Earthquake swarms frozen in an exhumed hydrothermal system (Bolfin Fault Zone, Chile)

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Abstract

Earthquake swarms commonly occur in upper-crustal hydrothermal-magmatic systems and activate mesh-like fault-fracture networks at zone of fault complexity. How these networks develop through space and time along seismic faults is poorly constrained in the geological record. Here, we describe a spatially dense array of small-displacement (< 1.5 m) epidote-rich fault-veins within granitoids, occurring at the intersections of subsidiary faults with the exhumed seismogenic Bolfin Fault Zone (Atacama Fault System, Northern Chile). Epidote faulting and veining occurred at 3-7 km depth and 200-300 °C ambient temperature. At distance [?] 1 cm to fault-veins, the magmatic quartz of the wall-rock shows (i) thin (<10- µm-thick) interlaced deformation lamellae, and (ii) crosscutting quartz-healed veinlets. The epidote-rich fault-veins (i) include clasts of deformed magmatic quartz, with deformation lamellae and quartz-healed veinlets, and (ii) record cyclic events of extensional-to-hybrid veining and either aseismic and seismic shearing. Deformation of the wall-rock quartz is interpreted to record the large stress perturbations associated with the rupture propagation of small earthquakes. Instead, dilation and shearing forming the epidote-rich fault-veins are interpreted to record the later development of a mature and hydraulically-connected fault-fracture system. In this latter stage, the fault-fracture system cyclically ruptured due to fluid pressure fluctuations, possibly correlated with swarm-like earthquake sequences.

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Key Points

- Epidote-rich veins exhumed from 3-5 km depth are well-exposed in the Atacama Desert and fill honey mesh-like fault-fracture networks.
- Wall-rock microstructures record rupture propagation; instead, fault-veins record cyclic veining and aseismic-seismic shearing.
- The epidote-rich fault-vein networks represent ancient seismogenic hydrothermal systems, possibly producing earthquake swarms.

Abstract

Earthquake swarms commonly occur in upper-crustal hydrothermal-magmatic systems and activate mesh-like fault-fracture networks at zone of fault complexity. How these networks develop through space and time along seismic faults is poorly constrained in the geological record. Here, we describe a spatially dense array of small-displacement (< 1.5 m) epidote-rich fault-veins within granitoids, occurring at the intersections of subsidiary faults with the exhumed seismogenic Bolfin Fault Zone (Atacama Fault System, Northern Chile). Epidote faulting and veining occurred at 3-7 km depth and 200-300 °C ambient temperature. At distance ≤ 1 cm to fault-veins, the magmatic quartz of the wall-rock shows (i) thin (<10-µm-thick) interlaced deformation lamellae, and (ii) crosscutting quartz-healed veinlets. The epidote-rich fault-veins (i) include clasts of deformed magmatic quartz, with deformation lamellae and quartz-healed veinlets, and (ii) record cyclic events of extensional-to-hybrid veining and either aseismic and seismic shearing. Deformation of the wall-rock quartz is interpreted to record the large stress perturbations associated with the rupture propagation of small earthquakes. Instead, dilation and shearing forming the epidote-rich fault-veins are interpreted to record the later development of a mature and hydraulically-connected fault-fracture system. In this latter stage, the fault-fracture system cyclically ruptured due to fluid pressure fluctuations, possibly correlated with swarm-like earthquake sequences.

Keywords: earthquake swarm, fault zone, seismically-active fault-fracture network, veining, deformation lamellae.

1. Introduction

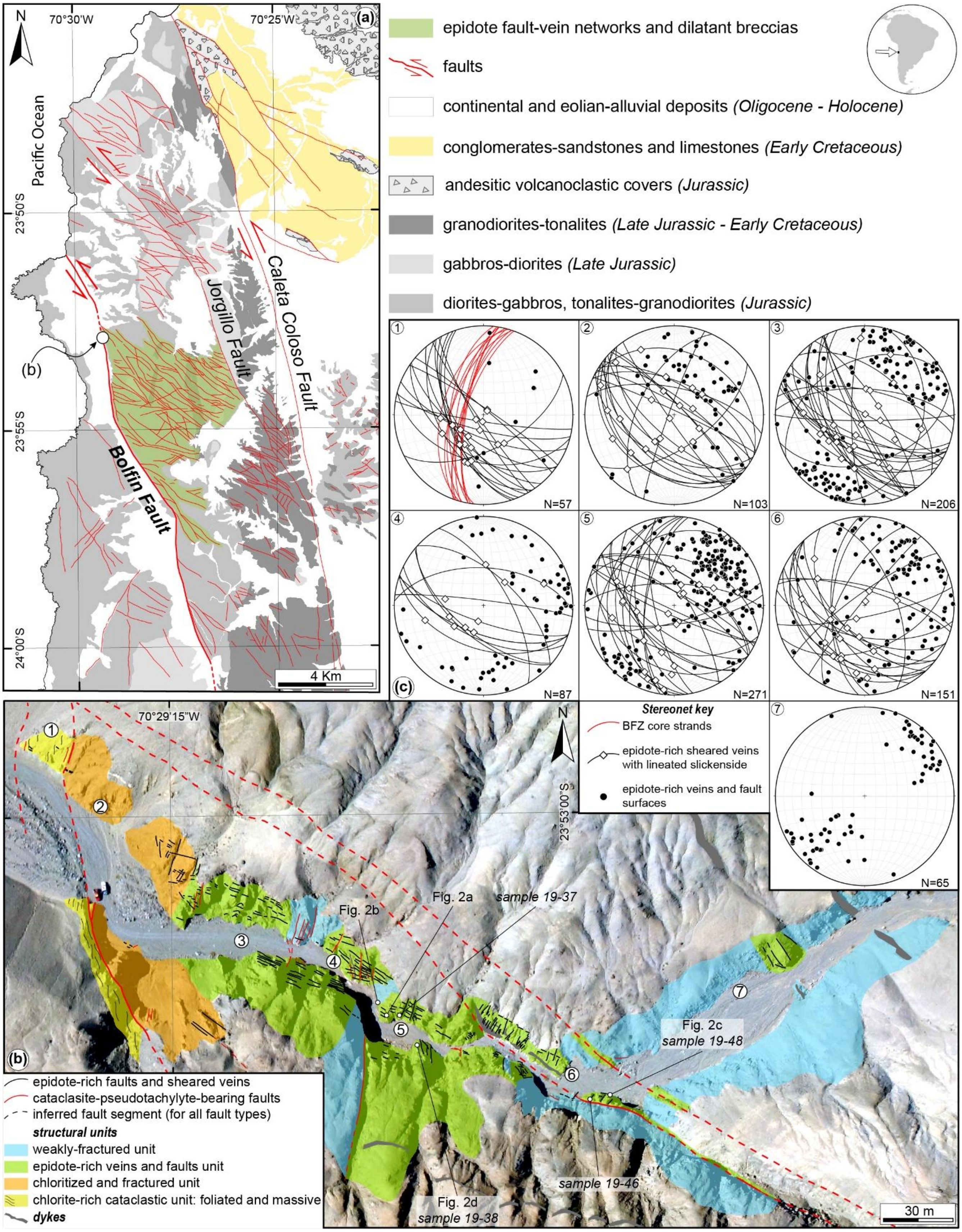
The thermo-hydro-mechanical and chemical properties of fault zones and their host rocks affect a wide range of processes in the Earth's crust, such as earthquake nucleation, propagation and arrest (e.g., Faulkner et al., 2006; Sibson, 1985; Wesnousky, 1988, 2006), crustal rheology (e.g., Behr & Platt, 2014; Handy et al., 2007) and migration of fluids (e.g., hydrothermal, magmatic, oil, gas; Cembrano & Lara, 2009; Mittempergher et al., 2014; Richards, 2013; Tardani et al., 2016). The mechanical and hydraulic proprieties of fault zones vary largely through space and time during the seismic cycle and are intrinsically coupled (Caine et al., 1996; Faulkner et al., 2010; Wibberley et al., 2008). In particular, permeability changes during the seismic cycle at seismogenic depths are expected to promote co- to post-seismic episodic fluid flow (i.e., fault-valve behavior; Sibson, 1989, 1992a, 1992b). Indeed, fault rupture events can lead to large, transitory increases of fault permeability (Cox, 2016; Sibson, 1989). Where ruptures breach overpressured fluid reservoirs, high-permeability fault segments provide conduits facilitating fluid redistribution in the Earth's crust. On the other hand, post- to inter-seismic fault healing and sealing due to compaction and precipitation of hydrothermal minerals in pores and fractures reduce fault permeability, eventually arresting fluid flow (Cox, 2016; Sibson, 1989, 1992b, 1992a).

The expression of the coupling among fault activity, fault permeability, fluid flow, fluid pressure and loading conditions in the geological record is documented by hydrothermal (e.g., epidote, quartz, chlorite, calcite, zeolite) fault-vein networks in exhumed fault zones over several geological settings (e.g., Cerchiari et al., 2020; Cox & Munroe, 2016; Dempsey et al., 2014; Lucca et al., 2019; Malatesta et al., 2021; Masoch et al., 2022; Micklethwaite et al., 2010; Ujiie et al., 2018). Mineralized fault-fracture networks display extensive hydrothermal alteration, mutually overprinting extension-to-hybrid vein arrays and dilatant breccias (Cox, 2016; Sibson, 2020). These features record significant stages of fluid flow and mineral precipitation during fault evolution, possibly associated with ancient seismic activity (e.g., Boullier & Robert, 1992; Cox, 2020; Cox & Munroe, 2016; Dempsey et al., 2014; Genna et al., 1996; Micklethwaite & Cox, 2004; Muñoz-Montecinos et al., 2020; Ujiie et al., 2018). In recently or currently active hydrothermal-magmatic settings, abundant fluid flow is commonly accompanied by earthquake swarms (e.g., Danré et al., 2022; Enescu et al., 2009; Fischer et al., 2014; Legrand et al., 2011; Mesimeri et al., 2021; Passarelli et al., 2018; Shelly et al., 2016; 2013; Yukutake et al., 2011), i.e., clusters of low magnitude seismic events without a characteristic mainshock (Mogi, 1963). Earthquake swarm events, lasting from a few days to months (e.g., Fischer et al., 2014), are driven by either pore fluid pressure fluctuations (e.g., Baques et al., 2023; Hill, 1977; Ross & Cochran, 2021; Shelly et al., 2022; Sibson, 1996) and aseismic slip (e.g., Danré et al., 2022; De Barros et al., 2020; Lohman & McGuire, 2007; Vidale & Shearer, 2006). Besides deviating from common mainshock-aftershock sequences, earthquake swarms generate also considerable non-double-couple (i.e., isotropic) seismic signal, as a result of tensile fracturing and hybrid faulting attributed to the ingression of pressurized fluids in the fault zone/system (Legrand et al., 2011; Phillips, 1972; Sibson, 1996; Stierle et al., 2014; Vavryčuk, 2002). Similar human-induced seismic sequences may be associated with industrial fluid injection in boreholes (e.g., Ellsworth, 2013; Goebel et al., 2016; Guglielmi et al., 2015; Healy et al., 1968).

There has been a great deal of progress in the last years regarding (i) the imaging of fault networks illuminated by earthquake swarms (e.g., Baques et al., 2023; Ross et al., 2020; Shelly et al., 2022), (ii) the determination of focal mechanisms of very small-in-magnitude earthquakes through seismological analysis (e.g., Essing & Poli, 2022; Mesimeri et al., 2021; Poli et al., 2021), and (iii) the relation of injected fluid volumes and rates with seismic energy release through fluid-injection experiments (e.g., Dorbath et al., 2009; Guglielmi et al., 2015; McGarr, 2014). Many authors proposed that swarm-like earthquake sequences activate km-scale mesh-like fault-fracture networks in zones of fault geometric complexity, such as fault linkages and step-overs (e.g., Hill, 1977; Ross et al., 2020; Ross et al., 2017; Shelly et al., 2022, 2015; Sibson, 1996; Sykes, 1978). However, to date, how a fault-fracture network develops both in space and time in seismically-active hydrothermal systems is poorly constrained due to

(i) the poor spatial resolution (> 10s of meters) of seismological and geophysical techniques relative to the length of (micro-)fracture processes and (ii) the limited exposure at the Earth's surface of exhumed fault-vein networks large enough to be comparable to currently active cases.

In this work, we examine an extensive epidote-rich fault-vein network located at a linkage zone of the Bolfin Fault Zone (BFZ), well-exposed at centimeter-to-decameter scales over tens of square kilometers in the Atacama Desert (Northern Chile). The BFZ is an exhumed, crustal-scale, seismogenic (pseudotachylyte-bearing) fault of the transtensional Coloso Duplex (Atacama Fault System, Chile, Figure 1) (Cembrano et al., 2005; Masoch et al., 2022, 2021; Scheuber & González, 1999). Based on the interpretation of field data and high-resolution (FEG-SEM) microstructural analysis of fault zone rocks, we reconstruct different stages during the development of an upper-crustal seismically-active hydrothermal system. The proximal wall-rock of small-displacement (< 1.5 m) fault-veins initially experienced a large transient stress pulse, attested by the occurrence of deformation lamellae within magmatic quartz. This deformed quartz is included as clasts within epidote-rich fault-veins, that record overprinting events of extensional veining and cataclasis. We interpret these microstructures as evidence of ancient swarm-like activity, from the first stages of dynamic crack propagation to the later cyclic crack opening and both seismic or aseismic slip, driven by fluid pressure fluctuations, within a mature and hydraulically connected fault-fracture system. These exposed fault-vein networks represent a unique geological record of the evolution in space and time of upper-crustal swarm-like seismic sources, from the early nucleation stage to the later development of a mature fault system.



(a)
N
70°30'W
70°25'W
Pacific Ocean
23°50'S
23°55'S
24°00'S
(b)
Jorgillo Fault
Caleta Coloso Fault
Bolfin Fault
4 Km
epidote fault-vein networks and dilatant breccias
faults
continental and eolian-alluvial deposits (Oligocene - Holocene)
conglomerates-sandstones and limestones (Early Cretaceous)
andesitic volcanoclastic covers (Jurassic)
granodiorites-tonalites (Late Jurassic - Early Cretaceous)
gabbros-diorites (Late Jurassic)
diorites-gabbros, tonalites-granodiorites (Jurassic)
(c)
N=57
N=103
N=206
N=87
N=271
N=151
N=65
Stereonet key
BFZ core strands
epidote-rich sheared veins with lineated slickenside
epidote-rich veins and fault surfaces
70°29'15"W
23°53'00"S
Fig. 2a
Fig. 2b
sample 19-37
Fig. 2c
sample 19-48
sample 19-46
Fig. 2d
sample 19-38
30 m
(b)
epidote-rich faults and sheared veins
cataclasite-pseudotachylyte-bearing faults
inferred fault segment (for all fault types)
structural units
weakly-fractured unit
epidote-rich veins and faults unit
chloritized and fractured unit
chlorite-rich cataclastic unit: foliated and massive
dykes

Figure 1. Geological setting of the Bolfin Fault Zone. (a) Simplified geological map of the Coloso Duplex. The BFZ bounds the western side of the crustal-scale transtensional duplex. The green area indicates the distribution of the epidote-rich fault-vein networks and dilatant breccias within the Coloso Duplex. Modified from Cembrano et al. (2005). (b) Structural map of the BFZ architecture at Sand Quarry locality. Clusters of epidote-rich fault-vein networks and breccias are associated with NW-striking, splay faults of the BFZ, and NE-striking faults. The faults splaying out from the BFZ represent transtensional faults within the duplex (thick red lines). Modified from Masoch et al. (2022). (c) Structural data of the fault core strands and epidote-rich fault-vein networks. Numbers in stereonets denote the location of structural sites in the map in (b).

2. The epidote-rich fault-vein networks of the Bolfin Fault Zone

The >40-km-long BFZ pertains to the 1000-km-long, Early Cretaceous, strike-slip intra-arc Atacama Fault System (Northern Chile; Figure 1) (Arabasz, 1971; Cembrano et al., 2005; Masoch et al., 2021; Scheuber & González, 1999; Seymour et al., 2021). The BFZ displays sinistral strike-slip kinematics and bounds the western side of the crustal-scale transtensional Coloso Duplex (Cembrano et al., 2005; Masoch et al., 2022, 2021) (Figure 1a). At regional scale, the BFZ has a sinuous geometry across Jurassic-Early Cretaceous diorite-gabbro and tonalite-granodiorite plutons (Figure 1a). The ancient (125-118 Ma) BFZ seismicity is attested by presence of pseudotachylytes, formed at 5-7 km depth and ≤ 300 °C ambient temperature (Gomila et al., 2021; Masoch et al., 2022, 2021). Seismic faulting occurred in a fluid-rich environment as documented by syn-kinematic chlorite-epidote (-quartz-calcite) veining and extensive propylitic alteration (Gomila et al. 2021).

In detail, the BFZ architecture consists of multiple (ultra)cataclastic strands, up 6-m-thick, within a 150-m-wide damage zone (see Masoch et al., 2022 for the description of the fault architecture; Figure 1b). The damage zone consists of variably fractured and brecciated rock volumes characterized by extensive epidote-rich fault-vein networks associated with NW-to-WNW-striking faults splaying from the BFZ (Figures 1b-c; 2) (Masoch et al., 2022). These subsidiary faults accommodated transtensional slip (Figure 1c) within the Coloso Duplex (Cembrano et al., 2005; Veloso et al., 2015), with an apparent cumulative strike-slip displacement up to 1 km (Cembrano et al., 2005; Jensen et al., 2011; Stanton-Yonge et al., 2020). The epidote-rich fault-vein networks consist of (i) small-displacement (< 1.5 m) sheared veins with lineated slickensides (Figure 2a-b, 2d-e), and (ii) extensional veins and dilatant breccias sealed by epidote + prehnite ± chlorite ± quartz ± K-feldspar (Figure 2b-c, 2f; see section 4.2). The small-displacement epidote-rich fault-veins extend up to tens of meters in length (Figure 1b). Sheared and extensional veins are arranged in four sets, dipping towards SW, NE, NW and S (Figure 1c). Epidote lineated slickensides are decorated by either stepped polished surfaces or mirror-like slip surfaces (Figure 2a, 2d), and their kinematics range from normal dip-slip to strike-slip (either sinistral and dextral; Figure 1c). Veins and breccias record repeated episodes of extensional fracturing and sealing, as they include angular fragments of earlier veins and breccias (Figure 2b-c). The epidote-rich fault-vein networks are surrounded by extensive reddish alteration haloes in the damaged wall-rock (Figure 2b-c, 2e-f). The epidote-rich fault-vein networks observed in the BFZ damage zone are spatially distributed within all the duplex (see Cembrano et al., 2005; Herrera et al., 2005) (Figure 1a).

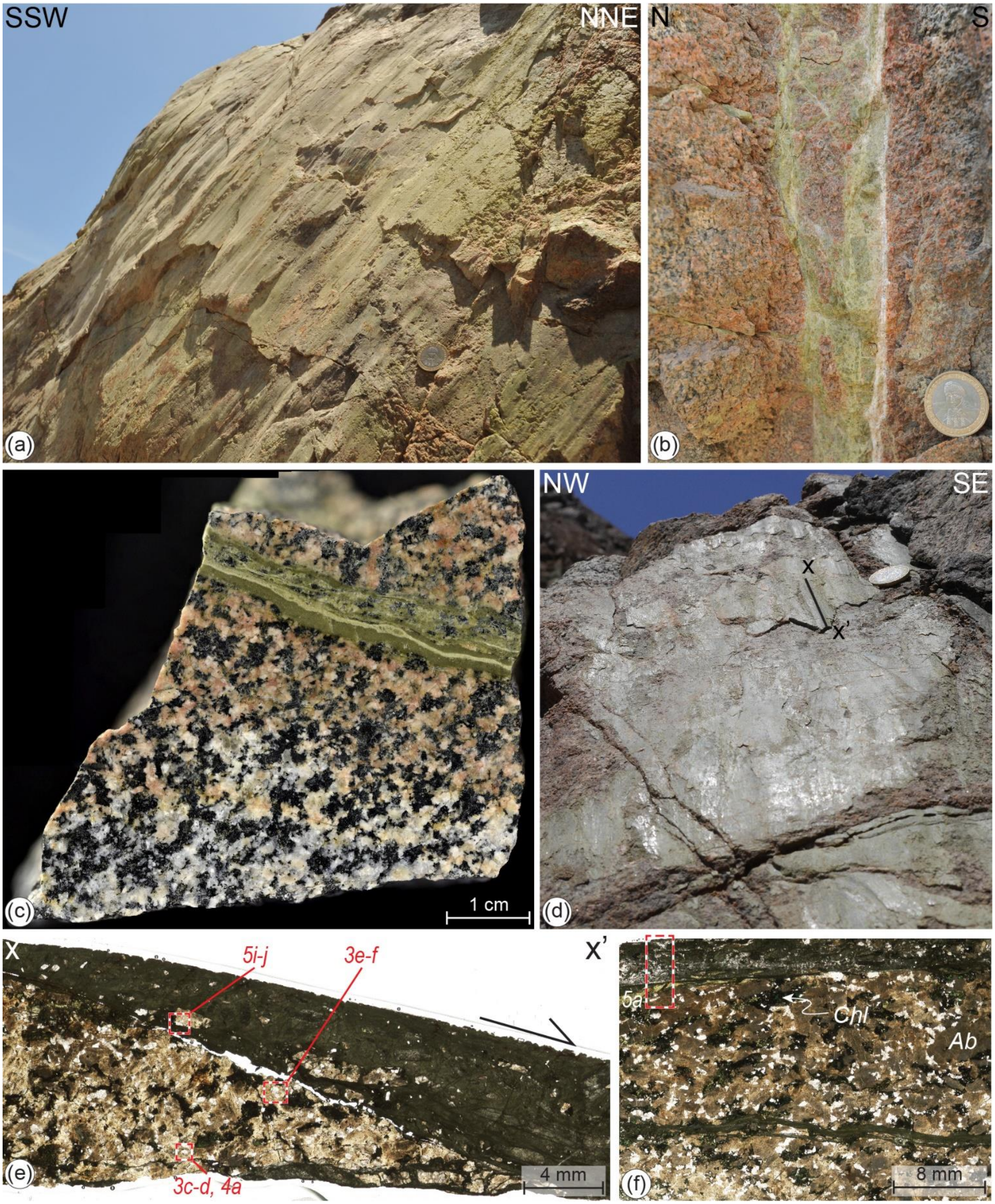


Figure 2. The epidote-rich fault-vein network of BFZ. Coin for scale. Mineral abbreviations: *Ab* = albite, *Chl* = chlorite. (a) Discrete extensional fault surface decorated by epidote slickenfibers. WGS84 GPS

location: 23.883944°S, 70.486689°W. Modified from Masoch et al. (2022). (b) Epidote-rich hybrid extensional-shear vein including angular fragments of earlier veins (dark green). The vein is reactivated by a whitish calcite-palygorskite vein (boundary on the right side), referable to post-Miocene deformation (see Masoch et al., 2021 for details). Sample 19-33. WGS GPS location: 23.99803°S, 70.44051°W. Modified from Masoch et al. (2022). (c) Polished sample of an epidote sheared vein surrounded by a reddish alteration halo on both sides. The pale green-colored cataclasite includes dark green fragments of early veins. Sample 19-48. WGS84 GPS location: 23.88442°S, 70.48567°W. Modified from Masoch et al. (2022). (d) Sheared vein with lineated and highly reflective (i.e., mirror-like) slickenside. The black line indicates the orientation of the thin section scan shown in (e). Sample 19-38. WGS84 GPS location 23.88424°S, 70.48642°W. (e) Plane-polarized light scan of thin section of a lineated sheared vein, showing the spatial distribution of the microstructures observed in the micro-damage zone and in the sheared vein (red lines). (f) Plane-polarized light scan of thin section of a sheared vein recording multiple episodes of extensional-to-hybrid veining and along vein-boundary shearing. Sample 19-46. WGS84 GPS location 23.88428°S, 70.48615°W.

3. Methods

Microstructural analysis was conducted on Syton-polished 100-μm-thick thin sections (n=10) cut parallel to the fault lineation and orthogonal to the fault/vein wall. We used a Tescan Solaris (Field Emission Gun – Scanning Electron Microscope; FEG-SEM) installed at the Department of Geosciences of University of Padova (Italy). The instrument is equipped with backscattered electron (BSE), cathodoluminescence (CL), electron backscattered diffraction (EBSD), and quantitative wavelength-dispersive spectroscopy (WDS) detectors. BSE and CL images were acquired at 5-10 kV and 0.3-3 nA, and 10 kV and 1-3 nA as accelerating voltage and beam current, respectively. The EBSD maps were acquired using the FEG-SEM equipped with a COMOS-Symmetry EBSD detector (AZtec acquisition software, Oxford Instruments), operating at 20 kV as accelerating voltage, 5-10 nA as beam current, 0.15-0.30 μm as step size, 70° sample tilt and high vacuum. EBSD data were elaborated with the MTEX toolbox (https://mtex-toolbox.github.io/).

The composition of main mineral phases was obtained by WDS-FEG analysis. Acquisition conditions were: 15 kV (accelerating voltage); 6 nA (beam current); 1 µm (electron beam size); 5 s (counting time for background), 15 s (for Si, Al, Ca, Fe), and 10 s (for Na, K, Mg, Mn, Ti, Cr) on peak. Albite (Si, Al and Na), diopside (Ca), olivine San Carlos (Mg), orthoclase (K), hematite (Fe), and Cr, Ti and Mn oxides were used as standards. Na and K were analyzed first to prevent alkali migration affects.

4. Results

4.1. Weakly-deformed granodiorite and micro-damage zone of the sheared veins

The weakly-deformed granodiorite consists of plagioclase (labradorite to andesine; Masoch et al., 2022), quartz, K-feldspar with myrmekite, biotite, minor amphibole, ilmenite and magnetite (Figure 2c). The magmatic quartz shows weak undulose extinction and has a dominant bright to light grey CL shade locally cut by CL-dark micro-fractures (>10 µm in thickness) sealed by hydrothermal quartz ± K-feldspar (Figure 3a-b).

The granodiorite adjacent to epidote-rich sheared veins is turned into reddish alteration haloes, up to 4 cm in thickness (Figures 2b-f), associated with (i) replacement of magmatic plagioclase by albite + epidote, and of magmatic biotite and amphibole by chlorite ± opaques (Figure 2e-f), (ii) pervasive micro-fracturing, filled with epidote ± chlorite ± prehnite (Figure 2c, 2e-f), and (iii) deformation of the magmatic quartz. Quartz deformation microstructures include interlaced deformation bands, up to 10-µm-thick, visible in CL by the darker shade crosscutting the bright to medium grey-shaded host quartz (Figure 3c-f). The deformation bands are in turn crosscut by thin (up to 15-µm-thick) micro-fractures healed by quartz ± K-feldspar ± albite (hereafter referred as “quartz-filled” veinlets), across quartz and K-feldspar grains (Figure 3c-f). These veinlets show a homogeneous dark CL shade and are oriented at high angle with respect to the vein boundary (Figure 3f). These deformation microstructures (hereafter referred to as “micro-damage zone”) fade away from the veins and disappear at distances ≥ 1 cm (Figure

3a-b). In the micro-damage zone, the quartz-filled veinlets increase in spatial density towards the veins (Figure 3c-f), while no apparent change in density of deformation bands is observed. In the footwall block, at < 100 µm distance from the sharp vein boundary, the magmatic quartz is strongly brecciated and healed by CL-dark grey-shaded quartz (also surrounded by epitaxial rim of CL-dark quartz; Figure 3g-h).

EBSD maps of the quartz show that the deformation bands visible in CL are oriented nearly orthogonal to the <c> axis (Figure 4a-b) and correspond to a minor crystallographic misorientation (< 2-3°; see profiles in Figure 4c) with respect to the host grain. These features are typical of deformation lamellae (Fairbairn, 1941; Trepmann & Stöckhert, 2003), either referred to as short-wavelength undulatory extension (Trepmann & Stöckhert, 2013) or fine extinction bands (Derez et al., 2015). Therefore, quartz deformation bands will be referred to hereafter as deformation lamellae. The EBSD maps also show that the quartz-filled veinlets overgrew in epitaxial continuity with the host magmatic quartz (Figure 4a).

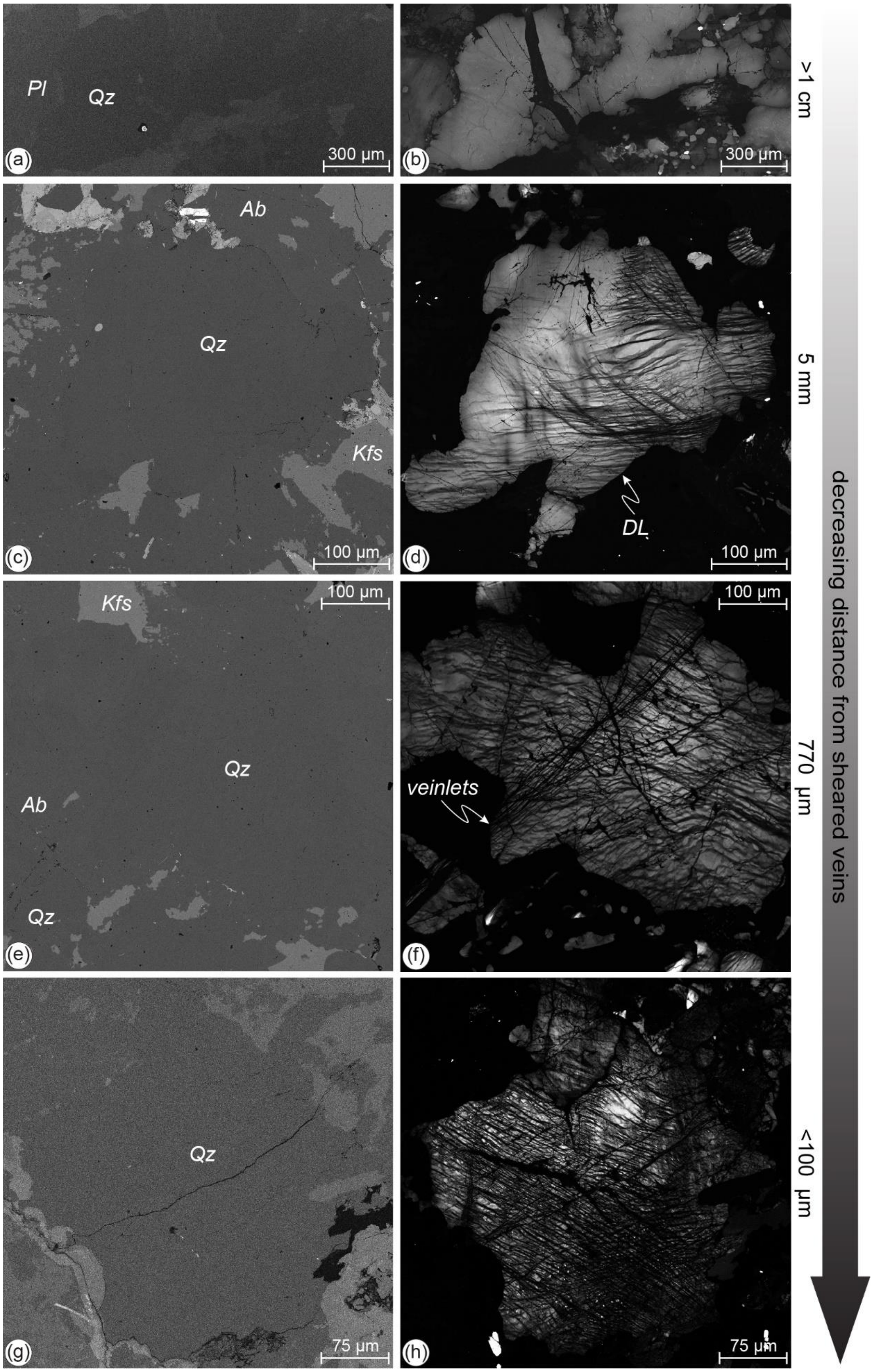

Pl
Qz
(a)
300 µm
(b)
300 µm
>1 cm
Ab
Qz
Kfs
(c)
100 µm
DL
(d)
100 µm
5 mm
Kfs
100 µm
Qz
Ab
Qz
(e)
100 µm
veinlets
(f)
770 µm
Qz
(g)
75 µm
(h)
75 µm
<100 µm
decreasing distance from sheared veins

Figure 3. Quartz microstructures in the weakly-undeformed granodiorite (a-b) and in the micro-damage zone of the veins (c-h). BSE images (left column) and their corresponding CL images (right column) with their distance to the vein boundary. Samples 19-37 and 19-38. Mineral abbreviations: *Ab* = albite, *Kfs* = K-feldspar, *Pl* = plagioclase, *Qz* = quartz. (a) Quartz grains outside the micro-damage zone. (b) Undeformed quartz grains show a homogeneous, bright CL signal. (c, e, g) Quartz grains appear almost undeformed in BSE images. (d, f, h) Deformed magmatic quartz shows bright to medium, CL grey-shaded domains, which are pervasively cut by interlaced darker deformation lamellae (DL). These deformation features are cut by CL-dark quartz-filled veinlets. (g-h) Quartz grain close to the vein boundary in the footwall side. In the CL image in (h), the quartz grain appears strongly brecciated (almost pulverized) and is healed by CL-dark quartz.

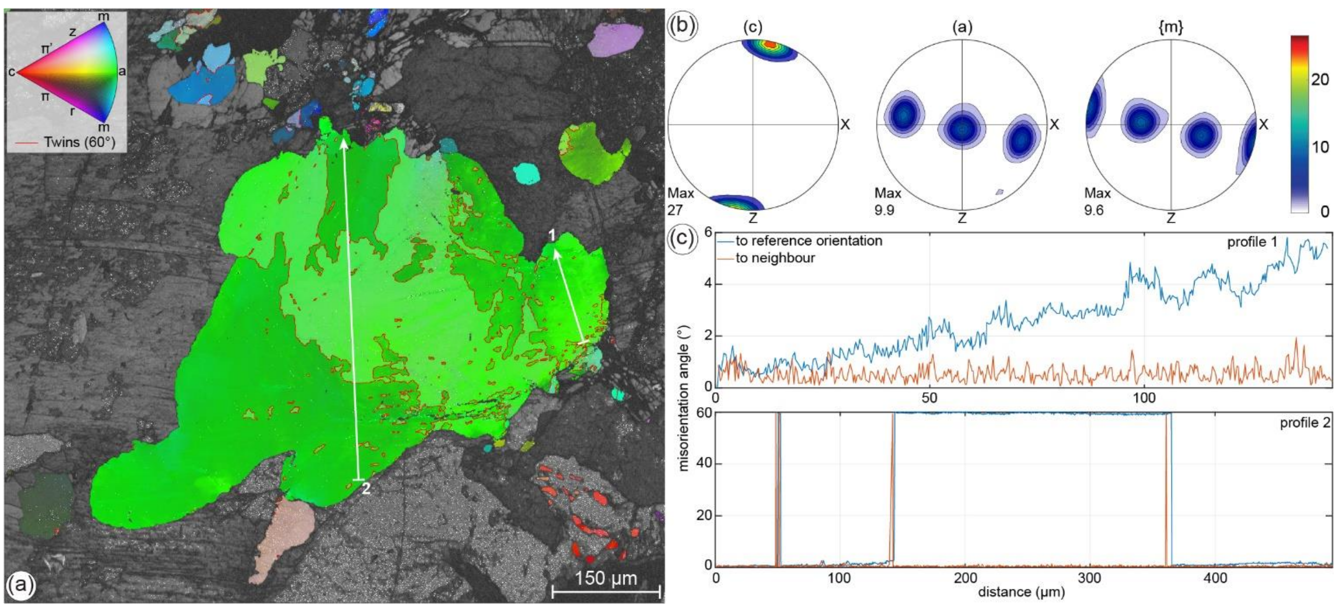


Figure 4. EBSD analysis of a deformed magmatic quartz in the micro-damage zone. (a) Inverse Pole Figure (IPF) map, color coded according to IPF legend. The analyzed large magmatic quartz grain is the same shown in Figure 3c-d. The IPF map is overlaid to the orientation contrast image. White lines mark the profiles plotted in (c). (b) Contoured pole figures. (c) Misorientation profiles.

4.2. Epidote-rich sheared veins

The epidote-rich sheared veins have a heterogeneous microstructure (Figures 2e-f, 5-6). Sample 19-48, which includes both sides of the wall-rock surrounding the vein, consists of both undeformed and cataclastic vein domains (Figures 2c, 2f, 6a). The undeformed domains consist of idiomorphic, zoned epidote (Al-rich; light: Fe-rich; Table S1 in the supporting information) ± prehnite (dark: Al-rich; light: Fe-rich; Table S1 in the supporting information), interstitial chlorite ± quartz ± K-feldspar, and wall-rock fragments (Figures 2c, 5a-b). Undeformed domains are generally present at the outer part of the vein, while the cataclastic domain is at the core (Figures 2c, 6a). The core of the vein consists of a porous fine-grained (< 20 μm in size) matrix of epidote including fragments of earlier vein fillings and of the wall-rock (Figure 2c).

In samples 19-37, 19-38, and 19-46, which only include one side of the footwall wall-rock, the sheared veins consist of layered (proto)cataclasites to ultracataclasites in sharp contact with the topping undeformed vein (Figures 2e-f, 5a, 6b). Close to the wall-rock, the (proto)cataclasites consist of a fine-grained (< 20 μm in size) matrix of zoned epidote ± prehnite with interstitial chlorite (Figure 5c-d), including fragments (up to cm in size) of earlier prehnite-epidote veins and wall-rock (Figure 5a, 5c-d), and some are foliated (Figure 5e). The ultracataclasites consist of a highly porous, fine-grained (≤ 500 nm in size) matrix of epidote and prehnite, with interstitial chlorite, and fragments (up to 100 μm in size) of idiomorphic epidote and prehnite crystals and wall-rock (Figure 5d, 5f-g). Above the lineated slickensides, multiple vein generations are present (Figure 2f, 5a, 5d, 5f). Some veins consist of zoned prehnite crystals elongated orthogonal to the vein boundaries (Figure 5f). Other veins consist of zoned epidote-prehnite crystals, which present localized (ultra)cataclasite layers at the vein boundaries, marking further lineated slickensides (Figures 2f, 5a, 5d).

Fragments of magmatic quartz within the veins appear brecciated under CL (Figure 5h). Micro-fractures are sealed by CL-dark quartz, which rims the brecciated magmatic quartz fragment (Figure 5h). This darker rim shows a faint oscillatory zoning in the external part (Figure 5h). Magmatic quartz included in large (mm in size) wall-rock fragments shows the same deformation features (i.e., deformation lamellae cut by epitaxial quartz-filled veinlets, Figure 5i-j) as observed in the micro-damage zone (Figure 3).

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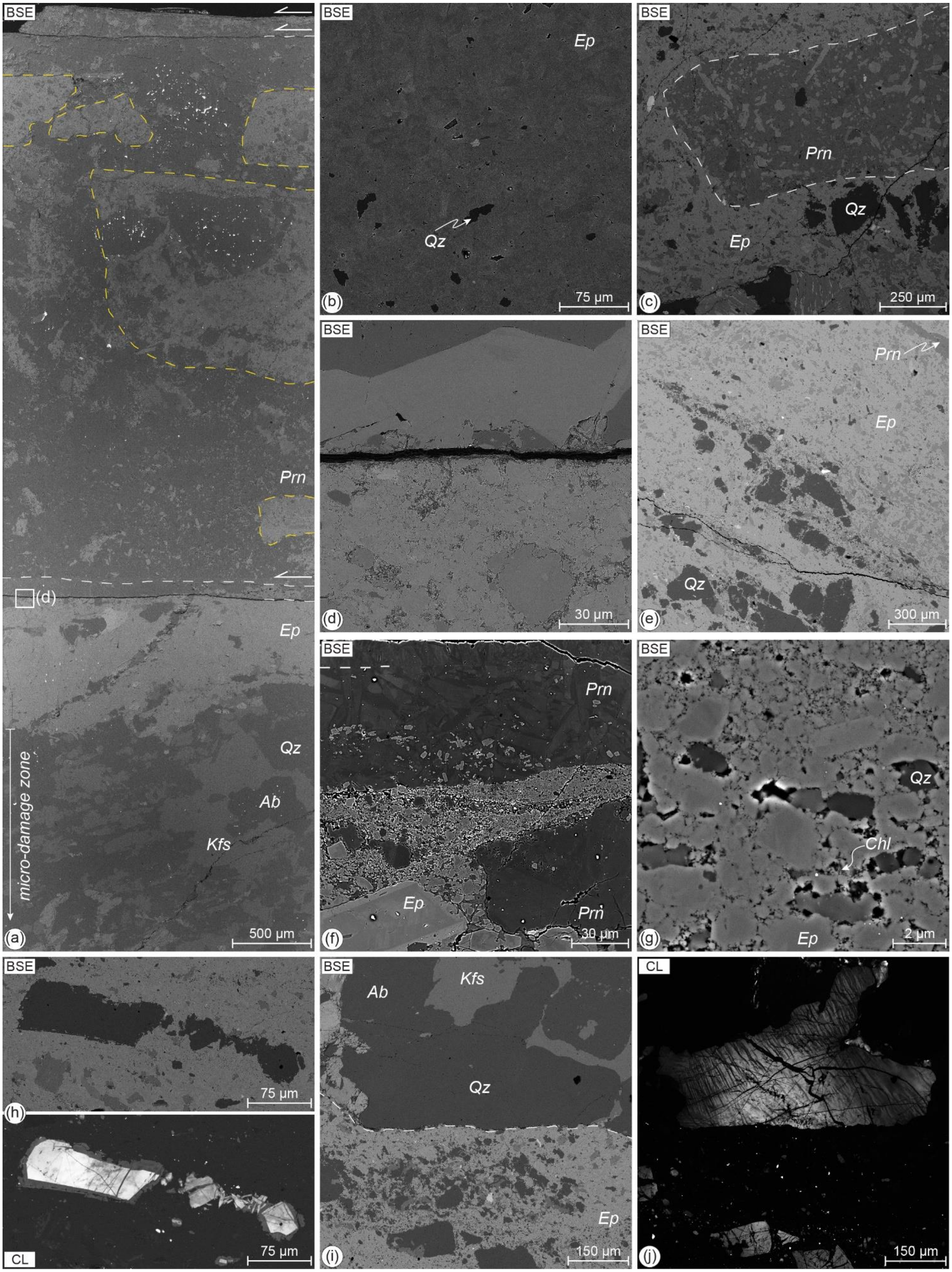
BSE
Prn
(d)
Ep
Qz
Ab
Kfs
micro-damage zone
500 µm
(a)
BSE
Ep
Qz
75 µm
(b)
BSE
Prn
Qz
Ep
250 µm
(c)
BSE
30 µm
(d)
BSE
Prn
Ep
Qz
300 µm
(e)
BSE
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(i)
CL
150 µm
(j)

Figure 5. Microstructures of the epidote-rich sheared veins (samples 19-37, 19-38, 19-46 and 19-48). Mineral abbreviations: *Ab* = albite, *Chl* = chlorite, *Ep* = epidote, *Kfs* = K-feldspar, *Prn* = prehnite, *Qz* = quartz. (a) Overview of an epidote-prehnite sheared vein and associated footwall block. The sheared vein recorded multiple extensional-to-hybrid veining and along vein-boundary cataclasis. The largest vein includes mm-large fragments of earlier veins (dashed yellow lines) within the cataclastic domain. Dashed white lines indicate the top of each vein boundary. The white box indicates the detail shown in (d). (b) Vein filling consisting of idiomorphic zoned epidote. (c) Angular fragment of an early prehnite-epidote vein (dashed white line) included in epidote-rich vein protocataclasite. (d) Cataclasite with epidote grains overprinted by an extensional vein with epidote-prehnite crystals. (e) Foliated cataclasite. The sigmoidal clast consists of wall-rock fragments with elongated tails of finer fragments and epidote grains. (f) Ultracataclasite, defining the slip zone of a discrete polished surface, includes angular fragments of zoned epidote (light grey) and prehnite (dark grey). Multiple events of extensional-to-hybrid veining reactivate the sheared vein. The latter vein is sealed by elongated prehnite crystals and reactivating a hybrid extensional-shear one. Note the fibrous prehnite crystals above the white dashed line. (g) Matrix of ultracataclasite consisting of epidote nanoparticles ($\leq$ 500 μm in size). Fragmented idiomorphic crystals of epidote and prehnite are included in the matrix. The ultrafine epidote grains have triple junctions and pores ($<<$ 1 μm in size), locally filled with chlorite. (h) Quartz fragments within an epidote cataclasite. The quartz fragments are brecciated and rimmed by CL-darker quartz. (i-j) Quartz grains in wall-rock fragments (the larger is marked by the dashed white line) show the same deformation features observed in the micro-damage zone of the veins, shown in Figure 3.

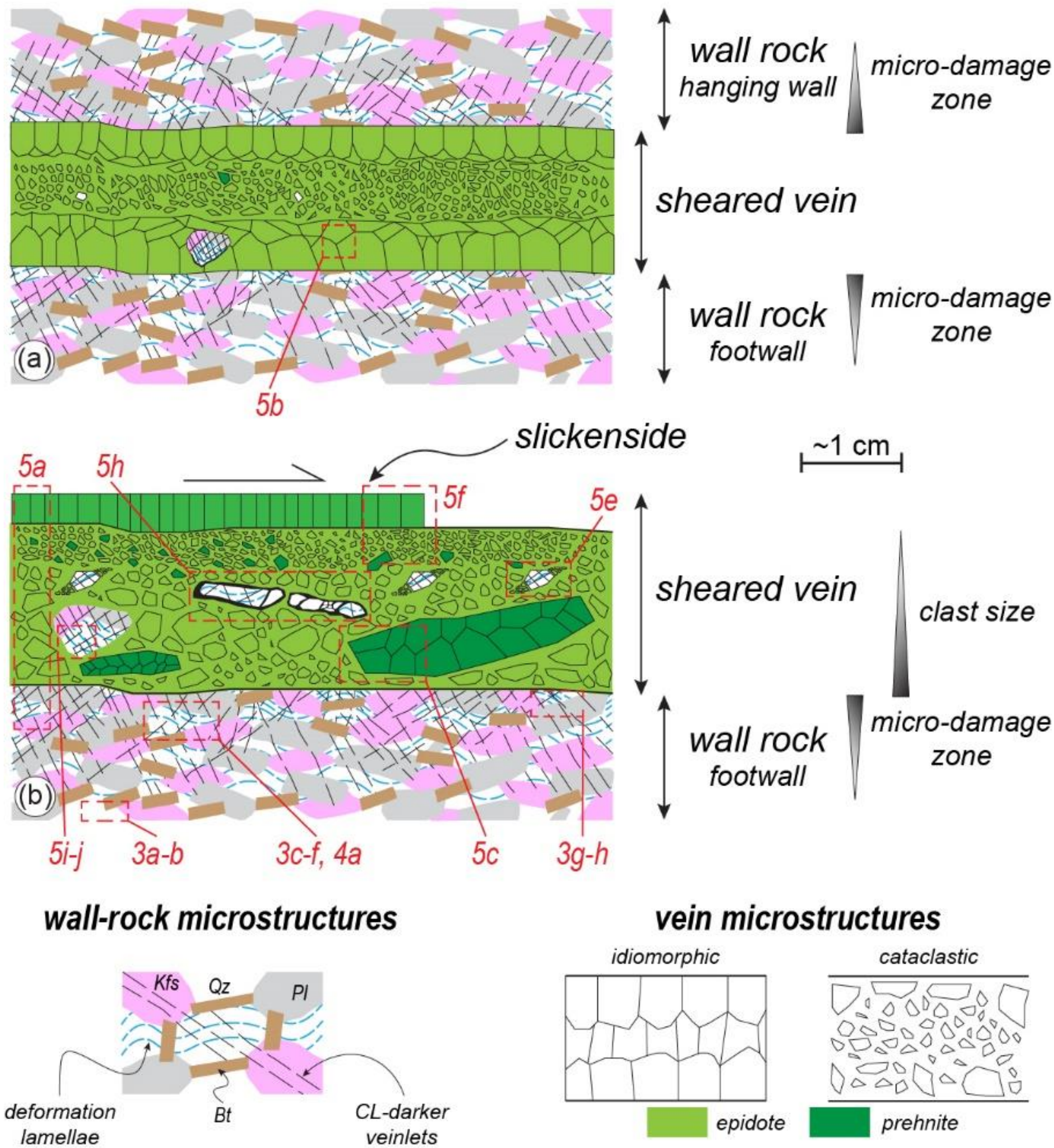


Figure 6. Schematic illustration summarizing the different microstructures observed in the epidote-rich sheared veins and associated wall-rock. (a) Sheared veins with both footwall and hanging wall blocks preserved. (b) Sheared veins with only the footwall block preserved.

5. Discussion

The epidote-rich fault-vein networks of the BFZ formed at temperatures ≤ 300 °C (Herrera et al., 2005; Masoch et al., 2022), i.e. at conditions close to the brittle-ductile transition for quartz-rich crustal rocks and corresponding to the base of the seismogenic upper crust (Scholz, 2019). Ancient (125-118 Ma) seismicity along the BFZ is attested by pseudotachylytes, produced in a fluid-rich environment (Gomila et al., 2021) along the main segments of the fault system (Masoch et al., 2022, 2021). The epidote-rich fault-vein networks represent a subsidiary linkage set of structures that accommodated slip deficit along, and/or slip transfer between, the main seismogenic segments, during fault system growth (Cembrano et al., 2005; Herrera et al., 2005; Masoch et al., 2022, 2021).

The SEM images document a polyphase deformation history associated with vein array formation, including (i) an initial stage (well-preserved in the wall-rocks nearby the epidote-rich veins, i.e., micro-damage zone) of fracture propagation with local fluid redistribution along micro-cracks, and (ii) following pulses of hydrothermal fluid infiltration, with of epidote ± prehnite, alternating with vein-parallel cataclastic shearing, which shaped the mature architecture of the fault-fracture system. Below, we discuss the microstructural observations and propose a conceptual model for the nucleation (section 5.1) and development (section 5.2) of a highly interconnected fault-fracture network in a seismically-active hydrothermal system (Figure 7), distinguishing two deformation environments (*rock-buffered* vs. *fluid-buffered*) based on the mineralogy of vein fillings. Lastly, we compare our findings with observations of currently active systems (section 5.3).

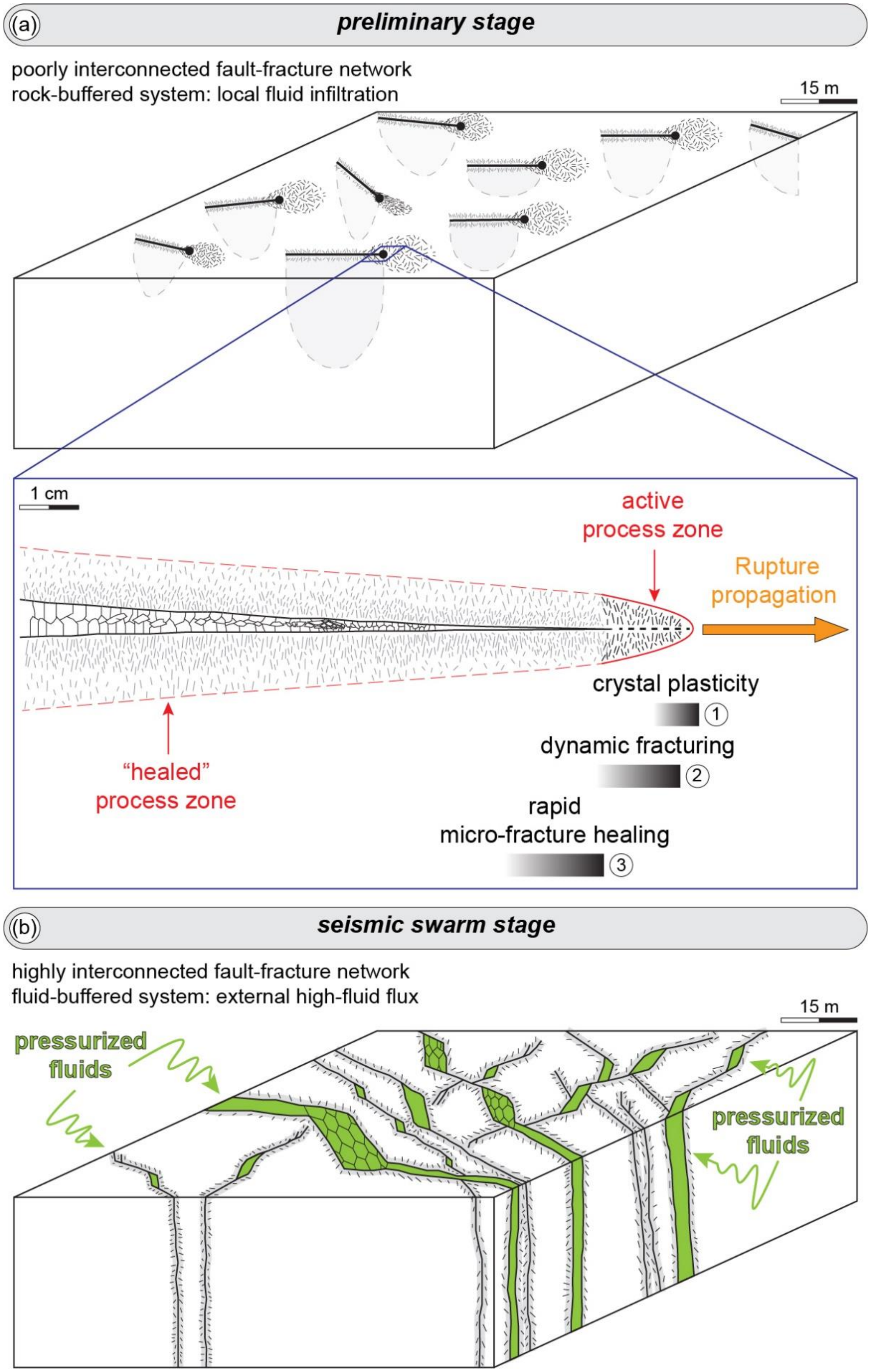
5.1. Wall-rock damage and local fluid redistribution during dynamic crack propagation

Quartz deformation lamellae and quartz-filled veinlets in the micro-damage zone (Figures 3c-h, 4) of the epidote-rich fault-veins formed at an early stage of development of the hydrothermal fault-vein system (Figure 7a), as attested by the presence of these microstructures within clasts inside the veins (Figure 5e-g). Quartz deformation lamellae have been reported in shock-impact rocks (e.g., Carter, 1965) and in exhumed middle-crustal shear zones from the Sesia-Lanzo Zone (Western Alps), associated with other high-stress deformation microstructures (e.g., twinning of jadeite, shattering of garnet), as evidence of upper-crustal seismic ruptures that transiently propagated in the underlying ductile crust (Trepmann & Stöckhert, 2003). Deformation lamellae were produced experimentally in natural quartz deformed under high stresses and relatively low temperatures (400 °C) (Trepmann & Stöckhert, 2013). Similarly, they develop in metals deformed at high-strain rates and low temperatures (Drury, 1993).

During an earthquake rupture propagation, a dynamic transient high-stress field is produced in the immediate surrounding of the rupture tip and leads to instantaneous rock failure and pulverization (Faulkner et al., 2011; Okubo et al., 2019; Reches & Dewers, 2005; Vermilye & Scholz, 1998) as recorded in the wall-rock of several exhumed pseudotachylyte-bearing faults (e.g., Di Toro et al., 2005; Mancktelow et al., 2022; Petley-Ragan et al., 2019). In contrast to seismic ruptures propagating at velocities of $1\text{-}4\times10^3$ m/s, micro-cracks may also propagate at extremely low velocities (sub-seismic: $10^{-9}\text{-}10^{-4}$ m/s) by sub-critical crack growth driven by stress corrosion (Atkinson & Meredith, 1987). Sub-critical crack propagation is particularly efficient in silicate-built rocks in the presence of pressurized water, which maintains crack connectivity, and at high fluid temperatures ($T \geq 200$°C), therefore at the ambient conditions during formation of the fault-vein networks described in this study. However, sub-critical crack propagation cannot explain the high-stress perturbations recorded by the quartz deformation lamellae in the wall-rock surrounding the epidote-rich fault-veins (Trepmann & Stöckhert, 2013) (Figures 3c-h, 4). Thus, in the relatively small-displacement (< 1.5 m) and up to 10s-m-long faults and hybrid fractures of the epidote-rich fault-vein networks, we interpret the occurrence of deformation lamellae in the wall-rock quartz to reflect the high-stress field associated with rupture tip propagation at seismic speeds during initial fracturing (Figure 7a). Blenkinsop & Drury (1988) proposed a similar interpretation for the formation of this low-temperature intra-crystalline deformation microstructure found in the damage zone of the Bayas Fault hosted in quartzites (Cantabrian Zone, Variscan Orogen, Spain).

Quartz-filled veinlets sharply crosscutting the quartz deformation lamellae (Figure 3d, 3f) within the micro-damage zone of the epidote-rich veins (Figures 2e-f, 3-4) increase in spatial density towards the vein boundary (Figure 3), are mostly oriented at high angle with respect to the vein boundary (Figure 3f, 3h), and are healed by the minerals (quartz, K-feldspar and albite) of the crosscut wall-rock (Figures 3c-h, 4). Moreover, at the vein boundary in the footwall blocks, the deformed magmatic quartz is strongly brecciated (Figure 3g-h), resembling *in-situ* shattered or pulverized fault rocks found in exhumed upper to mid-lower crustal seismic fault zones (e.g., Fondriest et al., 2015; Johnson et al., 2021; Mancktelow et al., 2022; Mitchell et al., 2011; Ostermeijer et al., 2022). We therefore infer that the quartz-healed veinlets also resulted from wall-rock damage associated with the dynamic stress field during earthquake rupture tip propagation. Micro-fracturing and rapid healing of seismic faults has been documented in pseudotachylyte-bearing faults hosted in quartzo-feldspathic rocks and referred to the initial stage of seismic rupture propagation (Bestmann et al., 2016, 2012; Mancktelow et al., 2022). Williams & Fagereng (2022) reviewed the role of quartz precipitation in healing seismic faults during the seismic cycle at different environmental conditions and by different mechanisms (e.g., fluid advection, fluid depressurization, dissolution-precipitation creep, frictional heating). The authors observed that, at crustal conditions similar at which the epidote-rich fault-vein networks formed (i.e., temperature ≤ 300 °C and 3-7 km depth), micrometer-thick veins can be completely healed by quartz in a timeframe spanning from days to hundreds of years, depending on the mechanisms involved in quartz precipitation. The quartz-filled veinlets are hundreds of µm in length (Figure 3d, 3f. 3h) and up to 15 µm in thickness (Figure 3f) with most veinlets ~2-3-µm-thick (Figure 3d, 3f, 3h). The co-seismic opening of these micro-cracks induced a sudden decrease of pore-fluid pressure ranging from near-lithostatic to sub-MPa levels (e.g., Brantut, 2020; Cox, 2016; Sibson, 1992a, 1992b) that likely resulted in quartz (super)saturation, and eventually into local fluid vaporization (Amagai et al., 2019; Williams, 2019), and in rapid precipitation of amorphous silica (Amagai et al., 2019). Assuming the healing rates estimated by Williams & Fagereng

(2022) (see their Figure 8 and their discussion), the quartz-filled veinlets could have reasonably healed in a timeframe as long as tens of years (considering the largest veinlets), during the co- to post-seismic phase. Moreover, the veinlet filling is controlled in composition by the crosscut wall-rock minerals (quartz ± K-feldspar ± albite; Figure 3c-h), discarding any extensive fluid advection from external reservoirs (Williams & Fagereng, 2022). This observation also indicates that the co-to-post-seismic micro-fracture formation and healing occurred in a *rock-buffered* system, where percolation of external hydrothermal fluids or fluid redistribution was still minor, owing to the still immature stage of development of a fully interconnected network of permeable fractures and more conspicuous fluid circulation (Figure 7a). In summary, the microstructures preserved in the deformed magmatic quartz in the proximity of epidote-rich sheared veins resulted from dynamic propagation of seismic ruptures and co- to post-seismic healing of a newly-produced micro-fracture network. Both low-temperature crystal-plasticity (deformation lamellae in quartz) and micro-fracturing accommodated the high-stress conditions around a propagating seismic rupture (Figure 7a).


(a)
preliminary stage
poorly interconnected fault-fracture network
rock-buffered system: local fluid infiltration
15 m
1 cm
active
process zone
Rupture
propagation
crystal plasticity
1
dynamic fracturing
2
rapid
micro-fracture healing
3
"healed"
process zone
(b)
seismic swarm stage
highly interconnected fault-fracture network
fluid-buffered system: external high-fluid flux
15 m
pressurized
fluids
pressurized
fluids

388

Figure 7. Conceptual model summarizing the development of the seismically-active hydrothermal system recorded in the studied epidote-rich fault-vein networks. (a) Stage 1: initial stages of dynamic propagation of small seismic ruptures. The fault-fracture network is poorly interconnected, and, in turn, fluid circulation is relatively low and at cm-scale (*rock-buffered system*). The blue box marks the zoom at the crack tip and shows the sequences of deformation processes that recorded the initial stages, well preserved in the wall-rocks, of seismic rupture propagation. (b) Stage 2: distributed swarm-like seismicity (*fluid-buffered system*). Highly-interconnected fault-fracture networks allow the ingression of overpressured fluids leading to swarm-like earthquake sequences, well recorded in the sheared veins. The cyclic deformation sequence is driven by fluid pressure fluctuations as illustrated in Figure 8.

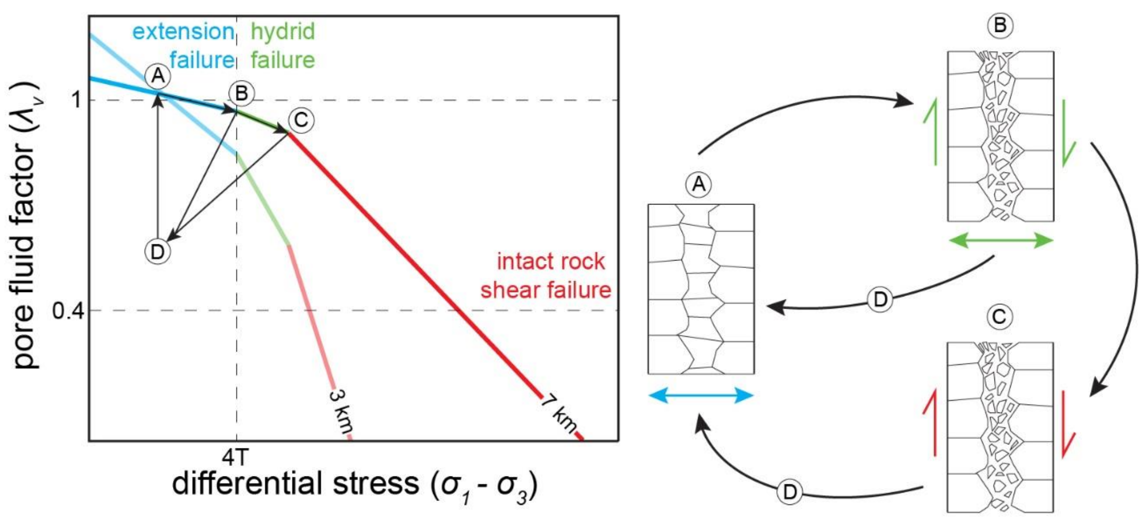


Figure 8. $\lambda - \Delta\sigma$ diagram (left) and cartoon (right) illustrating the deformation cycle governing seismicity during the swarm stage. Failure curves represented for the minimum and maximum formation depths of the epidote-rich fault-vein network. The schematic $\lambda - \Delta\sigma$ diagram illustrates the fluid pressure vs. tectonic stress paths recorded by the sheared veins, which show cyclic fluid-driven extensional-to-hybrid veining and shearing. The evolution of fluid pressure and stress states controls the temporal evolution and deformation path of swarm sequence till fluid depletion.

5.2. Pore pressure oscillations in a highly connected hydrothermal (fluid-buffered) fault-fracture network

The epidote-rich veining and shearing postdate the initial short-term co- to post-seismic deformation recorded in the deformed wall-rock magmatic quartz, as discussed in the previous section.

The initial fracturing and associated wall-rock damage was precursory to development of a more robust external fluid ingression within the initially low-permeability crystalline rocks (Figure 7). Robust fluid ingression was accompanied by a switch from the initially fluid-poor *rock-buffered* system to a *fluid-buffered* one (Figure 7b). In hydrothermal systems, rock failure is governed by fault-valve behavior (Sibson, 1989, 1992a, 1992b), associated with transient fluctuations in pore fluid pressure.

The epidote-rich fault-vein networks show cyclic and mutually overprinting events of extensional veining and shearing (Figures 2e-f, 5a-d). Cataclasites include fragments of earlier veins (Figures 2b-c, 2e-f, 5a-d), indicating that extensional veining preceded either hybrid extensional-shear fracturing (Figures 2b, 5c) or shearing (Figure 2a). Cataclasites are overprinted by extensional(-shear) veins, which show cataclastic shearing along vein boundaries (Figures 2f, 5a, 5d, 5f). Some cataclasites are foliated (Figure 5e) suggesting that slip likely occurred by aseismic fault creep (e.g., Chester & Chester, 1998; Rutter et al., 1986). On the other hand, most cataclasites display suspended clasts of wall-rocks and earlier veins (Figures 2e, 5a, 5c, 5h-j) similar to the microstructures observed in fluidized cataclasites and breccias, which have been interpreted as markers of co-seismic slip (e.g., Cox, 2016; Fondriest et al., 2012; Masoch et al., 2019; Smith et al., 2008).

The overprinting between extensional veining and shearing can be interpreted with the use of $\lambda - \Delta\sigma$ failure mode diagrams (Cox, 2010), where λ is the pore fluid factor ($\lambda = \frac{p}{\sigma_v}$; where p and σ_v is the pore fluid pressure and the vertical stress, respectively) and $\Delta\sigma$ is the differential stress ($\Delta\sigma = \sigma_1 - \sigma_3$; where σ_1 and σ_3 are the maximum and minimum principal compressive stresses, respectively). At low differential stresses ($\Delta\sigma < 4T$; where T is the tensile strength of the material) and larger rate of increase in pore fluid pressure respect to the increase in tectonic loading, hydraulic fracturing (and extensional veining) occurs before shear failure (Murrel-Griffith failure criteria; Price & Cosgrove, 1990) (step A, Figure 8). Opening of extensional fractures prevents further increase in fluid pressure and pressurizes the fracture network. The progressive increase in tectonic-related differential stress leads to hybrid extensional-shear failure (step B, Figure 8) to shear failure (step C, Figure 8), causing stress drop and fault depressurization (step D, Figure 8). The progressive increase in tectonic-related differential stress could be achieved because the NE-, SW- and NW-dipping small-displacement epidote-rich vein arrays are (near-)optimally oriented with respect to the tectonic stress field (i.e., nearly subvertical-oriented compression direction; Cembrano et al., 2005; Veloso et al., 2015). The described deformation cycle can repeatedly occur if the system is dominated by increase rate of fluid pressure larger than increase rate of tectonic loading (Cox, 2016; Phillips, 1972). However, we cannot rule out that part of the cyclic deformation history recorded by the epidote-rich veins is the result of deformation events unrelated to the coupled evolution of fluid pressure and tectonic differential stress.

5.3. Comparison with natural fluid-driven earthquake swarms

Earthquake swarms are characterized by a spatiotemporal clustering of large number of small magnitude events, without a clear triggering mainshock (Mogi, 1963). Such a behavior requires external mechanisms driving seimsicity, among which fluid diffusion and aseismic slip are the preferred ones (e.g., De Barros et al., 2020; Lohman & McGuire, 2007; Vidale & Shearer, 2006). Recent studies revealed that both processes can coexists with fluid diffusion favoring the occurrence of aseismic slip, which triggers seismicity by stress transfer ahead of the slip front (e.g., Danré et al., 2022; Guglielmi et al., 2015). The occurrence of swarms is also controlled by the complexity of fault systems, such as fault linkages, step-overs, or hydrated fracture zones (e.g., Essing & Poli, 2022; Legrand et al., 2011; Poli et al., 2017; Ross et al., 2020, 2017; Shelly et al., 2022). For instance, thanks to high-precision earthquake relocation, Shelly et al. (2022) documented that two conjugate sets of strike-slip faults well-oriented with respect to the far-field stress were activated during the swarm-like 2020 Maacama sequence. Most earthquakes had moment magnitude $M_W < 1$ and localized in overstepping segments of the Maacana Fault (Northern California). Moreover, swarm-like sequences produce both non-double-couple (i.e., isotropic) and double-couple events in the same period of time, resulting from co-seismic fault opening (dilation) and shearing, respectively (e.g., Legrand et al., 2011; Shelly et al., 2013).

Our geological observations (Figures 1-2, 5) show several analogies with the characteristics of earthquake swarms. At Stage 1, we infer the early development of a fault-fracture mesh within a low-permeability intact rock volume, producing the pathways for the ingression of external pressurized hydrothermal fluids sustaining the swarmogenic activity of Stage 2 (Figures 7b-8). The microstructures found in the micro-damage zones of the veins and hybrid fractures (i.e., quartz deformation lamellae and quartz-filled veinlets; Figures 3-4) are consistent with rupture propagation of small-in-magnitude earthquakes, possibly also accompanied by quasi-static crack growth (Stage 1, Figure 7a). The fault-fracture network progressively became hydraulically more connected during Stage 2 (Figure 7b). Cyclic fluid pressure fluctuations drove widespread epidote precipitation and development of the epidote-rich hybrid fracture and vein system (Figures 7b-8). We associate this stage with the activation of a swarmogenic system (Figure 7b) as suggested by the following analogies between our geological observations and earthquake swarms:

1. *Fault geometric complexity*: the small-displacement (< 1.5 m) veins are located at geometric complexities, such as fault linkages and intersections (Figure 1b), within the crustal Coloso Duplex (Cembrano et al., 2005; Masoch et al., 2022) (Figure 1a). The fault-vein system is arranged into sets (i.e., NW-, NE- and SW-dipping fault-veins; Figure 1c) (near-)optimally oriented with respect to the local-stress field (i.e., subvertical-oriented σ_1; Cembrano et al., 2005; Veloso et al., 2015). Many works have shown that fault geometric complexities are the *loci* for the development of earthquake swarms (e.g., Legrand et al., 2011; Ross et al., 2020, 2017), commonly activing fault-fracture networks well-oriented with the stress field (Shelly et al., 2022). Moreover, this structural arrangement forms a honey mesh-like fault network at

the scale up to 100s of meter (Figure 1b), which is the fault-fracture geometry commonly inferred to be activated during swarms (Hill, 1977; Sibson, 1996).

2. *Fluid diffusion within the fault system*: faulting was driven by the ingression of pressurized fluids within the fault system (section 5.2) and the veins recorded cyclic extensional-to-hybrid veining and shearing (Figures 2b-f, 5a-g), which might be interpreted as the source of non-double-couple (crack opening) and double-couple (shear fracture) processes occurring in swarm-like sequences (e.g., Legrand et al., 2011; Shelly et al., 2013). Bursts of short-lasting (tens to thousands of seconds) fluid pressure variations trigger repeated small earthquakes along active fault systems (Collettini, 2002; Essing & Poli, 2022; Piana Agostinetti et al., 2017). Similarly, such a repeated condition of fluid (over-)pressurization in short timespans drives the deformation cycle (i.e., crack opening followed by along vein-boundary slip) recorded in the veins (Figure 5a, 5c-g) and described by the diagram in Figure 8.
3. *Coexistence of both aseismic and seismic slip*: the sheared veins accommodated either aseismic fault slip, as attested by foliated cataclastic horizons (Figure 5e), and possible seismic fault slip, as documented by the occurrence of suspended clasts within cataclasites (Figures 2e, 5a, 5c, 5h-j), mutually overprinting crack opening (i.e., extensional veins) (Figure 5a, 5f). The occurrence of both slip behaviors, coupled with fluid pressure diffusion, has been recently observed in the both natural swarm-like sequences (Danré, De Barros, Cappa, et al., 2022) and fluid-injection experiments (Guglielmi et al., 2015).
4. *Small scale length*: the veins extend for tens of meters in length (Figure 1b) and have a thickness up to 2-3 cm (Figure 2b-c), resulted from multiple events of crack opening and fracture shearing (Figures 2b-c, 2e-f, 5a, 5c-d, 5f-g). Considering that each crack opening episode results in dilatant slip ranging from tens to hundreds of μm (Figures 2f, 5a, 5f), these

are equivalent to micro-seismic events with $-2 < M_W < 0$ (Wells & Coppersmith, 1994), which is the magnitude range typical of earthquake swarms (Mogi, 1963).

6. Conclusions

The extensive epidote-rich fault-vein networks of the damage zone of Bolfin Fault Zone and of the Coloso Duplex, at larger scale, are exceptionally well-exposed over tens of square kilometers in the Atacama Desert (Northern Chile) (Figure 1). The fault-vein networks are spatially distributed around major transtensional pseudotachylyte-bearing faults of the duplex, and consist of fault-veins with lineated slickenside, extensional veins and dilatant breccias (Figure 2). Based on microstructural analysis, we document that the wall-rocks in proximity to small-displacement (< 1.5 m) fault-veins initially experienced dynamic high stresses related to the propagation of small seismic ruptures in a poorly connected fault-fracture system with limited fluid infiltration (Figures 3-4, 7a). Instead, the epidote-rich fault-veins recorded cyclic crack opening and either seismic or aseismic shearing dominated by fluid pressure fluctuations in a mature and highly interconnected fault-fracture system (Figures 5-6, 7b, 8). As a consequence, the epidote-rich fault-vein networks of the Bolfin Fault Zone and, at larger scale, of the Coloso Duplex represent the mature architecture of a fault-fracture system in a high-fluid flux hydrothermal setting. Thus, the Coloso Duplex is interpreted as a fossil example of an upper-crustal seismogenic hydrothermal system, which generated fluid-driven earthquake swarms.

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CRediT author statement

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