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1 **Seismic cycle recorded in cockade-bearing faults (Col de Teghime, Alpine Corsica)**

2

3 Simone Masoch^{1*}, Michele Fondriest¹, Nereo Preto¹, Michele Secco^{2,3}, Giulio Di Toro^{1,4}

4

5 *1. Dipartimento di Geoscienze, Università degli Studi di Padova, Padua, ITALY*

6 *2. Dipartimento di Ingegneria Edile, Civile ed Ambientale (ICEA), Università degli Studi di Padova,*

7 *Padua, ITALY*

8 *3. Centro Interdipartimentale di Ricerca per lo Studio dei Materiali Cementizi e dei Leganti Idraulici*

9 *(CIRCe), Università degli Studi di Padova, Padua, ITALY*

10 *4. Sezione di Tettonofisica e Sismologia, Istituto Nazionale di Geofisica e Vulcanologia, Rome, ITALY*

11 *Corresponding author: Simone Masoch simone.masoch@gmail.com

12

13 **Keywords**

14 Fault zone rock; Cockade breccia; Fluidization; Inverse grading; Pressure growth; Alpine Corsica

15

16 **Highlights**

- 17 • Cockade breccias were found in transtensional brittle faults in Alpine Corsica.
- 18 • Core clasts show inverse grading within the slipping zones.
- 19 • Fluidization of granular fault rocks promotes elutriation of the finer clasts.
- 20 • Pressure growth controls formation of cockade breccias at shallow crustal levels.
- 21 • Cockade breccias are a geological marker of ancient seismic faulting.

22

23 **Abstract**

24 Few fault rocks are known to be associated undoubtedly with seismic faulting. Here, we

25 investigated the formation mechanism of cockade breccias found in transtensional faults cutting

26 marbles and quartzites from the Col de Teghime area (Alpine Corsica, France). Field surveys coupled

with detailed microanalytical investigations indicated that: (i) the core clasts of the cockades are composed of host rock fragments $>310\text{ }\mu\text{m}$ in size that are suspended in the slipping zones and arranged in inverse grading; (ii) the concentric rims of the cockades show a cyclic zoning made of saddle dolomite + Mg-calcite + goethite + anatase; (iii) the cockade-bearing veins are associated with minor fault veins filled with fine fragments ($< 300\text{ }\mu\text{m}$ in size) cemented by the same minerals of the cockade rims.

We propose that the cockade-bearing faults formed at shallow crustal depths ($< 2\text{ km}$) and recorded the main phases of the seismic cycle: (1) co-seismic fragmentation of the wall rocks in presence of fluids; (2) co-seismic fluidization of the rock fragments resulting in elutriation of the finer particles and formation of residual porous and well-sorted slipping zones, where cockades will nucleate. Inverse grading resulted from co-seismic shaking and shearing; (3) post-seismic to inter-seismic cementation by deposition of carbonate-rich rims due to slow mineral pressure growth, resulting in the suspension of the clasts within the slipping zones. The formation mechanism of cockade breccias proposed here provides an alternative view of earthquake-related processes in fluid-rich environments at shallow crustal depths.

1. Introduction

The study of fault zones exposed at the Earth's surface potentially allows geologists to investigate the deformation processes associated with the various phases of the seismic cycle, from co-seismic to inter-seismic (Cowan, 1999; Di Toro et al., 2012; Neimeijer et al., 2012; Rowe and Griffith, 2015; Scholz, 2019). Moreover, the microstructural, mineralogical and geochemical characterization and interpretation of fault rock assemblages may reveal important information about earthquake source processes and rupture dynamics, including estimates of the co-seismic fault strength or of the breakdown work, which in some cases cannot be retrieved through the inversion of seismic waves (Sibson, 1975; Chester et al., 2005; Di Toro et al., 2006). However, fault zone rocks are typically the result of long-lasting polyphase deformation and exhumation histories, which often

53 result in the formation of fault rock assemblages that are difficult to associate with particular phases
54 of the seismic cycles or with seismic vs. aseismic slip (Snoke et al., 1998; Cowan, 1999; Rowe and
55 Griffith, 2015). A further complication rises from the presence of fluids, which alter fault rock
56 assemblages but also play a pivotal role in fault and earthquake mechanics (Scholz, 2019). In practice,
57 it is extremely difficult to estimate the pore fluid pressure and the permeability of fault zones at depth
58 and during the several phases of the seismic cycle through the investigation of exhumed fault rocks
59 (Caine et al., 1996; Faulkner et al., 2010). This is because a wide range of physical and chemical
60 processes can modify the permeability of fault zone rocks throughout the seismic cycle. Qualitatively,
61 when seismic ruptures propagate breaching fluid reservoirs at depth, fault zones behave as conduits
62 allowing fluid discharge and, possibly, deposition of mineral ore bodies at geometrical fault zone
63 complexities (e.g., breccias in dilational jogs: Sibson, 1985; 1986). On the other hand, episodic to
64 cyclic ingressions of pressurized fluids (i.e., fault-valve behavior; Sibson, 1990) can trigger
65 earthquakes and can be associated with swarm activity in mesh-like arrays of small faults and veins
66 (i.e., high fluid-flux fault/fracture networks, Sibson, 1990; Dempsey et al., 2014; Cox and Munroe,
67 2016). Lastly, post- and inter-seismic precipitation of hydrothermal minerals in pores and fractures
68 will progressively reduce the permeability and eventually seal the fault zone (Tenthorey et al., 2003;
69 Cox, 2005).

70 A relatively common fault product in shallow crustal hydrothermal settings are cockade
71 breccias, or low-temperature hydrothermal fault vein infills characterized by up to decimeter-sized
72 clasts wrapped by concentric bands of cement (Frenzel and Woodcock, 2014 and references therein).
73 Frenzel and Woodcock (2014) proposed six formation mechanisms for cockade breccias. Only two
74 mechanisms are strictly associated with brittle faulting in presence of fluids: (i) repeated cockade
75 accretion-rotation associated with fracturing and, (ii) sustained suspension of clasts in rapidly
76 ascending fluids and simultaneous cement precipitation. The first mechanism provides evidence for
77 syn-tectonic mineralization (Genna et al., 1996; Frenzel and Woodcock, 2014), while, the second
78 implies the circulation of pressurized fluids associated with injection-driven swarm seismicity in

high-flux dilatant faults (Cox and Munroe, 2016). Additional evidence supporting a relationship between cockade breccia formation and seismic faulting is the inverse grading of the core clasts of the cockades in some breccia layers, suggesting either self-organization of the core clasts controlled by seismic shaking (Genna et al., 1996) or variation of flow velocities during co-seismic fluidization of the fragmented rocks (Cox and Munroe, 2016). Even though cockade breccias have often been reported both in the ore and structural geology literature (Bastin, 1950; Kutina and Sedlackova, 1961; Genna et al., 1996; Leroy et al., 2000; Frenzel and Woodcock, 2014), to our knowledge there are few studies that attempt to relate their peculiar microstructures to particular phases of the seismic cycle (e.g., Cox and Monroe, 2016; Berger and Herwegh, 2019).

In this study, we describe cockade-bearing transtensional faults cropping out in Alpine Corsica (Col de Teghime, France). The fault core rocks include cockade breccias, often with inverse grading of the core clasts, cemented by hydrothermal minerals. Field structural geology surveys and detailed microstructural and mineralogical observations allowed us to associate the formation and development of cockade breccias with the main phases (i.e., co-seismic to inter-seismic) of the earthquake cycle.

2. Geological Setting

2.1 Alpine Corsica

Alpine Corsica is a Tethyan-type accretionary wedge composed of continent- and oceanic-derived units stacked together during the Alpine orogenesis (Vitale Brovarone et al., 2013 and references therein). Alpine Corsica is divided into three main structural domains (continental-derived units, Schistes Lustrés and Nappes Supérieures) sealed by Miocene sedimentary deposits (Durand-Delga, 1984). In particular, the Schistes Lustrés complex is mainly oceanic-derived and consists of metaophiolitic sequences from the Ligurian-Tethyan Ocean (mantle ultramafic rocks, metagabbros, pillow lava and associated metasedimentary cover of marbles, quartzites, calcschists, etc.) wrapping

105 thin interlayered slices of continental basement rocks (granitoids and gabbro intrusions; Faure and
106 Malavieille, 1981; Durand-Delga, 1984; Dallon and Puccinelli, 1995; Meresse et al., 2012).

107 Since the Late Cretaceous, east-dipping intra-oceanic subduction driven by the convergence
108 of the Euro-Asia and Adria plates (i.e., Euro-Asia beneath Adria) formed an accretionary wedge by
109 piling up slices of oceanic rocks and sedimentary cover (Molli, 2008 and references therein). In
110 Alpine Corsica, this compressional stage was recorded by High Pressure – Low Temperature (HP-
111 LT) metamorphism (Jolivet et al., 1990; Molli, 2008). Because of the Mid-Eocene slab break-off and
112 the initiation of the Adria plate subduction, the active Apenninic margin began to roll back while
113 migrating to the East, shifting the tectonic regime in Alpine Corsica from compressional to
114 extensional (Molli and Malavieille, 2011).

115 Since the Oligocene, Alpine Corsica underwent multiple extensional stages due to the
116 lithospheric extension controlled by the continued eastward migration of Apenninic subduction
117 (Jolivet et al., 1990; Molli and Malavieille, 2011). The last extensional stage was recorded by
118 Tortonian to Serravallian in age NW-SE and N-S trending high-angle brittle normal faults that
119 accommodated at least 6 km of vertical throw in the Saint Florent area (Fellin et al., 2005; Cavazza
120 et al., 2007, Gueydan et al., 2017).

121

122 *2.2 Geology of the Col de Teghime area*

123 In the Col de Teghime area, metasediments overlaying the continental granitoids of Serra di
124 Pigno, a unit belonging to the Schistes Lustrés complex, crop out (Dallon and Puccinelli, 1995;
125 Meresse et al., 2012). The metasediments are composed of quartzites, metabasites, micaschists, pure
126 and impure marbles (Fig. 1a; see Meresse et al., 2012 for details). The contact between the
127 metasediments and the granitoid basement is marked by mylonites with HP-LT paragenesis (Dallon
128 and Puccinelli, 1995). Miocene NW-SE trending sub-vertical brittle fault zones crosscut the
129 metasediments and the continental granitoids with transtensive or strike-slip kinematics (Fig. 1b).
130 The cockade-bearing faults presented here are associated with this fault system.

131

132 **3. Methods**

133 Four fault zones exposed in the Col de Teghime area where studied in detail. Original field
134 surveys along with published geological maps (Faure and Malavieille, 1981; Dallon and Puccinelli,
135 1995) were used to trace major lineaments in the area using ArcGIS 10.6 software. At the four
136 selected localities, the attitudes and lineations of faults, veins, fractures and host rock foliations were
137 systematically measured. Measurements of attitudes and lineations of faults, veins, fractures and host
138 rock foliations were plotted onto stereonet (equal area, lower hemisphere) using Stereonet 10
139 (Allmendinger et al., 2011; Cardozo and Allmendinger, 2013). To describe fault zone rocks, we
140 referred to the classifications proposed by Sibson (1977) and Woodcock and Mort (2008).

141 Twenty-six oriented fault rock samples were collected, and microstructural observations were
142 conducted on thin sections cut perpendicular to the slip surfaces and fault vein boundaries and
143 oriented either parallel or perpendicular to fault lineations. Transmitted-light optical microscopy
144 (OM) was used to determine microstructural features at thin section scale, and to identify areas
145 suitable for further microanalytical investigations. Scanning electron microscopy (SEM) was used to
146 acquire high-resolution backscattered electron (BSE) images of the cockade breccias and coupled
147 with semiquantitative energy dispersion spectroscopy (EDX) elemental analyses. Electron
148 microscopy investigations were performed with SEM using a CamScan MX3000 operating at 25 kV
149 at Department of Geosciences at Università degli Studi di Padova, and FE-SEM using either a FEI
150 Quanta 650 operating at 15 kV at the University of Manchester, or FEI Quanta 200F operating at 20
151 kV at the Scientific Center for Optical and Electron Microscopy at ETH Zurich. Optical microscopy
152 cathodoluminescence (OM-CL) was applied to obtain information on chemical variations within the
153 cockade rims. The OM-CL was employed using a Nikon microscope equipped with a Nikon camera,
154 installed at the Department of Geosciences in Padova, working at 15-17 kV and 200-230 μ A in a
155 vacuum of 0.18-0.20 Torr.

156 High-resolution mineral phase identification was performed using Micro-Raman
157 spectroscopy, while the bulk mineralogy of the cockade breccias and veins was retrieved through X-
158 ray powder diffraction (XRPD). Micro-Raman spectroscopy was performed with a 532-nm green
159 laser (power of 3.0 mW) on polished thin sections using a Thermo Scientific DXR MicroRaman at
160 the Department of Chemical Sciences (Padova). The obtained spectra (range of 100-3574 cm⁻¹) were
161 elaborated with OMNIC Spectra software for baseline correction, eliminating the natural fluorescence
162 of carbonate crystals and mineral phase identification. X-ray powder diffraction (XRPD) analyses
163 were performed with a PANalytical X'Pert Pro diffractometer equipped with a Co radiation source,
164 operating at 40 mA and 40 kV (Department of Geosciences, Padova) in the angular range 3° < 2θ
165 < 85°.

166 Micro X-ray Computed Tomography (micro-CT) was performed on three cylindrical samples
167 (diameter × height = 5 × 5 mm) of the breccia to reconstruct the three-dimensional arrangement of
168 the cockades using a Skyscan 1172 tomograph installed at the Department of Geosciences (Padova).
169 The device was equipped with an X-ray source with voltage range of 20-100 kV, power range of 8-
170 10 W and a 11 Mp CCD detector. The scans of the samples were performed with a source voltage
171 and current of 70 kV and 141 μA, respectively, a sample-to-source distance of 53.010 mm, and a
172 camera-to-source distance of 211.545 mm; a 0.5 mm-thick Al filter was also applied. This resulted in
173 sample images with a pixel size (spatial resolution) of 4.35 μm. A total number of 1442 radiographs
174 per scan were acquired over a 360° rotation (angular step 0.3°, exposure 1050 ms). The reconstruction
175 of cross-sectional slices from 2-D X-ray projections was carried out using a modified FDK algorithm
176 (Feldkamp et al., 1984) for cone-beam geometry implemented in the Skyscan NRecon software.
177 Corrections for the beam hardening effect and ring artefacts were also applied during the
178 reconstruction process in order to improve image quality (Sijbers and Postnov, 2004; Boin and
179 Haibel, 2006).

180 Image analysis was performed on high-resolution scans of thin sections (samples CC01-12
181 and CC11-17), BSE images (CC11-17) and micro-CT slices (CC01-12) using the software Fiji

(Schindelin et al., 2012) to determine the clast size distributions (CSDs) in two dimensions of the core clasts in the cockade-bearing faults. Since some core clasts and the sealing cement have similar mineralogy (dolomite), automatic segmentation of the clasts in BSE images and micro-CT slices was problematic; thus, all the clast boundaries were traced manually. The clasts size was defined as the diameter d of the circle with the equivalent area A of the clasts and expressed as $d=2(A/\pi)^{0.5}$. Due to the spatial resolution of the images used for the analysis, a cut-off value of 25 square pixels was defined. This corresponds to $d\sim 30\text{ }\mu\text{m}$ for the high-resolution scans of thin sections and $d\sim 10\text{ }\mu\text{m}$ for the BSE images and slices of the micro-CT analysis, because smaller clasts were not recognizable in the processed images. Resulting CSDs were obtained using the procedure described by Monzawa and Otsuki (2003) to define the cumulative number of clasts, N , larger than a given diameter. The CSD curve was plotted in a $\log(N)$ - $\log(d)$ diagram and the distribution was described by the power-law relationship, $N \sim d^{-D}$ ($\log(N) \sim -D\log(d)$), where D represents the slope of the curve (Turcotte, 1986). Note that the investigated clast size range was too small (less than three orders of magnitude) to determine if the distribution was statistically self-similar. Instead, in this study, we determined D (i) to quantify the different CSDs of the clast fragments found in the cockade-bearing veins and, (ii) to compare these CSDs with those of the fine clasts-supported fault veins to discuss the formation mechanisms of the cockade breccias.

199

200 **4. Cockade-bearing faults**

201

202 *4.1 Field observations*

203 We focused here on two transtensional fault zones which are the best exposed in the study
 204 area. One fault zone is located on the eastern flank of Monte Secco (stop 1; $512 \pm 3\text{ m a.s.l.}$;
 205 $42^{\circ}4'20.6''\text{ N}$, $9^{\circ}22'51.7''\text{ E}$, Fig. 1). The outcrop extends for about 40 m in an abandoned quarry and
 206 offers a continuous exposure in a direction orthogonal to the strike of the fault zone. The main fault
 207 surface strikes from WSW-ENE to WNW-ESE with a mean value of $\text{N}105^{\circ}$ and dips 38° towards

208 NNE. Many fault slip surfaces, including the main one, have well-developed calcite slickenlines with
209 dextral transtensive kinematics (mean pitch of 45° to the East, Fig. 1b). The main fault surface is
210 lined by a reddish breccia fault core, up to 1 m thick, marking the contact between impure quartzites
211 in the footwall block and silica-enriched marbles in the hanging wall block (Fig. 2). The damage zone
212 is asymmetric: it is wider (up to 15 m thick) and more intensely deformed within the footwall
213 quartzites compared to marble (up to 5 m thick) in the hanging wall. Brittle deformation within the
214 damage zone is accommodated by joints and shear fractures, often filled by dolomite and calcite veins
215 (Fig. 2a). In the hanging wall, minor brittle faults with normal dip-slip kinematics and the same
216 mineral filling of the main fault (dolomite, calcite and goethite from XRPD analysis) accommodated
217 up to 25-40 cm of normal dip-slip displacement (Fig. 2f) Locally, the fault core rocks are injected
218 into the damage zone with veins up to tens of centimeters long (Fig. 2d). The fault core is composed
219 mainly by breccias (rarely proto-breccias, following the classification proposed by Woodcock and
220 Mort, 2008) cemented by a reddish- to brown-color fine matrix made of calcite and goethite (from
221 XRPD analysis) and includes fragments of the wall rocks with dimensions up to ~10 cm (Fig. 2b).
222 The breccia clasts are surrounded by cement rims forming a cockade-like texture. In this study, we
223 distinguish cockade-bearing veins from cockade-bearing faults. The latter includes one or more
224 cockade-bearing veins, cataclasites, principal slip surfaces, etc. In particular, the fault core and the
225 cockade breccias have the following features:

- 226 • the cockade-bearing veins are ~3-4 cm thick (Fig. 2c);
- 227 • the core clasts of the cockades have inverse grading with the smallest clasts at the bottom and
228 the largest ones at the top of the vein: see Fig. 2c-d);
- 229 • the core clasts of the cockades are very well-sorted with the largest and smallest clasts of ~1 cm
230 and ~310 µm in size, respectively (see CSDs in section 4.3.3);
- 231 • sub-vertical veins departing from the slipping zones inject the footwall block and are filled with
232 angular to sub-angular host rock fragments (Fig. 2d);

- 233 • the core clasts seem to be suspended within the reddish- to brown-color matrix (i.e., they are not
234 in contact; Fig. 2c-d);
- 235 • locally, toward the top wall of the thicker cockade-bearing veins, the sealing is made of calcite
236 instead of reddish in color matrix (Fig. 2c).

237 The other selected fault zone crops out on the western flank of the Monte Secco and Monte
238 Rossi ridge (stop 2; 465 ± 3 m a.s.l.; $42^{\circ}40'27.7''$ N, $9^{\circ}22'20.7''$ E, Fig. 1). The fault zone is NW-SE
239 trending, subvertical and exposed for 100-150 meters in an abandoned marble quarry where it cuts
240 impure grey-colored marbles (Fig. 3a). The main fault surface is marked by well-developed calcite
241 slickenlines and, locally, is a mirror-like surface sharply truncating clasts of the underlying breccias
242 (Fig. 3). The fault core has an average thickness of 20 cm and is made of fault breccias well-cemented
243 by a reddish matrix composed of calcite and goethite (XRPD analyses). The breccias have cockade-
244 like texture with core clasts of ~5-10 mm in size wrapped by calcite- and dolomite-built rims (Fig.
245 3c-d). The cockade breccias of this fault zone do not show inverse grading.

246

247 *4.2 Deformation history recorded in cockade-bearing faults*

248 From the outcrop to the microscopic scale, the cockade-bearing faults recorded a complex
249 deformation history. The cockade-bearing faults of the Col de Teghime area are not meant to
250 necessarily record the same series of deformation events from one site to another and can potentially
251 illustrate local complexities. For example, below we outline the series of veining and faulting events
252 (V1 to V8 from older to younger, see Fig. 4a-b) recorded within a cockade breccia from stop 1 (Figs.
253 1a, 2), where these fault rocks are better exposed:

- 254 • V1: dense network of minor fractures and veins filled with brownish in color calcite, cutting
255 the wall rocks;
- 256 • V2: minor faults marked by 50 μ m-thick ultracataclastic slipping zones parallel to cockade-
257 bearing veins (V3);
- 258 • V3: ~3-4 cm-thick cockade-bearing veins;

- V4: brown in color ultracataclastic fault veins filled by fine quartzite clasts that locally inject spatially related cockade-bearing veins (V3; Fig. 4a);
- V5-V6: multiple carbonate-bearing microveins cutting the host rocks and older veins and faults (V1-V4);
- V7: dolomite-bearing veins;
- V8: late precipitation of calcite cement, which partially sealed the cavities in the cockade breccias and in the fault core (Figs. 2e, 4, 5a-b).

A detailed microstructural and mineralogical investigation of selected samples was performed to characterize the cockade-bearing faults and further constrain the crosscutting relationships among the several veining and faulting events.

4.3 Microstructures and mineralogy of cockade-bearing faults

4.3.1. Optical and scanning electron microscope observations

Cockade-bearing veins contain core clasts of (i) host rock lithology and (ii) reworked fragments of older carbonate veins (V1; Figs. 4-7). At stop 1, the quartzite-built clasts are the most abundant (>95% in the studied samples), have an angular to sub-angular shape (partly rounded) and usually consist of cataclasite to ultracataclasite made of highly comminuted quartz grains with diameters of 60-10 μm (Figs. 4, 5a, 5e, 6a-b). Reworked-vein clasts are much less abundant (<5% in the studied samples) and consist of rhombohedral calcite and dolomite crystals of older vein cement containing few fine-grained quartzite fragments. The reworked-vein clasts tend to have elongated shapes (aspect ratio >2) but are randomly oriented with respect to the margins of the slipping zones (Figs. 4a, 6a-b). Both quartzite and reworked-vein clasts are well-sorted and disposed in inverse grading (see section 4.1). At stop 2, core clasts consist entirely of marble-built fragments (often of cataclasite) and do not show any grading distribution within the slipping zones (Fig. 7a-c). Cockade-bearing veins cut slipping zones filled with cortex-clast aggregates (CCAs; Figs. 7a, 7d-e) similar to

285 those produced in rotary-shear experiments reproducing fault slip in calcite-built gouge (Rempe et
286 al., 2014).

287 The clasts are surrounded by four concentric rims composed mainly of euhedral carbonate
288 minerals (Fig. 5). From the core clast outwards, the rim-forming carbonate minerals are: (1) saddle
289 dolomite, (2) Mg-calcite, (3) saddle dolomite and (4) Mg-calcite. With rare exceptions, each rim
290 entirely wraps the core clast and the more internal rims. In detail:

- 291 • Rim 1 is 50 to 200 μm thick and made of euhedral saddle dolomite with homogeneous
292 composition and extremely enriched in calcium and iron (semiquantitative EDX spot
293 analysis). Close to the external border, intracrystalline pores $<5\text{ }\mu\text{m}$ thick and parallel to the
294 dolomite cleavage are common;
- 295 • Rim 2 is 50-150 μm thick and made of brown in color euhedral Mg-calcite. The brown color
296 is due to the presence of goethite and anatase partially filling cleavage-parallel pores (Fig. 5c).
297 Goethite and anatase appear as either spherulitic- or acicular-shaped crystals in the SEM-BSE
298 images (Fig. 5f);
- 299 • Rim 3 is $\sim 40\text{ }\mu\text{m}$ thick and made of zoned euhedral saddle dolomite enriched in calcium and
300 iron. The rim does not have any goethite nor anatase crystals and has the $\sim 10\text{ }\mu\text{m}$ -thick edges
301 enriched in magnesium (dark gray in SEM-BSE images, Fig. 5a). Pores mimicking dolomite
302 cleavage are common.
- 303 • Rim 4 is made of euhedral Mg-calcite and is rich in spherulitic and acicular crystals of goethite
304 and anatase (Fig. 5a-b).

305

306 The cockades (core + rims) are separated by a late cement made of zoned, calcian saddle
307 dolomite (Fig. 8a). Pores ranging from $<100\text{ }\mu\text{m}$ to $\sim 0.5\text{ mm}$, locally filled by pure calcite with
308 blocky-equant grains (V8; Fig. 5a), are present within the late sealing cement.

309 Brown in color ultracataclastic (clast size $< 300\text{ }\mu\text{m}$) fault veins (V4) are frequently associated
310 with cockade-bearing veins (Fig. 8b-c): the fault veins V4 lay parallel to previous ultracataclasite-

filled slipping zones (V2) or cut the cockade-bearing veins (Fig. 4). The fault veins V4 are filled by angular quartzite clasts cemented by calcian dolomite. Pores are frequent ($< 20 \mu\text{m}$ in size) and partially sealed by goethite and anatase (Fig. 8c).

4.3.2 Cathodoluminescence observations

Saddle dolomite-built rims 1 and 3 show generally homogeneous dull red luminescence with sporadic bright red areas (Fig. 5d-e). In contrast, the Mg-calcite-built rims 2 and 4 have pronounced concentric zonings with luminescence varying between bright orange (indicative of higher Fe and lower Mn content) to yellow (indicative of higher Mn and lower Fe) (Götze, 2012 and references therein). The sealing cement is slightly more luminescent than the dolomite rims. However, the CL signal is generally saturated because of the high iron content (semi-quantitative EDX analysis) in the calcian dolomite (Fig. 5d-e). Lastly, the late pure calcite filling residual cavities (V8) are either zoned (Fig. 8d) or have a uniform bright luminescence (Fig. 5d).

4.3.3 Clast size distributions of the cockade cores

In all the analyzed samples, the upper limit of the CSD was represented by the largest clast and was affected by undersampling due to the limited extension of the investigated area (ca. $2 \times 3 \text{ cm}^2$). The lower cut-off of the CSD curves was artificial only in the case of cockade-absent ultracataclasites (V4, sample CC01-12; Fig. 9) whose distributions suffer from undersampling for particles $< 40 \mu\text{m}$ in size. For V4, the linear portion (range $40\text{-}200 \mu\text{m}$ in size) of the CSD curves has a slope $D \sim 2$ (Fig. 9). The lower cut-off of the CSDs curves of the cockade-bearing veins (V3) was representative of the real distribution, since there were very few clasts $< 310 \mu\text{m}$ in size (see Figs. 4, 6b and bottom right corner of Fig. 8b). The CSDs of V3 are composed by two segments: (i) a steep slope segment for clasts size ranges of $310\text{-}690 \mu\text{m}$ ($D=1.734$; sample CC01-12) and $460\text{-}1.25 \times 10^3 \mu\text{m}$ ($D=1.604$; sample CC11-17) and, (ii) a shallow slope segment ($D<1$) for clasts size ranges of $100\text{-}310 \mu\text{m}$ (CC01-12) and $80\text{-}460 \mu\text{m}$ (CC11-17) (Fig. 9). This CSD analyses indicate that the

337 cockade-bearing veins consist almost entirely of core clasts larger 300-400 μm with very few finer
338 particles.

339

340 *4.3.4 3-D microtomography reconstructions*

341 In 2-D views of the breccia samples, the core clasts appear to not be in contact (outcrop
342 exposures and thin sections of V3, Figs. 2c-d, 3c-d, 4a, 6, 7a-c, bottom right corner of Fig. 8b). This
343 observation, which is critical for the interpretation of these fault rocks, was tested with 3-D
344 microstructural imaging derived from micro-CT analyses. Three cylindrical cores were drilled along
345 a transect perpendicular to the vein walls to characterize the inverse grading in 3-D (see Fig. 10). The
346 3-D renderings were obtained with the Volume Viewer plugin available in Fiji software (Schindelin
347 et al., 2012). The 3-D imaging of the cockade breccias confirms that the core clasts do not touch each
348 other, and each cockade is separated from the others by calcian dolomite-built cement (Fig. 10a). The
349 cockade rims entirely wrap the core clasts, always have intact crystal terminations (i.e., idiomorphic
350 shape) and, locally, interfere each other forming triple junctions at the contact between the facing
351 rims of adjacent cockades (Figs. 6c, 7c). The cockade rims are truncated by younger faults and veins
352 cutting the cockade-bearing veins (V4-V7; Fig. 10b).

353

354 **5. Formation of cockade-bearing faults**

355

356 *5.1 Co-seismic fragmentation in presence of fluids*

357 Brittle deformation induced by earthquake ruptures is dominated by wall rock fragmentation,
358 shattering and pulverization due to dynamic stress loading and, in the presence of fluids, abrupt pore
359 pressure changes (Sibson, 1986; Dor et al., 2006; Reches and Dewers, 2005). These processes mainly
360 occur at propagating fault rupture tips and at geometrical complexities, such as extensional jogs,
361 where dilation breccias are frequently generated (Fig. 11a). Dilation breccias have been hypothesized
362 to result from wall rock implosion because of the sudden volumetric decompression when a fault

363 rupture reaches an extensional jog (Sibson, 1985; 1986). Implosion breccias generally display a
364 shattered to crackle fabric with minimal displacement between the angular fragments of the wall rock
365 (Sibson, 1986; Tarasewicz et al., 2005; Woodcock and Mort, 2008; Fondriest et al., 2015; 2017). In
366 the cockade-bearing faults studied here, the core clasts have angular to sub-angular shapes and are
367 well-sorted (Figs. 4, 5, 6, 7a-c, 9, 10), suggesting that implosion of the wall rock or dynamic stress
368 wave loading fragmentation alone cannot explain the formation of these fabrics. Therefore, frictional
369 sliding associated with abrasive processes within the slipping zones occurred and have possibly
370 produced grain size reduction and chipping of the angular-shaped fragments of the wall rocks (Sibson,
371 1986) (Figs. 5, 6, 7b-c).

372 Cockade-bearing faults are associated with veins filled with carbonates (Fig. 4), suggesting
373 that faulting occurred in the presence of CO₂-rich fluids. Since mobilization of fragmented granular
374 material (breccias and gouge) is a common mechanism associated with co-seismic fluid injection
375 within slipping zones (e.g., Monzawa and Otsuki, 2003, Smith et al., 2008; Fondriest et al., 2012),
376 grain mobilization could have also favored both mechanical attrition processes, microfracturing and
377 spallation, but also chemical wearing resulting in the removal of asperities and partial rounding of the
378 clasts (Snoke et al., 1998; Blenkinsop, 2000; Oliver and Bons, 2001).

379 However, based on field and microstructural observations, the formation of the veins, where
380 cockade breccias are found, might also result from hybrid fracturing and shearing in presence of
381 pressurized fluids. We dismiss that the formation of core clasts resulted from brecciation due to
382 gravitation collapse in dilatant fractures, since we never found any feature suggesting this origin, such
383 as kinked bedding bordering the breccia veins (in our case, the foliated marbles, see Figs. 2-3) or
384 sediment and clay filling (e.g., Walker et al, 2011; Woodcock et al., 2014).

385 In summary, since cockade-bearing veins (i) are bordered by host rocks with cataclastic fabric
386 (Fig. 7), (ii) cut and are cut by principal slip surfaces (Fig. 3), (iii) include partly rounded fragments
387 of the host rocks (quartzites and ultracataclasites; Figs. 5-6) and (iv) are associated with injection-
388 like veins filled with angular to sub-angular host rock fragments (Fig. 2b-d), we conclude that they

possibly formed by cataclastic processes in presence of pressurized fluids. Moreover, injection-like veins have been previously related to seismic faulting, as a result of rupture propagation (e.g., Rowe et al., 2012).

5.2 Co-seismic grain sorting and inverse grading

The CSDs of the core clasts in the cockade-bearing faults suggest that a grain sorting mechanism removed preferentially the smaller clasts ($< 300\text{-}400\text{ }\mu\text{m}$ in size in average; Fig. 9). Furthermore, field and microstructural observations highlight that cockade-bearing veins are spatially associated and sometimes cut by fault veins filled by finer clasts (V4) (Fig. 4). The clasts in the fault vein V4 are smaller ($< 300\text{ }\mu\text{m}$ in diameter) than in the cockade-bearing veins (see CSDs in Fig. 9). Their systematic association suggests that cockade-bearing veins and fault veins V4 may be formed by the same genetic processes. Below, we present a conceptual model that relates clast sorting and inverse grading different phases of the seismic cycle.

During rupture propagation and seismic slip, large and abrupt pore pressure changes may occur leading to fluid migration along fault and fluidization of fault materials (Sibson, 1986; 1990; Rowe et al., 2012). In a granular flow driven by fluidization, fluids have enough energy to transport clasts. How far the clasts can be sustained and transported by the fluids is a function of several variables, including clasts size: finer clasts can be transported farther compared to the larger ones, which are left behind as the fluid flow loses energy (Williams, 1976; Di Felice, 1995). According to this model, well-sorted fault rocks are formed with the larger clasts concentrated where the flow rates are larger and the smaller clasts are transported towards the end of the ruptured fault. Evidence of sorting in fault rocks resulting from fluidization has been reported both in natural faults and experimental fault gouges indicating that grain sorting is often associated with seismic faulting (e.g., Boullier et al., 2009; Fondriest et al., 2012; Cox and Munroe, 2016; see Fig. 9). It is reasonable to infer that the clasts found at the core of cockades in cockade-bearing veins may represent the clasts

close to the source point of fragmentation and the smaller clasts in ultracataclastic fault veins V4 reflect the distal part of a fluid flow driven by a single release of fluids.

According to Cox and Munroe (2016), fluid velocities required for fluidizing particles and elutriating them can be estimated using the Ergun equation (Ergun, 1952) and the equation for turbulent flow proposed by Gaskell (1992). The Ergun equation relates the drag exerted on an aggregate of particles of diameter d by a fluid with superficial flow velocity u_s :

$$\frac{\Delta p}{L} = \frac{150\mu(1-\epsilon)^2 u_s}{\psi^2 \epsilon^3 d^2} + \frac{1.75(1-\epsilon)\rho u_s^2}{\psi \epsilon^3 d} \quad (\text{Eq. 1})$$

where Δp is the fluid pressure drop; L is the height of the fluidized layer; ψ is the particle sphericity; ϵ is the porosity; and μ and ρ are the fluid viscosity and density. When the force exerted on particles by the upward flow of fluid equals the gravity force on the particles, the ratio between the fluid pressure drop and the height of the fluidized layer is given by:

$$\frac{\Delta p}{L} = (\rho_p - \rho)(1 - \epsilon)g \quad (\text{Eq. 2})$$

where ρ_p is the particle density and g is the gravity acceleration (Di Felice, 1995). Therefore, Eqs. (1) and (2) can be combined and solved to estimate the minimum fluidization velocity u_m :

$$u_m = \frac{150\mu(\epsilon - 1) + \sqrt{(150\mu(1 - \epsilon))^2 + 7g\rho(\rho_p - \rho)\epsilon^3 d^3}}{3.5\rho d}. \quad (\text{Eq. 3})$$

For packed aggregates the porosity at minimum fluidization velocity (ϵ_{mf}) is empirically related to the particle sphericity as $\epsilon_{mf} = (0.071/\psi)^{1/3}$ (Wen and Yu, 1966). The velocity required to elutriate spherical particles u_t is given by (Gaskell, 1992):

$$u_t = \sqrt{\frac{3(\rho_p - \rho)gd}{\rho}} \quad (\text{Eq. 4}).$$

Fluidized cockade-bearing fault rocks formed at temperatures $\leq 150^\circ\text{C}$ and confining pressures < 50 MPa (see sections 5.3 and 6). For modelling the fluidization behavior, we assumed a water density and viscosity of 943 kg/m^3 and $1.9 \times 10^{-4} \text{ Pa}\cdot\text{s}$, respectively (NIST Standard Reference Database Number 69) and particle density of 2650 kg/m^3 (Fig. 12a). The estimated velocity required to elutriate clasts $\leq 310 \mu\text{m}$ was 0.13 m/s for spherical particles. At this velocity, spherical particles with diameter $\leq 2.3 \text{ cm}$ were kept in suspension, consistent with what we observed in cockade-bearing faults of the Col de Toghime area. Indeed, the largest diameter for a cockade core clast was $\sim 1 \text{ cm}$. Similar slipping zones with the finer particles almost completely absent have been previously reported in the literature, for example, in the Borcola Fault Zone (Southern Alps, Italy) where Fondriest et al. (2012) proposed that fluidization and elutriation of particles $< 300 \mu\text{m}$ result in the formation of peculiar grain sorting within the slipping zones (see Fig. 9 for CSDs comparison). This simplified fluidization model predicts sorting behavior that is consistent with our microstructural observations and we can explain the well-sorted CSDs with a combination of hydrodynamic processes leading to fluidization of granular fault rocks and elutriation of the finer fraction.

Some cockade-bearing faults present inverse grading of the core clasts (Figs. 2c-d, 4). Inverse grading within individual fault-rock units is reported in different tectonic settings (Boullier et al., 2009) as well as for cockade breccias (Genna et al., 1996; Cox and Munroe, 2016). A possible explanation for inverse grading in fault rocks is the Brazil-Nut Effect (also called “Muesli Effect”) controlled by repeated seismogenic shaking (Genna et al., 1996; Frenzel and Woodcock, 2014). The Brazil-Nut Effect has been deeply studied in material sciences with experimental and numerical modeling approaches (e.g., Rosato et al., 1987). Due to the collision of particles within a vibrating vessel, the concentration of larger particles in the upper side of the vessel is governed by kinematic sieving and, thus, the smaller particles settle down towards the bottom (Fig. 12b). Alternatively, Cox and Munroe (2016) proposed that inverse grading of the cockade breccias layers in the Rusey fault

464 zone (North Cornwall, UK) and Roamane fault zone (Porgera, Papua New Guinea) was driven by
465 variations in fluid velocity in fluidized breccias due to the slower flow along the walls of fluid
466 conduits. Lastly, inverse grading may also result from simple shear of particles both in dry conditions
467 and in presence of fluids (Williams, 1976; Siman-Tov and Brodsky, 2018): in a mixture of particles
468 of different size, smaller particles pass through the void space more easily than the larger ones. Thus,
469 shearing of particles promotes downward motion of the smaller ones leading to size segregation (Fig.
470 12c).

471 To summarize, it is not possible to exclude that Brazil-Nut Effect and simple shear operate
472 together in the formation of inverse grading. Surely, in a fluidized-granular flow, collision between
473 particles and shearing are possibly leading to a vertical organization with the larger particles towards
474 the hanging wall. However, we prefer co-seismic fluidization of granular fault rocks and elutriation
475 of finer clasts as the primary mechanism leading to the inverse grading and grain sorting in the studied
476 cockade-bearing faults (Fig. 11a-b).

477

478 *5.3 Post-seismic to inter-seismic pressure growth*

479 The formation of cockade breccias requires the presence of pore space between core clasts to
480 develop the cockade rims. Therefore, once cockades start to grow, the core clasts are separated
481 (Genna et al., 1996; Frenzel and Woodcock, 2014; Cox and Munroe, 2016). Indeed, the 3-D micro-
482 CT rendering reconstructions proved that clasts at the core of cockades are not in contact (Fig. 10)
483 but are separated by concentric rims of saddle dolomite (rims 1 and 3) and Mg-calcite associated with
484 microcrystals of goethite and anatase (rims 2 and 4; Fig. 5). Another necessary condition for
485 formation of cockade breccias is ingression of fluids among the core clasts leading to precipitation of
486 the cockade rims. As reviewed by Frenzel and Woodcock (2014), several physical and chemical
487 processes lead to the formation of such a particular breccia. The authors pointed out that six
488 mechanisms promote the formation of cockade-like texture: (i) cut effect (actually, this is not a
489 mechanism of formation), (ii) partial metasomatic replacement of clast minerals, (iii) infall of clasts

490 during cementation, (iv) pressure growth of minerals, (v) repeated cockade rotation-accretion
491 associated with fracturing, and (vi) sustained suspension of clasts in rapidly ascending fluids and
492 simultaneous cementation. Our 3-D micro-CT reconstructions dismiss that the core breccias studied
493 here are related to cut effect (“mechanism” i) due to the 2-D nature of outcrop cuts and thin sections
494 (Fig. 10). Based on our field, microstructural and mineralogical observations, we can exclude that
495 fluid-rock interaction promoting concentric replacement of the pristine clast minerals occurred to
496 form the cockade-bearing faults in the Col De Teghime area (mechanism ii). Infall of clasts during
497 cementation (mechanism iii) should generate asymmetric rims, which is inconsistent with the
498 symmetric concentric rims observed in our samples. Thus, one or more of the other mechanisms (iv
499 to vi) or other unknown ones control the formation of cockade breccias from the Col de Teghime
500 area.

501 Rim precipitation may start while the core clasts are kept in suspension in the fluid flow (i.e.,
502 fluidized flow behavior in Fig. 12a). Cox and Munroe (2016) described similar microstructures to
503 those presented here, and proposed that growth of cockades rims occurred simultaneously to
504 suspension of core clasts during fluidization of the granular fault rocks. This scenario implies that
505 either (i) formation of carbonate-built rims occurred with fast, almost instantaneous, precipitation
506 rates or (ii) the core clasts were kept in suspension for a long time span leading to the formation of
507 such zoned carbonate-built rims. In the first case, experiments of hydrothermal flows showed that
508 microcrystalline quartz can precipitate from supersaturate fluids in few minutes, when pressurized
509 fluids were continuously pumped within a vessel partly filled with rock fragments where silica
510 minerals precipitated (Okamoto et al., 2010). Recent flash depressurization experiments suggested
511 that amorphous silica nanoparticles are produced instantaneously by explosive flash vaporization
512 (Amagai et al., 2019). The amorphous nanoparticles crystallized into quartz grains of 1-2 μm and 10-
513 20 μm in size after 1 and 15 days, respectively. Unfortunately, there are no experimental data
514 regarding precipitation of carbonates from super-saturated solutions induced by rapid
515 depressurization. Also modelling of the precipitation rates is poorly constrained because it is

516 controlled by several poorly known parameters (e.g., temperature, pressure, pH, presence of
517 impurities, level of saturation) in natural faults. Perhaps precipitation rates of carbonate minerals
518 comparable to a co-seismic instantaneous precipitation are approached during fast travertine growth
519 due to sudden degassing of water supersaturated in calcium carbonate. In this case, carbonate
520 precipitation rate reaches values of $\sim 0.3 \mu\text{m/s}$ (i.e., 10 m/yr; Chafetz and Folk, 1984). However, this
521 particular precipitation rate is achieved when droplets of water supersaturated in calcium carbonate
522 are suddenly vaporized because of an impact on a surface (i.e., waterfall environment): these are
523 clearly different conditions from those occurring during seismic faulting. Based on these limited
524 evidences, though we cannot exclude that the formation of the rims of the cockades occurred during
525 seismic slip and associated fluid flow, this formation mechanism seems unlikely because of the too
526 low precipitation rates. In the second case (hypothesis that the core clasts were kept in suspension for
527 a long time span leading to the formation of such zoned carbonate-built rims), based on the modelling
528 presented in section 5.2, the flow velocity to keep particles in suspension might have reached values
529 around 10^{-1} m/s (Fig. 12a). The critical question is how long such high-flow velocities can be attained
530 and sustained in a fault-related hydrothermal system. In fault-related hydrothermal systems, fluid
531 flow is intermitted because of fault-valve processes linked to seismic activity (Sibson, 1981; 1990).
532 Since such a high flow velocity can occur for short periods of time (i.e., during the peak of the fluid
533 flow) due to the release of fluids during the seismic event, it is unrealistic that core clasts were
534 continuously kept in suspension for the time span required to form thick and chemically zoned
535 cockade rims. Alternatively, according to the model by Cox and Munroe (2016), injection-driven
536 swarm sequences can produce the high fluid fluxes necessary to both keep in suspension continuously
537 the core clasts and simultaneously form the cockade rims in all the directions. In this case, the core
538 clasts are repeatedly fluidized and it should be expected that cockades rotate and interact with each
539 other during suspension and settle down and start to be cemented when the fluid pressure is reduced.
540 These processes would affect the symmetry of the concentric cockade rims and potentially lead to
541 their breakage. We have never observed such microstructural evidence in the cockade breccias of the

542 Col de Teghime area. Moreover, the lack of symmetric distribution of core clasts within the slipping
543 zones with the finer ones close to the vein boundaries and the larger ones in the central part of the
544 vein due to the velocity gradient within the vein, as found by Cox and Munroe (2016) and the presence
545 of triple junctions at the contact between adjacent cockades (see Figs. 6c, 7c) dismiss the possibility
546 that the driving mechanism controlling the formation of cockade breccias presented here is the
547 combination of simultaneous suspension of the core clasts and precipitation of the carbonate-built
548 rims. Lastly, there is no evidence for long-lasting and large fluid circulation (= meter-thick vein
549 deposits) associated with the NW-SE trending fault system in the area of the Col de Teghime.

550 Based on the points discussed above, we speculate that pressure growth (also called
551 crystallization pressure; Weyl, 1959) is the main mechanism compatible with the formation of the
552 microstructures in the cockade breccias of the Col de Teghime area (Fig. 11c). Indeed, mineralogical
553 and chemical zonings can easily develop in longer time spans, suggesting that the formation of the
554 cockade rims occurred during the post-seismic to inter-seismic phase of the seismic cycle (from
555 months to thousands of years; Scholz, 2019), when the fault zone sealed due to the infiltration of
556 chemically diverse fluids. Pressure growth develops crystal faces projecting in all the directions if the
557 mineral phases have high surface energy and surface energy anisotropy (e.g., pyrite vs. quartz or
558 calcite and quartz; Spry, 1969). Another observation consistent with pressure-growth mechanism is
559 the lack of any deformation of the cockade rims. For instance, truncation of concentric rims has been
560 proposed as indicator of cockade breccias resulting from rotation-accretion mechanism and
561 suggesting syntectonic cockade breccia formation (Genna et al., 1996; Frenzel and Woodcock, 2014;
562 Berger and Herwegh, 2019). Moreover, pressure growth of crystals in stationary condition within
563 pressurized fluids is compatible with the hypothesis that core clasts were separated from each other
564 without any remarkable modification of the clast arrangement (inverse grading) derived from the
565 previous sorting of the fluidized granular material during seismic slip. Importantly, experimental
566 evidence shows that pressure growth in rocks can uplift a dead weight (Taber, 1916; Gratier et al.,

2012) and achieve magnitudes of 30 MPa or larger (Zheng et al., 2018; 2019, in the case of reaction-induced fracturing) resulting in fracturing of porous rocks (Noiriel et al., 2010).

Microstructural observations indicate that, in each cockade, the rims surround completely the core clasts and each rim grows in epitaxial way over the previous one. This suggests that concentric carbonate-built rims are free to grow in a highly porous medium with low packing forming perfect euhedral facets in all the directions (Fig. 11c). Initial accretion of the rims, possibly initiated during seismic slip, derives from supersaturated fluids promoting dolomite precipitation, then the accretion with epitaxial growth is governed by lower levels of supersaturation inhibiting ongoing nucleation and promoting the growth of concentric rims in all the directions. Indeed, epitaxial growth in presence of fluids is the most energetically favorable process of crystal growth as proved by experiments and numerical modeling (Putnis and Putnis, 2007; Mithen and Sear, 2014). On the other side, in fault veins with abundant ultrafine clasts (V4; see Figs. 8b-c, 10b) which act as multiple seeds for crystal precipitation and where the pore space between clasts is reduced, the epitaxial growth of concentric carbonate rims and the formation of cockades are inhibited.

Frenzel and Woodcock (2014) argued that cockade breccias resulting from pressure growth of crystals can form only in open spaces in subaerial environments where well-developed crystals can growth facets projecting outwards from the core clasts. However, the network of faulting and veining events cutting the cockade-bearing faults cannot form at the Earth's surface (see Fig. 2c-d, 4, 7a). Moreover, in hydration reactions (e.g., $\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca}(\text{OH})_2$ or slow explosive cement) the pressure induced by crystal growth exceeds 20-30 MPa. These experimental observations are also supported by conceptual and thermodynamic models suggesting that local significant crystallization pressures (up to 10s MPa) can be associated with supersaturated fluids both in diagenetic environments and in high-fluid pressure crack-sealing veining (the latter case is consistent with our study; Maliva and Siever, 1988; Wiltschko and Morse, 2001). If similar pressure magnitudes are achieved during the growth of dolomite and calcite, then cockades growth may easily occur at 1-2 km depth.

592 Presence of saddle dolomite in the cockade cement suggests that carbonate precipitation
593 occurred between 60°C and 150°C (Warren, 2000 and references therein). The origin of CO₂-rich
594 fluids may be various (meteoric, hydrothermal, mantle, mixing etc.) and would require further
595 analyses that are outside the scope of this paper to be constrained. The high content of Fe in the
596 carbonate cement and widespread precipitation of goethite suggest that fluids were enriched in Fe.
597 Instead, variations in mineral composition in the concentric rims and the sealing cement may reflect
598 fluctuations in fluid saturation levels. Mineralogical investigations highlight that saddle dolomite is
599 enriched in Ca and Fe. At rapid growth rates, dolomite shows strong enrichment of Ca and slight
600 enrichment of Fe over Mg related to high temperature conditions promoting the formation of non-
601 stoichiometric dolomite (Searl, 1989). Further evidence of relatively rapid crystallization rate is the
602 widespread presence of cavities in the dolomite cement (Fig. 5) which indicates that the growth rate
603 of cockade rims was slightly higher than the precipitation rate, but did not proceed at co-seismic
604 instantaneous precipitation rates (e.g., Bons et al., 2012).

605

606 **6. Implications for the mechanics of cockade-bearing faults**

607 Based on field and microstructural observations, each cockade-bearing vein recorded a single
608 slip event (Figs. 4, 7a). The cockade-bearing faults are cut by other slip surfaces and slipping zones,
609 suggesting that the fault cores accommodated multiple slip events (Figs. 3c, 4, 7a). Though we could
610 not determine the displacement accommodated by the studied cockade-bearing faults because of
611 limitations in the outcrop exposures, we did constrain the vertical displacement accommodated by
612 the cockade-bearing faults from meters to tens of meters based on the following field evidences:

- 613 (i) several NW-SE trending cockade-bearing faults separate the contact between the
614 continental granitoids and the quartzites and calcschists by tens of meters (see Fig. 1);
- 615 (ii) minor brittle faults in the hanging wall and with the same kinematics and mineral filling
616 of the main fault in Fig. 2 accommodated up to 25-40 cm of normal displacement,
617 suggesting larger slips for the main cockade-bearing fault.

618 The NW-SE trending fault system, which the cockade-bearing faults belong to, cuts the HP-HT
619 units of the Schistes Lustrés and was exhumed 14-10 Ma according to fission track data (Fellin et al.,
620 2005; 2006). Additionally, in the fault zone at stop 2 (Figs. 1, 3), slipping zones with CCAs are cut
621 by the cockade-bearing slipping zones (Fig. 7). CCAs in calcite gouges were experimentally produced
622 only at low normal stress (< 5 MPa; Rempe et al., 2014) and found in natural faults in the Italian
623 Central Apennines exhumed from < 2 km depth (Smith et al., 2011). Consequently, the presence of
624 cockade-bearing veins cutting the CCAs-bearing slipping zones suggests that the cockade-bearing
625 faults were exhumed from shallow crustal levels. In conclusion, since the studied faults zones are late
626 Miocene in age, this limits the depth of the cockade-bearing faults to less than 2 km.

627 At shallow crustal levels (< 2 km), low mean stresses and the necessary porosity (i.e., open
628 space between the core clasts) allow pressure growth to operate and build the cockades. Otherwise,
629 at deeper levels, compaction of the core clasts and mineral growth competition might impede the
630 formation of such symmetric cockade rims by pressure growth. However, the formation of such
631 idiomorphic cockade rims controlled by pressure growth imply nearly hydrostatic loading conditions,
632 otherwise significant deviatoric stresses would control rims formation with mineral growth parallel
633 to direction of minimum compressive stress (i.e., σ_3 ; see Cox and Munroe, 2016). This suggests that
634 the cockade-bearing faults of the Col de Teghime were maintained relatively pumped by fluids at
635 shallow crustal level (< 2 km, low mean stresses). Moreover, the cockade breccias of the Col de
636 Teghime area mainly formed at fault geometrical irregularities (i.e., fault dilatant sites; e.g., Holland
637 et al., 2006; 2011; von Hagke et al., 2019; see Fig. 2), which were relatively unloaded compared to
638 the rest of the fault. In an extreme case, the core clasts produced and suspended by fluids at fault
639 dilatant sites during the seismic event were left in a pool-like cavity close enough to the surface to
640 allow them to remain open (i.e., the shoulders of the cavity sustained the load). This environment is
641 similar to the one typical of pisoids formation, large (>2 mm) carbonate grains formed by accretion
642 of carbonate wrapping pre-existing nuclei (Melim and Spilde, 2018 and references therein) in cave
643 environments. Kettermann et al. (2019) proposed that tectonic caves can be produced till 800 m depth

644 in deep dilatant zones, where host rock fragments and sediments collapse filling partially or entirely
645 the cave system. At this depth, open fissures and tabular tilted blocks (see Kettermann et al., 2019 for
646 their definition) can evolve in faults because of transition of failure modes from the tensile mode to
647 the shear mode (Holland et al., 2006; 2011; von Hagke et al., 2019). In fact, though we dismiss that
648 the formation of core clasts in the cockade breccias resulted from gravitation collapse in dilatant
649 fractures, we cannot exclude that some of the faults discussed here become open fractures in their
650 very shallow sections.

651 No reworked cockades were found as core clasts within the slipping zones of the Col de
652 Teghime area. Instead, cockade-bearing faults are cut through by other fault veins (V4). This suggests
653 that post-seismic cement precipitation promoted hardening of the slipping zones, lowering
654 permeability and porosity of the granular fault rocks and increasing their strength and cohesion close
655 to the values of the intact host rocks. This was previously proposed for fault zones in crystalline
656 protoliths such as the Gole Larghe Fault Zone (Italian Southern Alps; Di Toro and Pennacchioni,
657 2005). Thus, at shallow crustal levels (i.e., at relative low confining stress), hydrothermal
658 precipitation and formation of cockade breccias may represent a fault hardening process inhibiting
659 seismic reactivation of preexisting slipping zones and promoting the nucleation and propagation of
660 seismic faulting on newly formed slipping zones. Such a process has significant implications for the
661 evolution of the fault zone architecture and the long-term mechanical behavior of fault zone.

662

663 **7. Conclusions**

664 We described cockade-bearing transtensional faults in Col de Teghime area (Alpine Corsica).
665 The combination of field structural surveys and detailed microstructural and mineralogical
666 observations allowed us to build a conceptual model for the formation of cockade breccias. The model
667 includes the main phases of the seismic cycle:

1. Co-seismic fragmentation of the wall rocks at geometrical irregularities (e.g., dilation jogs) in the presence of CO₂- and Fe-rich fluids and mechanical wear leading to the formation of core clasts.
2. Co-seismic fluidization of the rock fragments resulting in grain elutriation and sorting of the finer clasts (found in fault veins V4 possibly associated with the distal parts of the fluidized clasts), and promoting the development of inverse grading within the slipping zones. Inverse grading of well-sorted and larger grains is possibly due to either collision between clasts (Brazil-Nut Effect) and shearing.
3. Formation and separation of cockades during the post-seismic to inter-seismic phase driven by pressure growth which controls the precipitation of concentric rims made from the interior to the exterior of (1) saddle dolomite, (2) Mg-calcite, (3) saddle dolomite and (4) Mg-calcite. In rims 2 and 4, goethite and anatase crystals are found in micropores mimicking the habit of the carbonate minerals. Saddle dolomite enriched in Ca and the widespread presence of pores in the dolomite cement suggests that cockade-bearing faults experienced relatively rapid crystallization rate.

The development of cockades is strongly controlled by the availability of free pore space between particles and grain size. Indeed, ultrafine and highly packed clasts inhibit the development of cockade breccias, as it was found in fault veins V4 which were interpreted as the distal part of elutriated clasts from co-seismic fluidization. In the cockade-bearing faults, the presence of open cavities and filling by calcite may support the hypothesis of late infiltration of meteoric fluids.

According to this study, and differently from previously published ones, pressure growth can control the formation of cockade breccias also at shallow depths (< 2 km) in the Earth's crust. Moreover, according to our observations and those reported in previous studies, hydrodynamic elutriation seems to be a common mechanism for the formation of well-sorted fault rocks (i.e., breccias and cataclasites) lacking sub-millimeter-sized particles. Finally, cockade breccias may allow

694 us to investigate the mechanical and chemical processes operating during the seismic cycle at shallow
695 crustal levels in fluid-rich tectonic settings.

696

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707

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Figure Captions

973 **Fig. 1.** Geological setting of the Col de Teghime area (Alpine Corsica). (a) Simplified geological map
974 with main stops (1 to 4) and orientation of points of view of Figs. 2-3. Modified from Faure and
975 Malavieille (1981), and Dallan and Puccinelli (1995). (b) Stereonets of the orientations and lineations
976 of faults collected at each stop. The fault planes are in black color and the average attitude of the main
977 fault is in red color. Arrows indicate the direction of movement of the hanging wall.

978
979 **Fig. 2.** Faults and fault zone rocks at Stop 1. (a) Panoramic view of the outcrop (top) and sketch with
980 lithologies, main fault rock domains, and localities of the collected samples (bottom). (b) The
981 transition between the fault core and the damage zone is marked by sharp boundaries (dashed white
982 line). The fault core is easily recognizable because of the reddish- to orange-color matrix that supports
983 breccias. Dashed black lines define the metamorphic foliation. Cover lens for scale. (c) Cockade-
984 bearing faults with inverse grading distribution of the cm-size clasts. Core clasts are surrounded by
985 mm-thick rims of dolomite, calcite, goethite and anatase forming cockade-like texture. The upper part
986 of the cockade-bearing vein is locally sealed by carbonate cement (Cc). Faults veins cut the cockade-
987 bearing veins (green in color arrows indicate shear sense). Late carbonate-bearing veins (LCV) cut
988 the entire fault core. Coin for scale. (d) Well-developed inverse grading within the cockade-bearing
989 vein. Injection-like veins are visible intruding the footwall (white arrows). (e) Cavities (i.e.= voids
990 not filled by cement) up to 10s of centimeters in size are only partly filled with white in color calcite
991 crystals within the cockade-bearing faults. Sample CC05-17. (f) Minor brittle normal dip-slip fault
992 cutting the marbles in the hanging wall. This fault accommodates normal dip-slip displacement up to
993 40 cm.

994
995 **Fig. 3.** Faults and fault zone rocks at Stop 2. (a) Fault surface of the NW-SE trending main fault
996 marked by calcite slickenlines cutting the marbles. The field photo was taken looking the fault surface
997 upwards. (b) Well-developed calcite slickenlines on the fault surface of the NW-SE trending main
998 fault with marbles in hanging wall. Compass for scale. (c-d) Zoom on cockade-bearing faults showing

999 fault breccias with fragments surrounded by mm-thick reddish rims forming cockade-like texture
1000 cemented by white in color calcite. Yellow in color arrows indicate the cockade breccias in (c). The
1001 cockade breccias are cut by mirror-like slip surfaces. White in color arrows indicate truncated
1002 cockades of the cockade-bearing vein. White in color calcite-built concretion (Cc) due to very late
1003 stage karst process within the fault zone in (c). Coin for scale.

1004

1005 **Fig. 4.** Cockade-bearing faults. (a) Key-type polished sample (sample CC01-12) with multiple
1006 cockade-bearing veins and inverse grading. (b) Sketch of the sequence of faulting and veining events.
1007 See main text for description.

1008

1009 **Fig. 5.** Cockade breccias (sample CC01-12). (a) Core clast partly contoured by the dashed white-
1010 colored line and surrounded by the four concentric rims of (from the core clast outwards): (1) saddle
1011 dolomite enriched in Ca and Fe; (2) Mg-calcite with goethite and anatase microcrystals; (3) zoned
1012 saddle dolomite; (4) Mg-calcite with goethite and anatase microcrystals. The cavities between the
1013 cockades are filled by calcian dolomite “sealing cement” and late stage pure calcite (V8). (b)
1014 Elaborated EDX map showing the spatial distribution of mineral phases in the cockade breccia. (c)
1015 Under the optical microscope (OM) in parallel-polarized light (PPL), the dolomite-built rims are
1016 transparent, while the hydroxide- and oxide-rich rims are brownish in color. (d) OM
1017 cathodoluminescence (OM-CL) images of the same area as in (c): the CL signal for dolomite is mostly
1018 “quenched”; while, for calcite it indicates strong chemical zoning. (e) OM-CL image of cockade
1019 breccia showing the carbonate-built rims surrounding entirely the core clasts made of the quartzite
1020 host rock. The dashed white-colored lines mark the core clasts. (f) Acicular- and spherulitic-shaped
1021 crystals of goethite (Gt) and anatase (Ant) partly filling the micropores parallel to the calcite habit.

1022

1023 **Fig. 6.** Microstructures of the cockade-bearing faults. (a) High-resolution scan of a cockade-bearing
1024 vein which does not have inverse grading within the slipping zone (sample CC11-17). The cockade-

bearing vein is bordered by slipping surfaces. The core clasts do not show any preferential orientation within the slipping zone. Dashed red-color box marks the zoom in (b). (b) Zoom on the slipping zone (photomosaic of BSE images). The core clasts are made of both quartzite and reworked-vein fragments and are wrapped by carbonate-built rims, forming cockade-like texture. The cockades are sealed by a dolomite in composition cement. Pores are black in color in BSE image. (c) Core clast made of cataclastic to ultracataclastic quartzite (cross-polarized light micrograph from sample CC01-12). The cockade rims separate the core clasts and, when cockades are in contact with the adjacent ones, they form triple junctions.

Fig. 7. Slipping zones of cockade-bearing faults at Stop 2. (a) Scan of the thin section of sample CB04-07. The cockade-bearing vein is cut by multiple mirror-like slip surfaces, which truncate the cockades. The cockade-bearing vein cuts a slipping zone filled with cortex-clasts aggregates (CCAs). Below the CCAs-bearing slip zone, multiple slip surfaces and zones are recognized. Slip zones consist of protobreccias and cataclasites. Dashed yellow-colored boxes indicate the zooms in (b-e). (b-c) Parallel-polarized light micrographs of the cockades. The core clasts consist of fragments of the marble-built host rock wrapped by carbonate-built rims with opaque minerals. The cockade rims appear “dusty” because of the opaque minerals (goethite from XRPD analysis). The cockades are sealed by white in color calcite cement and, locally, form triple junctions, when they are in contact with the adjacent ones as shown in (c). (d-e) Parallel-polarized light micrographs of the CCAs similar to those experimentally produced by Rempe et al. (2014). The CCAs consist of marble fragments, calcite and opaque minerals.

Fig. 8. Microstructures of the faulting and veining events in the cockade-bearing faults (sample CC01-12). (a) Dolomite-rich vein V7 cuts and intrudes the brownish ultracataclastic fault vein V4 and the cockade-bearing vein V3. (b) Cockade-bearing vein (V3) cut by fault vein V4. The latter is made of fine angular quartzite fragments sealed by calcian dolomite. (c) Zoom on the matrix of V4

1051 made of calcian dolomite, goethite and anatase. (d) OM-CL image of a cavity (V8) filled by pure
1052 calcite with strong chemical zoning. OM-PPL image of (d) on the top right corner.

1053

1054 **Fig. 9.** Cumulative clast size distributions (CSDs) of the (1) cores (i.e.= core clasts) of the cockade
1055 breccia with inverse grading (V3, sample CC01-12), (2) cores of the cockade breccia without inverse
1056 grading (sample CC11-17), (3) clasts of the fine grained cataclastic fault vein (V4, sample CC01-12)
1057 and, for comparison, (4) clasts in similar dolomite-bearing fault veins from strike-slip faults cutting
1058 dolostones (Fondriest et al., 2012; green in color curve). The CSDs in the cockade-bearing faults and
1059 from the dolomite-bearing fault veins described by Fondriest et al. (2012) are compatible with a
1060 process of elutriation of clasts smaller than 300 μm in diameter due to co-seismic fluidization. The
1061 elutriated smaller clasts are thought to form the ultrafine cataclastic fault veins (V4, see also the
1062 conceptual model discussed in Fig. 11). Clasts were drawn by hand and their distribution determined
1063 with the software Fiji (Schindelin et al., 2012) as discussed in section 3. The thick vertical gray in
1064 color line at a clast size of $\sim 310 \mu\text{m}$ marks the abrupt change in slope of the CSD for the cockade-
1065 bearing veins due to the lack of fine particles. The dashed black segments are the slopes of the CSDs
1066 before their abrupt change in slope.

1067

1068 **Fig. 10.** 3-Dimensional reconstructions based on micro-CT analysis of the cockade-bearing fault in
1069 three volumes throughout the cockade-bearing vein (V3) with inverse grading (sample CC01-12).
1070 Core clasts do not touch each other and are separated apart by carbonate-built rims. (a) The darkest
1071 grey levels are given by quartzite-built clasts and by the presence of open cavities. (b) Fine angular
1072 clast-supported fault vein (V4) cuts the cockade-bearing vein (V3). (c) The smallest cockades are
1073 found towards the footwall.

1074

1075 **Fig. 11.** Conceptual model of the formation of cockade-bearing faults (right column) and its
1076 relationship to fault displacement and time during the seismic cycle (left column). (a) Co-seismic

1077 fragmentation: earthquake rupture propagation along a fluid-rich fault and consequent fragmentation
 1078 and implosion of the wall rocks. (b) Zoom on fault dilatant site: co-seismic fluidization due to
 1079 ingress of CO₂- and Fe-rich fluids promotes (1) collision, abrasion, comminution of wall rock
 1080 fragments; (2) sorting and elutriation of finer clasts (see Fig. 12a); (3) inverse grading associated with
 1081 shacking (Brazil-Nut Effect) and shearing (see Fig. 12b-c). (c) Post-seismic fault sealing: formation
 1082 of cockades due to precipitation of saddle dolomite + Mg-calcite + goethite + anatase by pressure-
 1083 growth mechanism at fault dilatant sites, which are relatively unloaded compared to the rest of the
 1084 fault. The formation of cockade rims results in the progressive separation of the core clasts. Pressure
 1085 growth preserves the clast arrangement (inverse grading) resulted from the sorting of the fluidized
 1086 granular material during seismic slip. The finer elutriated clasts will form the distal parts of the
 1087 fluidized material (see also the fault veins V4 in Fig. 4).

1088

1089 **Fig. 12.** Physical processes promoting clast size selection and inverse grading. (a) Modeled
 1090 relationships between superficial flow velocity and particle diameters for minimum fluidization
 1091 (blue-color curve; u_m) and entrained flow regime (orange-color curve; u_t) for spherical particles. The
 1092 vertical dashed black line indicates the cut-off value of 310 μm in diameter observed in the cockade-
 1093 bearing veins (Fig. 9). As a result, a superficial flow velocity of 0.13 m/s is required to elutriate clasts
 1094 $\leq 310 \mu\text{m}$ in size. According to this model, at the superficial velocity of 0.13 m/s clasts $\leq 2.3 \text{ cm}$ in
 1095 diameter can be fluidized (i.e., float in the flow; see horizontal dashed black line in the upper
 1096 diagram). See the text for the boundary conditions assumed for the modeling. (b) Brazil-Nut Effect:
 1097 sequences of shaking of a 50/50 binary mixture with size ratio 1:5 from the initial random placement
 1098 to the configuration (i.e.= inverse grading) obtained after 300 shakes. Seismic shaking is expected to
 1099 yield similar effects on granular materials (modified from Rosato et al., 1987). (c) Simple shear of
 1100 particles of different size leads to downward motion of the smaller ones (passing through the voids)
 1101 and formation of inverse grading.

- ① Stops
 ▷ Field view
 $\rightarrow^{10}$ Foliations
- Definite contacts
 - - - Inferred contacts
 — Transtensional faults
- Schistes Lustrés Complex**
 Continental granitoids
 Marbles
 Quartzites & Calcschists
 Prasinites

$D = 2.375$ ($R^2=0.975$)

$D = 1.734$ ($R^2=0.988$)

$D < 1$ (for $d < 310 \mu\text{m}$)

$D = 1.604$ ($R^2=0.962$)

$D < 1$ (for $d < 460 \mu\text{m}$)

ST13-Layer A from Fondriest et al. (2012):

$D = 1.558$

$D < 1$ (for $d < 300 \mu\text{m}$)

(a) co-seismic fragmentation

(b) co-seismic fluidization

(c) post-seismic to inter-seismic fault sealing

a) Modelling of flow behavior

b) Brazil-Nut Effect

c) Simple Shear Granular Flow