



Shallow seismic damage and structural inheritance at the onset of faulting

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ABSTRACT

Faults accommodate shear motion in the upper crust through brittle deformation like fracturing and cataclastic flow. The width of the embrittlement, the lateral extent of the fault, and the grain size distribution within the fault core seem to scale with shear displacement, though scaling laws have large uncertainties. Inherited structures may drive strain partitioning, restrict damage extension, and either favour or hinder seismic slip propagation. It is difficult to explore these features in natural faults since delicate structures such as crackle breccias and gouges are reworked during exhumation, overprinted during multiple deformation cycles, and altered by surface weathering.

The Bedretto Underground Laboratory represents a unique chance to study the structure of immature faults at depth, whose pristine structures are hardly preserved elsewhere in the field. The exceptional exposure allowed for a detailed analysis of a fault zone named Waterfault, which exploited the pre-existing fabrics of a mylonitic shear zone in the Rotondo granite. The limited extension of the damage zone and the scarce presence of cataclastic products indicates that the fault's activity was short-lived, possibly stemming from a single slip event. The presence of pulverised rocks, restricted to the hanging-wall side, suggests that faulting was produced during the propagation of a low magnitude earthquake. The pre-existing mylonitic fabrics provided a strong mechanical anisotropy, which confined the damage zone and favoured the lateral extension of the fault. We argue that the WF structures illustrate the onset of faulting along pre-existing anisotropies, revealing their role in the partitioning of energy and strain.

1. Introduction

Faults are zones of brittle damage that accommodate shear deformation in the upper crust. Their definition can be broad, spanning from embryonal sub-metre shear fractures all the way up to complex lithospheric volumes that host major earthquakes (e.g., Scholz, 2018). The wide morphological variety reflects evolutive processes featuring progressive accumulation of damage and self-organisation of structures with strain (distributed versus localised). As such, different sized structures in the field can represent frozen instants of the evolution of a fault. This concept is corroborated by scaling laws that connect length, thickness, and damage, measured with systematic field studies (e.g., Torabi and Berg, 2011). A different perspective is instead drawn at the

early stages of fault formation, where structural inheritance, i.e., pre-existing and precursory structures (*sensu* Crider and Peacock, 2004), imposes the initial geometry, lateral extension, and roughness. The initial stages of faulting are indeed favoured by the presence of mechanical anisotropies in the host rocks, determined either by joints, veins, dykes, foliations, and/or pre-existing brittle-ductile shear zones (e.g., Butler et al., 2008; Nevitt et al., 2023). Phyllosilicate foliation, for example, provides a directional mechanical weakness, which can be exploited by brittle deformation even with severely misoriented stress fields (e.g., Shea and Kronenberg, 1992; Ramamurthy et al., 1993; Collettini et al., 2009; Massironi et al. 2011; Tesei et al., 2012).

Precursory structures originate at environmental conditions close to that of faulting. These include the brittle damage that immediately

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predates localisation of strain and cataclasis. Traces can be preserved at the termination of small faults in nature, but this type of damage is better documented with laboratory rock deformation experiments. Precursory damage is either in the form of distributed fractures, progressively coalescing into a localised shear zone (Tullis, 1988; Renard et al., 2019), or localised fractures at the tip of a propagating shear crack (Griffith et al., 2009). Both processes may occur rapidly leading to paroxysmal failure of the entire sample, matching earthquake-like strain rates.

If the shear fracture tip propagates dynamically, i.e., during an earthquake, wave radiation and extreme dynamic stress values at the rupture front promotes the fine shattering or “pulverisation” (Dor et al., 2006) of the host rock, developing characteristic structures (e.g., Brune, 2001; Aben et al., 2017; Griffith et al., 2018; Cortinovis et al., 2024), such as: asymmetric distribution of damage, tensile fractures, mosaic breccias, and grain size distributions with high fractal number. Experimental and natural case studies on dynamic pulverisation are mostly reported on homogeneous host rocks, e.g., carbonates (Sagy and Korngreen, 2012; Fondriest et al., 2015; Schröckenfuchs et al., 2015; Billi et al., 2023; Cortinovis et al., 2024), sandstones (Aben et al., 2016), and crystalline rocks (Dor et al., 2006; Doan and Gary, 2009; Rockwell et al., 2009; Mitchell et al., 2011; Doan and d’Hour, 2012; Rempe et al., 2013; Fondriest et al., 2017; Griffith et al., 2018).

Nonetheless, inherited structural and compositional anisotropies may play a fundamental role in controlling rupture pattern and damage distribution in the host rock during seismic propagation. Bi-material mechanical interfaces, for example, are well known to control the propagation and the anisotropic distribution of dynamic damage (e.g., Ben-Zion and Shi, 2005). Less is known about the effect of pre-existing fabrics at the meso- and micro-scale, especially because exhumed faults rarely preserve the inherited fabrics and pulverisation overprint is extensive. The Bedretto tunnel (Central Swiss Alps) provides exceptional exposure of pristine (unweathered) fault zones in the Rotondo granite at different overburden depths, from ~400 to ~1500 m (e.g., Ma et al., 2022). In this study we analyse a fault zone that exploited a mylonitic shear zone exposed inside the Bedretto tunnel. Through meso- and micro-structural investigation we demonstrate that inherited fabrics have a strong effect on the early formation of fault zones.

2. Geological setting

The Bedretto tunnel is located within the Rotondo granite, the largest Early Permian intrusion characterising the polymetamorphic crystalline basement of the Gotthard nappe (295 Ma, Rast et al., 2022). In the tunnel, the Rotondo granite is characterised by two main units, the isotropic, fine-grained RG₁ and the porphyritic, foliated RG₂ (Rast et al., 2022). Both are overprinted by a dominant set of ductile and brittle shear zones developed at different times and metamorphic conditions, prior and during the Alpine orogenesis (Ceccato et al., 2024 and references therein). The regional-scale deformation pattern of the Gotthard nappe is dominated by E-W and NE-SW-trending amphibolite/greenschist facies ductile shear zones, which controlled the localisation and geometry of later-stage brittle fault zones at shallower conditions (Zangerl et al., 2006; Lutzenkirchen and Loew, 2011).

In this contribution, we focus on the analysis of one of these brittle fault zones developed during late Alpine collision (D₄ set of Ceccato et al., 2024). The D₄ set of deformation structures includes mainly strike-slip, zeolite- and clay-bearing brittle fault zones developed at shallow conditions ($T < 200^\circ\text{C}$, corresponding to < 7 km depth; e.g., Lutzenkirchen and Loew, 2011). K-Ar illite dating on brittle fault zones belonging to the same regional-scale fault pattern in the Central Alps define prolonged activity between 15 and 5 Ma (Kralik et al., 1992; Zwingmann and Mancktelow, 2004; Pleuger et al., 2012). Potential seismic fault activity is related to the latest stages of distributed brittle deformation connected to the regional Periadriatic and Rhone-Simplone faults (Pleuger et al., 2012). The occurrence of paleoseismic activity

along the Periadriatic fault system is supported by Miocene (16–19 Ma) pseudotachylites (seismic frictional melts; e.g., Müller et al., 2001). Furthermore, zeolite-bearing brittle fault zones developed in other crystalline units of the European Alps, and related to the Periadriatic fault system, have been previously correlated with potential swarm-like paleoseismicity at hydrothermal conditions (e.g., Dempsey et al., 2014).

The examined fault crops out at TM 2848 (TM: tunnel metre from the entrance, m) in the Bedretto tunnel at ~1400 m below the surface, almost beneath the Pizzo Rotondo peak (Fig. 1a and b). It is entirely hosted inside the porphyritic facies RG₂ of the Rotondo granite (Fig. 1b). A large water outflow springs from an opening of the brecciated fault materials (Fig. 1c), which is why it was assigned the name Waterfault, hereafter WF. As several of the faults mapped inside the tunnel, the WF exploited a pre-existing mylonitic (ductile) shear zone and brittle damage does not extend past its boundaries (Lutzenkirchen and Loew, 2011). The WF is oriented 65/315 (Dip/Dip direction), consistently with the predominant local set of lineaments (set 1, Achtziger-zupancić et al., 2024), which features lateral persistence up to several hundreds of metres.

3. Materials and methods

Oriented samples of the fault and wall rocks were collected directly from the tunnel wall using chisel and hammer. Samples with low cohesion were carefully extracted to preserve the original structures, dried, and embedded and consolidated in epoxy. Thin sections of all samples were cut perpendicular to the WF plane and parallel to dip direction for optical microscopy. Clayey samples were lapped using oil-based lubricant to avoid swelling. Samples were also prepared for electron microscopy analysis by lapping thick sections with diamond suspension down to 0.25 μm .

Thin sections were imaged in high resolution on a Leica DM6 M petrographical microscope using plane polarised light and crossed polars with first order retardation plate (Fig. 2,3). The use of the plate facilitates the recognition of the original structures (mylonite) overprinted by the brittle damage. Further microstructural imaging was performed on a Focused Ion Beam (FIB) Scanning Electron Microscope (SEM) ThermoFisher Scios 2 LoVac, hosted at the HPHT laboratory of INGV (Rome, IT). Back-scattered images were collected with a working distance of 7 mm at 10 kV and 0.4 nA (Fig. 4,5). Electron back scattered diffraction (EBSD) analysis (Fig. 6) was carried out on the same microscope using a Lumis EBSD detector. Operating conditions were 18 mm working distance at 25 kV and 52 nA. EBSD maps have a step of 0.8 - 1.6 μm . Post-processing of the EBSD data was operated with MTEX open-source MATLAB toolbox (version 5.11.2; Bachmann et al., 2010). Grain and sub-grain boundaries were segmented using 10° and 2° as misorientation angle threshold, respectively.

2D grain size distribution analysis was performed on images using FIJI software (Schindelin et al., 2012). Analysis of the intact mylonite was carried out with RGB segmentation of thin sections, exploiting differences in grain colour introduced by the retardation plate. Analysis of the fault rocks was carried out on both thin section and SEM images using as threshold the grayscale range of quartz and plagioclase fragments, the dominant phases. Split grains were segmented only if the boundaries were split open to a detectable dimension (> 1 pixel) and cohesive grain boundaries were ignored. The dimension of grains was defined as the equivalent diameter (of a circle with equal area) and analysed using cumulative particle size distribution (PSD) with binning of 0.1 in $\log_{10}$ space. The purpose of this analysis is to evaluate the grain size of the source rock (grains) against the products of brittle deformation (clasts). Alternative models are not considered here given the wider availability of power-law fits in the literature, which provide an optimal comparison with our results.

The fracture density, obtained from grain size analysis of clasts, was used to calculate the specific surface area (A_{ss}) and surface energy (E_G), following the procedure outlined in Pizzati et al. (2023). Starting from

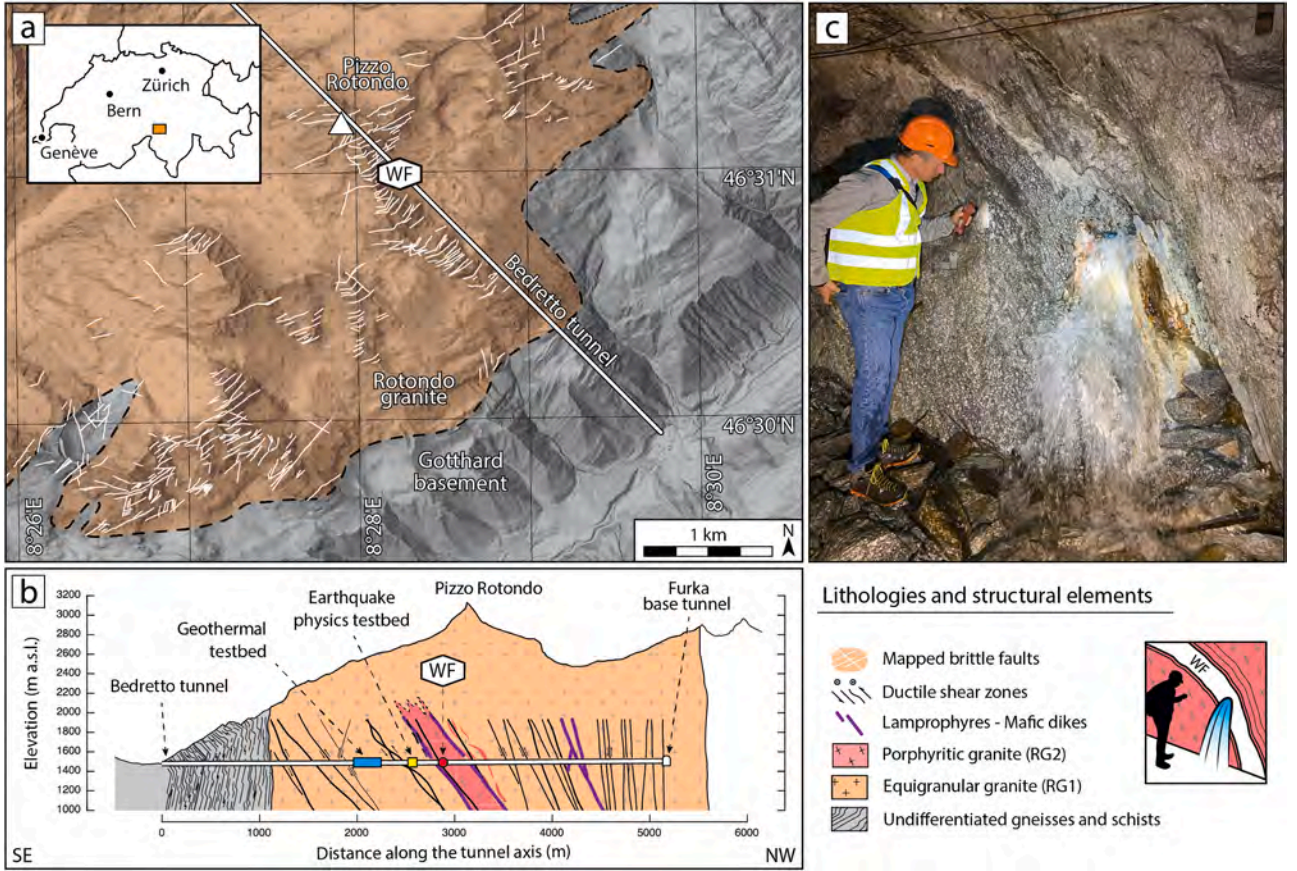


Fig. 1. Geological setting and Waterfault: (a) Simplified geological map of the area surrounding the Bedretto tunnel and location of the Waterfault (WF), showing the fault pattern as interpreted from remote sensing analysis (white lines) (b) Cross-section drawn parallel to the tunnel trace, highlighting the Rotondo granite units and principal ductile shear zones (modified after [Rast et al., 2022](#)). Locations include the earthquake physics and geothermal testbeds of the Bedretto Underground Laboratory for geosciences and geoenergies. (c) The WF exposed at tunnel metre 2848, displaying the large water outflow. Prof. P. M. Mai kindly posing as scale.

the binary images, the measured area of each clast was converted to an equivalent diameter, which were classified in bins. The median diameter and the volume fraction of each bin were used to calculate the Sauter mean diameter D_{32} (Eq. 5 in [Pizzati et al., 2023](#)) and then the specific surface area as:

$$A_{ss} = \frac{6}{\rho D_{32}} \quad (1)$$

where ρ is the average rock density. The specific surface area was then used to calculate the surface energy density:

$$E_G = A_{ss} \gamma_w \lambda \rho w \quad (2)$$

where γ_w is the specific surface energy density and w the thickness of the pulverised fault rocks. λ is the surface area correction factor (mean value of 1.28), which was calculated as function of the factor k (set to 1 since particles mean aspect ratio ranged from 1 to 10), particle perimeter P , and particle equivalent perimeter P_{eq} ([Johnson et al., 2021](#); [Davies et al., 2019](#)):

$$\lambda = k \frac{P}{P_{eq}} \quad (3)$$

Sample preparation for K-Ar illite and K-feldspar dating (careful selection, dispersion in water and sieving) was carried out at the Geo-science Centre of the Georg-August-Universität Göttingen. The grain sizes adopted for the analyses ($< 0.2 \mu\text{m}$, $< 2 \mu\text{m}$, $2-6 \mu\text{m}$) were concentrated from the $< 63 \mu\text{m}$ fraction of the samples through differential settling and ultra-centrifugation following the combined Atterberg-centrifugation-method. XRD analysis was performed using a

XRD-Eigenmann ORION Komet P2 diffractometer. Quantitative mineralogical compositions were estimated through Rietveld modelling on non-oriented powder preparation. The same spectra were used for quantification of white mica polytype through peak comparison following [Grathoff & Moore \(1996\)](#). Illite crystallinity was determined from oriented sample preparations and calibrated against the collection of Crystallinity Index Standards (CIS-Warr 2018). Duplicate K measurements were performed by flame photometry using a BWB-XP flame photometer™. Measurement of Ar was conducted in a stainless steel extraction and purification vacuum line coupled to a Thermo Scientific ARGUS VI™ noble gas mass spectrometer operating in static mode. Samples were initially pre-heated at 120°C for 24 h under vacuum, in order to reduce atmospheric argon adsorption in the analyzed material. Afterwards, the samples were placed on a Mo-crucible and fused at 2000°C , from which the resulting gases were purified using a setup of Ti-sponge and SORB-ACs getters™. Details about the analytical procedures followed in Göttingen and the strategies for interpretation of K-Ar ages in illite are presented in [Hueck et al. \(2022\)](#).

4. Results

4.1. Meso-and microstructures

In the tunnel, the exposed cross-section of the WF (south-western tunnel wall) reveals a clear inner zonation and a strong asymmetry ([Fig. 2a,b](#)). Indeed, the high strain domain, the fault core, is emplaced at the southernmost reach of a mylonitic shear zone and the low strain domain, the damage zone, extends mostly inside the hanging wall. Seven key facies, labelled from footwall (WF-1) to hangingwall (WF-7), can be

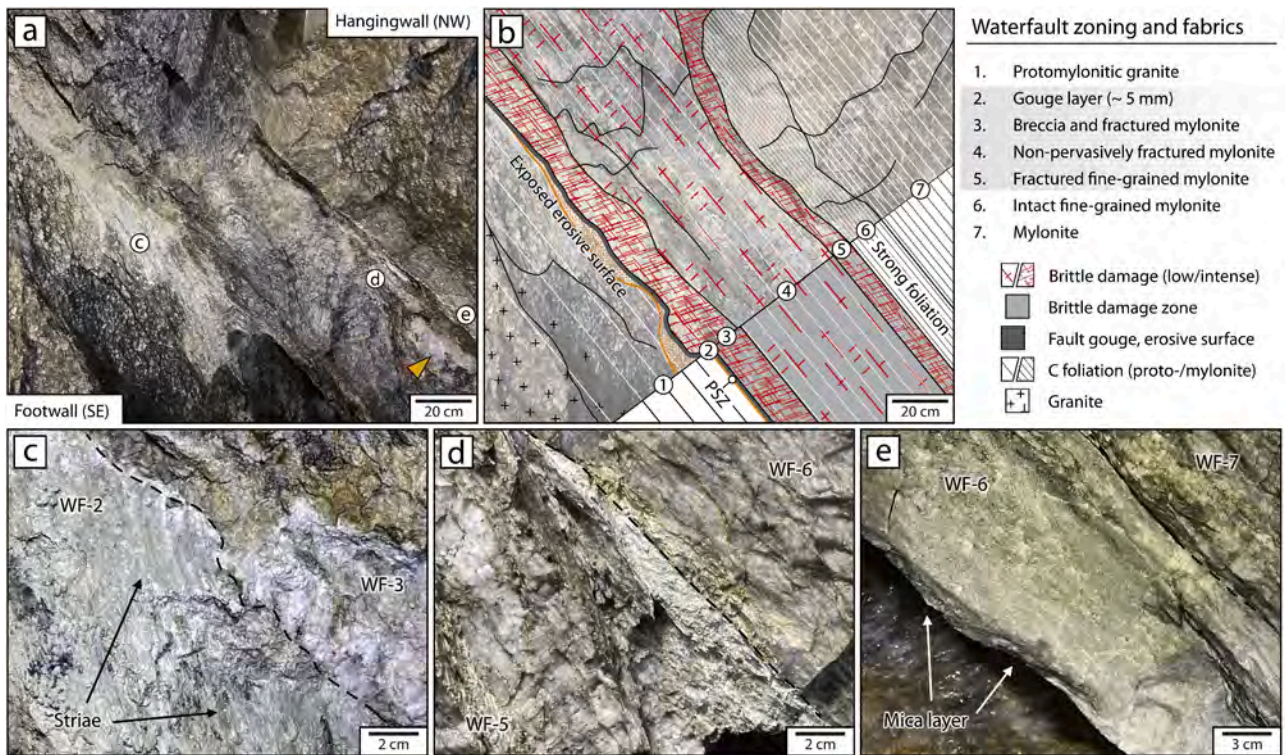


Fig. 2. Waterfault outcrop in the tunnel: (a) exposure of the fault zone on the south-western tunnel wall, with a well-exposed erosive surface decorated by white gouge. The boundaries of the damage zone are distinguished by marked fracturing parallel to the mylonite foliation. Pods of quartz sub-parallel to the foliation are found close to the hangingwall (orange arrow). (b) Line drawing highlighting the zoning of the WF, mylonitic foliation, and the extension of the brittle damage. (c) Close-up of the erosive surface decorated with abundant fault gouge and displaying dip-parallel striae. (d) Transition between the fragmented and the intact fine-grained mylonite. Note the dusty material at the interface. (e) Transition between the fine-grained (WF-6) and the coarse-grained (WF-7) mylonite in the hangingwall. Also note the thick layer of white mica at the transition between WF-6 and the missing WF-5. Dashed lines indicate the boundary between two facies.

examined (Fig. 2) and distinguished recognising meso- and microscopic differences in fabrics. A summary of the main characteristics of each facies is reported in Table 1.

The footwall is represented by undamaged mylonite (< 3 cm) whose foliation rapidly fades to protomylonite then to porphyritic granite within 1 m from the WF. No evidences of open fractures nor cataclasis are seen in this facies (F-1). Healed fractures and fluid inclusions are instead widespread and mark an earlier brittle history, complicated by cycles of ductile-brittle deformation. This deformation will not be treated in this manuscript.

A continuous, thin layer of fine-grained gouge (~ 5 mm) lays on a sharp erosive surface on the footwall (Fig. 2c). This facies (WF-2) represents the principal slip zone (PSZ) of the fault. On the other side of the PSZ, a layer of cataclastic breccia (WF-3) extends for a few centimetres inside a coarse but well-foliated mylonitic fabric. Sampling of the gouge and breccia (WF-2,3) resulted in abundant non-cohesive material, which yielded > 30% in weight of dry powder fraction smaller than 125 μm . Past the breccia layer, the damage remains intense but without apparent shear strain up to 10 cm, and then severely decreases in a ~40 cm thick volume of foliated mylonite (WF-4). At ~ 55 cm from the erosive surface, the coarse mylonite is in sharp contact with a fine-grained mylonite with a thickness of ~ 20 cm. The first 5–10 cm of the fine-grained mylonite (WF-5) are dusty and easily break upon recovery, while the upper portion (WF-6) appears pristine (Fig. 2d). The two facies are separated by a white mica-rich layer (Fig. 2e). WF-6 displays another sharp boundary with the outer, coarser and intact mylonite (WF-7), whose foliation persists for several metres away from the WF.

The asymmetry of the brittle structures is clear also at the micro-scale through analysis of thin sections. The erosive surface appears sharp down to the grain scale and presents mild gouge-filled grooves carved inside the cohesive wall rock. WF-2 gouge is fine-grained (Fig. 3b), as

also suggested by the recovery of the gouge, and does not show anisotropic fabrics. The WF-3 breccia contains far larger clasts that retain the original mylonite fabric.

On a closer inspection, these clasts are finely powdered to grain sizes comparable to that of the gouge (compare Fig. 3b and Fig. 3c), but the fragments are not displaced (Fig. 3c). The WF-5 fragmented fine-grained mylonite presents similar damage (Fig. 3d), where the mylonitic fabric is preserved but grains present a pervasive network of intra- (Fig. 3e) and inter-granular (Fig. 3f) fractures. The immediately adjacent WF-6 fine-grained mylonite appears identical to WF-5 but shows no trace of brittle damage. The coarse hangingwall mylonite is composed of large feldspar crystals (> 5 mm, Fig. 3k) surrounded by seams of fine-grained, recrystallised quartz and plagioclase (Fig. 3l) and presents no brittle damage.

Brittle damage in all samples is easily observed in plane polars (Fig. 3a,d,g,j) due to the brown mineralisation of microscopic oxides and phyllosilicates, probably clays (Lutzenkirchen and Loew, 2011; Volpe et al., 2023). From this, we recognise a consistent pattern of elongated fractures at high angle (> 45°) to the WF PSZ and dipping in the same direction (see also Fig. 3c,e).

4.2. Analysis of brittle deformation in the fault rocks

4.2.1. Fracture pattern and particle size distribution

To analyse the extent of brittle damage we use sample WF-5, which presents fracturing as in WF-3 but it was easier to recover preserving its original fabric. Back-scattered SEM images reveal the pervasive brittle damage at the grain scale. Different types of fractures are distinguished. The first type consists of throughgoing fractures (longer than the average grain size) that produce shard-like fragments (Fig. 4a and Fig. 4b orange arrows). These fractures are oriented at high angle to the

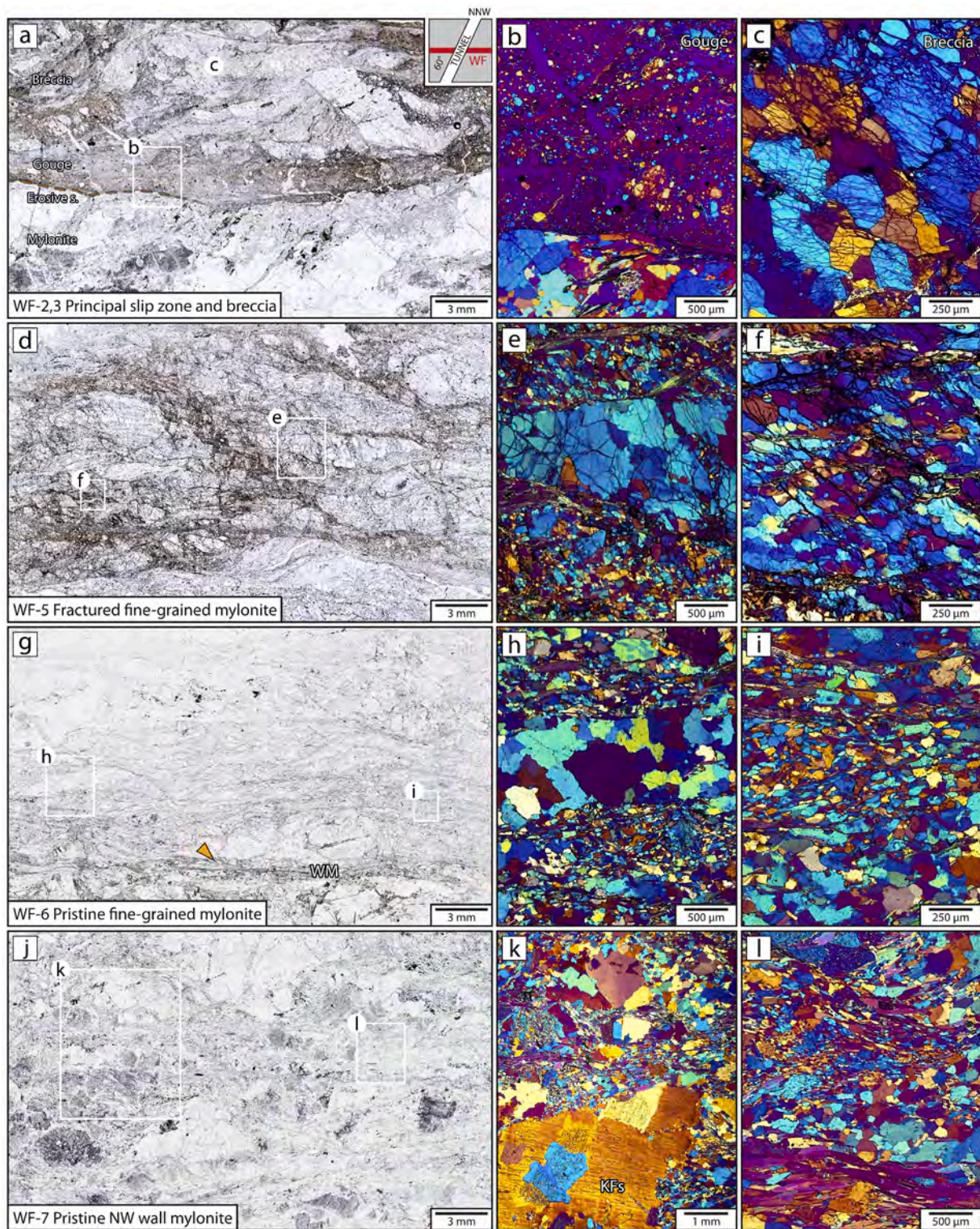


Fig. 3. Microstructures: Petrographic thin sections of four selected zones from WF and wall rock. The images on the left column have been photographed under plane polarized light and provide a qualitative overview of the intensity of brittle damage (dark patterns). The centre and right columns were photographed using crossed polarized light, filtered through a first order retardation plate, and are used to infer the intensity of the brittle overprint on original mylonite fabric. The inset in panel (a) shows the orientation of the tunnel axis with respect to the thin sections (WF in red, vertical direction dashed in black). WF zone codes on the left-hand side refer to the labeling of zones in Fig. 2. (a) Principal slip zone of the WF showing the limited thickness of the gouge layer (< 5 mm) with close-up in (b), the erosive surface (dashed orange line), and the fragmented breccia with close-up in (c). Note in (c) that pervasive brittle damage did not displace the original mylonite fabric in the large clasts of the breccia. (d) Fragmented fine-grained mylonite with pervasive brittle damage highlighted by dark fine-grained oxides and phyllosilicates, close-up of damage in (e) in coarse quartz ribbons and (f) in fine-grained quartz-plagioclase seams. (g) Undamaged fine-grained mylonite found adjacent to the fragmented mylonite and separated by a white mica (WM) rich layer (orange arrow), close-up of quartz ribbons in (h) and fine-grained quartz-plagioclase seams in (i). (j) WM-rich undamaged mylonite with close-up of fine-grained seams in (k) and large K-feldspar (KFs) porphyroclasts in (l).

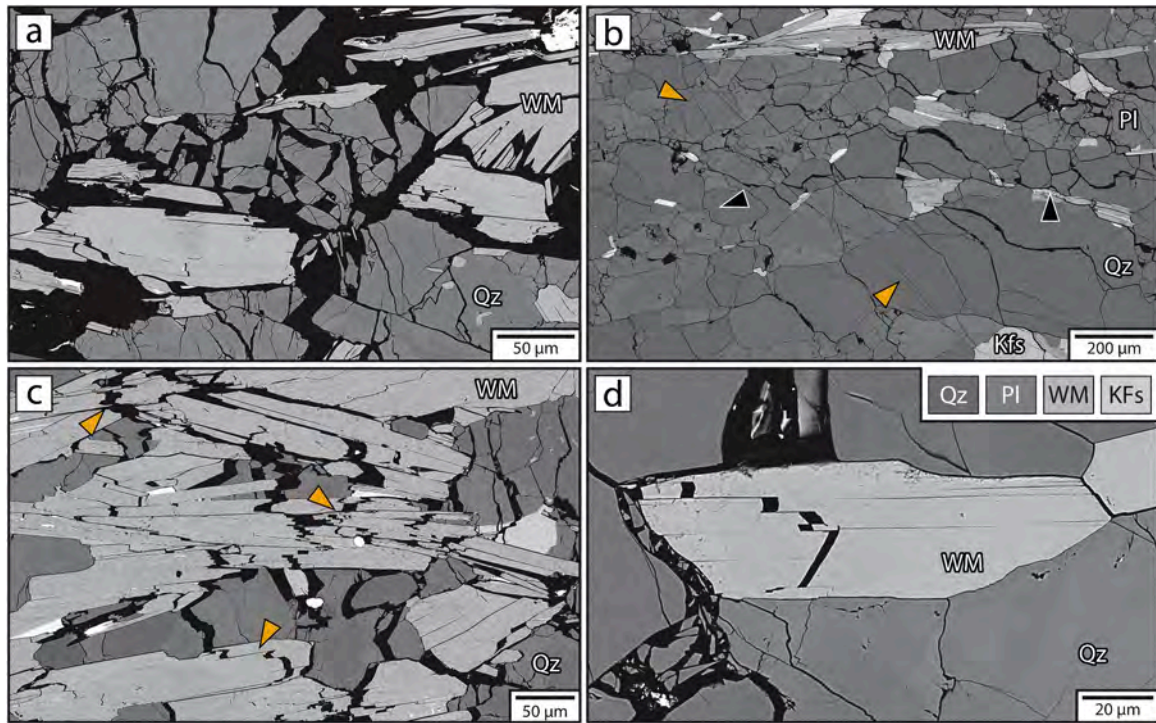


Fig. 4. Close up of fractured grains: Back-scattered (BS) images of sample WF-5. (a) Dislocated fragments showing sub-rounded fractures (quartz), sharp angular boundaries, and shard-like shapes. (b) Fragmented fine-grained mylonite (WF-5) showing negligible opening of intra- (orange arrows) and inter-granular (black arrows) fractures. (c) Aggregate of quartz and white mica displaying oriented fractures (sub-vertical) typical of tensional boudinage (horizontal direction, sub-parallel to the foliation), including stepped tearing of mica crystals (orange arrows). (d) Stepped tearing of white mica showing delamination along the cleavage planes and no dominant shear component. Qz-quartz. Pl - plagioclase. WM - white mica. KFs-K-feldspar. A biotite crystal (light colour) is observed in the top side of panel b.

local phyllosilicate foliation (WM, Fig. 4a) and break through large grains causing severe grain size reduction. The second type consists of inter-granular fractures (Fig. 4b, black arrows) that disaggregate the original mylonitic grains, exploiting the grain boundary network. Fractures propagating through mica grains have a distinct geometry. Pure tensile fractures split the mica platelets (Fig. 4c, orange arrows) perpendicular to the cleavage planes, which slid, displacing the fracture into a stepped pattern with no dominant shear direction (stepped tearing, Fig. 4d). No kinking nor folding is observed in the mica crystals.

We also used SEM imaging to analyse a large area of WF-5 (Fig. 5a) and quantify the effect of fracturing at the micro-scale. The cumulative grain-size (equivalent diameter) curve is not easily fit using a single power law regression, implying at least a bi-modal distribution of the clasts. We therefore individuated two different linear slopes (fractal dimension, D), measured above and below a grain size threshold of $90\text{ }\mu\text{m}$. Fractal dimensions of ~ 1.3 and ~ 2.6 ($R^2 > 0.99$) are found for the $18\text{--}90\text{ }\mu\text{m}$ and $90\text{--}450\text{ }\mu\text{m}$ ranges, respectively (Fig. 5f, Table 2). This distribution persists even when the investigation area is restricted to a smaller section where grains are displaced from their original position in the mylonite (Fig. 5b,e, Table 2). The Feret diameter of fragments, which connects the most distant points on the segmented perimeter, has a preferential orientation (blue orientations, Fig. 5c) consistent with the direction of the throughgoing intragranular fractures, which produce elongated, shard-like fragments (Fig. 5d).

For comparison, we analysed the pristine fine mylonite WF-6 and the gouge from the PSZ WF-2 using the petrographic thin section optical images (crossed polars and first order retardation plate, Fig. 3b,i). In the pristine mylonite, the segmentation yields a curve with a fractal dimension $D = 1.362$ ($R^2 = 0.989$), comparable to that of the

fragmented grains in the smaller range ($18\text{--}90\text{ }\mu\text{m}$) previously investigated. At equivalent diameters $> 90\text{ }\mu\text{m}$, the fractal dimension yields values larger than 3. In the gouge, the $18\text{--}90\text{ }\mu\text{m}$ range has a substantially different fractal dimension $D = 2.422$ ($R^2 = 0.997$) compared to those of the intact and fractured mylonite. The fractal dimension for larger grain sizes is very high, $D > 4$.

A final analysis on the grain of the pristine mylonite WF-6 is carried out using EBSD mapping. This analysis yielded few grains to construct the grain size distribution curve but allowed to better constrain the characteristic grain size of the mylonite. The area-weighted mode is $\sim 90\text{ }\mu\text{m}$ (Fig. 5f, grey histogram), which corroborates the threshold chosen for the double fit. While distinct from number-weighted data, this area-weighted mode qualitatively indicates that propagating cracks are most likely to interact with the boundaries of $\sim 90\text{ }\mu\text{m}$ grains, the dominant microstructural feature in the investigated (2D) volume.

4.2.2. Crystal plasticity in the fractured rocks

To evaluate the presence of crystal plasticity associated with the brittle event, as well as to investigate the occurrence of any relationship between crystal orientation and fracture propagation, we performed EBSD analysis on the fragmented (WF-5, area framed in Fig. 5b) and pristine (WF-6) fine-grained mylonite, focusing on the quartz fraction. WF-5 area was selected to include shard-like fragments from a coarse quartz grain (Fig. 6a). It is possible to observe intracrystalline lattice distortion (up to $\pm 10^\circ$ Fig. 6a), locally organised in sub grain-domains bounded by high misorientation gradients ($> 2^\circ$, Fig. 6c). Although the same amount of intragranular distortion is observed in the pristine mylonite (Fig. 6b), sub-grain boundaries and Dauphiné twins appear more coherently oriented in WF-5 (Fig. 6e) than in WF-6 (Fig. 6f), and

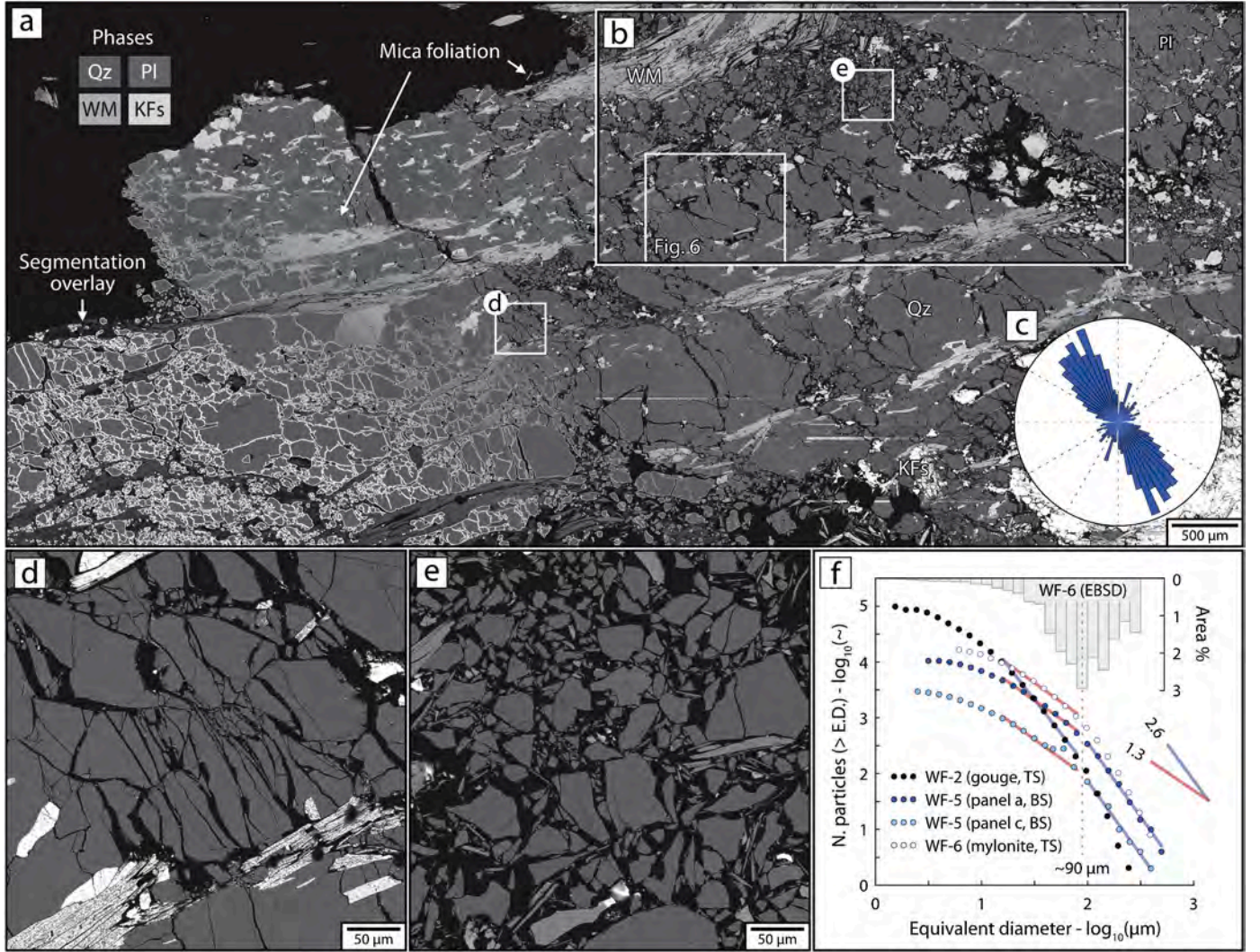


Fig. 5. Fragmented mylonite analysis: (a) Back-scattered (BS) image of sample WF-5 (Fig. 2, Fig. 4d) used for grain size analysis of the fragmented mylonite. Boxes (d) and (e) indicate the locations of the close-up images in the respective panels. The segmentation of the clasts is partially displayed in the bottom left corner with white contour lines. (b) Area containing well-dislocated clasts, restricted for analysis. (c) Rose diagram showing the area-weighted orientation density of the Feret diameter of the analysed particles. The diagram shows high density of particles at high angle to the mica foliation. This orientation is dominated by shard grains as in the close up (d). (d) Close-up of fractured Qz grains showing high aspect ratio (shards). (e) Close-up of dislocated Qz clasts showing angular shape with curved boundaries. (f) Particle size distribution expressed as the cumulative number function of equivalent diameter analysed in the whole area a) (upper blue dots), area restricted in panel (b) (lower blue dots). Two additional analyses show the particle size distribution of the intact mylonite (WF-6, Figs. 2 and 3g, white dots) and the gouge layer (WF-5, Figs. 2 and 3a, black dots), both analysed on thin-section optical image (TS). The slope of the curve (orange and blue lines) represents the fractal dimension D , whose values (reported in Table 2) appear to change significantly for grain sizes smaller or higher than $90 \mu\text{m}$ (dashed line). The colour of the lines is used to recall values fractal dimensions close to the two reference ones (1.3 and 2.6) reported in the graph. The grey histogram shows the distribution of grain sizes weighted by grain area, data from EBSD analysis (Fig. 6d).

they share a similar direction with the fracturing pattern. This feature is not discussed further since some discrete fractures show no crystalline mismatch nor local distortion of the surrounding grain (6a,c, orange arrow), questioning its meaning in the context of the fragmentation event.

4.3. Surface energy estimation

To calculate the surface energy associated with the shattered mylonite, we assumed an average density of $\rho = 2600 \text{ kg/m}^3$, surface energy $\gamma_w = 1 \text{ J/m}^2$, and fragment aspect ratio of 1 - 10. We also picked a reference thickness of the pulverised rocks $w = 0.2 \text{ m}$, which is restricted to the most pulverised areas of the WF, corresponding to facies WF-3 and WF-5. The calculation of A_{SS} was performed with 13 logarithmic bins from $10^{1.3}$ to $10^{1.95} \mu\text{m}$ and 11 logarithmic bins from $10^{1.95}$

to $10^{2.5} \mu\text{m}$, separately, according to the breakdown in fractal dimension at $90 \mu\text{m}$ (Fig. 5f). We did not include the change in A_{SS} in the surface energy density E_G calculation because we assumed that the entirety of A_{SS} was produced by pulverisation, yielding A_{SS} values between 42.8 and $13.4 \text{ m}^2/\text{kg}$. This method disregards the energy spent on subsequent cataclasis on fault (WF-2), assuming a monogenetic origin of the pulverised damage zone. The calculation yields $E_G \approx 28$ and 8.8 kJ/m^2 , for a total $E_G \approx 36.8 \text{ kJ/m}^2$. Alternatively, the calculation was performed in the entire fragment size range, divided in 24 logarithmic bins, yielding $A_{SS} \approx 18.6 \text{ m}^2/\text{kg}$ and $E_G \approx 12.1 \text{ kJ/m}^2$. The two total values of E_G were used as lower and upper bound for the box in Fig. 7. Given the absence of strain markers (slip along mylonite foliation), energies are reported with a slip range typical of small magnitude events ($< 1 \text{ cm}$, e.g., Abercrombie and Rice, 2005) but we do not exclude larger values. Nevertheless, the results well-fit with the estimated energies of

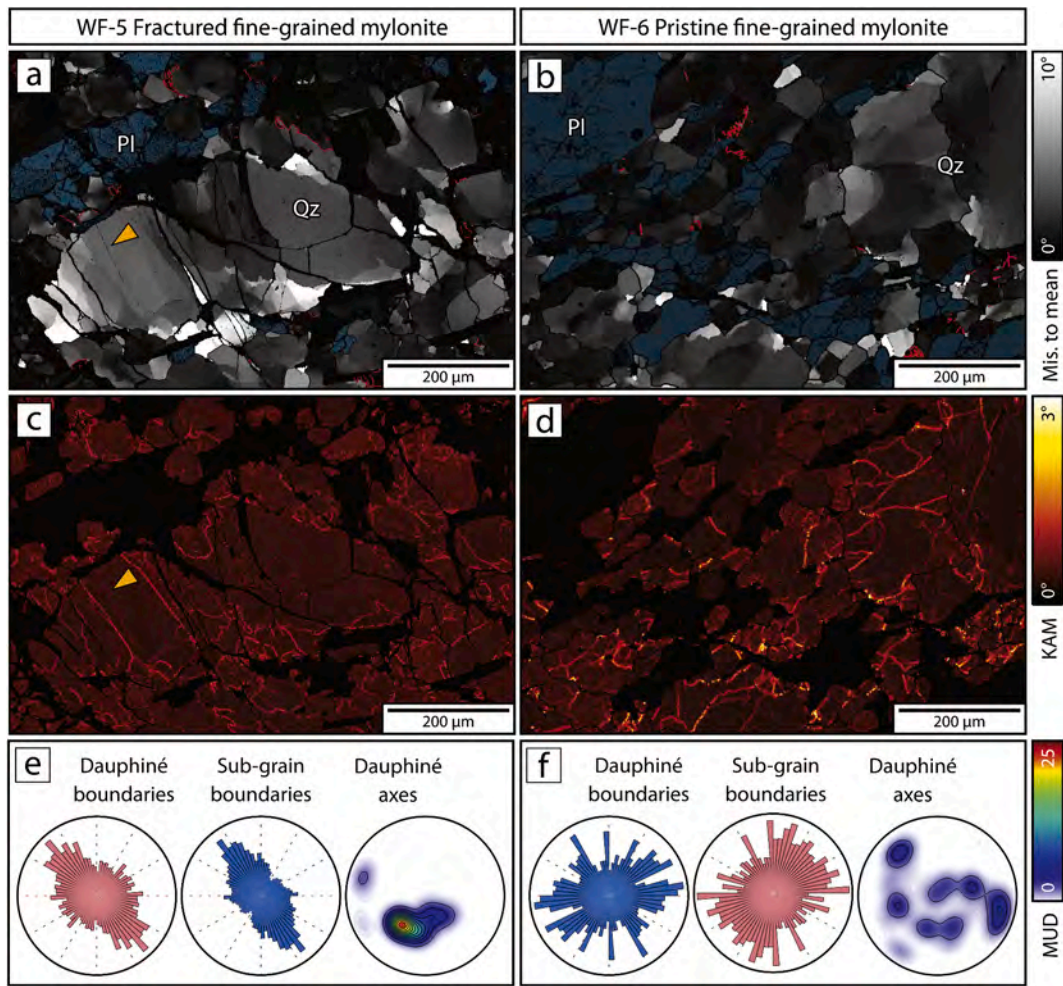


Fig. 6. EBSD analysis of quartz grains: (a,b) EBSD maps of the misorientation of quartz grains averaged by the mean orientation of each grain, showing the distortion within the grains. Dauphiné twins are traced with red lines, plagioclase grains are shaded in dark blue. (c,d) Kernel averaged misorientation (order 2) highlighting areas with steep misorientation gradients, e.g., dislocation walls. The orange arrows indicate the absence of distortion in proximity of a tensional fracture. (e,f) Rose diagrams showing the length-weighted 2D orientation of Dauphiné twin boundaries (60° twist along $\langle 0001 \rangle$, tolerance $\pm 5^\circ$, pink) and subgrain boundaries (blue) of quartz. The orientation density of the dauphiné twin axes of quartz is represented with pole figures (equal area projection, upper hemisphere, contouring half width 10°).

earthquakes in natural settings (Fig. 7, Cocco et al., 2023).

4.4. Dating of the gouge

All analysed grain size fractions ($< 0.2 \mu\text{m}$, $< 2 \mu\text{m}$, $2\text{--}6 \mu\text{m}$) of the gouge contain variable amounts of quartz, illite/muscovite, albite, minor content of K-feldspar, and chlorite (Fig. 8a). The illite in the finer grain size fractions contains illite/smectite mixed layers. The illite crystallinity index (Kübler Index, KI) increases in the smaller grain-size fractions (Fig. 8c) and corresponds to anchizonal to epizonal conditions. The polytype quantification pattern indicates that $> 75\%$ of illite corresponds to the $2M_1$ polytype in all fractions. The three grain-size fractions of illite and k-feldspar yield ages restricted within a short span between 12 and 13.5 Ma (Fig. 8d).

5. Discussion

The exposure of faults and other shear zones in the Bedretto tunnel represents a unique chance to study in-situ undisturbed meso- and micro-structures. Thanks to the new maintenance of the tunnel promoted by the Bedretto Lab team within the FEAR ERC-Synergy project, we could investigate the Waterfault (WF), one of the principal faults that cut the Rotondo granite, at $> 1 \text{ km}$ depth. The WF belongs to a set of structures

with average orientation NE-SW, which preferentially overprinted pre-existing ductile shear zones. In this set, the “MC” fault was selected as the ideal target for experiments of fault reactivation and triggered seismicity envisioned by the FEAR project by means of fluid injection (Volpe et al., 2023; Achtziger-Zupančič et al., 2024).

5.1. Pulverisation in an immature fault zone

WF is one of the main outflows of groundwater in the tunnel, which springs at high rates (i.e., tens of L/min) from a localised opening in the tunnel wall (Fig. 1c). The outflow exploited a preferential pathway in the fault core, the most damaged part of the fault, which corresponds to the breccia and gouge materials (WF-2,3, Fig. 2b). The gouge-filled PSZ lays sharply on an erosive surface on the WF footwall. This positioning reflects a strongly asymmetric distribution of brittle damage, with no fractures observed in the footwall protomylonite (WF-1). In the hangingwall, most of the breccia is crackle-like (or mosaic) and the original mylonitic fabric is easily recognised (Fig. 3c,f). The fragmented grains show negligible displacement and rotation (Fig. 4,5) compared to those typical of cataclastic flows, while there is a pervasive network of tensile fractures oriented perpendicular to the mylonitic foliation (Fig. 5c). Boudinaged mica grains also suggest pure tensile fragmentation favoured by sliding along the cleavage planes (Fig. 4d). Similar fracturing

Table 1

Waterfault facies: Quick reference to sampled facies and their characteristics relevant for the discussions. The terms coarse vs fine are only for qualitative and comparative purposes. Thickness values are approximative and measured locally.

Label	Facies	Zone	Meaningful fabrics	Thickness
WF-1	Protomylonitic granite	Footwall	Protomylonite without open fractures or evidences of cataclasis. Only a thin layer (< 3 cm) of fine-grained mylonite with mica-rich layers is observed adjacent to WF-2.	100 cm
WF-2	Gouge layer	Fault PSZ, fault core	Continuous layer of gouge. Quartz and feldspar porphyroclasts (> 50 μ m) are enveloped by a fine matrix (aphanitic) enriched in phyllosilicates.	0.5 cm
WF-3	Breccia and fractured mylonite	Fault core	Coarse grained mylonite with SC foliation, characterised by intense fracturing and cataclasis. Presence of high-angle tensional fractures and oblique cataclastic shear bands close to WF-2. Away from WF-2 clasts are organised in a mosaic breccia.	< 15 cm
WF-4	Non-pervasively fractured mylonite	Damage zone, hangingwall	Similar to WF-3 mylonite but with far less brittle damage.	45 cm
WF-5	Fractured fine-grained mylonite	Damage zone, hangingwall	Fine-grained mylonite decorated with mica-rich layers, especially at the boundary with WF-6. Intense damage with high-angle tensional fractures and rare cataclastic shear bands. The fracture network is pervasive down to the grain scale, but clasts show mosaic structure.	<10 cm
WF-6	Intact fine-grained mylonite	Hangingwall	Fine-grained mylonite similar to WF-5 but devoid of relevant brittle deformation.	< 20 cm
WF-7	Mylonite	Hangingwall	Coarse-grained mylonite without relevant brittle damage.	> 500 cm

Table 2

Fractal dimension of particle size distribution.

Eq. Diameter (μ m)	18 < ED < 90		90 < ED < 450		
	D	R ²	D	R ²	
WF-2 (Gouge)	2.422	0.997	4.423	0.998	Clast size
WF-5 All	1.335	0.990	2.644	0.997	Clast size
WF-5 reduced	1.369	0.994	2.639	0.991	Clast size
WF-6 (Mylonite)	1.362	0.989	3.380	0.996	Grain size

and fragmentation patterns are observed in natural (Mitchell et al., 2011; Doan and d'Hour, 2012; Rempe et al., 2013; Melosh et al., 2014; Fondriest et al., 2015; Aben et al., 2016; Fondriest et al., 2017;

Cortinovis et al., 2024) and experimental (Doan and Gary, 2009; Aben et al., 2017) events associated to off-fault damage during coseismic deformation in cohesive rocks. These observations collectively suggest that the damage is restricted to the tensile stress lobe nearby a propagating seismic rupture (Fig. 9), as theorised in the field (Wilson et al., 2005; Rockwell et al., 2009; Mitchell et al., 2011) and demonstrated in models numerical simulations (e.g., Ben Zion and Shi, 2005; Griffith et al., 2009; Okubo et al., 2019). Since shear localised close to the footwall (WF-2, Fig. 2b) while tensile damage is restricted to the hanging wall, the WF likely emplaced within the mylonite in a trans-tensional regime (Fig. 9).

The location of the PSZ suggests that the WF developed by exploiting the interface between materials with contrasting mechanical properties. Generally, pulverisation damage is observed in the stiffer side of bi-material interfaces (e.g., Ben-Zion and Shi, 2005), which is illustrated in large faults juxtaposing different lithologies. In the WF case there is a clear separation between the fine-grained mylonite and either the protomylonite (Fig. 2c, 3a) or the mica-rich layers (Fig. 2d, 3g) at the two sides of the WF. This suggests that the fine-grained mylonite is stiffer or/and that its elastic properties are highly anisotropic. This elastic anisotropy is typical of layered rocks where the highest and lowest speed (proportional to stiffness) of S-waves is parallel and perpendicular, respectively, to the foliation (Ji and Salisbury, 1993).

Despite the fact that the fault core samples of this non-cohesive rock yield > 30% of fine-grained (< 125 μ m) powder, there is only limited evidence of cataclastic reworking, which is instead restricted to a thin principal slip zone (PSZ) close to the footwall (WF-2, Fig. 3a). The fault appears thus overall immature due to the small thicknesses of both the fault zone (< 1 m) and fault core (cataclastic breccia and gouge, << 15 cm), as defined in Childs et al. (2009). Furthermore, we observed no relevant shear deformation outside of the ~5 mm thick PSZ, absence of chemical healing (i.e., cementation) and recognisable brittle overprints. For instance, the mosaic breccia fragments preserve the original mylonite fabrics but no trace of cemented fractures, which are typical of pulverised zones that experienced different seismic cycles (Doan and d'Hour, 2012; Aben et al., 2016; Fondriest et al., 2017). These delicate, non-cohesive microstructures would thus only be preserved if the activity on the fault was limited in time, potentially representing the result of a single seismic slip event.

5.2. Constraints on fault activity

Several structural elements suggest that the brittle fabrics of the WF formed during a relatively short coseismic activity. The illite crystallinity index (KI) and the predominance of 2M₁ illite polytype is associated with anchizonal to epizonal temperature conditions (> 200 °C; Fig. 8b,c). The estimated temperature range is consistent with the upper crustal conditions in Miocene times (e.g., Lutzenkirchen and Loew, 2011; Ceccato et al., 2024), but higher than those inferred for cohesive, zeolite-rich cataclasites documented in the tunnel (Lutzenkirchen and Loew, 2011). K-Ar dating results in a time span of ~12–13 Ma, consistent with the regional pattern of K-Ar illite ages for fault zone activity in the Central Alps, accommodating regionally distributed microseismic/aseismic strain (e.g., Kralik, 1992; Muller et al., 2001; Pleuger et al., 2012; Zwingmann and Mancktelow, 2004). According to these observations, the recorded activity would be constrained to upper crustal conditions (< 7 km depth), at temperatures of ~200 °C, and at around 12 Ma. These conditions are quite contrasting with the grain-scale microstructures of the breccia, which preserves delicate pulverised aggregates with no evidence of recovery and sealing. In fact, pulverisation processes in granite at depth are often accompanied by chemical healing and sintering (Sullivan and Peterman, 2017; Song et al., 2020; Johnson et al., 2021). Another hint is the absence of frictional melts in the principal slip zone in the WF, which would form during seismic slip in deeper seated faults due to the enhanced dissipation of energy as heat (Toffol et al., 2024; Ortega-Arroyo et al., 2025).

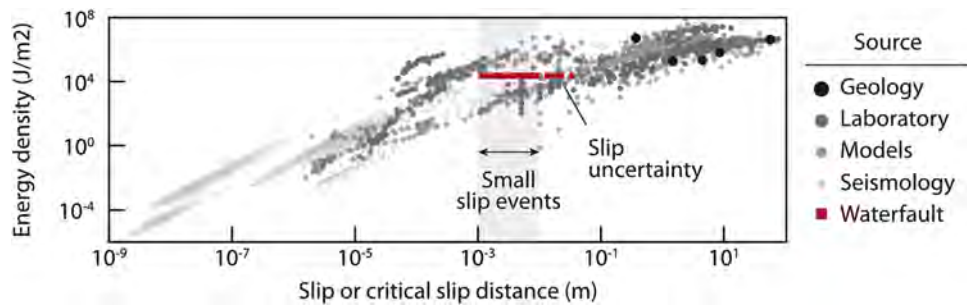


Fig. 7. Fracture and surface energy: estimated surface energy of WF in the framework of existing fracture energy density data (grey data by Cocco et al., 2023).

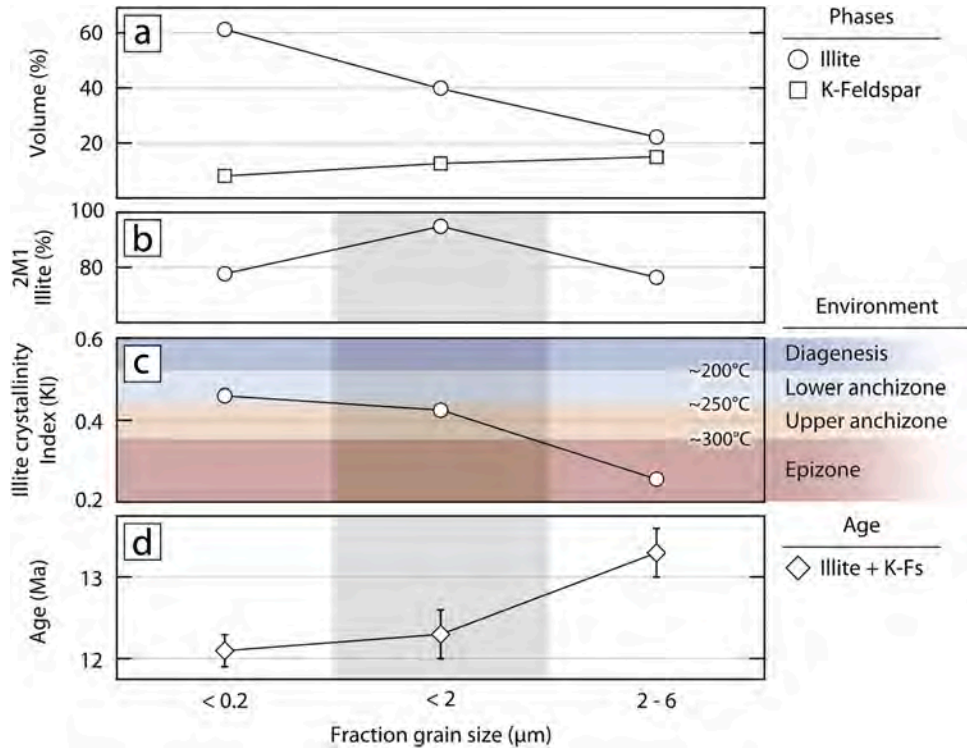


Fig. 8. Mineralogical analyses and K-Ar dating: (a) Volume proportion of illite and K-feldspar phases in the different grain-size fraction of the gouge, obtained from Rietveld refinement of X-Ray Powder Diffraction patterns. (b) Relative proportion of the 2M₁ polytype. (c) Illite crystallinity index calibrated to CIS values of Warr (2018). The temperature ranges are after Merriman and Frey (1999). (d) Age vs. grain-size diagram presenting the result of K-Ar illite + K-feldspar dating.

A shallower origin of pulverisation would imply that the dates yielded by this analysis are inherited from an earlier event at higher temperatures that opened the system to fluids. This is compatible with faulting events in the Rotonondo area dating at 12–13 Ma (Lützenkirchen and Loew, 2011; Ceccato et al., 2024), which were likely followed by chemical recovery of cohesion, setting the conditions for pulverisation at shallower depths. This is also supported by the relatively large proportion of potentially inherited K-feldspar in the analysed fine grain sizes (see Fig. 8a).

The current products of pulverisation at shallow conditions would then be linked to low magnitude events since the affected volume is very small (Aben et al., 2017). Neogene and neotectonic (micro-) seismic activity (Magnitude = 1–2.5) is documented in the region surrounding the Rotonondo granite from both geological, historical, and seismological evidence (Ustaszewski and Pfiffner, 2008; Ustaszewski et al., 2007; Hetényi et al., 2018; Houlie et al., 2018). A more recent reactivation of the fault at lower temperatures is also potentially supported by the occurrence of illite/smectite mixed layers in the finer grain size fractions (e.g., Viola et al., 2016). This case study highlights once again the importance of detailed microstructural characterisation of the dated

material, to give proper contextualisation and validation to the tectonic and faulting processes addressed (e.g., Tartaglia et al., 2020).

5.3. Pulverisation and fabric inheritance

Differently from classic case-studies in which the pulverised rock volumes extend by several to hundreds of metres (e.g., Brune, 2001; Dor et al., 2006; Mitchell et al., 2011; Fondriest et al., 2015), the WF provides the potential to study brittle damage in the earliest stages of fault formation, which are rarely accessible in exhumed terrains. In this context, it is interesting to observe the influence of pre-existing fabrics on the development of the WF.

The foremost characteristic is that the WF is a narrow volume characterised by sharp boundaries with the wall rocks. Brittle damage is most intense at the two boundaries (WF-2,3 and WF-6) and does not extend past them, where the mylonitic granite is still intact. The structural inheritance imposed by the pre-existing mylonitic shear zone is evident as both boundaries are coincident with the mylonite foliation. This means that the alignment of crystals (especially micas) provided a mechanical anisotropy - planes of weakness - to relieve transient stress

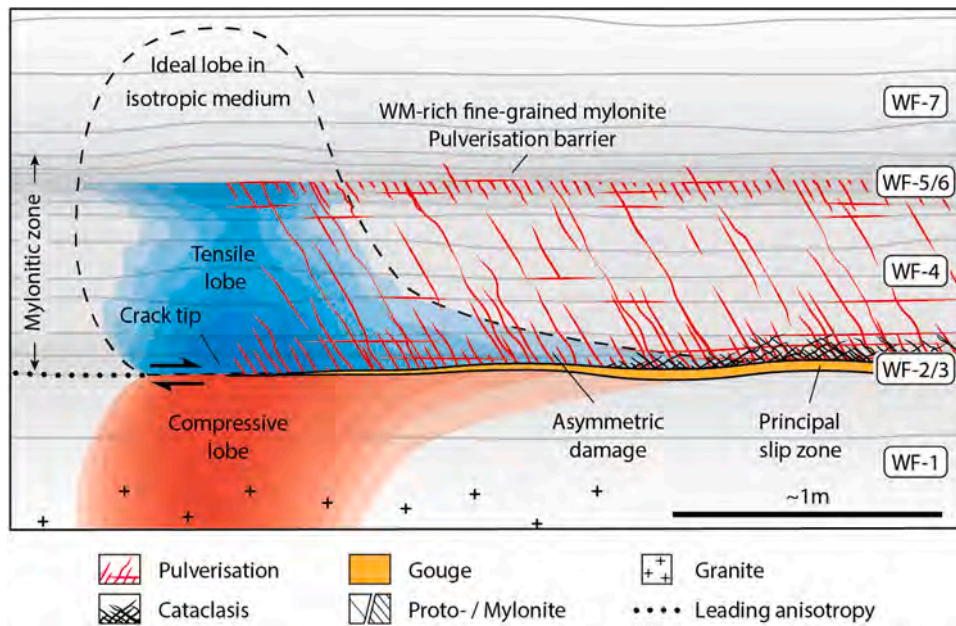


Fig. 9. Interpretation of rupture propagation in the pre-existing mylonite and early formation of the WF. The crack tip is propagating on the mylonite's leading anisotropy (foliation), located in correspondence of the current facies WF-2. The drawing shows the ideal associated compressive and extensive lobes. Pulverisation is asymmetrically produced within the tensile lobe, which is in turn limited by the pre-existing mylonite anisotropy. Cataclasis is limited to the slipping portion of the fault trailing the crack tip.

pulses. This is particularly evident at the micro-scale, where tensional, high-angle brittle fractures are transferred laterally by sliding along the mica cleavages (Fig. 4c,d). As revealed by EBSD investigations (Fig. 6), fracture orientations are not affected or related to quartz grain crystallographic orientation. This further suggests that the anisotropic elastic/mechanical properties of quartz seem not to affect the propagation and orientation of fractures during the dynamic event. Similarly, crystal defects such as inherited sub-grain boundaries and dislocation walls seem to not have any effect on fracture propagation and directionality. This is clear when analysing large quartz grains that show fractures that do not exploit nor induce oriented regions with high dislocation density (KAM map, Fig. 6c, orange arrow). However, it is likely that the observed fractures might result from the linkage of smaller and shorter fracture segments which are crystallographically controlled (e.g., Timms et al., 2010).

Analysis of the fine-grained mosaic breccia (Fig. 5a) provides further insights on the role of pre-existing fabrics. The particle size distribution (Fig. 5f) shows two distinct trends separated by an equivalent grain size (diameter) of $\sim 90 \mu\text{m}$. Power law fit yields a fractal dimension of ~ 2.6 for grains larger than $90 \mu\text{m}$, which is a far higher value than those expected for comminution by cataclastic means (Sammis et al., 1987; Biegel et al., 1989). Given that there is no evidence of local shear dislocation in WF-5 (Fig. 5a), this fractal dimension may indicate instead the effects of pulverisation and the pervasiveness of the fracture network (see also Muto et al., 2015), reflected by the relevant yield of fine fraction during sieving. On the other hand, the change of slope seems to indicate a characteristic scale below which the pulverisation was not efficient. This characteristic scale ($90 \mu\text{m}$) coincides with the area-weighted mode of mylonite grains (Fig. 5f). Indeed, for grains smaller than $90 \mu\text{m}$, the dimension drops to ~ 1.36 , which is very similar to the distribution of grain sizes observable in the pristine mylonite (Fig. 5f). Finally, the grain size distribution in the PSZ gouge (WF-2) yields a power law fit with fractal dimension of ~ 2.42 for particles smaller than $90 \mu\text{m}$. This result highlights the role of cataclasis in comminuting the initial grain sizes, including the smaller ones. Fabric inheritance is therefore obliterated in the PSZ due to large strains and fractal values approach those expected for the active deformation mechanisms (Biegel et al., 1989).

5.4. Concluding remarks on strain partitioning at the early stages of faulting

The structural scenario in the Rotondo granite features immature faults that exploit pre-existing anisotropies, mostly represented by mylonitic shear zones. The lateral continuity of the faults (D_4 set) prompts the idea that, despite the immature stage, brittle damage managed to propagate efficiently along the pre-existing inverse-kinematics ductile shear zones (D_2 , Ceccato et al., 2024). Indeed, the mica-rich mylonitic fabrics represent planes of weakness (e.g., Shea and Kronenberg, 1992; Massironi et al., 2011; Crider, 2015), planar anisotropies that reduce the geometric incompatibilities for mode II-III crack motion and favour frictional sliding (Collettini et al., 2019, and references therein). The lateral continuity of these immature faults ($> 100 \text{ m}$, Achtziger-zupancič et al., 2024) and their high content in fine-grained products may then match those of more mature ones (Sagy et al., 2007), which require instead larger slip to form (e.g., Torabi and Berg, 2011). The amount of fault gouge produced by shear deformation might in fact be overestimated due to the contribution of pulverisation (see also Reches and Dewers, 2005). In our case, note the high yield of fine grained products with particle size distribution close to that of high-strain cataclastic products (Table 2).

On the one hand, it is thus clear that the mylonitic foliation is an important factor to minimise the energy spent during the embrittlement of the incipient fault zone and its lateral extension. Symptomatic is the small extension of the damage zone, which is bounded by the prominent foliations at the WF walls. This phenomenon is, again, related to the preferential slip on the mica cleavage (Shea and Kronenberg, 1992), which efficiently relieves the local stress and transfers it towards the leading crack tip. Furthermore, efficient pulverisation of the mylonite along the grain boundaries allows efficient formation of fine-grained gouge (see also Reches and Dewers, 2005), promoting localisation along the mylonitic foliation. This facilitates the early formation of a throughgoing fault core and limits damage in the wall rocks.

On the other hand, the pervasive damage of the mosaic breccia down to the μm -scale suggests that the fine-grained medium - the mylonite - is also an important sink of energy in the tensile lobe that progresses at the crack tip. The dense network of grain boundaries and mylonite

anisotropies augment the number of initiation sites for precursory fractures, draining energy from into the new free surfaces and hindering the propagation speed of the leading crack (Cox and Scholz, 1988). This mechanism justifies the abundance of immature gouge-bearing faults (Lutzenkirchen and Loew, 2011) in the Rotondo Granite despite the low strain inferred in this unit.

CRedit authorship contribution statement

G. Pozzi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft. **A. Ceccato:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **K. Wemmer:** Data curation, Formal analysis, Methodology, Writing – review & editing. **M. Hueck:** Data curation, Formal analysis, Methodology, Writing – review & editing. **S. Aretusini:** Data curation, Formal analysis, Methodology, Writing – review & editing. **E. Spagnuolo:** Data curation, Formal analysis, Methodology, Writing – review & editing. **A. Zappone:** Validation, Writing – review & editing. **M.A. Meier:** Validation, Writing – review & editing. **M. Cocco:** Funding acquisition, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Massimo Cocco reports article publishing charges was provided by European Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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