suspended in foliated clay-rich fault gouges (Cladouhos, 1999). The foliated calcite-rich matrix is microstructurally similar to the one found in sheared calcite veins (see Fig. 11b and 8c).

Foliated cataclasites and ultracataclasites made of dolomite/calcite mixtures are frequent within the CU1 and CU2 and decorate the faults marking the contact between the two structural units. Moreover, the pluri-centimeter thick slipping zone associated with the master fault and bordering the Quaternary deposits consists of reddish and whitish foliated ultracataclasites (Fig. 3c). Here, ultracataclasites consist of dolomite and calcite (reddish in color ultracataclasite) or dolomite (whitish ultracataclasite) clasts $< 200\ \mu\text{m}$ in size immersed in an ultra-fine grained ($< 1\ \mu\text{m}$) foliated dolomite matrix with calcite cement (Fig. 11c). Rounded clasts of microcrystalline chert (up to hundreds of micrometer in size) and fine-grained iron oxides suggest mixing of quaternary-derived material within the slipping zone.

The occurrence of fluidization structures such as (i) cataclastic to ultracataclastic layers with

irregular cusped-lobate boundaries (Fig. 11c), and (ii) injection veins filled with micrometric calcite crystals or cement-supported ultracataclasites (Fig. 11d), is widespread in the slipping zones lining the master fault and also within some of the foliated cataclasites of the CU and BU. In addition, many of the dolomite-calcite foliated cataclasites and ultracataclasites are cut by mirror-like surfaces with truncated grains.

6.4. Deformation bands

Few-millimeters-thick deformation bands are observed to cut through the CU1 in areas where the cataclasites appear less cemented or even loose (Fig. 8e). These granular bands are found in the footwall within a maximum distance of 10-20 m from the master fault. According to Fossen et al. (2007), these features can be classified as cataclastic bands since they cut through relatively high porosity cataclastic material and are characterized by a less porous core, which has undergone grain size reduction by cataclasis and pore-space collapse. The cataclastic bands are up to 2-3 mm thick, consist of fine-grained comminuted dolomite (average grain size $< 10 \mu\text{m}$) with some larger dolomite clasts up to 300-500 μm in size and very rare calcite cement (Fig. 11e-f). The latter occurs in areas with crystals that are usually 10-20 μm in size. The core of the cataclastic bands is typically 200-400 μm thick and exhibits a grain-size reduction that goes down to less than 1 μm (Fig. 11f). Clasts with size $> 10 \mu\text{m}$ often have an angular shape, with fracturing occurring along cleavage surfaces; conversely, clasts $< 5 \mu\text{m}$ in size are rounded and may form intra-clast bridges. Due to lack of structural markers in the walls, offset cannot be calculated, though it is likely that cataclastic bands accommodated some shear strain other than only compaction.

7. Discussion

7.1. Structural complexity of the VCFZ

The spatial distribution of the mapped structural units and the orientation of joints and subsidiary faults in the damage zone, support their genetic link with the activity of the VCFZ (e.g., Destro, 1995; Bai and Pollard, 2000). The occurrence of the LSDZ as an isolated fault bounded block adjacent to the fault core is interpreted as the expression of differences in the protolith (bed thickness, grain size, presence of fenestrae, etc.), which have resulted in a minor overall deformation. However, the limited three-dimensional exposure of this block in the field inhibits a more comprehensive understanding of the spatial relationship with the surrounding structural units. The strike-slip kinematics of NE-SW striking high-angle faults in the upper part of the creek are interpreted as tear faults likely accommodating lateral variations in displacement within the VCFZ. The occurrence and geometry of secondary dolostones and related veins (i.e., BU), developed in the *Calcare Massiccio* and *Verde Ammonitico* formations raises the question whether this major dolomitization pulse was triggered by thrusting or Quaternary extension. The evidence that secondary dolostone pervasively occurs along a shallow-dipping zone involving both protolith lithologies implies that dolomitization exploited the thrust damage zones, thus being synchronous to or postdating the contractional event responsible for the tectonic juxtaposition of the *Calcare Massiccio* onto the *Verde Ammonitico*, well preserved to the East (Fig. 1b). On the other hand, secondary dolostones are systematically crushed within fault rocks of the CU1, unequivocally associated with the Quaternary master fault, indicating that dolomitization preceded extensional faulting. Moreover, cataclasites are cemented by calcite veins. The latter have also been involved in the deformation, thus providing another indirect evidence for the different environmental conditions during extension. It follows that the relative timing of the major dolomitization pulse can be constrained as syn- to post-thrusting in the area, but still in the contractional tectonic regime (Middle to Late Pliocene). A detailed study of the evolution of dolomitization is out of our purposes in this work and is the subject of specific ongoing research.

In the study area, the presence of the thrust did not affect the extensional fault geometry, which cuts through the pre-existing structural fabric, but the related dolomitization is inferred to

have influenced both the width of the footwall damage zone and the frequency and density of fracturing within the high- and low-strain structural units.

7.1.1. Origin of the CU

Field and microstructural observations, including fragmentation in the cataclasites locally showing lack of shearing, suggest that *in-situ* shattering (equivalent to rock pulverization in crystalline lithologies), played a major role in the early stages of formation of the CUs. Pulverized fault rocks are rock volumes that appear to have been shattered *in-situ*; they typically have very fine grain size (i.e., < 1 mm) and lack of evidence of significant shearing. *In-situ* shattering has been already reported both in crystalline (Brune, 2001; Dor et al., 2006a, 2006b; Mitchell et al., 2011) and carbonate fault zone rocks (Agosta and Aydin, 2006; Fondriest et al., 2015; Schröckenfuchs et al., 2015).

Both theoretical and experimental investigations (e.g., Ben-Zion and Shi, 2005; Dor et al., 2006a, 2006b; Doan and Gary, 2009; Yuan et al., 2011) suggest a coseismic origin for pulverized rocks, and interpret rock pulverization as a consequence of high strain rate dynamic loading associated with the propagation of single or multiple earthquake ruptures along faults with different geometries and kinematics. More recently Doan and d'Hour (2012) and Aben et al. (2016) demonstrated that multiple milder dynamic loadings can lead to the development of pulverization bands up to hundreds of meters thick without invoking the large scale propagation of supershear rupture fronts, which are generally infrequent rupture modes (i.e, reported for straight and long boundary faults; e.g., Bouchon et al. 2003). In the VCFZ the CU1 forms a continuous band almost 40 m thick lining the master fault and is characterized by a rather homogeneous cataclastic fabric with a very fine grain size (<1-2 mm). Minor faults within the CU1 are associated with thin ultracataclastic layers that cross-cut each other but do not affect the entire cataclastic rock volume. Small rock volumes (few meters at maximum) affected by intense fracturing but lacking significant shear deformation are embedded within the CU1 (Fig. 8f-g). Moreover, looking at the microscale

within the cataclastic rocks, exploded clasts and relics of older *in-situ* shattered microstructures were often observed. This suggests that the propagation of multiple seismic ruptures (see section 7.2) might have produced *in-situ* shattering up to several meters from the master fault (Fig. 12a-d). During each shattering event, coseismic strain localization along multiple slip surfaces evenly distributed in the fractured rock mass was likely to be activated (Ma and Andrews, 2013; Fondriest et al., 2015). Further displacement and strain (i.e., widening of the single cataclastic bands) were then accumulated during post-seismic and interseismic stages (Fig. 12c-d). Therefore the occurrence of multiple shattering episodes which produced thick bands of intensely fragmented rocks, subsequently affected by shear strain localization, can explain the development of a 40 m thick homogeneous CU1 which would be difficult to develop only by catclasis.

7.2. Evidence of coseismic slip

Field and microstructural observations of faults and fault zone rocks suggest the propagation of seismic ruptures within the VCFZ. Faults are typically characterized by the presence of polished (i.e. mirror-like) slip surfaces associated with ultracataclastic and cataclastic slipping zones. Mirror-like slip surfaces are common in faults cutting carbonates (Fondriest et al., 2012; Siman-Tov et al., 2013; Tesei et al., 2013) and are described as naturally polished fault surfaces with high visible-light reflectivity, which implies an extreme smoothness at the microscale, below the wavelength of visible light (e.g., Siman-Tov et al., 2013). Recent experimental studies on both dolomite and calcite gouges and solid rocks (Fondriest et al., 2013; Smith et al., 2013; Siman-Tov et al., 2015; Smith et al., 2015) show that mirror-like slip surfaces form at seismic slip rate (~ 0.1 -1 m/s) and are associated with strong dynamic weakening and shear strain localization. Conversely to mirror-like surfaces formed at sub-seismic slip rates (~ 10 $\mu\text{m/s}$) in calcite gouges (Verberne et al., 2013), mirror-like surfaces produced at seismic slip rates (~ 1 m/s) sharply truncate large grains (hundreds of micrometers in size) and cover most of the experimental fault surface (Fondriest et al., 2013; Siman-Tov et al., 2015). Therefore, the occurrence within the VCFZ of mirror-like fault surfaces

truncating mm- to cm-in size grains (e.g., Figs. 8d; 9e) is a potential indicator of seismic rupture propagation.

A further possible evidence of seismic slip along the studied faults is the presence of sub-micrometric calcite euhedral grains organized in a foam texture in the sheared calcite veins (Figs. 8c; 10b). Similar microstructures were produced in experiments simulating seismic slip in calcite and dolomite gouges (De Paola et al., 2011; Fondriest et al., 2013; Smith et al., 2013; De Paola et al., 2015; Green et al., 2015; Mitchell et al., 2015; Smith et al., 2015). These foam-like textures were associated with grain-size dependent (grain boundary sliding aided by diffusion creep) fault weakening mechanisms activated during seismic slip (De Paola et al., 2015), possibly followed by sintering processes occurring at the end of seismic slip (Di Toro et al., 2015; Green et al., 2015). Moreover, these microstructures were found to be spatially related to both sheared and undeformed calcite veins sub-parallel to fine-grained ultracataclastic principal slip zones. This and the above observations are in good agreement with microstructures from other carbonate-bearing faults, in which a close association of mirror-like slip surfaces, ultracataclasites, principal slip zone veins and fluidized cataclasites was also observed (e.g., Tesei et al., 2013). The sequential opening and shearing of veins sub-parallel to localized slipping zones suggest the cyclic build-up of fluid overpressure during deformation through a fault-valve mechanism, which is thought to be associated with seismic slip events (Sibson, 1981; 1990).

The cataclastic units and the slipping zones therein include exploded clasts up to 1-2 cm in size with radial fractures embedded in a micrometric in size matrix composed of angular clasts with no evidence of shearing (Figs. 9c-d). This occurrence within dolostones has been already reported by Fondriest et al. (2015) and interpreted as the result of *in-situ* shattering due to the propagation of seismic ruptures along neighbor faults. In the VCFZ these features are typically associated with mirror-like slip surface suggesting a related seismic origin.

The possibility to relate the occurrence of foliation in mixed calcite-dolomite gouges and cataclasites to coseismic sliding has been recently investigated by Smith et al. (2016) by performing

high-velocity (imposed slip rate $V < 1.13$ m/s) shear experiments on mixtures of calcite-dolomite gouges. Their results show that a well-organized foliation can develop quickly from an initial random distribution as displacement is distributed along a shear band before dynamic weakening occurs. When the latter takes place, deformation is localized to a discrete slip surface, which cuts sharply the foliated gouge and accommodates most of the strain. The described microstructures exhibit striking similarities with the foliated cataclasites documented in the VCFZ (Fig. 11a) suggesting a common seismic origin.

A feature that has been documented both at the meso- and microscale related to the master fault and some foliated cataclasites within the VCFZ is the presence of "fluidization textures". These fluidized layers develop up to 5 cm away from the slip surface and include wavy borders and injection of material in the surrounding cataclasite (e.g., Fig. 11c). In the Kodiak accretionary complex (Alaska, USA), Brodsky et al. (2009) described cusplate-lobate, locally intrusive, contacts between black in color aphanitic rocks with flame-like and laminar to convolute flow structures interpreted as pseudotachylytes and foliated illite-rich cataclasites. Similar fluidal structures were described in slipping zones cutting carbonates and were tentatively associated with seismic faulting (Smith et al., 2011; Fondriest et al., 2012; Rowe et al., 2012). The formation of fault rocks with intrusive geometry (e.g., pinch out terminations) and laminar- to turbulent-like flow structures plus, in some cases, cusplate-lobate contacts with the wall rocks, is thought to be the result of fluidization of the slipping zone material. Triggering mechanisms may be thermal decomposition (e.g., Collettini et al., 2013), pressurization of fluids trapped in the pore spaces of the gouge (e.g., Rowe et al., 2012) or focused injection of pressurized fluids from the fault surroundings during rupture propagation (e.g., Sibson, 1990; Fondriest et al., 2012). The fluidized features in the VCFZ compare well with laminar grain flow layers characterized by grain preferred orientation parallel to the fault surface (Rowe and Griffith, 2015). Consequently, the presence of calcite-cemented cataclasite and the occurrence of laminar grain flow structures in the slipping zones along the master fault suggest the presence of pressurized fluids during seismic faulting along the VCFZ.

669

670 *7.3. Implications for the interpretation of seismicity in the Central Apennines*

671 In the previous sections we documented the evidence of seismic rupture propagation within
672 the footwall of the VCFZ and the occurrence of both inherited compressional- and present active
673 extensional- structures. Here we relate these structural features to the active fault network inferred
674 from high-precision hypocenter relocations for the L'Aquila 2009 seismic sequence by Valoroso et
675 al. (2013; 2014).

676 In the case of the L'Aquila 2009 earthquake sequence (mainshock M_w 6.1 April 6, 2009),
677 Valoroso et al. (2013; 2014) depicted the seismic faults of the area by means of high-precision
678 relocation of ~64,000 events, both foreshocks and mostly aftershocks during 2009, with a
679 completeness magnitude of 0.7 (Fig. 13a). The relative hypocenter location precision was smaller
680 than the dimension of seismic ruptures (e.g., ~ 30 m for $M_L = 1.0$, Sibson, 1989) with a precision
681 ranging from few meters to tens of meters. The L'Aquila Fault, responsible for the mainshock, was
682 described as a fault striking NW-SE and dipping 50° towards SW for a length of about 18 km
683 (Valoroso et al., 2013). In particular, in its central sector the L'Aquila Fault is imaged as a fault
684 zone dipping at high angle (~ 55°) towards SW and cutting at 3-5 km depth a well-defined fault
685 structure dipping at low angle (~ 15°) (i.e., the dashed green line in Fig. 13b) towards SW (Fig. 13a-
686 b). The possible focal mechanism solutions on the low-angle structure are consistent either with a
687 low-angle plane dipping towards SW or with a series of closely spaced high-angle planes dipping
688 towards NE. Some authors (Chiaraluce et al., 2011; Valoroso et al., 2013) interpreted the low-angle
689 planes as the shallow flat portions of a thrust inherited from the Miocene-Pliocene compressional
690 phase. The thrust has been reactivated as a low-angle extensional fault during the Present extension
691 (Speranza et al., 2003). Moreover, the projection of this plane to the surface, coincides with the
692 central sector of the GSM (Chiaraluce et al., 2011). This fault network imaged by seismic inversion
693 compares well with the structural setting that we described in the VCFZ, where low-angle thrusts

are reactivated as (minor, at least in terms of displacement) extensional faults (Figs. 6b-c) and a major extensional Andersonian-type fault cuts the older thrust zone (Fig. 13c-d).

Another important comparison with the L'Aquila seismic sequence regards the kinematics of focal mechanism solutions for both foreshocks and aftershocks. Chiaraluce et al. (2011) documented a strong predominance of extensional solution (i.e., normal and transtensional, 82%), with strike-slip focal mechanism solutions (13%) typically located at linkage areas between fault segments. A minor occurrence of compressive earthquakes (i.e., thrust and transpressive, 5%) is dispersed in the fault system. This distribution compares well with the kinematics measured on fault surfaces in the VCFZ. Although evidence of extension-related thrust kinematics was not found, extensional and transtensional faults were the most recurrent structures. Moreover, strike-slip kinematics were associated with faults interpreted as kinematic tears.

Therefore, all the documented similarities between the VCFZ and the buried structures activated during the L'Aquila 2009 seismic sequence described through seismological techniques (Chiaraluce et al., 2011; Valoroso et al., 2013, 2014) allow the VCFZ to be considered a valid exhumed analog of the structures responsible for the present seismicity in the Central Apennines.

8. Conclusions

The active Campo Imperatore Fault System (CIFS) cuts the dolostones bounding the inner part of the Gran Sasso Massif in the Italian Central Apennines. The exposed segment of the VCFZ strikes about SE-NW (i.e., sub-parallel to the main seismogenic faults of the Central Apennines) cuts through dolostones and limestones, accommodated about 2 km of maximum vertical throw and was exhumed from about 2 km depth since the Early Pleistocene.

Within the VCFZ we mapped five main structural units based on fault zone rocks and damage intensity: namely they are the Low Strain Damage Zone, the High Strain Damage Zone, the Breccia Unit, the Cataclastic Unit 1 and the Cataclastic Unit 2. At the base of the badlands the master fault (attitude of N209/54°) juxtaposes the Quaternary deposits in the hangingwall with the

cataclastic dolostones in the footwall. Faults in the footwall are mainly synthetic and antithetic to the master fault, but a set of NE-SW trending strike-slip faults are well exposed in the upper part of the creek and interpreted as kinematic tears. The spatial distribution of the fault and fracture network affecting the VCFZ suggest a close relationship between these structural units and extensional deformation active in the area since Early Pleistocene times. However, dolomitization in the Breccia Unit occurred along the damage zone of a shallow-dipping thrust juxtaposing the Lower Jurassic *Calcare Massiccio* Fm. onto the Middle Jurassic *Verde Ammonitico* Fm. The same thrust zone, not affected by dolomitization, is exposed immediately to the East of the VCFZ. This evidence, coupled with the attitude parallel to low-angle bedding surfaces of dolomite veins in the Breccia Unit, and the systematic deformation of Breccia Unit rocks by cataclasis on the extensional master fault and subsidiary ones, indicate that dolomitization was syn- or post-thrusting, but occurred still during the contractional regime, before regional extension affected the area. The presence of a continuous ~ 40 m thick band of Cataclastic Unit 1 lining the master fault is interpreted as the result of *in-situ* shattering due to the propagation of multiple seismic ruptures and subsequent slip localization and cementation along a multitude of subsidiary faults. Past seismic behavior of the exposed faults is suggested by the occurrence of mirror-like slip surfaces truncating dolomite grains, foam-like textures in the sheared calcite-bearing veins and *in-situ* shattering associated with mirror-like slip surfaces and fluidized cataclasites.

For the L'Aquila 2009 seismic sequence, high-precision hypocenter relocation imaged a fault network characterized by a principal high-angle fault cutting a low-angle plane at shallow depth (3-5 km). The low-angle plane was interpreted as a flat portion of a thrust inherited from the compressional phase during Miocene-Pliocene and exploited as low-angle extensional fault during Present extension. This structural setting compares well with the reactivation of thrust-related features and fault network geometry described in the VCFZ. Therefore, the VCFZ provides a suitable exhumed analog of seismically active buried fault zones in the Central Apennines, such as those that caused the L'Aquila 2009 seismic sequence.

746

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Figure captions

Figure 1. Geological setting of the Campo Imperatore area. (a) Structural map of the Gran Sasso area (modified after Storti et al., 2013). (b) Geological map of the study area simplified after the published Foglio 349 “Gran Sasso d’Italia” (Ispira, 2012). Quaternary colluvial deposits are the infilling of the Campo Imperatore intramontane basin and correspond to the non-colored areas. NNE-SSW striking normal faults dissect and displace the thrust system. The Omo Morto thrust fault runs on the northern side of Mt. Aquila and disappears before Vado di Corno, where the fault zone (VCFZ) is exposed within badlands. (c) Stratigraphic column of the Campo Imperatore area (modified after Cardello and Doglioni, 2014). (d) Geological cross section across the Campo Imperatore intramontane basin (modified after Ispira, 2012). To the NE of the Mt. Brancastello strata at the hangingwall of the thrust are overturned, while in the Campo Imperatore plain normal faults cut and dislocate the thrust system. (e) Stereographic projection of bedding surfaces measured within the VCFZ result in a monocline with constant attitude of $N270/20^\circ$ (stereographic projection in the figure is equal area, lower hemisphere).

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exception of the Breccia Unit, which dips at low angle and outcrops where the creek is more eroded. The axes are in scale X:Y = 1:2.

Figure 3. Core of the Vado di Corno Fault Zone. (a) The structural units distinguished in the footwall block of the VCFZ show a great variability in appearance due to changes in the bulk deformation intensity and deformation processes. (b) The base of the badlands is marked by the contact between the Quaternary deposits in the hangingwall (reddish in color) and the cataclasites in the footwall (white in color) along the master fault. (c) The core of the master fault is < 20 cm thick and exhibits an alternation of reddish Quaternary deposits and whitish cataclastic layers with irregular borders resembling fluidization textures typical of sedimentary flame structures. (d) Stereoplots of both non- and lineated fault and joints across the studied creek. Thick great circles are mean attitude of principal synthetic and antithetic fault strands, while dashed great circles represent mean orientation of the NE-SW striking tear faults (stereographic projection in the figure is equal area, lower hemisphere).

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 1244 fracture sets closely spaced (< 1 cm) typically isolates rock fragments of 1-2 cm in size. (c) Fracture
 1245 traces perpendicular to the master fault. The frame dimension is 40 x 60 cm and its attitude is
 1246 N292/66°. (d) Fracture traces parallel to the master fault. The frame dimension is 40 x 60 cm and its
 1247 attitude is N204/74°.

1248
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 1252 *Massiccio* Fm. onto the *Verde Ammonitico* Fm. exhibits reactivation as normal fault with fault-drag-
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 1254 (c) Line drawing of (b). (d) Dolomite veins exploit preexisting discontinuities in the protolith, such
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1258
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 1260 of the protolith that are preserved (i.e., *Verde Ammonitico* Fm.). (b) Diffuse presence of dolomite
 1261 and calcite veinlets in the Cataclastic Unit 2 with lateral continuity up to ten cm and aperture of
 1262 about 5 mm. (c) Stereoplot of poles to veins in the Cataclastic Unit 2. Veins have typically high dip
 1263 angle ($> 70^\circ$) and are slightly clustered around a dip of N0°, N140° and N270° (stereographic
 1264 projection in the figure is equal area, lower hemisphere). (d) Microbreccias occur locally at the
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1267

1268 **Figure 8.** The Cataclastic Unit 1. (a) The Cataclastic Unit 1 is typically well cemented and cut by
1269 hundreds of minor faults with thin (< 2 cm) ultracataclastic layers. (b) Decametric lithons of the
1270 CU2 embedded in the CU1. (c) Minor calcite veins (white at BSE-SEM image) cross-cut by Riedel
1271 shear fractures with low displacement (< 1 mm). (d) Lineated mirror-like slip surfaces. (e)
1272 Deformation bands are sometimes observed within more granular cataclastic units. (f-g) Small rock
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1276 **Figure 9.** Microstructures of the highly localized sheared calcite veins. (a) The slipping zone
1277 records a succession of multiple vein deposition and then shearing, testified by calcite levels with
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1279 interpreted as likely the expression of different strain accommodated by each calcite level. Here, the
1280 last vein precipitation event is preserved and characterized by polygonal calcite crystals up to 150
1281 μm in size and the presence of cavities. (b) Ultrafine grained calcite crystals (typical size of 1 μm)
1282 surround rounded micrometric dolomite clasts in high strain domains within sheared calcite veins.
1283 (c) The calcite matrix exhibits a foam texture. Calcite crystals have straight boundaries and triple
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1285 the slipping zone sharply truncating large dolomite clasts (see arrow). Occasionally, pockets of
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1287 sheared fractures cut and dislocate the PSS. All images are BSE-SEM.

1288

1289 **Figure 10.** Microstructures of non-foliated cataclasites. (a) Slipping zone grading from cataclasite
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1292 shattering in the VCFZ. Dolomite clasts are radially fractured and lack of evidence of shearing; they

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Figure 11. Microstructures of foliated cataclasites and cataclastic bands. (a) Foliated cataclasite with layering of calcite- and dolomite-rich bands. Layers are organized in a S-C type foliation, consistent with the direction of shear. Elongated “tails” of fine dolomite and calcite crystals are observed around big dolomite and calcite clasts (about 200 μm in size). The slip surface cuts abruptly the foliated cataclasite. (b) Foam texture in the deformed calcite matrix, similar to the one observed in the highly localized sheared calcite veins (Fig. 9c). (c) Irregular wavy boundaries between the calcite-rich domains and dolomite dominated areas in the foliated ultracataclasites. (d) Injection of calcite cement-supported ultracataclasite (comprising mostly grains from the Quaternary deposits) in the dolomite-rich ultracataclasite (i.e., CU1). (e-f) The contact between the shattered cataclasite and the cataclastic band is sharp and characterized by an increase in the fine part in the matrix. All images are BSE-SEM.

Figure 12. Conceptual model for the formation of the cataclastic unit. (a-b) The propagation of seismic ruptures along the master fault result in the formation of a comminuted *in-situ* shattered dolostone band. The presence of a host rock already damaged allows *in-situ* shattering to occur at lower strain rates to those expected for the same intact rock (Doan and d’Hour, 2012). (c) Localization in the *in-situ* shattered dolostone along the master fault and subsidiary faults leads to grain rotation, matrix development and obliteration of the host rock original sedimentary features. Eventually calcite-rich fluids percolate and cement the cataclastic band. (d) The cataclastic unit widens as it records multiple cycles of seismic rupture propagation – *in-situ* shattering – localization – cementation. The conceptual model is based on the interpretation of the exposures of

the footwall of the VCFZ. Given the absence of outcrops of the hangingwall, the deformation has only been inferred and colored in light gray.

Figure 13. Earthquake distribution in the L'Aquila 2009 seismic sequence. (a) Map of the relocated earthquakes for the L'Aquila 2009 seismic sequence (modified after Valoroso et al., 2013). Red dots: foreshocks; black dots: aftershocks; red stars: main earthquakes; green lines: active mapped faults; yellow lines: co-seismic surface ruptures. GSFS is Gran Sasso Fault System. (b) Vertical section of aftershocks distribution at depth with seismotectonic model of the area (modified after Valoroso et al., 2013). The low-angle plane was interpreted as a shallow flat portion of a thrust reactivated as normal fault during the seismic sequence. (c) Map of lineaments from the geological map in Fig. 1b in the study area. (d) Simplified geological section from Fig. 2b evidencing the major faults within the studied creek. Note the similarity of the fault network, at smaller scale, with the vertical cross section shown in Fig. 13b.

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Figure 10. Microstructures of non-foliated cataclasites. (a) Slipping zone grading from cataclasite to ultracataclasite towards the slip surface (top of the image, OM). (b) Extended plagues of calcite cement may occur as infilling of pores within the dolomite matrix (BSE-SEM image). (c) *In-situ* shattering in the VCFZ. Dolomite clasts are radially fractured and lack of evidence of shearing; they are interpreted as “exploded” (OM image). (d) In the *in-situ* shattered rocks, the dolomite matrix

consists of angular clasts, less than 10 μm in size, which underwent grain size reduction by splitting (BSE-SEM image). (e) Mirror-like slip surface truncating dolostone clasts embedded in a very fine dolomite matrix (OM image).

Figure 11. Microstructures of foliated cataclasites and cataclastic bands. (a) Foliated cataclasite with layering of calcite- and dolomite-rich bands. Layers are organized in a S-C type foliation, consistent with the direction of shear. Elongated “tails” of fine dolomite and calcite crystals are observed around big dolomite and calcite clasts (about 200 μm in size). The slip surface cuts abruptly the foliated cataclasite. (b) Foam texture in the deformed calcite matrix, similar to the one

observed in the highly localized sheared calcite veins (Fig. 9c). (c) Irregular wavy boundaries between the calcite-rich domains and dolomite dominated areas in the foliated ultracataclasites. (d) Injection of calcite cement-supported ultracataclasite (comprising mostly grains from the Quaternary deposits) in the dolomite-rich ultracataclasite (i.e., CU1). (e-f) The contact between the shattered cataclasite and the cataclastic band is sharp and characterized by an increase in the fine part in the matrix. All images are BSE-SEM.

Figure 12. Earthquake distribution in the L'Aquila 2009 seismic sequence. (a) Map of the relocated earthquakes for the L'Aquila 2009 seismic sequence (modified after Valoroso et al., 2013). Red dots: foreshocks; black dots: aftershocks; red stars: main earthquakes; green lines: active mapped faults; yellow lines: co-seismic surface ruptures. GSFS is Gran Sasso Fault System. (b) Vertical section of aftershocks distribution at depth with seismotectonic model of the area (modified after Valoroso et al., 2013). The low-angle plane was interpreted as a shallow flat portion of a thrust reactivated as normal fault during the seismic sequence. (c) Map of lineaments from the geological map in Fig. 1b in the study area. (d) Simplified geological section from Fig. 2b evidencing the major faults within the studied creek. Note the similarity of the fault network, at smaller scale, with the vertical cross section shown in Fig. 12b.

Figure 12. Conceptual model for the formation of the cataclastic unit. (a-b) The propagation of seismic ruptures along the master fault result in the formation of a comminuted *in-situ* shattered dolostone band. The presence of a host rock already damaged allows *in-situ* shattering to occur at lower strain rates to those expected for the same intact rock (Doan and d'Hour, 2012). (c) Localization in the *in-situ* shattered dolostone along the master fault and subsidiary faults leads to grain rotation, matrix development and obliteration of the host rock original sedimentary features. Eventually calcite-rich fluids percolate and cement the cataclastic band. (d) The cataclastic unit widens as it records multiple cycles of seismic rupture propagation – *in-situ* shattering – localization – cementation. The conceptual model is based on the interpretation of the exposures of the footwall of the VCFZ. Given the absence of outcrops of the hangingwall, the deformation has only been inferred and colored in light gray.

Highlights

- Fault rock distribution of the VCFZ footwall-block was mapped in detail
- Evidence of extensional reactivation of an older thrust zone was documented
- Thick cataclastic bands are suggested to form by pulverization and cataclasis
- Microstructural investigations testified the past seismicity of the VCFZ
- Fault structure resembles the fault network activated by L'Aquila 2009 earthquake