

Deformation style and fault rock heterogeneity along the southwestern East Anatolian Fault

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ABSTRACT

The East Anatolian Fault (EAF) is a plate-boundary strike-slip fault system of the Eastern Mediterranean characterized by one of the highest seismic hazards in the region. While its present-day kinematics and seismicity are well constrained, the geological record of fault rocks that archive long-term deformation remains poorly known. Here, we integrate meso-microstructural analyses and X-ray diffraction data from key exposures along the southwestern EAF to characterize deformation mechanisms across distinct fault rocks and structural levels. Our results reveal the along-strike, present-day coexistence of different deformation styles. Calc-mylonites at İslahiye document ductile deformation at mid-crustal conditions. Block-in-matrix serpentinite shear zones at Kırıkhan preserve the interplay between distributed creep and localized brittle failure. Carbonate cataclasites and ultracataclasites at Dursunlu provide evidence of brittle failure. Mineralogical data indicate that serpentinites are dominated by lizardite and chrysotile—minerals with low frictional strength and tendency to creep—whereas carbonates are frictionally stronger and more prone to stress accumulation, thereby favoring seismic failure at shallow crustal levels. The fault rocks provide geological analogues illustrating how complex faults can represent archives of deformation representative of different crustal levels. These distinct deformation styles are consistent with the variability in slip modes observed along the modern EAF, although a direct spatio-temporal correspondence cannot be established. Therefore, we encourage future research on the long-term evolution of this plate boundary, to better link past deformation with present-day seismicity. The EAF stands as a natural laboratory bridging geological and geophysical perspectives on fault mechanics and earthquake nucleation in the Eastern Mediterranean.

1. Introduction

Faults are dynamic and evolving structures that develop increasingly intricate architectures over space and time. Prolonged and multiple activity, coupled with the inherent heterogeneity of the deformed rocks, results in a complex assemblage of fault rocks that record variations in deformation mechanisms, pressure–temperature (P–T) conditions, fluid–rock interactions, and stress states over different structural levels and geological timescales (Evans and Chester, 1995; Vermilye and Scholz, 1998; Phillips and Searle, 2007; Smith et al., 2011, 2017; Hadizadeh et al., 2012; Del Sole et al., 2025). These evolving conditions directly

influence fault permeability, rheology, and strength, ultimately controlling whether deformation is accommodated seismically or aseismically (Caine et al., 1996; Faulkner et al., 2003; Tullis and Burgmann, 2007; Moore and Rymer, 2012; Curzi et al., 2024). Complex fault rock assemblages have been extensively documented along major strike-slip fault zones, including the San Andreas Fault in California (Rybacki et al., 2011; Moore and Rymer, 2012), the Carboneras Fault in Spain (Faulkner et al., 2003; Del Sole et al., 2025), the Altın Tağh Fault in China (Li et al., 2002; Wang et al., 2005), the Yangsan Fault in Korea (Choi et al., 2024), and the North Anatolian Fault in Turkey (Kaduri et al., 2017).

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Among these systems, the East Anatolian Fault (EAF) stands out as one of the most prominent active structures in the Eastern Mediterranean. While extensively investigated from a seismotectonic perspective (Yıldız et al., 2020; Güvercin et al., 2022), its fault rock record remains poorly characterized, limiting our ability to link deformation processes at the microscale to seismic behavior. This knowledge gap is particularly critical because geodetic and seismological studies have shown that slip along the EAF is strongly heterogeneous: some segments deform predominantly by aseismic creep, whereas others are locked and prone to host large earthquakes (Vernant, 2015; Aktuğ et al., 2016; Dogan et al., 2019; Tatar et al., 2021; Güvercin et al., 2022; Cakir, 2023; Ergintav et al., 2024; Akgün et al., 2024; Billi et al., 2024). The 2023 Mw 7.8 Kahramanmaraş earthquake sequence, which ruptured a previously

locked portion of the southwestern part of the fault, highlighted the seismic hazard associated with these locked segments, whereas other sections to the northeast show persistent aseismic slip (Güvercin et al., 2022; Fielding et al., 2023; Kwiątek et al., 2023; Wang et al., 2023).

Furthermore, strong earthquakes along the EAF tend to migrate through space and time from NE to SW in cycles lasting hundreds of years, forming earthquake supercycles, in which the number of strong earthquakes progressively increases southwestwards (Dal Zilio and Ampuero, 2023; Xu et al., 2023; Billi et al., 2024). Towards this sector, indeed, seismic deformation tends to spread across a broad deformation zone around the main fault (off-fault), whereas in the NE, seismic deformation is more localized and channeled along the narrow main fault trace (on-fault) (Billi et al., 2024).

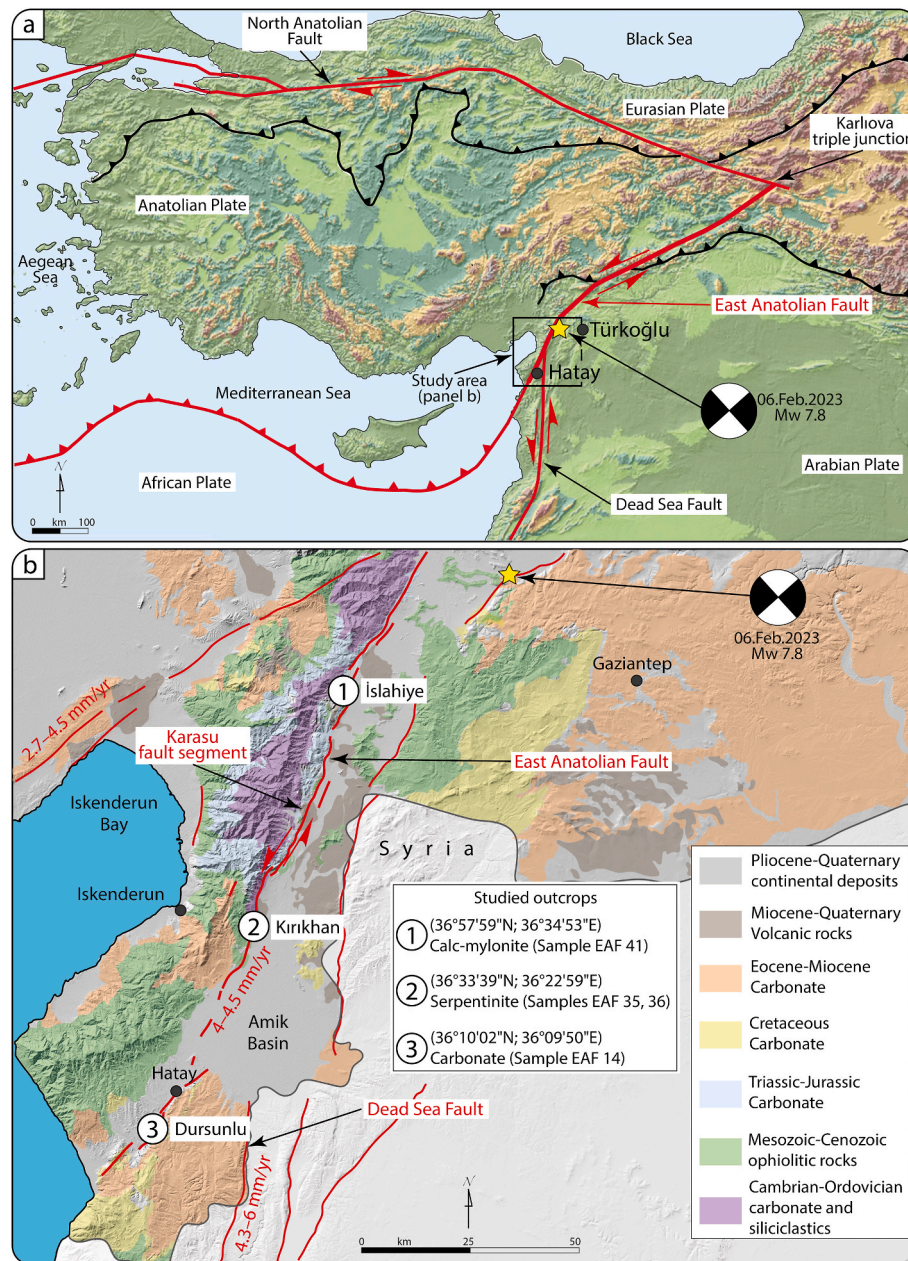


Fig. 1. (a) Topographic map of Anatolian region showing major structures (modified from Whitney et al., 2023) and the study area. The focal mechanism solution of the most recent earthquake along the East Anatolian Fault (Mw 7.8) is shown (datum from USGS available at <https://www.usgs.gov/news/featured-story/m78-and-m75-kahramanmaras-earthquake-sequence-near-nurdagi-turkey-turkiye>). (b) Geological map of the study area (simplified from 1/5000,000 scale geological map from Ulu, 2022) overlain on shaded relief image of 3 arc-second resolution SRTM data). The location of the studied outcrops along the East Anatolian Fault are shown. Red numbers indicate slip-rate values for the individual fault segments (from Yönlü and Karabacak, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

This along-strike variability reflects not only differences in stress accumulation but also variations in lithological heterogeneity, fault zone rheology, and fluid circulation. In this sense, the study of exhumed fault rocks provides a crucial geological counterpart to present-day geodetic and seismic observations, enabling us to decode the long-term deformation mechanisms that govern seismic versus aseismic slip. Below, we analyze key fault rock types exposed along the EAF—including calc-mylonites, serpentinites, and (ultra)cataclastic carbonates—using optical and scanning electron microscopy and X-ray diffraction. By characterizing their microstructures and mineral assemblages, we provide basic information to understand how lithological contrasts and deformation mechanisms can contribute to kinematic partitioning and seismic versus aseismic behavior along one of the most seismically active strike-slip faults in the Mediterranean region.

2. Geological setting

The EAF is a ~580 km long, segmented, left-lateral strike-slip fault zone that defines the southeastern boundary of the Anatolian Plate. It extends from the Karlıova triple junction in the northeast, where it meets the North Anatolian Fault (NAF), to Hatay in the southwest, where it connects with the Dead Sea Fault (DSF) (Duman and Emre, 2013; Köküm and İnceöz, 2018, Fig. 1a). Together with the NAF, the EAF accommodates the westward extrusion of the Anatolian Plate resulting from the ongoing Arabia–Eurasia collision (Şengör et al., 1985; van Hinsbergen et al., 2024).

The EAF is subdivided into multiple fault segments which are separated by stepovers and bends that localize restraining uplifts and releasing basins (Duman and Emre, 2013) and which are characterized by different slip rates (Fig. 1b; Karabacak et al., 2023; Yönlü and Karabacak, 2024). At its southwestern termination, the EAF is linked to the DSF through a releasing stepover of ~10–20 km that controls the development of the Amik pull-apart Basin (Duman and Emre, 2013; Köküm and İnceöz, 2018, Fig. 1b). Present-day slip rates, constrained by geodetic and geologic data, average ~9–10 mm/yr between Karlıova and Türkoğlu and decrease southwestward to ~4–4.5 mm/yr toward Hatay (Karasu Fault segment; Köküm and İnceöz, 2018, Fig. 1a).

The tectonic evolution of the EAF reflects a progressive shift in regional stress regimes during the Cenozoic. In its northeastern sector, paleostress analyses document: (i) NW–SE extension from the Middle Eocene to the Middle Miocene, (ii) NNE–SSW compression during the Late Miocene–Early Pliocene, marking the onset of hard collision between Arabia and Eurasia, and (iii) a dominantly strike-slip regime since the Late Pliocene, with σ_1 oriented N–NE and local partitioning into transtensional and transpressional domains (Köküm and İnceöz, 2018).

Thermo-baric constraints from metamorphic massifs (e.g., amphibolite to green schist-facies assemblages recording ~0.6–0.8 GPa and 550–650 °C; Kaymakci et al., 2010; Whitney et al., 2023) combined with low-temperature thermochronological data across Eastern Anatolia further document the regional geodynamic evolution. Thickening of the crust to ~45 km and uplift of the East Anatolian Plateau were achieved during Neogene shortening related to the Arabia–Eurasia collision (Whitney et al., 2023; van Hinsbergen et al., 2024). Exhumation histories derived from low-temperature thermochronology (apatite fission track, apatite and zircon (U–Th)/He analyses) indicate cooling and unroofing since the Late Miocene (~5 Ma), reflecting plateau uplift and distributed deformation accommodated by both strike-slip and shortening structures (Whitney et al., 2023). The timing and mechanism of localization of the EAF remain debated: while Whitney et al. (2023) suggest that underthrusting of the Arabian lithosphere beneath Anatolia triggered fault nucleation at ~5 Ma, van Hinsbergen et al. (2024) emphasize that distributed Neogene shortening and plateau growth provided the primary driving force, with the EAF emerging as part of this regional reorganization.

The EAF cuts across various rock types with contrasting mechanical properties. In its northeastern sector, it deforms Mesozoic–Cenozoic

volcanic and sedimentary successions, while to the southwest it primarily involves Paleozoic–Cenozoic carbonates (Yilmaz, 1993; Kaymakci et al., 2010). Metamorphic rocks (schists, marbles, quartzites, phyllites), ophiolitic bodies (harzburgites, dunites, peridotites, serpentinites), and volcanic rocks (basalts) are also disrupted along the fault zone (Robertson et al., 2004; Kaymakci et al., 2010). The exposure of fault-related rocks along the EAF thus records deformation under variable pressure–temperature conditions, ranging from shallow brittle regimes in sedimentary and carbonate units to higher-temperature deformation in exhumed metamorphic rocks and ultramafic bodies (Robertson et al., 2004; Kaymakci et al., 2010; Köküm and İnceöz, 2018).

The EAF has hosted numerous destructive earthquakes throughout its history (Yıldız et al., 2020). Most recently, on February 6, 2023, two major earthquakes (Mw 7.8 and Mw 7.7; Kahramanmaraş earthquakes) ruptured large portions of the fault system in rapid succession, causing over 50,000 fatalities and widespread destruction across southeastern Türkiye and northern Syria (Kwiatk et al., 2023; Wang et al., 2023; Provost et al., 2024, Fig. 1).

3. Methods

We conducted mesostructural analyses at three localities along the southern portion of the EAF over a total distance of approximately 100 km (Fig. 1b). These sites host fault rocks representative of different deformation conditions and styles. To maintain consistency in terms of EAF geometry and current slip-rates, we focused on a single segment of the EAF (Karasu fault segment), characterized by slip rates of 4–4.5 mm/yr (Karabacak et al., 2023; Yönlü and Karabacak, 2024, Fig. 1b). We then performed observations of hand samples of fault rocks using a high-resolution scanner (Epson Perfection V370 Photo). We prepared petrographic thin sections on selected fault rock samples. Then, we conducted optical microscopy using a Zeiss Axioskop microscope equipped with a Pentax K1 mark II camera at the Microanalysis and Electron Microscopy Laboratory of CNR-IGAG in Rome and scanning electron microscopy (SEM) using a Zeiss EVO MA10 at the Laboratory of Sapienza University of Rome. We also conducted X-ray diffraction (XRD) analyses on six samples to quantify the mineral content of the analyzed rocks. XRD measurements were performed using a Bruker D8 Advance system (CuK α radiation) at 40 kV and 30 mA in the X-ray Laboratory of Sapienza University of Rome. Whole-rock powders were analyzed over a 2θ range of 2–70°, with a step size of 0.02° 2θ and a 1-s counting time per step. Quantitative mineral phase estimations were performed based on peak areas and mineral intensity factors, using calibration constants from Moore and Reynolds (1997).

4. Results

4.1. Mesostructural observations and sampling

4.1.1. İslahiye

This outcrop is located close to İslahiye, about 50 km west of Gaziantep (Fig. 1b; Lat.: 36°57'59"N, Long.: 36°34'53"E), where the EAF juxtaposes shallow water Triassic–Jurassic carbonate against serpentinite (Fig. 2a–d). The fault is NE–SW striking, steeply dipping (85°) toward NW, and exhibits along-strike undulations (Fig. 2a–d). Locally preserved slickenfibers indicate left-lateral strike-slip motion (Fig. 2a). Along the fault, carbonate is characterized by a layer of foliated calc-mylonite, from which sample EAF41 has been collected (Fig. 2c). Foliations strike NNE–SSW and dip 45°–80° to the NW (Fig. 2a). The foliated calc-mylonite layer tapers upward and varies in thickness from a few centimeters to ~1 m (Fig. 2a and d). Above it, the carbonate is non-mylonitic and affected by minor faults within a cataclastic zone up to ~50 cm thick that preserves relic bedding (Fig. 2a and d). These minor faults are parallel to the EAF. Above the cataclastic zone, carbonate preserve their E–W striking bedding, show roughly bedding-perpendicular fractures,

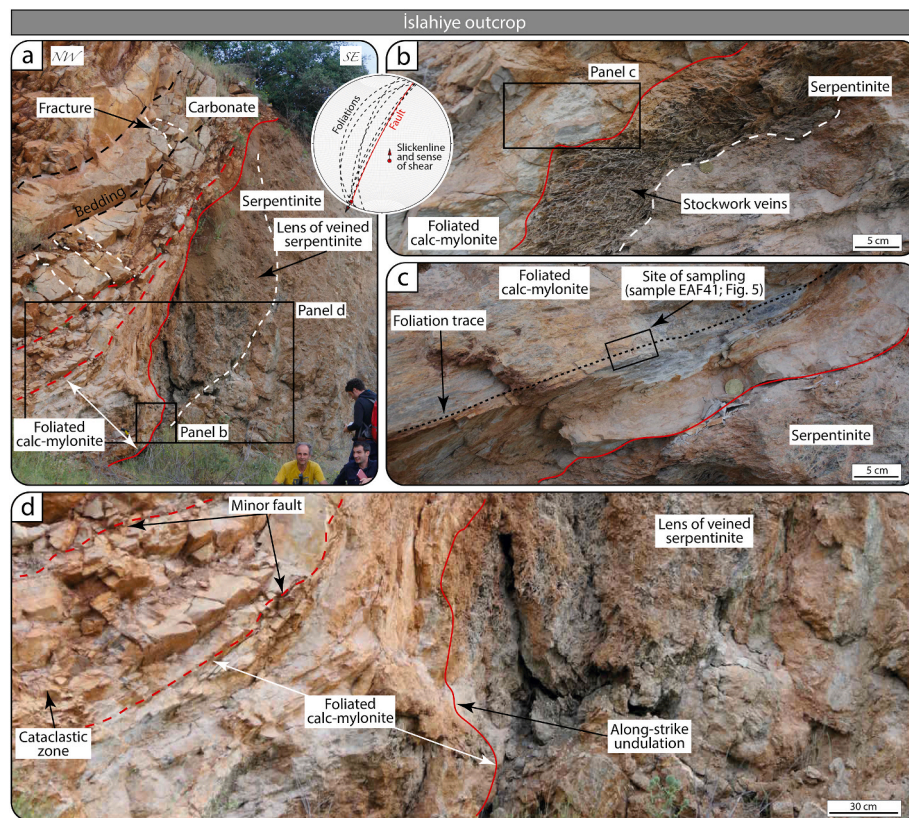


Fig. 2. (a) Exposure of the NE-SW striking East Anatolian Fault close to İslahiye, where shallow water carbonate and serpentinites are juxtaposed. Along the fault, an up to c. 1 m thick level of foliated calc-mylonite is exposed. (b) Detail of the East Anatolian Fault where foliated calc-mylonite and serpentinites are exposed. Note the stockwork veins within the first 20 cm of serpentinites along the East Anatolian Fault. (c) Detail of the foliated calc-mylonite and site of sampling for micro analyses. (d) Detail of the outcrop showing the transition from the foliated calc-mylonite to the overlying non-mylonitic carbonate. The latter hosts minor faults within a cataclastic zone up to ~50 cm thick that preserves relic bedding.

and are devoid of veins (Fig. 2a and d). The serpentinite along the fault is characterized by a ~20 to 150 cm thick layer with stockwork veins

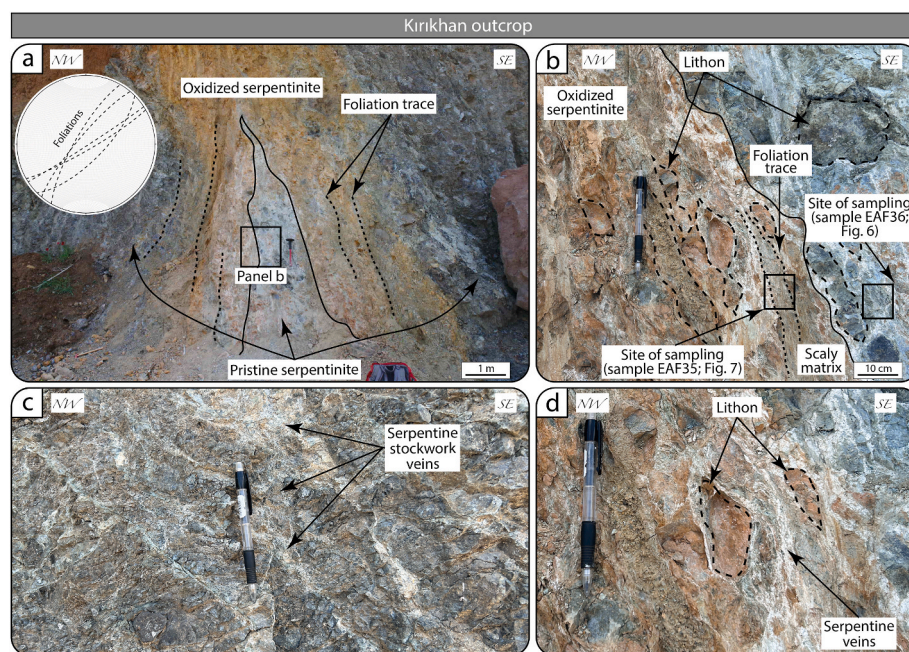


Fig. 3. (a) Exposure of the East Anatolian Fault close to Kırkhan, where serpentinites are characterized by a scaly matrix with NE-SW striking, subvertical, and closely spaced foliations embedding lensoidal lithons of serpentinite with vertical long axis. (b) Detail of massive lensoidal serpentinite lithons embedded in scaly matrix and site of sampling for micro analyses. (c) Serpentine stockwork veins within pristine serpentinite. (d) Serpentine veins within brownish oxidized serpentinite.

(Fig. 2b). This layer is parallel to the fault and has a lensoidal shape (Fig. 2a). Beneath it, the serpentinite is massive and lacks veining (Fig. 2a).

4.1.2. Kırıkhan

This outcrop is located close to Kırıkhan (Fig. 1b; Lat.: $36^{\circ}33'39''\text{N}$, Long.: $36^{\circ}22'59''\text{E}$), where the EAF is represented by a shear zone in serpentinite (Fig. 3a). We observed brownish lenses of oxidized serpentinite (Fig. 3a and b) embedded within greenish, pristine serpentinite. These lenses have an elongated shape with vertical long axis (Fig. 3a). Both oxidized and pristine serpentinite have a typical scaly matrix embedding sigmoidal, centimetric-decametric lithons of massive serpentinite (Fig. 3a and b). These features define a block-in-matrix type serpentinite shear zone (Shervais et al., 2011; Tarling et al., 2019; Cox et al., 2021; Smith et al., 2024). The scaly matrix is characterized by anastomosing foliation surfaces that surround centimetric to decametric lithons with subvertical long axes (Fig. 3b). Foliation is predominantly steeply dipping and strikes mainly NE-SW (Fig. 3a and b), sub-parallel to the regional orientations of the EAF. Both oxidized and pristine serpentinite are cut by serpentine veins (Fig. 3c and d). In oxidized serpentinite, veins mainly outline lithons (Fig. 3d), whereas in pristine serpentinite they form a stockwork, occurring both around and within lithons (Fig. 3c). Samples of oxidized (EAF35) and pristine (EAF36) serpentinite were collected (Fig. 3b).

4.1.3. Dursunlu

This outcrop is located close to Dursunlu, about 10 km south of Hatay (Fig. 1b; Lat.: $36^{\circ}10'02''\text{N}$, Long.: $36^{\circ}09'50''\text{E}$), where the Late Miocene-Recent (Perinçek and Çemen, 1990; Over et al., 2004) Amik Basin occurs in correspondence of the stepover between the EAF and the DSF, associated with extensional deformation (Fig. 1b). Here, the fault system lies within the northern margin of the Amik Basin and represents the southernmost termination of the Karasu fault segment (Fig. 1b). The stepover connecting the EAF with the DSF is expressed by a set of sub-parallel normal faults cutting through Eocene shallow water carbonates overlain by Aquitanian-Burdigalian clastic sediments, indicative of shallow deformation. The master fault dips $60\text{--}70^{\circ}$ toward the W (Fig. 4a), whereas carbonate bedding gently dips ($\sim 20^{\circ}$) to the W (Fig. 4a). The master fault plane, sampled for microtextural and XRD analyses (sample EAF14), bears grooves and striae indicating a dip-slip motion (Fig. 4b and c). Riedel shear fractures on the fault plane further confirm a normal sense of displacement (Fig. 2c). In the fault hanging wall, a talus breccia is exposed and locally cut by calcite veins arranged

parallel to the master fault, whereas in the footwall the carbonate is deformed into a fault breccia.

4.2. Microstructural observations

The calc-mylonite (sample EAF41), cut orthogonal to the mylonitic foliation (Fig. 5a), exhibits a well-developed mylonitic foliation defined by elongated calcite crystals, with long axes reaching up to $2\text{ }\mu\text{m}$ and with mean length-to-width ratio of 3:1 (Fig. 5b). This foliation wraps around sigmoidal calcite porphyroclasts up to 2 mm in length, whose long axes are aligned parallel to the foliation (Fig. 5b). Within the calc-mylonite, two generations of foliation-parallel calcite veins are present. The first generation comprises calcite veins up to $\sim 0.5\text{ cm}$ thick, consisting of millimeter-to micrometer-sized crystals displaying grain boundary migration (GBM) recrystallization (Fig. 5c). The second generation, up to $\sim 1.5\text{ cm}$ thick, is characterized by brownish calcite cement composed of fine-grained calcite crystals and containing angular fragments of the calc-mylonite (Fig. 5d). SEM observations reveal an extremely closely spaced mylonitic foliation, with foliation planes separated by ~ 5 to $50\text{ }\mu\text{m}$ (Fig. 5e). These planes contain clay minerals and exhibit undulations with a wave amplitude of up to $10\text{ }\mu\text{m}$ (Fig. 5f). Calcite porphyroclasts show a σ -type morphology, with a rounded core fringed by calcite mantle precipitated in pressure shadows, forming asymmetric wings aligned with the mylonitic foliation (Fig. 5e).

The pristine serpentinite (sample EAF36; Fig. 6a) exhibits foliation planes that enclose sigmoidal lithons, which contain veins filled with serpentine minerals (Fig. 6a–d). Compared to the oxidized serpentinite, the pristine serpentinite contains a larger proportion of lithons. Between the lithons, shear zones up to $\sim 1\text{ cm}$ thick are characterized by a fine-grained matrix containing micrometric, rounded serpentinite clasts (Fig. 6b). SEM observations indicate that lithons and foliation planes consist of serpentine minerals (Fig. 6e–and f). Locally, lithons display stockwork veins filled with chrysotile, lizardite, and aragonite (Fig. 6b–d). Aragonite veins are also observed within foliation. Relic of pyroxenes are preserved between stockwork veins (Fig. 6f).

The oxidized serpentinite (sample EAF35; Fig. 7a) is characterized by closely spaced ($\sim 2\text{ }\mu\text{m}$) foliation planes, which commonly form S-C/C' fabrics (Fig. 7b and c). Lithons contain veins filled with serpentine minerals (Fig. 7c). Shear-related features are evident at the interface between the lithons and the surrounding foliation planes, where serpentine slickenfibers are present (Fig. 7d). SEM observations reveal both sigmoidal and angular lithons. The sigmoidal lithons are foliated, with foliation parallel to the lithon boundaries (Fig. 7e), whereas the

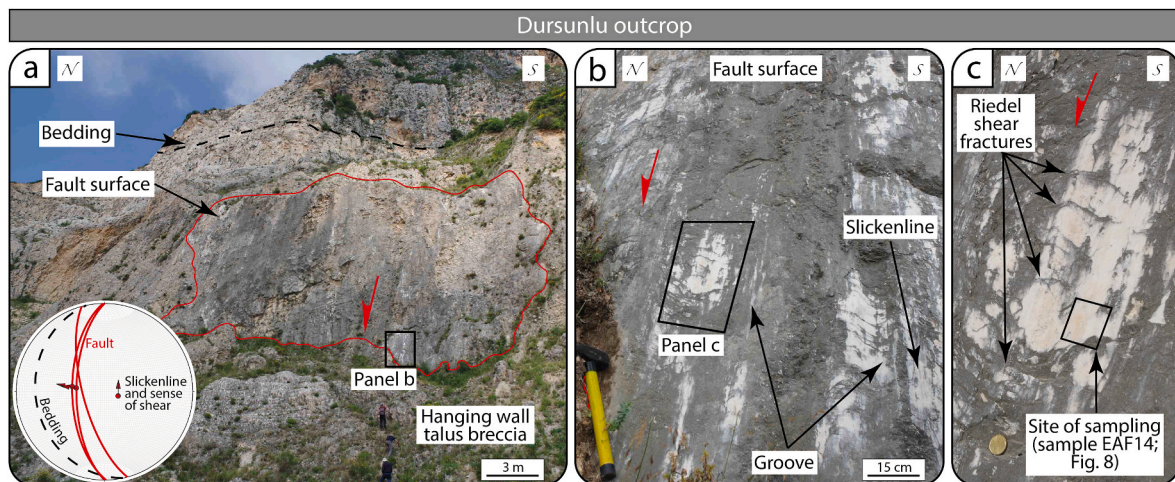


Fig. 4. (a) Extensional fault associated with the East Anatolian Fault close to Dursunlu and hosted within shallow water carbonate. (b and c) Detail of the normal fault plane showing grooves, striae, and Riedel shear fractures constraining dip-slip normal sense of shear. The site of sampling for micro analyses is shown in (c). Schmidt nets (lower hemisphere projection) show attitudes of faults with related kinematic indicators, foliation, and bedding.

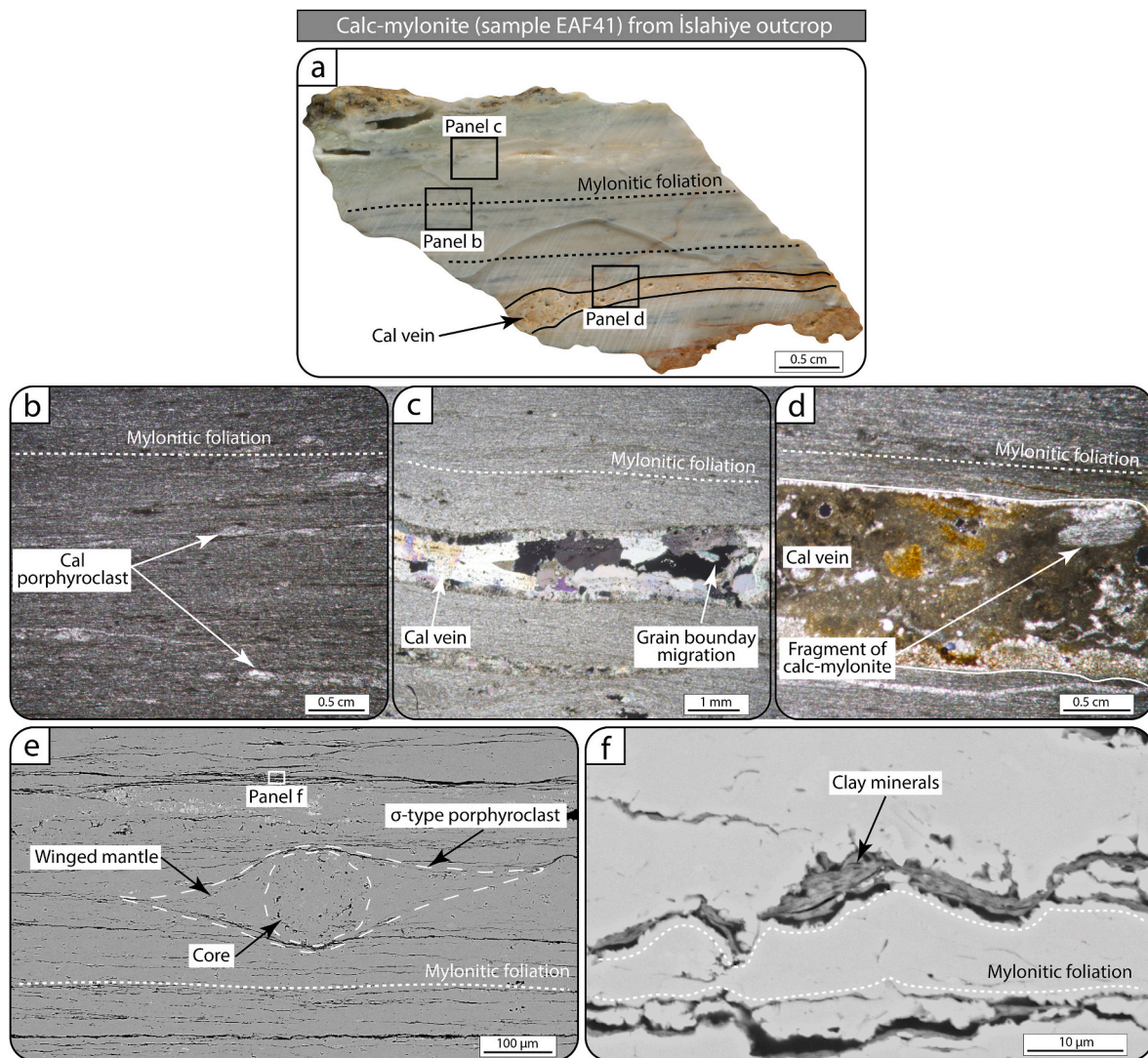


Fig. 5. (a) High-resolution scan image of calc-mylonite (sample EAF41) from İslahiye outcrop showing sites for microtextural observations. (b) Optical microphotograph of the mylonitic foliation surrounding calcite porphyroclasts. (c) Optical microphotograph of a calcite vein showing grain boundary migration between calcite crystals. (d) Optical microphotograph of calcite vein with brownish, fine-grained calcite cement and containing angular fragments of calc-mylonite. (e) SEM micrograph showing a σ -type calcite porphyroclast. (f) SEM micrograph showing a detail of mylonitic foliation containing clay minerals. Acronym: Cal-calcite.

angular lithons consist of brecciated and fractured serpentine fragments (Fig. 7e). The foliation planes within oxidized serpentinite are pervasive and contain fine-grained serpentine minerals (Fig. 7f).

The fault rock along the normal fault plane consists of a cataclasite (sample EAF14; Fig. 8a) with angular to rounded calcite vein clasts and host rock, with clast diameters reaching up to ~ 0.5 cm (Fig. 8a–d). Along and below the fault plane, a series of up to ~ 0.5 cm thick ultracataclastic layers occur (Fig. 8b–d). These layers are subparallel to the fault plane, exhibit undulating boundaries, and are characterized by a brownish, very fine-grained matrix (Fig. 8b–d). Fragments of calcite veins and host rock, up to 0.1 cm in diameter, occur within the ultracataclastic layers (Fig. 8b–d). SEM observations reveal that ultracataclastic layers are composed of micrometric calcite grains with a maximum diameter of ~ 10 μ m (Fig. 8e and f).

4.3. XRD analyses

X-ray diffraction (XRD) analyses reveal significant mineralogical variability across the different fault-rock domains (Fig. 9 and Table 1).

The calc-mylonite (sample EAF41) is dominated by calcite (98 wt%), with minor amounts of smectite and apatite (1 wt% each) and traces of

kaolinite and ankerite (Fig. 9a).

Lithons within pristine serpentinite (sample EAF36a) exhibit a serpentine-rich assemblage with abundant chrysotile (67 wt%) and lizardite (8 wt%), minor chlorite (1 wt%), and subordinate carbonates (aragonite 14 wt%, magnesium calcite 1 wt%, trace ankerite). Accessory oxides include magnetite (2 wt%) and maghemite (7 wt%) (Fig. 9b). In contrast, lithons within oxidized serpentinite (sample EAF35a) shows enrichment in serpentine minerals (chrysotile 87 wt%, lizardite 7 wt%) with subordinate amounts of iron oxides (magnetite 1 wt%, maghemite 1 wt%) and oxyhydroxide (goethite 4 wt%) and trace of phlogopite and ankerite (Fig. 9c).

The foliated matrix of pristine serpentinite (sample EAF36b) displays a mixed serpentine–carbonate mineral assemblage, with chrysotile (39 wt%), lizardite (7 wt%), and abundant aragonite (48 wt%). Subordinate minerals include magnesium calcite (2 wt%), iron oxides (magnetite 1 wt%, ilmenite 2 wt%), andradite (1 wt%) and trace of ankerite (Fig. 9d). Conversely, the foliated matrix of oxidized serpentinite (sample EAF35b) is strongly serpentinitized, dominated by chrysotile (87 wt%) and lizardite (7 wt%), with minor ankerite (2 wt%) and goethite (4 wt%) (Fig. 9e). These data suggest that serpentinite alteration, possibly related to fluid-rock interaction, promotes the development of secondary Fe-

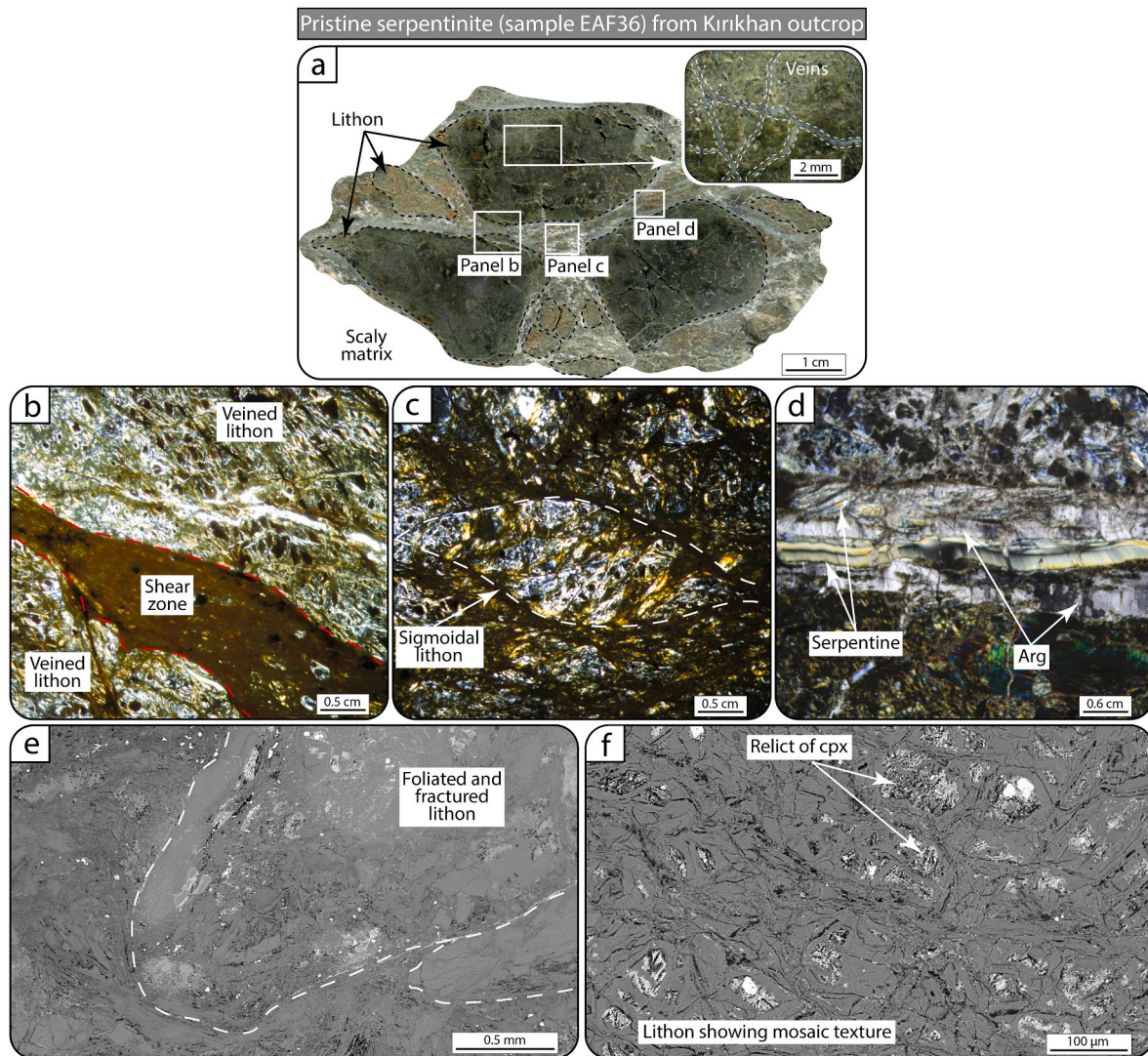


Fig. 6. (a) High-resolution scan image of pristine serpentinite (sample EAF36) from Kırıkhan outcrop showing sites for microtextural observations. (b) Optical microphotograph showing a shear zone localized between lithons. (c) Optical microphotograph showing a sigmoidal lithon embedded within foliation. (d) Optical microphotograph showing aragonite and serpentine minerals within veins. (e) SEM micrograph showing a foliated and fractured lithon. (f) SEM micrograph showing a lithon characterized by mesh veins and relict of pyroxene. Acronyms: Arg-aragonite; Cpx-clinopyroxene.

oxides and hydroxides, whereas pristine counterparts retain significant carbonate content (e.g., aragonite).

The ultracataclasite (sample EAF14) is monomineralic, consisting entirely of calcite (100 wt%) (Fig. 9f).

5. Discussion

Field and microstructural data collected along the southwestern EAF document pronounced along-strike variability in deformation style. At İslahiye, calc-mylonites testify to ductile deformation under mid-crustal conditions (at temperatures of at least 250 °C; Burkhard, 1993; Herwegh and Kunze, 2002), whereas at Kırıkhan serpentinites display block-in-matrix shear zones recording mixed brittle–ductile behavior (Tarling et al., 2019; Cox et al., 2021; Pozzi et al., 2023; Smith et al., 2024). At Dursunlu, carbonate host cataclasites and, in particular, ultracataclasites that are microstructures potentially supporting the occurrence of seismic slip under brittle conditions, as documented from data from natural faults (Bradbury et al., 2011; Smith et al., 2011; Collettini et al., 2014) and high-velocity friction experiments (e.g., Smeraglia et al., 2017). These observations collectively indicate that deformation along the studied portion of the EAF was accommodated

through a broad spectrum of mechanisms, ranging from aseismic creep to brittle failure. The variability documented in the fault rocks can, in principle, be attributed either to deformation occurring at different structural levels or to changes in slip rate. Although our dataset does not allow us to unequivocally exclude either scenario, we note that all sampled sites lie along the southwestern termination of the EAF, a segment characterized—at least at present—by spatially homogeneous slip rates (~4–4.5 mm/yr; Fig. 1b). For this reason, we consider deformation at different structural level to be the most plausible explanation.

The İslahiye outcrop indicates that this portion of the EAF was active in the geological past—although not necessarily directly related to the present-day fault—and was progressively exhumed during subsequent EAF activity. Indeed, the foliated calc-mylonite (which is parallel to the EAF) is overprinted by brittle deformation features, including minor faults, cataclasites, and fractures (Fig. 2), consistent with progressive exhumation. Exhumation data derived from low-temperature thermochronology (apatite fission track and apatite- and zircon-(U-Th)/He analyses) are currently available only for EAF segments located ~400–500 km northeast of our study area (Whitney et al., 2023), and comparable constraints for the southwestern EAF are lacking. We therefore cautiously propose that the observed transition from ductile to

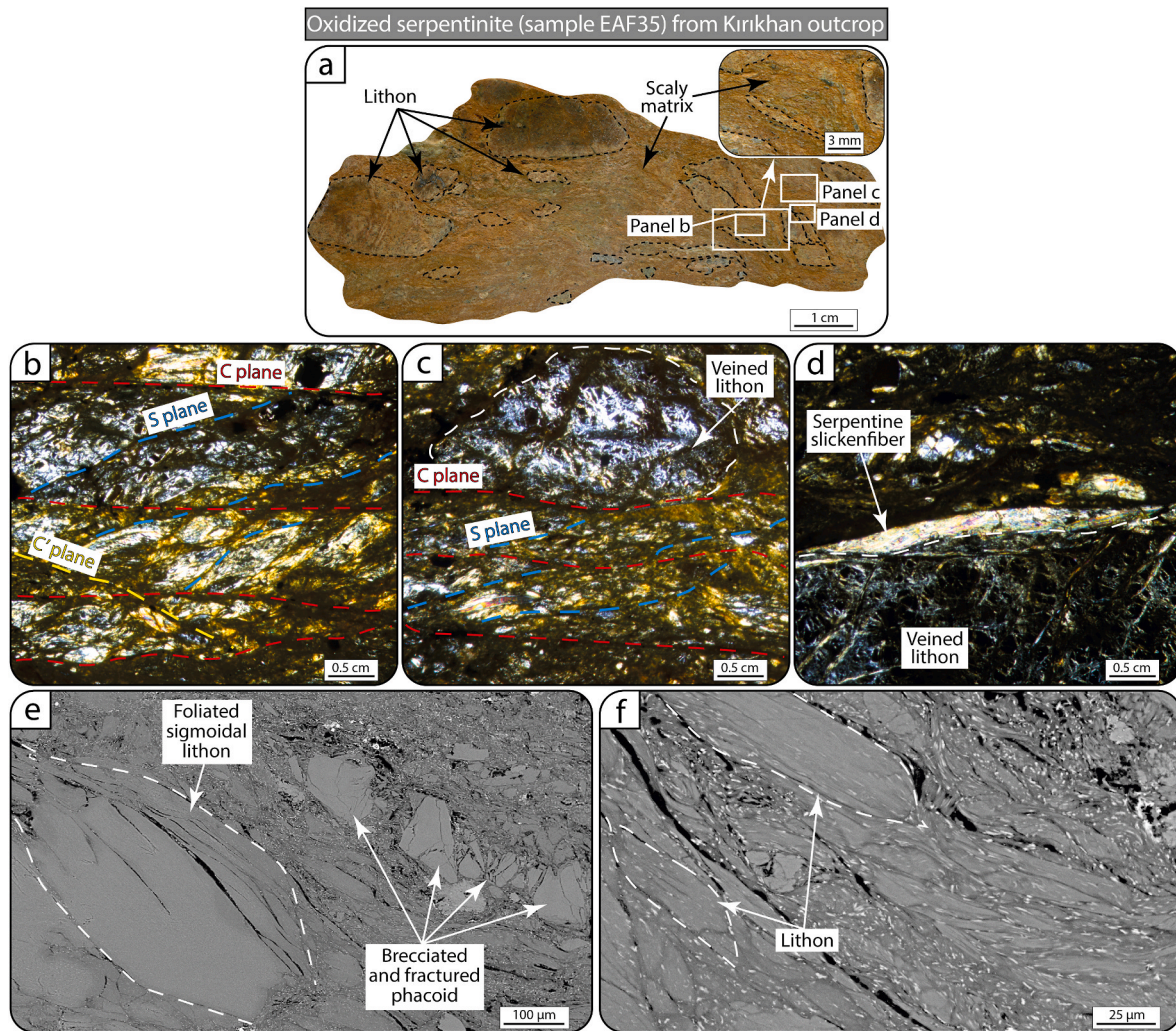


Fig. 7. (a) High-resolution scan image of oxidized serpentinite (sample EAF35) from Kırıkhan outcrop showing sites for microtextural observations. (b and c) Optical microphotograph showing foliation defining S-C/C' fabric. (d) Optical microphotograph showing a serpentinite slickenfiber at the boundary between lithons and surrounding foliation. (e) SEM micrograph showing foliated sigmoidal lithon and brecciated and fractured lithons. (f) SEM micrograph showing sigmoidal lithons embedded within foliation. Serpentine minerals are present both in lithons and foliation.

brittle deformation (both at the scale of İslahiye outcrop and consistently expressed along strike throughout the studied segment) could reflect (differential) vertical exhumation along the studied fault segment (Fig. 10). On this ground, future work, including for instance thermochronology and geochronology is needed to further test this hypothesis.

Along the studied segment of the EAF, strain preferentially localizes within serpentinites, which display pervasive deformation and the development of stockwork veins (Fig. 2). Laboratory experiments show that serpentinites exhibit a wide range of frictional strengths depending on their mineral assemblage. Indeed, antigorite is comparatively strong ($\mu \approx 0.5$), whereas lizardite- and chrysotile-rich assemblages are weak ($\mu = 0.15\text{--}0.30$). Lizardite is weak from low temperature up to $\sim 170^\circ\text{C}$, while chrysotile is weak at room temperature ($\mu \approx 0.2$) but becomes significantly stronger above $\sim 200^\circ\text{C}$ ($\mu \approx 0.6\text{--}0.7$) (Tesei et al., 2018; Viti et al., 2018). Our XRD analyses (Table 1) confirm that serpentinites along the EAF (samples EAF35a, 35b, 36a, and 36b) are dominated by chrysotile and lizardite, phases known to favor low-strength behavior and aseismic deformation. The observed pervasive S-C/C' fabrics and block-in-matrix textures are consistent with low temperature weak deformation mechanisms inferred from the above discussed rock mechanics experiments (e.g., Tesei et al., 2018) and with interpretations from similar natural structures (e.g., Smith et al., 2024). Recent experiments also demonstrate that serpentinite gouges can exhibit low

permeability and high pore-fluid pressures, further stabilizing creep or, conversely, promoting transient instabilities depending on the fluid regime (Scuderi and Carpenter, 2022). The pervasive formation of (stockwork) veins filled by lizardite, chrysotile, and aragonite point to fluid involvement that likely modulate strength and slip behavior over time.

In the Dursunlu outcrop, carbonate cataclasites and ultracataclasites document brittle deformation under shallow conditions. Similar ultracataclasites worldwide are often interpreted as possible fossilized earthquake products (Chester and Chester, 1998; Rowe and Griffith, 2015). In this case, their formation reflects the shallow structural position of the Dursunlu outcrop, where the normal faulting is related the releasing stepover between the EAF and the DSF rather than the regional strike-slip motion of the EAF. This is consistent with laboratory experiments showing that calcite-dominated rocks have relatively high friction coefficients ($\mu \approx 0.6\text{--}0.8$; e.g., Collettini et al., 2014), favoring stress accumulation and seismic rupture under shallow crustal conditions. Hence, Dursunlu provides the shallowest structural analogue to the brittle end-member of the deformation spectrum observed farther northeast along the same fault segment, where deeper and more ductile structures crop out (Fig. 10).

The documented contrasts of deformation styles (Fig. 10) mirror modern geophysical observations. Geodetic and seismic data show that

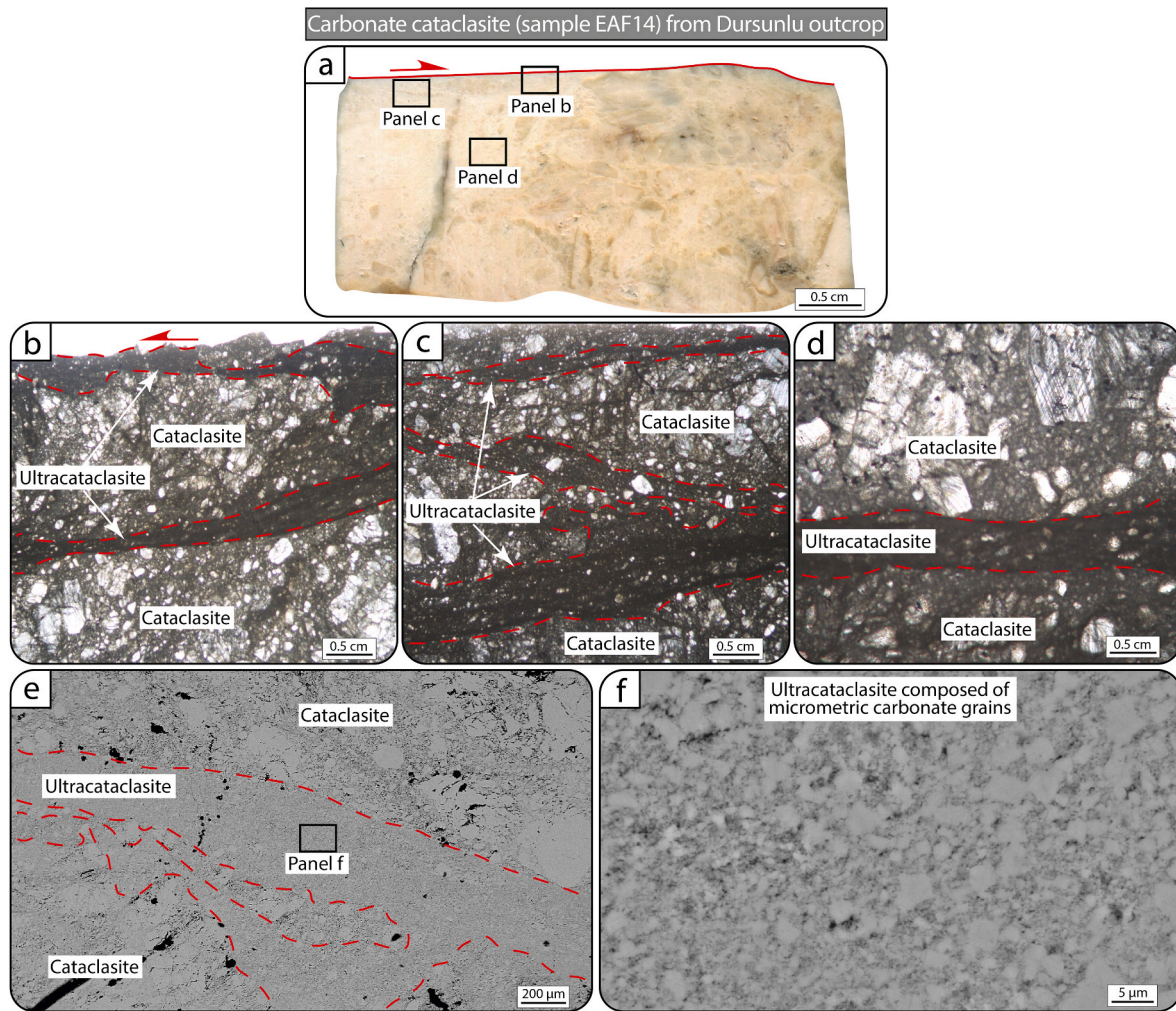


Fig. 8. (a) High-resolution scan image of cataclasite along the carbonate normal fault (sample EAF14) from Dursunlu outcrop. (b-d) Optical microphotograph showing ultracataclasite layers. (e) SEM micrograph showing an ultracataclasite layer having undulated boundaries. (f) SEM micrograph showing the micrometric carbonate grains composing the ultracataclasite layers.

slip along the EAF is partitioned into creeping, locked, and hybrid segments (Aktuğ et al., 2016; Vernant, 2015; Güvercin et al., 2022; Çakır et al., 2023). We propose that, at a first approximation, carbonate-dominated segments are prone to stress accumulation and seismic rupture, as exemplified by the 2023 Mw 7.8–7.6 Kahramanmaraş earthquakes. Conversely, serpentinite-dominated domains, characterized by low friction, represent geological analogues of the creeping sections. Block-in-matrix serpentinite shear zones, with their interplay of ductile creep and brittle failure, may record the hybrid slip behavior revealed by microseismicity and creepmeters. However, this general behavior may evolve with progressive cementation and porosity reduction of the matrix: in such conditions, the rheological contrast between the rigid blocks and the weak matrix can invert, with the matrix becoming stronger than the blocks, ultimately favoring seismic rupture nucleation within the matrix itself (Vannucchi et al., 2022).

Integrating multiscale structural evidence and XRD results with published experimental frictional data supports the interpretation that structural levels, coupled with the mineralogy of deforming rocks, influence strain accommodation likely through space and time-dependent mechanisms. We emphasize that a direct correspondence with present-day slip modes cannot be established based on the available data. Moreover, as discussed above, the along-strike variability we document may also reflect along-dip sampling of the fault zone. In this view, exhumation has brought to the surface rocks that, toward the northeast,

record deformation at progressively deeper structural levels.

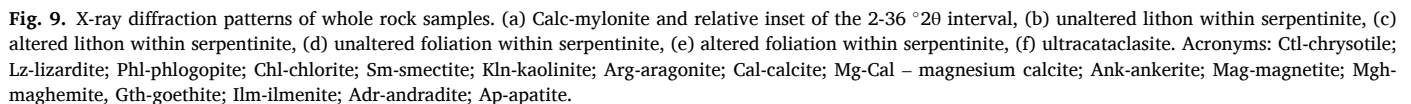
Our observations provide a preliminary framework for interpreting deformation processes along the southwestern EAF. However, such framework requires further testing through integrated structural, thermochronological, and geophysical investigations.

6. Conclusions

The southwestern EAF offers a natural laboratory where the fingerprints of ductile creep, mixed brittle–ductile shear, and brittle failure are exposed along different portions of the fault.

The along-strike variability documented in our study broadly mirrors the present-day distribution of creeping, locked, and hybrid segments along the EAF. However, our data do not allow for a direct spatial or temporal correlation with modern slip partitioning. The analyzed fault rocks record a fossil deformation history, the timing and depth of which remain poorly constrained. Accordingly, we avoid establishing a one-to-one correspondence between exhumed structures and present-day mechanical behavior. Instead, we interpret these results as a geological analogue illustrating how deformation mechanisms are modulated across different structural levels.

By integrating field observations, microstructural, mineralogical, and published petrophysical constraints, this study suggests that structural level and petrophysical properties play a first-order role in controlling whether deformation proceeds aseismically or through seismic



Whole-rock composition of the sampled fault rocks. Ctl-chrysotile; Lz-lizardite; Phl-phlogopite; Chl-chlorite; Sm-smectite; Kln-kaolinite; Arg-aragonite; Cal-calcite; Mg-Cal – magnesium calcite; Ank-ankerite; Mag-magnetite; Mgh-maghemite; Gth-goethite; Ilm-ilmenite; Adr-andradite; Ap-apatite; tr-trace (<1%).

rupture. Although exhumation data are currently unavailable for the southwestern EAF, the transition from ductile to brittle deformation structures may reflect differential exhumation along this fault segment. This hypothesis remains to be tested, and our study provides a framework for future research into the tectonic and exhumation history of the region.

CRedit authorship contribution statement

M. Curzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **L. Aldega:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **A. Billi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Carminati:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **V.**

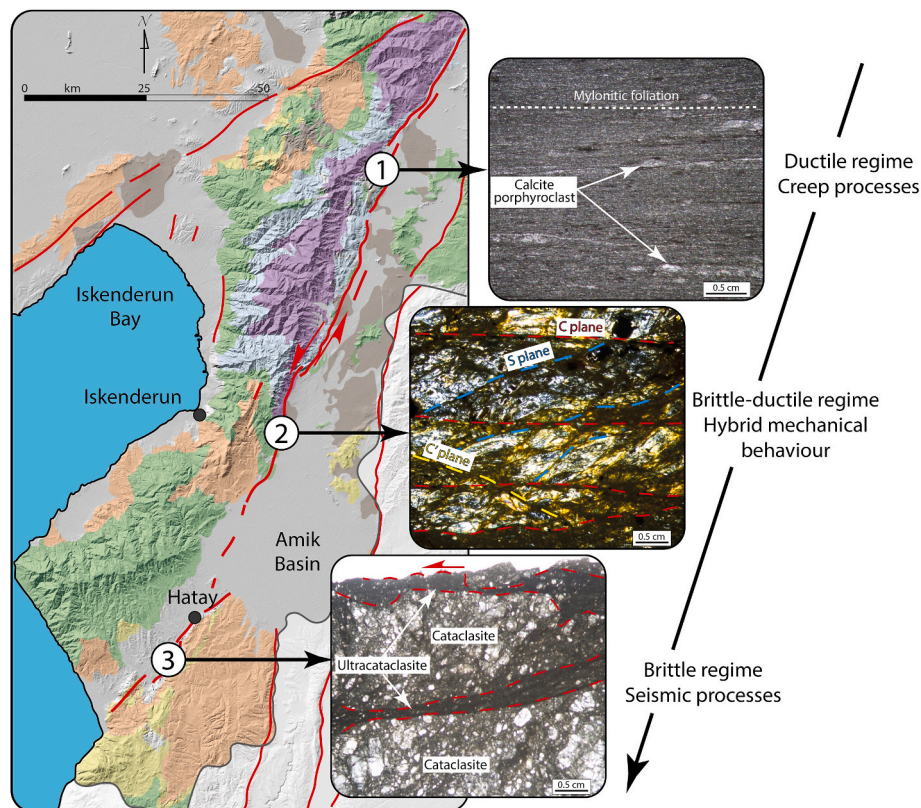


Fig. 10. Synthesis of deformation styles and fault-rock types along the southwestern EAF. (1) At İslahiye, calc-mylonites record a ductile regime dominated by creep, with a penetrative mylonitic foliation wrapping around calcite porphyroclasts. (2) At Kırıkhan, serpentinite shear zones show block-in-matrix structures and S–C fabrics, indicative of a mixed brittle–ductile regime with hybrid mechanical behavior combining distributed creep and localized brittle failure. (3) At Dursunlu, carbonate-hosted cataclasites and ultracataclasites developed along the EAF–DSF stepover reflect a brittle regime. The along-strike variability in deformation styles highlights the strong lithological and rheological control on seismic versus aseismic fault behavior.

Karabacak: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **L. Smeraglia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation, Conceptualization. **T. Uysal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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