A Closer Look into Slickensides: Deformation On and Under Fault Surfaces

Daniel Ortega-Arroyo[1] and Matej Pec[1]

[1]Massachusetts Institute of Technology

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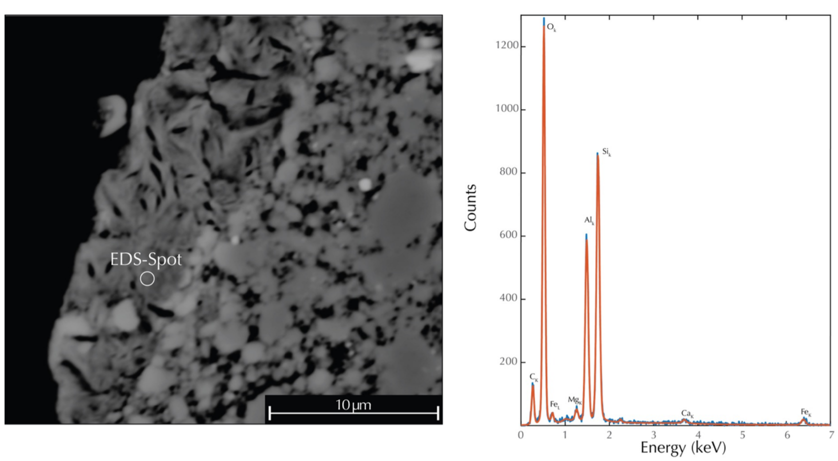
Abstract

Accurate descriptions of natural fault surfaces and associated fault rocks are important for understanding fault zone processes and properties. Slickensides–grooved polished surfaces that record displacement and wear along faults– develop measurable roughness and characteristic microstructures during fault slip. We quantify the roughness of natural slickensides from three different fault surfaces by calculating the surfaces power spectra and height distributions and analyze the microstructures formed above and below the slickensides. Slickenside surfaces exhibit anisotropic self-affine roughness with corresponding mean Hurst exponents in directions parallel– 0.53±0.07– and perpendicular –0.6±0.1– to slip, consistent with reports from other fault surfaces. Additionally, surfaces exhibit non-Gaussian height distributions, with their skewness and kurtosis roughness parameters having noticeable dependence on the scale of observation. Below the surface, microstructural analyses reveal that S-C-C' fabrics develop adjacent to a C-plane-parallel principal slip zone characterized by a sharp decrease in clast size and a thin ([?]100 µm) nanoparticulate-rich principal slip surface (PSS). These microstructures are present in most analyzed samples suggesting they commonly form during slickenside development regardless of lithology or tectonic setting. Our results suggest that 1) PSS likely arise by progressive localization along weaker oriented fabrics 2) deformation along PSS's is energetic enough to comminute the rocks into nanometric grains, and 3) fault geometry can be further characterized by studying the height distributions of fault surfaces, which are likely to impact stress distributions and frictional responses along faults.



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Daniel Ortega-Arroyo & Matej Pec

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA

Corresponding author: Daniel Ortega-Arroyo (dortega@mit.edu)

Key Points:

- Fault surfaces exhibit a non-Gaussian self-affine roughness with scale-dependent skewness and kurtosis.
- Progressive localization of strain along oriented fabrics give rise to slickenside structures
- Nanoparticulate layers are common on fault rocks regardless of lithology or tectonic setting

Key Words: fault mirror, slickenside, fault surface roughness, principal slip zone, nanograins

Abstract

Accurate descriptions of natural fault surfaces and associated fault rocks are important for understanding fault zone processes and properties. Slickensides--grooved polished surfaces that record displacement and wear along faults-- develop measurable roughness and characteristic microstructures during fault slip. We quantify the roughness of natural slickensides from three different fault surfaces by calculating the surfaces power spectra and height distributions and analyze the microstructures formed above and below the slickensides. Slickenside surfaces exhibit anisotropic self-affine roughness with corresponding mean Hurst exponents in directions parallel-- 0.53±0.07-- and perpendicular --0.6±0.1-- to slip, consistent with reports from other fault surfaces. Additionally, surfaces exhibit non-Gaussian height distributions, with their skewness and kurtosis roughness parameters having noticeable dependence on the scale of observation. Below the surface, microstructural analyses reveal that S-C-C' fabrics develop adjacent to a C-plane-parallel principal slip zone characterized by a sharp decrease in clast size and a thin (≤100 μm) nanoparticulate-rich principal slip surface (PSS). These microstructures are present in most analyzed samples suggesting they commonly form during slickenside development regardless of lithology or tectonic setting. Our results suggests that 1) PSS likely arise by progressive localization along weaker oriented fabrics 2) deformation along PSS's is energetic enough to comminute the rocks into nanometric grains, and 3) fault geometry can be further characterized by studying the height distributions of fault surfaces, which are likely to impact stress distributions and frictional responses along faults.

Plain Language Summary

Grooved, polished rock surfaces known as slickensides are associated with wear along faults, which makes them useful indicators of the kinematics and grain-scale processes occurring during fault slip. We study naturally formed slickensides from three different faults with different rock compositions. Slickenside surfaces reveal directionally dependent textures with respect to the grooves that exhibit similar patterns over a wide range of length scales, as many other faults do. The slickenside heights, however, do not follow a normal distribution, and the shape of the distributions varies with the scale of observation.

Microscopic observations below the surface show that oriented patterns form next to the slickenside surface with most of the deformation concentrated within a narrow region (≤100 μm) near the surface. This region is mostly composed of ultra-fine particles (≤1 μm) and other frictionally produced films. Our results suggest that 1) such fault surfaces emerge through progressive deformation along ever weakening regions and 2) faults can release enough energy to break the rocks into nano-sized particles during slip. Further, our results highlight additional geometrical information of the surface which can impact how stress is distributed along faults and consequently how faults slip.

1. Introduction

Geologic observations indicate that slickensides—smooth, striated rock surfaces-- and associated fault rocks record motion and mechanical wear between faulted blocks (e.g. Doblas, 1998; Fleuty, 1975; Lyell, 1871; Petit, 1987). The direct imprint of wear recorded along slickensides makes them particularly useful kinematic indicators as well as indicators of the grain scale processes leading to- and occurring during–slip. Studies on natural and experimental fault surfaces have suggested a wide range of processes can be recorded within slickensides and associated fault rocks such as: mechanical amorphization and silica gel formation (Houser et al., 2021; Kirkpatrick et al., 2013; Ohl et al., 2020; Pec et al., 2012, 2016; Rowe et al., 2019; Taylor et al., 2021; Toy et al., 2017), extreme comminution and nanoparticle formation (Di Toro et al., 2011; Houser et al., 2021; Kuo et al., 2016; Ohl et al., 2020; Power & Tullis, 1989; Siman-Tov et al., 2013; Sun & Pec, 2021; Tisato et al., 2012; Toy et al., 2017; Verberne et al., 2014, 2019; Viti et al., 2016), localized frictionally induced heating (Ault et al., 2019; Evans et al., 2014; Houser et al., 2021; Ohl et al., 2020; Rowe et al., 2019; Siman-Tov et al., 2015; Taylor et al., 2021; Toy et al., 2017; Verberne et al., 2014), frictional melting (Magloughlin & Spray, 1992; Nielsen et al., 2010; Spray, 1989, 1992), crystal-plastic deformation (Bestmann et al., 2011; J. Chen et al., 2020; Ohl et al., 2020), rupture propagation direction (Kearse et al., 2019; Macklin et al., 2021) and temporal changes in coseismic slip (Otsubo et al., 2013), highlighting their potential usefulness for deciphering the physico-chemical processes that occur during fault slip. Such observations are crucial for the understanding of the microphysical origins of friction and could eventually lead to constraining microstructural fingerprints associated with high slip velocities, which remains one of the outstanding questions in the study of fault zones (Rowe & Griffith, 2015).

Slickensides further allow us to study and characterize in detail and over many scales the geometry of single fault segments (Bistacchi et al., 2011; Brodsky et al., 2016; Candela et al., 2009, 2012; J.-J. Lee & Bruhn, 1996; Power et al., 1987). This is particularly important as fault geometry has been shown to be a major factor contributing to earthquake rupture nucleation, propagation and arrest (e.g., Ben-Zion & Rice, 1997; Cattania & Segall, 2021; Sagy & Lyakhovsky, 2019; Scholz, 2019; Tal et al., 2020). The irregularities on the surface geometry, known as roughness, exert a direct control on surface properties that control surface interactions such as real area of contact, friction, wear, and lubrication (e.g., Bhushan, 2013; Boneh & Reches, 2018; Bowden et al., 1939; Dieterich & Kilgore, 1996; Tal et al., 2020).

Over the last decades, studies have shown that fault roughness exhibits a self-affine geometry that spans many scales of observation (Bistacchi et al., 2011; Brodsky et al., 2016; S. R. Brown & Scholz, 1985; Candela et al., 2009, 2012; X. Chen et al., 2013; Kirkpatrick & Brodsky, 2014; J.-J. Lee & Bruhn, 1996; Power et al., 1987; Shervais & Kirkpatrick, 2016; Siman-Tov et al., 2015; Toy et al., 2017). In contrast to a self-similar geometry that is scale independent, a self-affine fractal is scale dependent. This means that in order to observe self-similarity, i.e., scale-invariance, an affine transformation that scales the axes of the fractal surface (e.g., length vs. width) differently is needed (Mandelbrot, 1985). Due to current limitations of subsurface imaging techniques, most of our understanding of fault processes relies on the study of exhumed fault surfaces, experiments, and numerical models.

Current fault zone models feature a zone of distributed fracturing with increasing intensity that culminates in a highly strained fault core characterized by an abundance of highly fractured and comminuted fault rocks (Caine et al., 1996; F. M. Chester & Logan, 1986; Faulkner et al., 2010). The architecture of fault zones is then generally described by: a) distribution and number of cores, b) width and intensity of fracturing within the damage zone, and c) distribution of subsidiary faults (Faulkner et al., 2010, 2011). Fault zones that are currently exposed experienced a number of discrete slip events that ultimately lead to fault zone development (e.g., Gold et al., 2020; Shervais & Kirkpatrick, 2016). Slickensides can form between two shearing blocks and subsequently form prominent fault surfaces. The architecture of a fault zone, structures found within fault zones, and the strain partitioning between them, need to be known so that their potential effect on ground motion can be evaluated. Rupture models typically rely on the interaction of one or few rough fault segments (e.g., Bruhat et al., 2020; Cattania & Segall, 2021; Graves & Pitarka, 2016; Ulrich et al., 2019) with recently developed models accounting for a much larger number of interacting slip surfaces (Chu et al., 2021; Tsai et al., 2021; Tsai & Hirth, 2020).

Thus, this work aims to thoroughly describe the geometry of discrete slip surfaces and identify the dominant deformation mechanisms occurring during slip and slickenside development. We examine the surface and associated microstructures of individual principal slip structures recorded along natural slickensides from three different fault systems hosted within different lithologies. We start by studying the roughness of each slickenside using Fourier Power Spectrum Density analyses (PSD) to derive their respective Hurst exponent, otherwise known as the roughness coefficient. The geometry of the different slip surfaces is further characterized by statistically describing the height distributions of the surfaces at multiple scales of observation. Our work on slickensides is then extended beyond the surface to the fault rocks that host them by conducting detailed microstructural and grain size distribution analyses of the rock volume surrounding the fault surface. Lastly, we discuss the implications of our observation on our understanding of fault processes

2 Methods

We focused on slickenside surfaces collected from 3 different fault systems--a strike slip Plan de los Plátanos fault (PP) in SE Jalisco, Mexico, the Big Piute Ranges low angle normal fault (BP), and Waterman Hills detachment fault (WH), both in SE California-- that represent different lithologies and/or tectonic settings as summarized in Fig. 1. At each locality, we aimed to sample specimens that preserved both sides of the fault surface, if possible, to better capture the structures and materials that comprise slickensides. The faults--PP, BP, and WH-- cut through primarily andesite, quartzite, and mylonitic metasedimentary (*MMS*) rocks, respectively.

2.1 Brief Geologic Background of Analyzed Samples

2.1.1 Plan de los Plátanos Fault

The Plan de los Plátanos is right lateral strike slip fault that accommodates ~430 m of displacement. It is located NW of Autlán de Navarro, Jalisco, Mexico within the Jalisco Block, a rigid tectonic block developed during the Miocene that moves independently from the Rivera and North American plates bounded by the Tepic-Zacoalco Rift and the Colima Rift (De la Teja Segura & Roque Ayala, 2007; Ferrari et al., 2000; Rosas-Elguera et al., 1996). The PP fault is a subvertical structure that cuts through Laramide-folded Tertiary andesite-rhyolite tuffs that overlain the Tepaltepec cretaceous volcano-sedimentary sequence, intruded by the late Cretaceous- early Paleogene Tomatlan granitic batholith (De la Teja Segura & Roque Ayala, 2007).

The PP slickenside sample was collected from a minor splay exposed on the side of the road near the town of Jalocote (De la Teja Segura & Roque Ayala, 2007). The sample records multiple slickenside surfaces hosted in a porphyritic andesite with sericitized plagioclase phenocrysts in the 0.1-1.0 mm range. The rock is hydrothermally altered with secondary chlorite and iron oxides comprising the bulk of the fracture fill along with few quartz-rich veins. Despite the heavy alteration and hosting of slickensides, the host rock seldom records pervasive/distributed deformation as the primary igneous texture is relatively intact a few cm away from the slip surface.

2.1.2 Big Piute Normal Fault

The Big Piute Mountains lie in the eastern Mojave Desert within a late Cretaceous ductile deformation belt of synkinematic metamorphism and granitoid pluton emplacement. Thick-skinned thrusting places Proterozoic crystalline basement over recumbently folded Paleozoic meta-sediments. A sequence of Tertiary sedimentary and volcanic rocks overlies Mesozoic, Paleozoic and Proterozoic rocks. Tertiary faults cut through all strata and account for 20-30% crustal extension accommodated in the region (Fletcher & Karlstrom, 1990).
Slickensides from this location were collected from small subsidiary faults within the damage zone of the BP that likely accommodated no more than a few meters of displacement. Unlike the other samples, the slickenside in these faults are hosted within a monomineralic quartzite host rock with a primary grain size ranging from 200 μm - 1 mm.

2.1.3 Waterman Hills Fault

The Waterman Hill Detachment Fault (WHDF) is a low angle detachment fault thought to accommodate more than 40 km of total slip located within Central Mojave Metamorphic Core Complex exposed along the Mitchell Range N of Barstow, SE California (Glazner et al., 1989). The WHDF juxtaposes Tertiary sedimentary and volcanic strata against Mesozoic granodiorites and the Waterman Gneiss comprised by mylonitized late Proterozoic to Paleozoic metasedimentary and metaigneous lithologies (Fletcher et al., 1999; Glazner et al., 1989).

The samples were collected from a minor fault exposure found within the mylonitic footwall of the WHDF. The fault surface occurs at the lithological boundary of metaigneous, quartzitic and metacarbonate protoliths. The slickensides are hosted within a thick cataclasite (larger than the hand samples) comprising multiple lithologies. The rock itself is overprinted by hydrothermal alteration and calcite-filled fractures.

2.2 Sample Preparation

The collected hand samples were cleaned of any loose debris and dirt prior to any surface measurement. After surface measurements are performed, we prepared 20 thin sections perpendicular to the plane of the slip surface following (Tikoff et al., 2019) orientation convention, where *XZ* and *YZ* correspond to thin sections oriented parallel and perpendicular to the slip lineations, respectively.

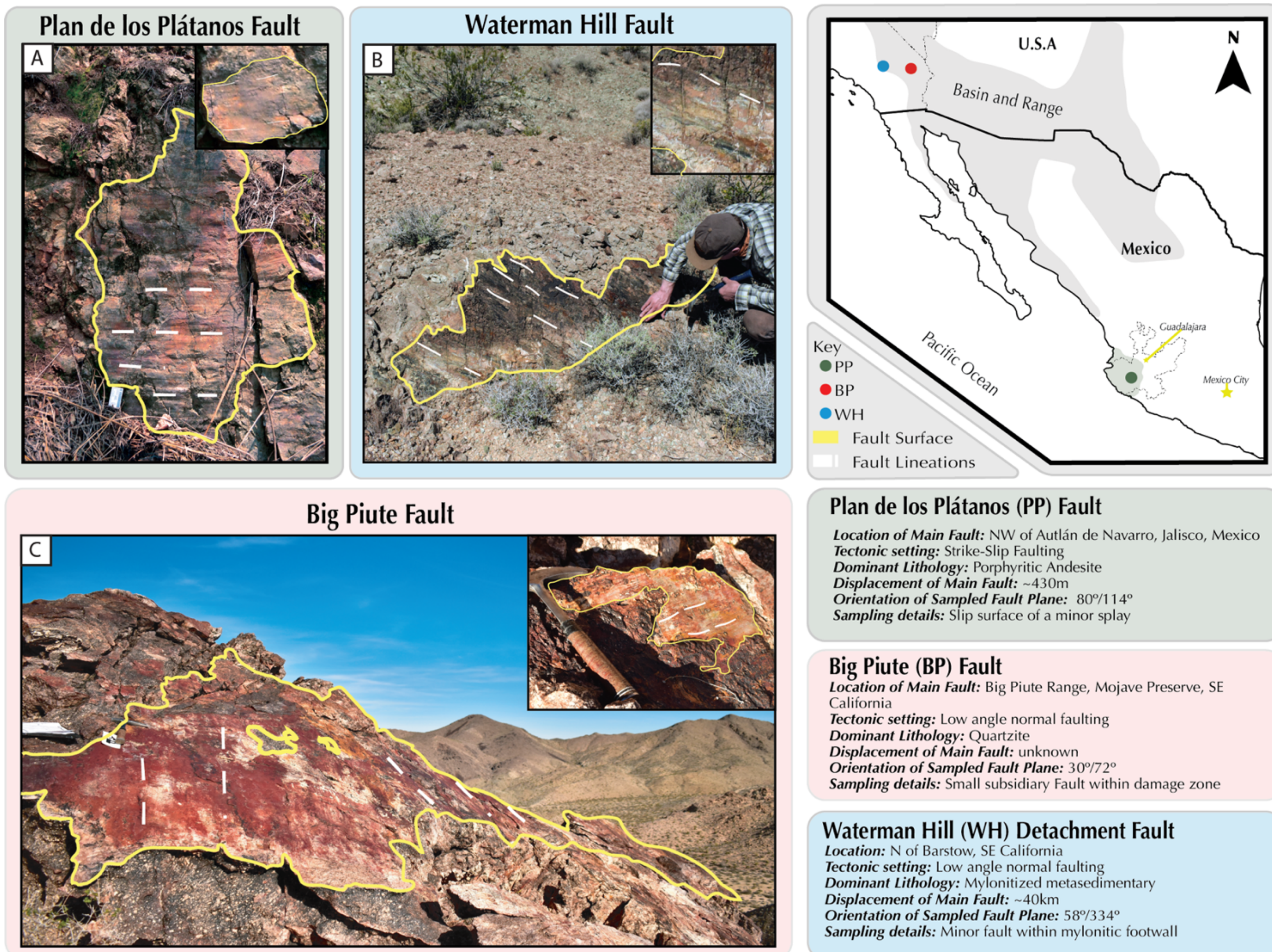

Plan de los Plátanos Fault
A
Waterman Hill Fault
B
U.S.A
Basin and Range
Mexico
Guadalajara
Mexico City
Pacific Ocean
N
Key
PP
BP
WH
Fault Surface
Fault Lineations
Big Piute Fault
C
Plan de los Plátanos (PP) Fault
Location of Main Fault: NW of Autlán de Navarro, Jalisco, Mexico
Tectonic setting: Strike-Slip Faulting
Dominant Lithology: Porphyritic Andesite
Displacement of Main Fault: ~430m
Orientation of Sampled Fault Plane: 80º/114º
Sampling details: Slip surface of a minor splay
Big Piute (BP) Fault
Location of Main Fault: Big Piute Range, Mojave Preserve, SE California
Tectonic setting: Low angle normal faulting
Dominant Lithology: Quartzite
Displacement of Main Fault: unknown
Orientation of Sampled Fault Plane: 30º/72º
Sampling details: Small subsidiary Fault within damage zone
Waterman Hill (WH) Detachment Fault
Location: N of Barstow, SE California
Tectonic setting: Low angle normal faulting
Dominant Lithology: Mylonitized metasedimentary
Displacement of Main Fault: ~40km
Orientation of Sampled Fault Plane: 58º/334º
Sampling details: Minor fault within mylonitic footwall

Figure 1. Studied fault surfaces. Yellow line highlights slip surfaces and white dotted lines indicate slip lineations. A) Slickensides at the right lateral strike-slip, Falla de Plan de los Plátanos, ID card for scale (8.56 cm long). B) Minor slip surface cutting through the mylonitic footwall of the WH. C) Subsidiary fault within the BP fault damage zone. Insets are close-ups of sampled regions.

2.3 Roughness analysis

We characterized and quantified the slickenside roughness of the different fault surfaces over six orders of magnitude in length scale ranging from 100's of nm to 3 cm. Each surface (between 100 mm^2 to 1000 mm^2) was measured by a Taylor Hobson TALYSCAN 150 profilometer using a no-contact laser gauge with a 252 nm vertical resolution. A constant 2 mm s^{-1} traversing speed and a 5 μm spacing were used for each measurement unless otherwise indicated. At the micron scale, the slip surfaces' topography was measured by manually tracing the surface profile of selected thin sections imaged through Scanning Electron Microscopy (SEM).

2.3.1 Hurst Exponent Calculation

The TALYSCAN 150 measurements were processed in MATLAB to remove any planar inclination trend associated with the initial sample placement on the profilometer. 1) The measurements- in the form of an elevation matrix- are then rotated such that the horizontal axis (*x*-axis) of the 3D and digital elevation models (DEM) are parallel to the slip lineations. Once the trend has been removed from the elevation matrices, we proceeded to calculate the Hurst exponent using power spectrum density analyses (PSD) (c.f., Bistacchi et al., 2011; Candela et al., 2009, 2012; Jacobs et al., 2017; Siman-Tov et al., 2013). Profiles parallel and perpendicular to the slip lineations are extracted from each surface. A one-dimensional Hann window function is then applied to each line scan to correct for measurement artifacts, particularly near the edges, as suggested by Jacobs et al., (2017). 3) The Fourier power spectrum $P(k)$ is calculated for each profile as a function of wavenumber (k) and normalized by dividing the power spectrum by the length of the corresponding profile. 4) The power spectra for both the parallel and perpendicular directions to slip are averaged at each wavenumber to reduce noise associated with each individual profile. 5) The Hurst exponent is then calculated from the best fit to a power-law of the form $P(k)=Ck^{1-2H}$, where H is the Hurst exponent, and C is the pre-factor. The workflow is illustrated in Fig. 2.

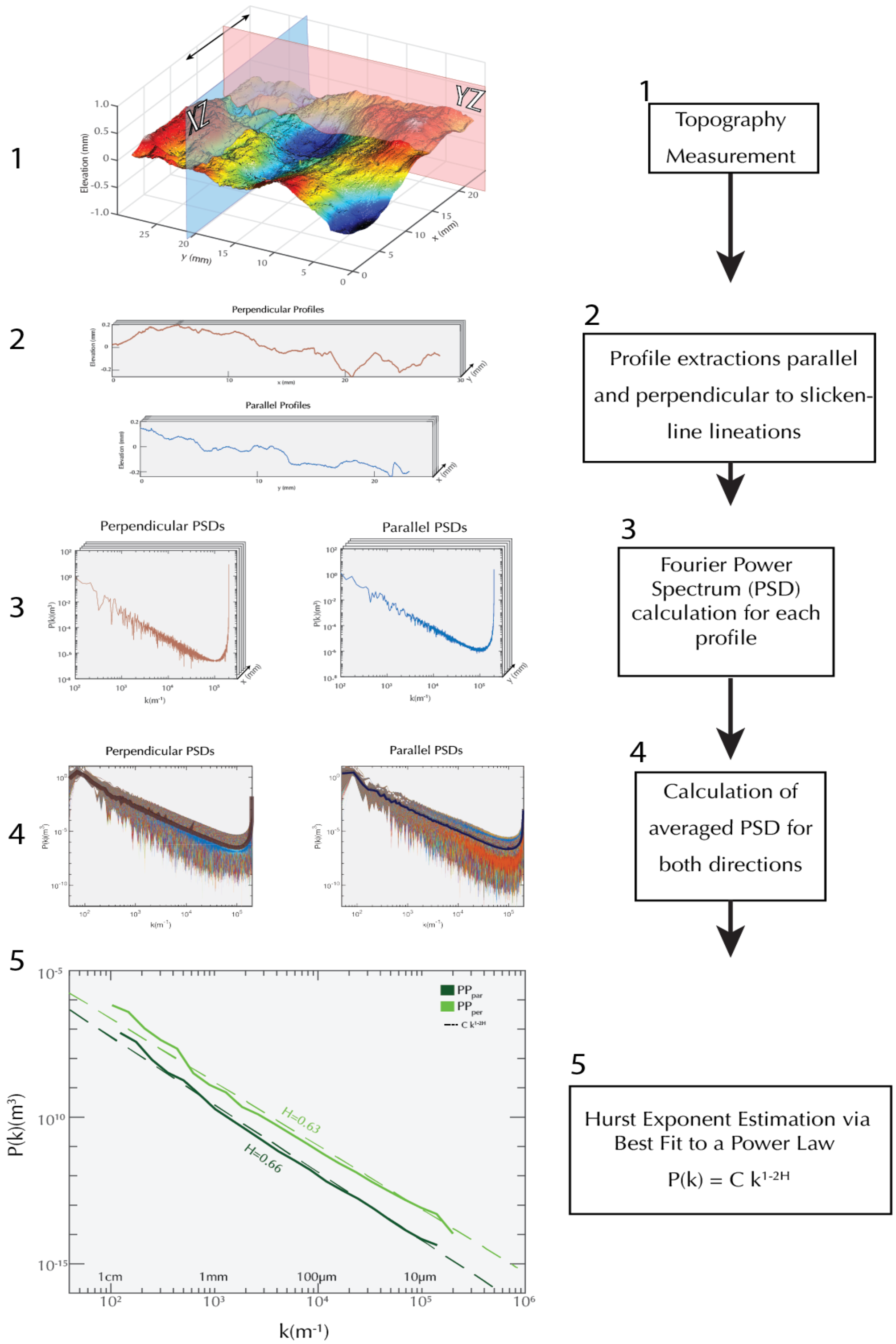


Figure 2. Calculation of Hurst Exponent. See text for details.

2.3.2 Multiscale Surface Texture Analysis

Given that the roughness measurements are inherently a superposition of surface texture information from different length scales, we performed a multiscale surface texture analysis (MSA) in addition to the Hurst exponent calculation. A MSA consists of decomposing the surface topography at various cutoff wavelengths to separate the surface texture into 1) *form*, 2) *waviness* (macro-roughness), and 3) *roughness* (micro-roughness) as shown in Fig. 3 (C. A. Brown et al., 2018). We used a Gaussian 2D filter to separate the data into three different bandwidths with cutoff wavelengths centered at 5 mm and 500 μm. Care is taken that the energy of the signal is preserved, i.e., that the original signal can be fully reconstructed when all components are added together. Furthermore, for each component, we calculate the kurtosis (S_{kur}) and skewness (S_{sk}) of the height distribution.

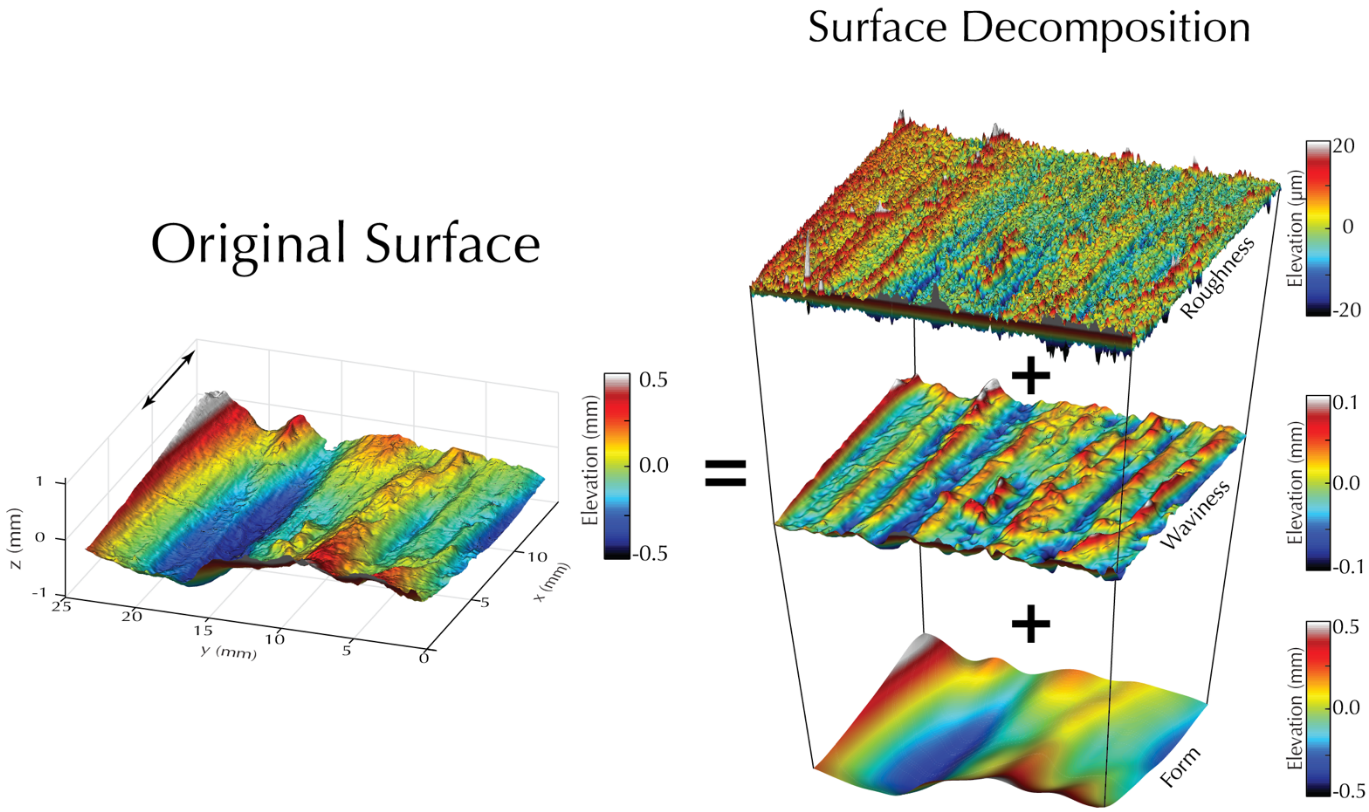


Figure 3. Schematic of a Multiscale Surface Texture Analysis shows how a surface measurement is decomposed into characteristic wavelengths.

2.4 Microstructural Analyses

We aim to identify the microphysical processes occurring within the slickenside volume and adjacent fault rocks. We study a) the grain size distributions and b) the morphologies and crosscutting relationships preserved in, and adjacent to the slickensides to reveal their relationship to fault surface development.

2.3.1 Imaging conditions

Thin sections oriented parallel (*XZ*) and perpendicular (*YZ*) to the slip direction were analyzed using a ZEISS AX10 Petrographic microscope and ZEISS Merlin HR-SEM equipped with a Backscattered electron (BSE) detector.

The SEM was operated with a beam current of 5 nA and a 15 kV accelerating voltage unless otherwise indicated. To capture the range of structures and grain sizes, images were acquired at various magnifications resulting in a 0.77 nm/px to 2.06 μm/px resolution.

2.2.2 Grain Size analysis

Grain size measurements were obtained by manually tracing petrographic microscopy and BSE images obtained at progressively higher magnifications as illustrated in Fig. 4. At each magnification we trace the maximum number of discernible grains/clasts, typically 300-3000 segmented grains per image range are used. Segmented images were then imported to *ImageJ* to calculate the area (A) of each grain in pixels. Grains with areas smaller than 20 pixels, i.e., the smallest grain size that could still be clearly recognized as such, were excluded. The size of each grain is then approximated by calculating the diameter of a circle with the same area. The equivalent diameters (d_{eq}) were calculated as

$$d_{eq} = 2\sqrt{\frac{A}{\pi}}, \quad (1)$$

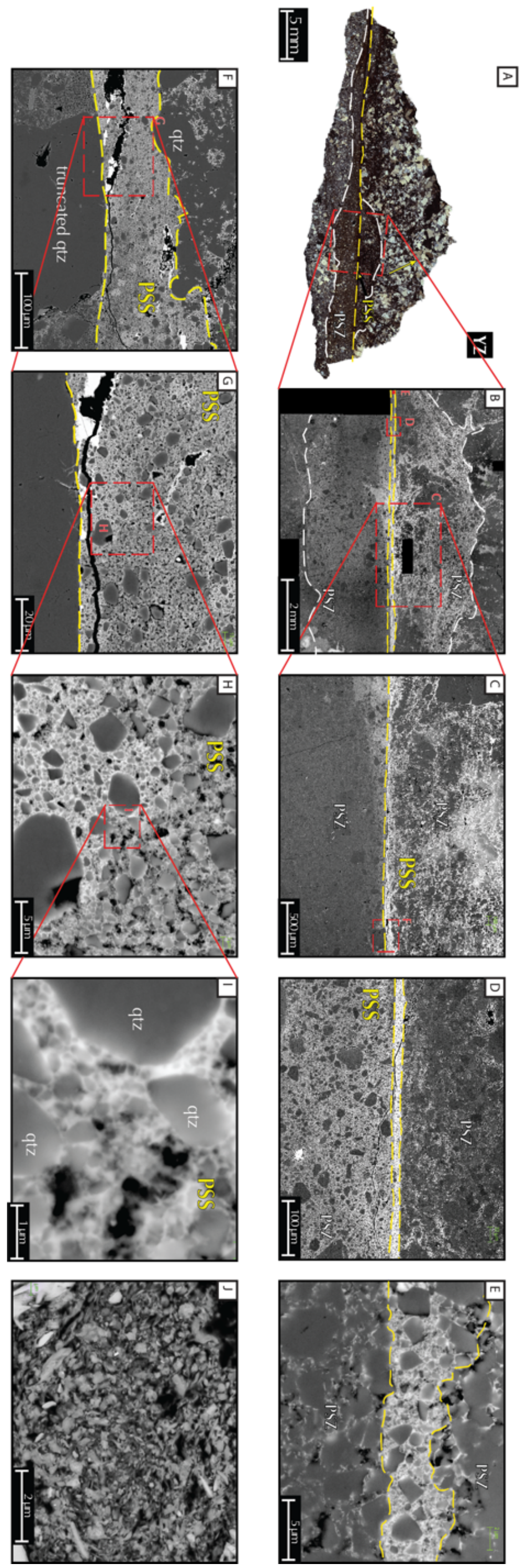
and collected in a histogram with twenty bins for each magnification.

The bins from each magnification are plotted in a logarithmic scale to determine the slope (S_n) and intercept (I_n) of the best power-law fit. The frequency of each bin is then multiplied by a factor (L_n) that reflects the relative magnification at each image to correct for undercounting of the total number of grains from analyzing progressively smaller areas. The factor, L_n, is determined by:

$$L_n = 10^{I_{max}-I_n}, \quad (2)$$

where I_{max} corresponds to the intercept of the lowest magnification. The results from all magnifications are then combined into a single plot.

D-values of 0-2 are commonly measured in two-dimensional analyses (e.g., analysis of SEM images) and correspond D-values between 1-3 from three dimensional analyses such as sieving and Coulter counting (Glazner & Mills, 2012). To draw comparison with D-values reported in other studies that utilized three-dimensional methods the following conversion, $D_{2D}=D_{3D}-1$, from Heilbronner & Barrett (2014) is used.



282 **Figure 4.** Set of images at progressively higher magnifications used in the GSD determination of
283 quartzite hosted slickenside. See text for details.

3. Results

3.1 Roughness Analysis

Roughness plays a significant role in the contact behavior of surfaces and is usually described as the deviations normal to a surface. We analyzed the roughness of our slickenside samples using the Fourier power spectrum density (PSD) approach to calculate their respective Hurst exponents followed by a multiscale analysis of the surfaces' height distributions.

In Figure 5 we show the wide variety of surface textures that can be qualitatively grouped into two general domains, "*smooth*" and "*rough*", based on the amplitudes and frequency of the dominant asperities.

3.1.1 Power Spectral Density Results

The averaged power spectral density (PSD) curves for all roughness measurements are shown in Fig. 6. PSDs are obtained from profiles scanned parallel (*par*) and perpendicular (*per*) to the slip lineations, i.e., the *x*- and *y*-directions, as illustrated in Fig. 2.

Spectra for most measurements show only limited variability in the slope of profiles measured parallel to lineations with a mean Hurst exponent of 0.53 ± 0.07 and a range of 0.41-0.63. In contrast, the perpendicular profiles showed a wider variability with values of H_{per} ranging from 0.45-0.72 and a mean of 0.60 ± 0.10. The pre-factor is directly proportional to root mean squared roughness (*RMS*) by

$$\boldsymbol{RMS} = \sqrt{\left[\frac{\mathrm{Ck}^{-2H}}{-2H}\right]_{k_{min}}^{k_{max}}} \tag{3}$$

And thus, a higher C indicates overall higher roughness amplitude, whereas a lower H indicates a larger contribution of smaller wavelengths/higher spatial frequency, i.e., surfaces relatively rougher at smaller length scales than a self-similar surface ($H = 1$) with the same C would be. While the samples studied in this paper show a relationship between the pre-factors and H, the inclusion of measurements from Bistacchi et al., (2011) and Candela et al., (2013) indicates no clear trend (Fig 6B). Furthermore, measurements of the various hand samples obtained from the same fault surface show a wide range in both H and C values, Table 1.

Table 1. Hurst (H) and Pre-exponent (C)

Fault	H_{par}	H_{per}	C_{par}	C_{per}
Plan de los Plátanos				
	0.61	0.58	2.5×10^{-3}	2.2×10^{-3}
Big Piute				
Min	0.41	0.45	3.4×10^{-5}	2.2×10^{-3}
Max	0.52	0.72	2.2×10^{-3}	1.8×10^{-2}
Waterman Hill				
Min	0.51	0.48	4.9×10^{-4}	2.2×10^{-3}
Max	0.65	0.71	3.5×10^{-2}	6.2×10^{-2}

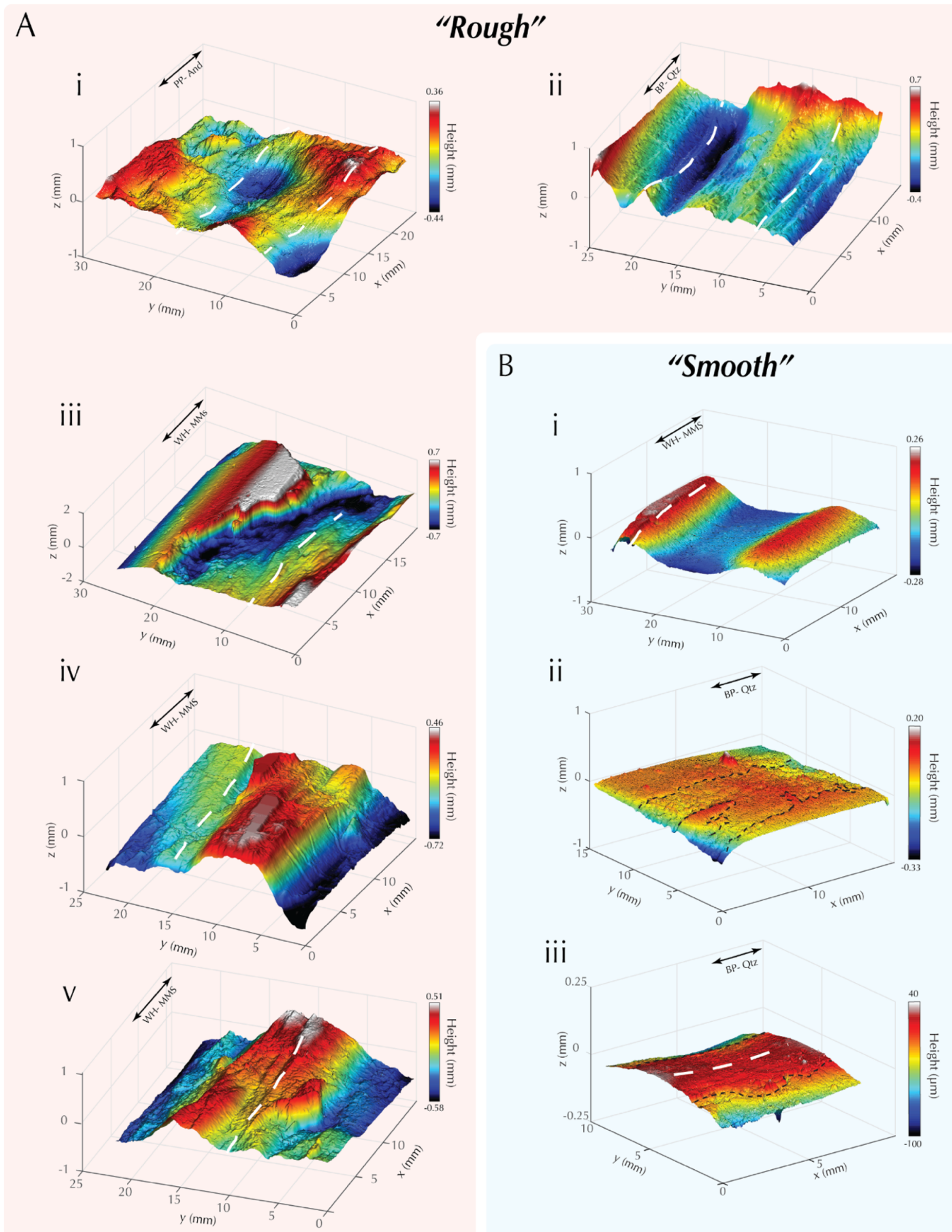

A
"Rough"
i
PP- And
Height (mm)
0.36
-0.44
z (mm)
y (mm)
x (mm)
ii
BP- Qtz
Height (mm)
0.7
-0.4
iii
WH- MMs
Height (mm)
0.7
-0.7
iv
WH- MMS
Height (mm)
0.46
-0.72
v
WH- MMS
Height (mm)
0.51
-0.58
B
"Smooth"
i
WH- MMS
Height (mm)
0.26
-0.28
ii
BP- Qtz
Height (mm)
0.20
-0.33
iii
BP- Qtz
Height (µm)
40
-100

Figure 5. Topography of the different surfaces collected via laser profilometry qualitatively grouped in A) rough and B) smooth surfaces. White dotted lines highlight grooves and lineations. Black dotted lines highlight transitions in roughnesses. PP-, WH-, and BP- indicate the fault system, whereas And (andesite), MMS (mylonitic meta-sedimentary), and Qtz (quartzite) indicate the respective lithologies.

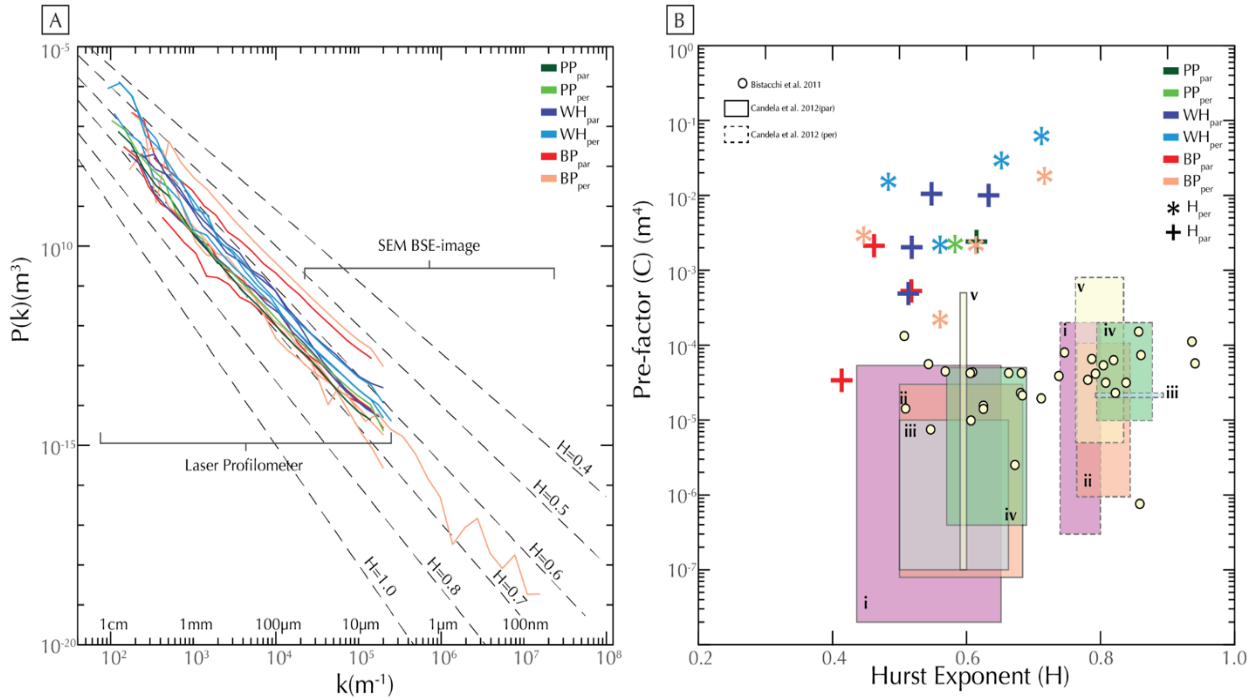


Figure 6. Results from PSD analysis. A) Shows the Fourier power spectra for all studied samples. Note similar slopes fit most samples; rougher samples plot higher in the graph. B) Pre-factor and Hurst exponents obtained from (A), Gole Larghe Fault Zone (Bistacchi et al., 2011) and i) Bolu, ii) Vuache-Sillingy iii) Dixie Valley iv) Corona Heights and v) Magnola faults (Candela et al., 2012). Note data from (Bistacchi et al., 2011) does not specify direction of slip (circles), whereas data from (Candela et al., 2012) is plotted as a range from minimum to maximum values for H and C for both parallel (filled square) and perpendicular (squares with dash lines) directions to slip.

3.1.2 Height Distributions

Skewness (S_{sk}) and kurtosis (S_{kur}) are statistical measures that describe the symmetry and peakedness of the height distributions. A distribution is known as a Gaussian when $S_{sk}=0$ and $S_{kur}=3$. A high kurtosis ($S_{kur}>3$) corresponds to a distribution with a greater peakedness than a Gaussian, which indicates more height measurements are centered near the mean height, whereas the converse is true for a low kurtosis ($S_{kur} <3$). Furthermore, a positive and negative skewness indicates most measurements lie either below or above the mean surface, respectively, as illustrated in Fig. 7A. The samples show a wide range of S_{sk} and S_{kur} values, with no systematic variation with respect to lithology or fault system. However, samples wherein lineations are more apparent and visually rougher tend to have more positive skewness whereas, kurtosis is generally higher for smoother samples. The departure from a Gaussian height distribution also appears to be affected by the scale of observation with smaller wavelength having overall higher kurtosis values as documented in Fig. 7A-C. Note also surface decomposition in Fig. 3, which illustrates the distinct roughness at different scales.

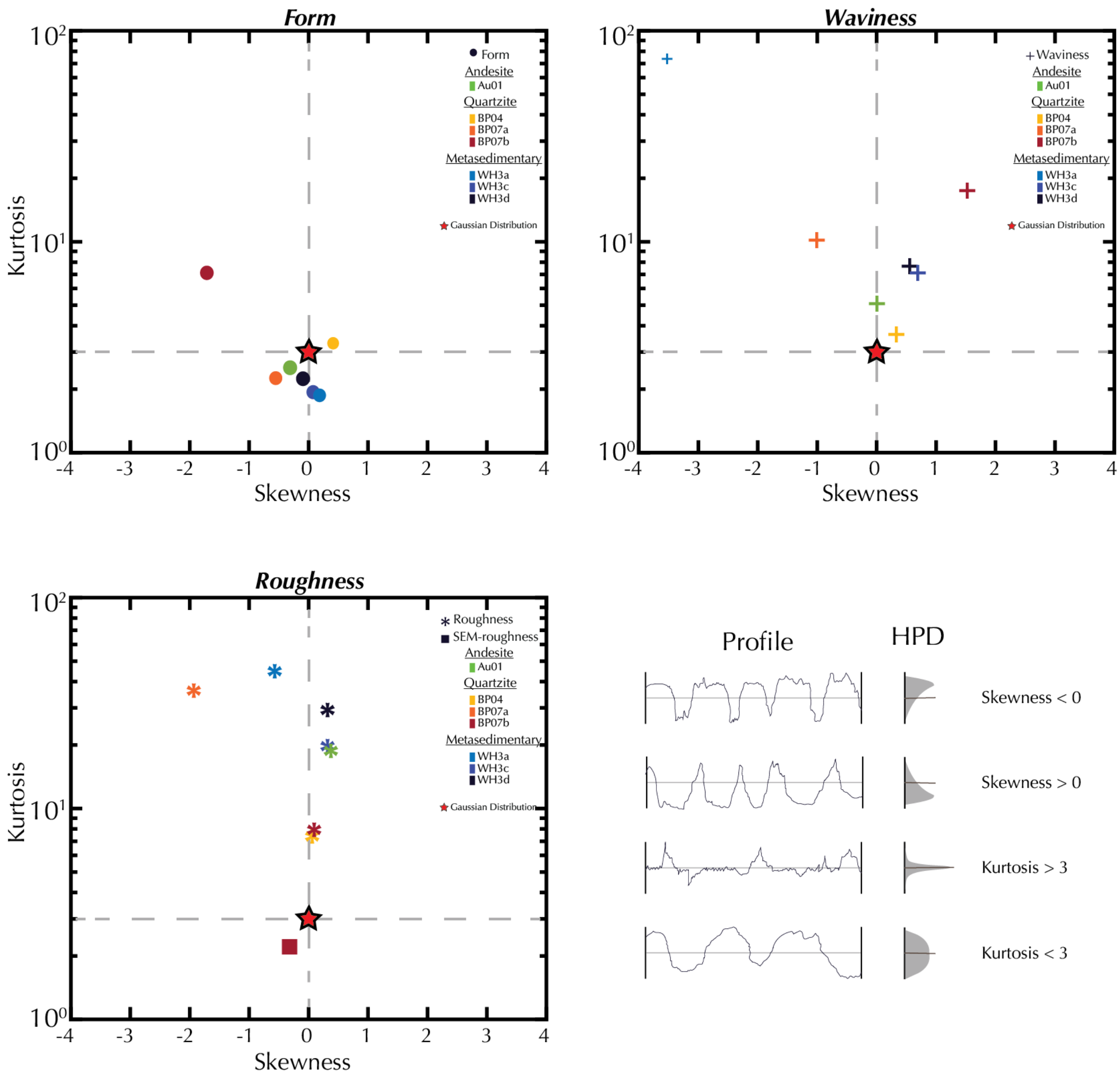


Figure 7. Skewness and kurtosis for samples A) *Form*, B) *Waviness*, and C) *Roughness*. D) Schematic surface profiles with positive and negative skewness and kurtosis values higher and lower than three, after Gadelmawla et al., (2002).

3.2 Structural and Microstructural Observations

With the aim of interpreting the processes involved in fault slip and slickenside development, we selected one sample from each locality that best preserves the slickenside features to conduct SEM-BSE imaging and describe the microstructures in greater detail. We focused on the morphologies at the surface and throughout the rock volume adjacent to the slip surface. For each sample, we specifically examine a) the size and spacing of the lineations, b) orientation of structures on the slip surface, c) the structures within the host rock immediately adjacent to the slip surface, and d) the grain size distribution.

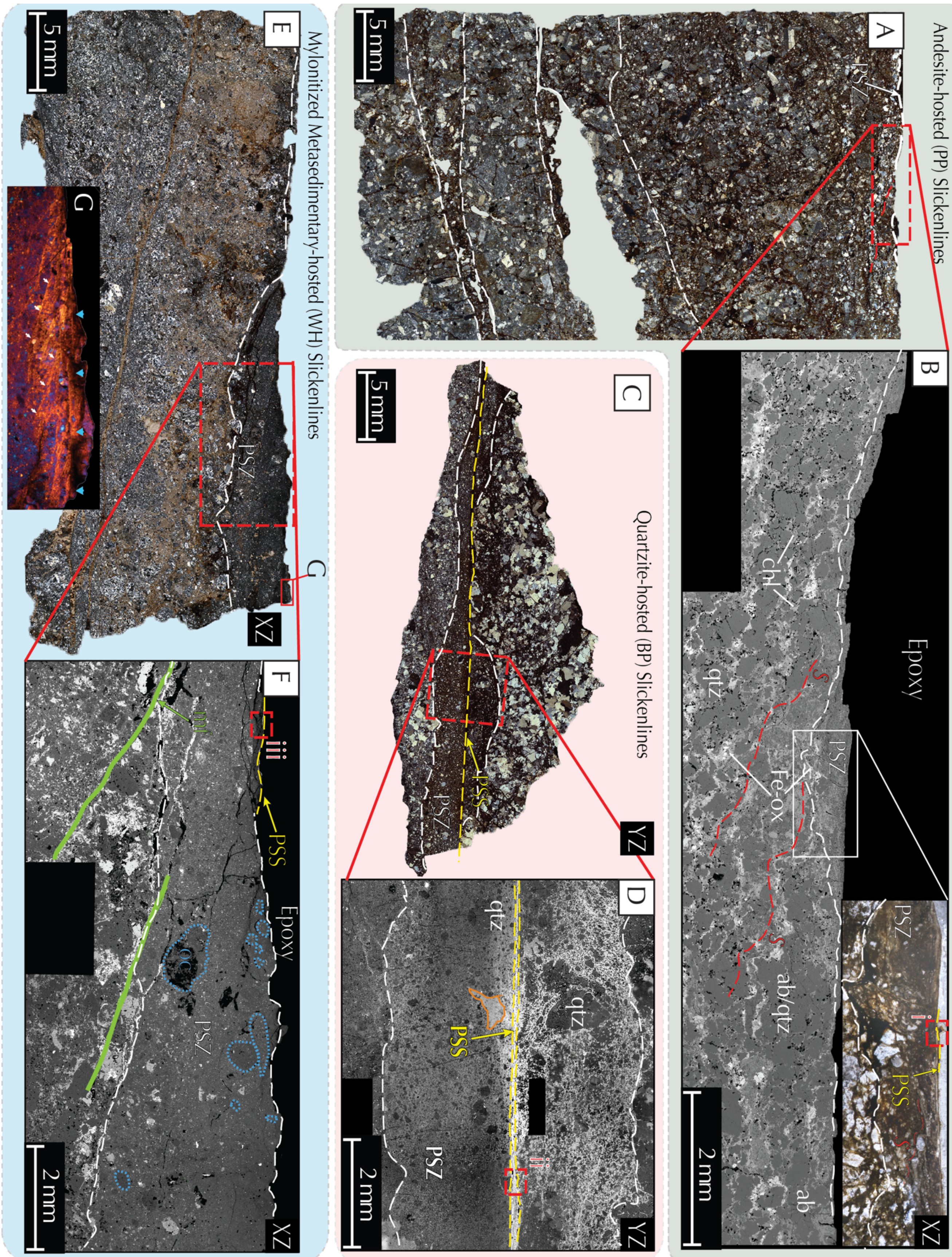

Andesite-hosted (PP) Slickenlines
A
PSZ
5 mm
B
Epoxy
chl
qtz
PSZ
Fe-ox
ab/qtz
ab
PSZ
i
PSS
2 mm
XZ
Quartzite-hosted (BP) Slickenlines
C
PSS
PSZ
YZ
5 mm
D
qtz
qtz
PSS
ii
PSZ
2 mm
YZ
Mylonitized Metasedimentary-hosted (WH) Slickenlines
E
PSZ
G
XZ
5 mm
G
F
iii
ml
PSS
Epoxy
oc
PSZ
2 mm
XZ

Figure 8. Selected samples for microstructural analysis. White and yellow dashed lines highlight Principal Slip Zones (PSZ) and Principal Slip Surfaces (PSS), respectively. A) Andesite hosted slickenside thin sections under cross-polarized light (XPL). Note relatively undeformed primary igneous fabric at the bottom of the image and multiple slip zones. B) SEM-BSE close-up of A. characterized as a zone of highly comminuted grains of irregular thickness. Dark grey colors correspond to quartz (qtz) and albite (ab), bright grey chlorite (chl), white Fe-ox, whereas black spots within the rock volume correspond to porosity. Note S-C cataclasite with top to the left sense of shear. Inset: plane polarized light (PPL) close-up of PSZ fluidized ultra cataclasite. Note tails around larger clasts. C) Quartzite hosted slickensides under XPL, preserving opposing segments of the fault surface. D) SEM-BSE close-up of C. Note the principal slip zone (PSZ) is characterized by highly comminuted grains in the μm-size range, whereas the principal slip surface (PSS-yellow) is localized to few tens of microns and decorated by an abundance of Fe-oxide minerals (bright colors). Note asymmetry in Fe-oxide distribution and comminution between both sides of the fault. Charging artifact denoted by orange lines. E) Slickenside hosted in mylonitic metasediments under XPL. F) Close-up of E shows the presence of a Principal Slip Zone (PSZ) of variable thickness characterized by sharp grain size reduction towards the slip surface and towards a thin Principal Slip Surface (PSS). Note the presence of older cataclastic clasts (OC) within the PSZ. Micro-faults (mf-green) are also observed offsetting the PSZ. G) Close-up of E under XPL with gypsum lambda plate inserted highlights region adjacent to surface where localized shear bands (two main orientations outlined by white and teal arrows) exhibit strong and spatially coherent optical anisotropy.

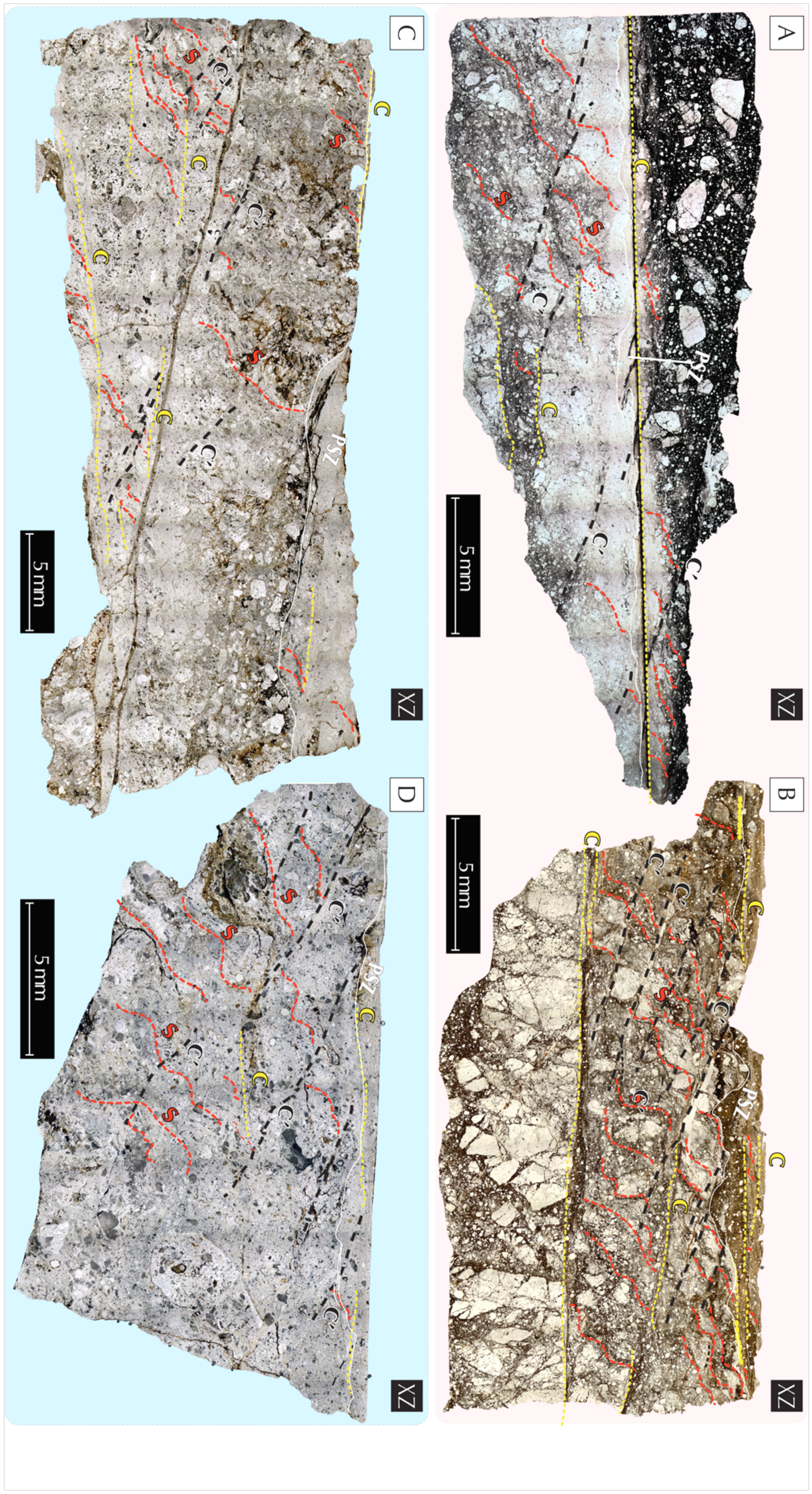

A
B
C
D
XZ
5 mm
PSZ
C
C'
S

Figure 9. Photomicrographs of foliated cataclasites with S-C-C’ fabrics under plane polarized light (PPL). S-, C- and C’- planes outlined by dotted red, yellow, and black lines, respectively. Vertical shaded strips are artifacts from stitching of images. PSZ outlined by thin white dashed line characterized by a sharp decrease in grain size. Note C-planes are parallel to PSS and undulation in PSZ contact follow the edges of S-, C-, and C’-planes. Slickenside hosted in A-B) Quartzite and C-D) mylonitic metasedimentary rocks

3.2.1 Plan de los Plátanos Fault

The main slip surface is covered by a thin film that is glossy and smooth, with specularly reflective patches. The lineations have an average width of 527 ± 83 μm and spacing of 0.85 ± 0.18 mm that remain relatively constant throughout the length of the sample (Fig. 5A). Secondary fractures perpendicular and diagonal to the lineations crosscut the surface.

Below the exposed surface, we identified S-C-like fabrics and a quartz-rich vein with predominantly ductile fabrics that soles into the slip surface. The quartz grains are elongated, exhibit undulose extinction and host multiple inclusions. All fabrics are then cut by a principal slip zone (PSZ) comprising a fluidized ultracataclasite of variable thickness (100-500 μm) that is characterized by a sharp decrease in grain size from the host rock towards the slip surface (Fig. 8A-B). In addition to the main exposed surface, other minor slip surfaces were identified splaying within the sample.

The PSZ features a quartz-rich zone (~10 μm thick) of increased cohesion (ICZ) next to the surface, wherein grains exhibit serrated, interlocked grain boundaries, triple junctions, and sintering microstructures, followed by sharp break towards a ~5 μm thin principal slip surface (PSS) (Fig. 10A and Fig. 11A).

The PSS is characterized by a predominance of mostly rounded submicron-size grains/particles embedded within "*wispy*" phyllosilicate-like matrix enriched in Al and Fe compared to the PSZ (Fig. 10A-Fig 11A). In regions where the PSS is thicker, the PSS exhibits a denser morphology with little to no porosity, albeit fractured, with similarly rounded nm-size grains/particles as well as elongated grains preferentially aligned subparallel to the surface (Fig. 10B).

3.2.3 Big Piute Slickensides

The slip surfaces are flat and smooth, i.e., no grooves are perceived with the naked eye, particularly in the direction parallel to the lineations. Iron-oxides (Fe-ox) decorate the slip surfaces, including botryoidal hematite. The lineations are marked by alternating smeared Fe-ox bands with a spacing of 8.2 ± 0.5 mm and 1-3 mm wide grooves (Fig. 5 Bii-iii).

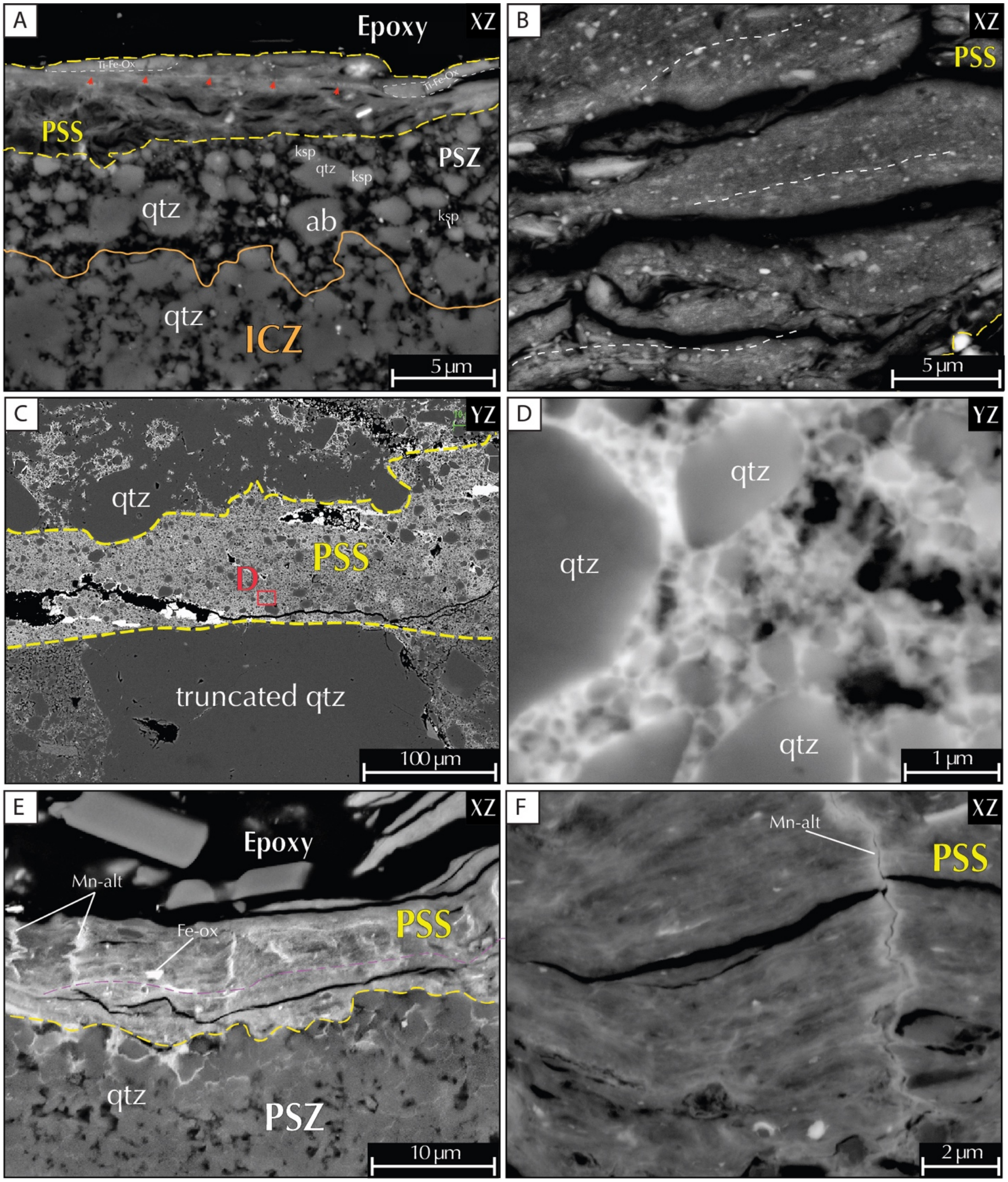
Across the XZ orientation, the sample exhibits a foliated cataclasite microstructure with an S-C-C' fabric that transitions into the PSZ and PSS (Fig 9A-B). The foliations are defined by sigmoidal dark brown layers that bound asymmetric quartzite clasts and clast aggregates with their *tails* preferentially oriented ~45° to the fault surface (S-foliation), C'-shear bands developed oblique to the S- and C- orientations, and localized micro-shears sub-parallel to the slickenside surface (C-surface) (F. M. Chester et al., 1985; A. Lin, 2001; Passchier & Trouw, 2005). The waviness of the contact between the host rock and the PSZ follows the orientation of the S-, C-, and C'- planes.

The clast size of the cataclasite and spacing between S-C-planes gradually fines and rotate until it transitions into an ultracataclasite that makes up the PSZ and a 18 ± 11 μm thin PSS. (Figs. 8C-D, 9A-B, and 10C-D). The PSS is characterized by truncation and plucking of grains from the PSZ and matrix comprising rounded nanometric grains with little to no fractures cemented by a matrix of Fe-ox. Void spaces along fractures within the PSS are then filled by an alternating growth of Fe-ox and quartz, (Fig 10C).

3.2.3 Waterman Hill Slickensides

The surface forms a resistant ledge, is smooth and specularly reflective. The lineations are marked by cm-scale undulations within mirror-polished regions and by 520 ± 160 μm wide grooves in portions of the surface that are not specularly reflective.

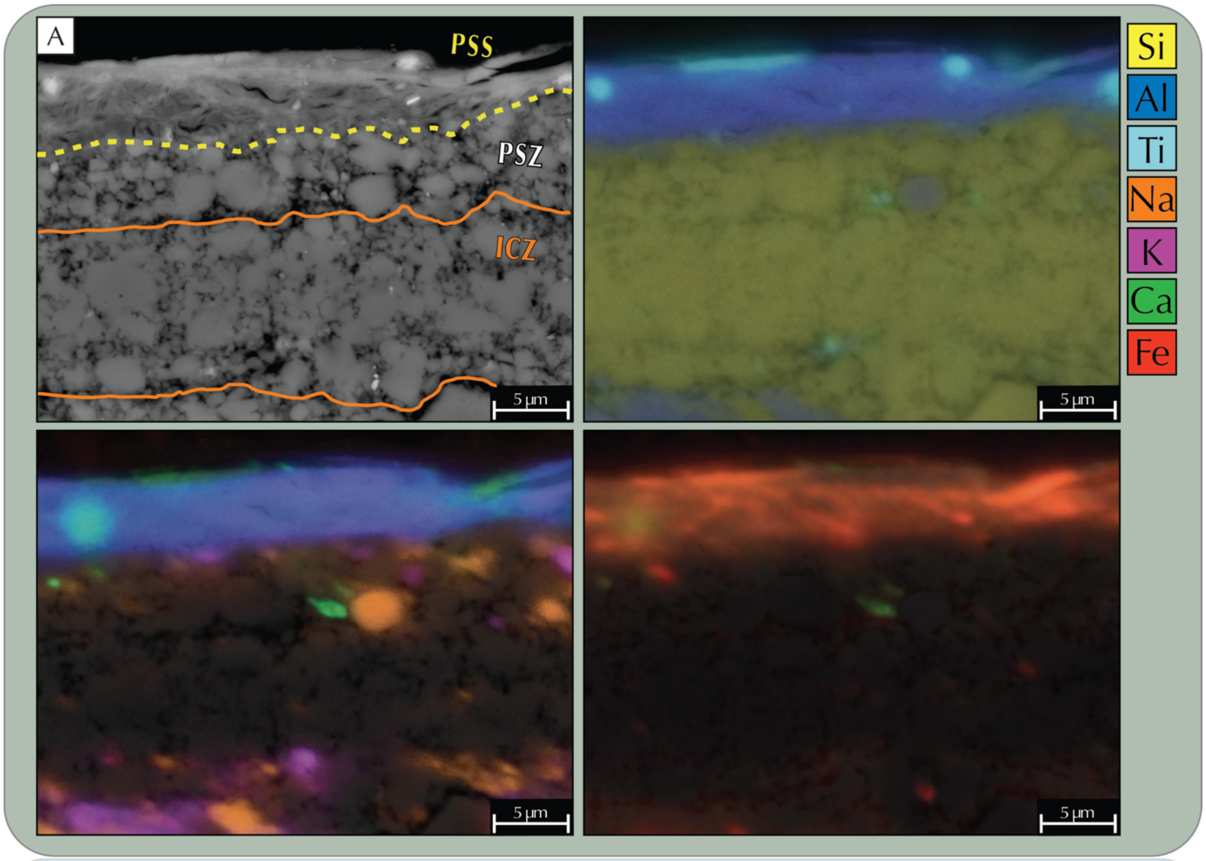
We observe that the WH slickenside samples also exhibit a region of extremely comminuted grains, PSZ, adjacent to the slip surface, and S-C-like fabrics throughout its host rock. Unlike the other samples, the PSZ here varies significantly in thickness, from ~100 μm to 5 mm, along the direction of slip (*XZ*). Regions where the PSZ is thicker coincide with numerous micro-faults that displace the PSZ but do not crosscut the mirror-polished surface. The PSZ contains clasts of earlier, more consolidated cataclasites (OC). Immediately adjacent to the slip surface, two main features are prominent: a) the presence of Reidel-like and boundary (subparallel to the slip surface) shear bands that exhibit extreme grain size reduction and uniform optical anisotropy, Fig. 8E, and b) a dense thin film (PSS) that coats the PSZ that features elongated grains preferentially oriented subparallel to the surface embedded within a potentially partially amorphous matrix, Fig. 10F, similar to Fig. 10B. Nanosized grains are also observed to be common within the matrix of the PSZ.

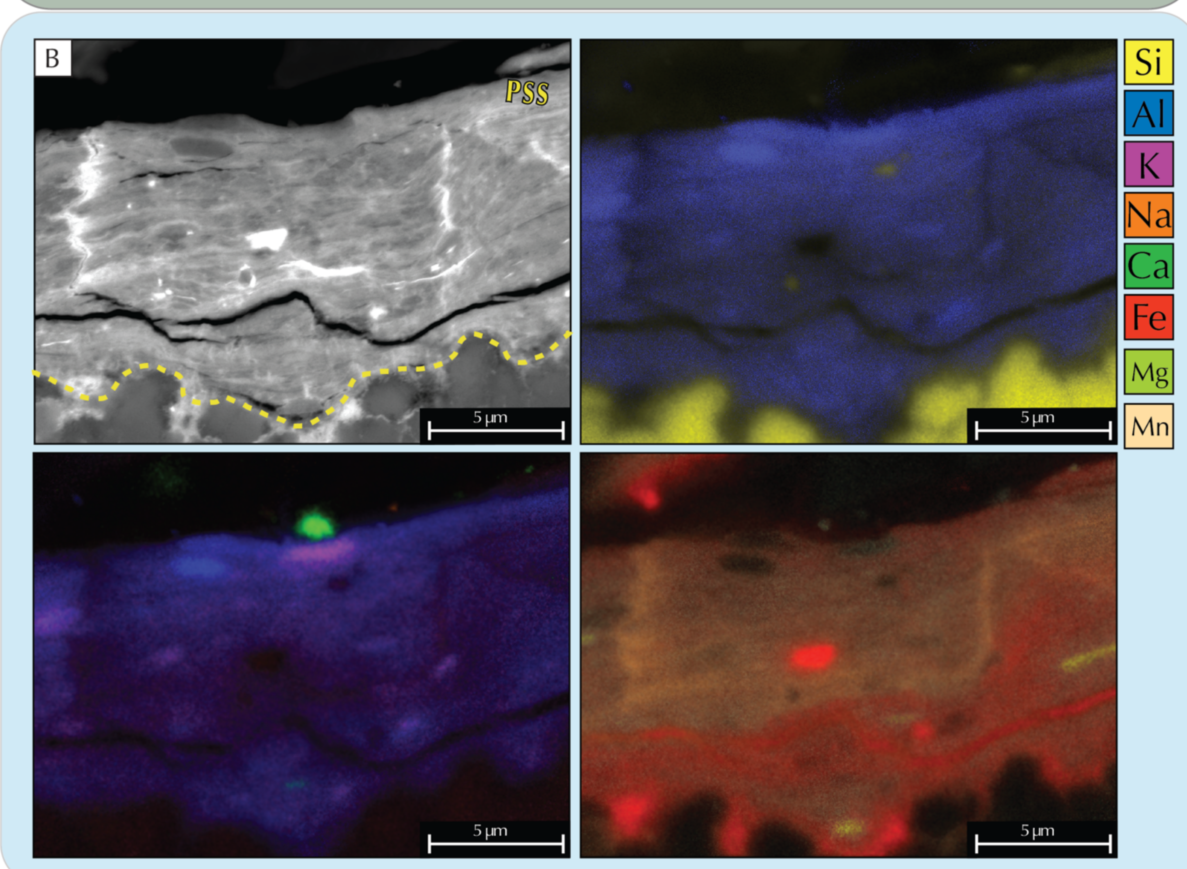

A
Epoxy
XZ
PSS
PSZ
ksp
qtz
ksp
qtz
ab
ksp
qtz
ICZ
5 µm
B
XZ
PSS
5 µm
C
YZ
qtz
PSS
D
truncated qtz
100 µm
D
YZ
qtz
qtz
qtz
1 µm
E
XZ
Epoxy
Mn-alt
PSS
Fe-ox
qtz
PSZ
10 µm
F
XZ
Mn-alt
PSS
2 µm

455

456

Figure 10. SEM-BSE images of the Principal Slip Zones. **Andesite hosted slickensides:** A-B) SEM-BSE operated with 20 kV accelerating voltage and 8.0 nA beam current. A) Close-up of PSZ in Fig 8B.i, showing the presence of a thin PSS and a quartz-rich Increased Cohesion Zone (ICZ) and PSS. Note the PSS is a thin layer (a few microns thick) comprising a randomly oriented Al- and Fe-rich "wispy" phyllosilicate-like matrix and submicron sized particles. Note the roundness of most clasts and Fe-rich veinlet in PSS, red arrows. The ICZ is characterized by a decrease in porosity, grains with irregular and serrated grain boundaries, and sintering microstructures. B) Close-up of dense region of PSS. Note the presence of rounded nano-sized particles and elongated preferentially oriented grains, highlighted by white dashed lines. **Quartzite hosted slickensides:** C) Close-up of the PSS from Fig 8D.ii. Image shows a sharp decrease in grain size from the PSZ (outside of the yellow boundary) towards the PSS, which is characterized by a Fe-oxide-rich layer of micron-sized grains supported in a fine grain matrix. Note truncation of quartz clast by the PSS. D) Close-up of PSS matrix shows matrix comprises predominantly submicron-sized qtz grains and Fe-ox cement (bright colors). Note roundness and lack of fractures on matrix grains and euhedral growth of Fe-oxide blades into void spaces. **MMS hosted slickensides:** E) Close-up into the PSS Fig 8F.iii, shows it comprises a dense layered possibly amorphous matrix with rounded grains and preferentially oriented elongated grains. Note bright vertical features enriched in Mn. Layering is highlighted by a magenta dotted line. F) Close-up of PSS. Note dense matrix with little to no porosity and sub-micron rounded grains.


A
PSS
PSZ
ICZ
5 μm
5 μm
5 μm
5 μm
Si
Al
Ti
Na
K
Ca
Fe


B
PSS
5 μm
5 μm
5 μm
5 μm
Si
Al
K
Na
Ca
Fe
Mg
Mn

476

Figure 11. Compositional EDS maps of Principal Slip Surfaces. A) Andesite hosted slickensides: from Fig. 10A Note Si-rich (quartz) Increased Cohesion Zone (ICZ) and Al, Fe and Ti enriched PSS. B) MMS hosted slickensides: Close-up of PSS in Fig 10E showing PSS is enriched in Al, Fe. Bright fractures enriched in Mn. Note thin Al-, K-, and Mg-rich rods preferentially aligned subparallel to the slip surface.

3.3 Grain Size Distribution

To characterize the comminution processes occurring during slip, we analyzed the grain size distribution of the fault rocks adjacent to the slip surface. Here we present the results of the grain size analyses performed on two sequences of petrographic microscopy and SEM images taken at increasing magnifications from selected samples from the BP and PP faults. The results are plotted on log-log plots of frequency vs. equivalent diameter to determine the fractal grain size distribution (GSD), Fig. 12.

We did not perform grain size analysis on samples from the WH Fault. It was not possible to accurately identify individual grain boundaries as the particles appear embedded within a cement of similar composition. Furthermore, when the boundaries between particles could be accurately identified, they exhibit interlocked grain boundaries, suggesting static crystal growth and healing (Keulen et al., 2008), and thus obscuring the grain sizes related to the comminution process.

The grain size distribution for the quartzite sample shows a power-law functional relationship over six orders of magnitude (10's nm-1's mm) with a constant slope *of* $D = 2.67 \pm 0.03$ despite the sharp decreases in grain size observed within the transition from the host rock towards the PSZ and PSS respectively, Fig. 8C-D. However, it is observed that at the lower grain size range (less than 100 nm), the distributions start to plateau as the grain size approaches the resolution limit of the SEM (a single pixel at the highest magnification equals 0.77 nm). The smallest grain sizes are found within the unconsolidated gouge with an equivalent $d_{min} = 18\ nm$, whereas the smallest observable grains within the matrix of the PSS corresponded to 30 nm.

In contrast to the monomineralic quartzite, the andesite hosted slickensides exhibit two distinct parts that can be discriminated by a break in the GSD slope. Two D-values are obtained: a lower, $D_< = 2.05 \pm 0.19$ for small grain sizes ($d<d_k$), and $D_> = 2.72 \pm 0.06$, for large grain sizes ($d > d_k$), where $d_{k.} \approx 2\ \mu m$ and is the grain size at the intersection of the two curve fits. This intersection (dk) occurs where grains measured only in the PSS and PSZ overlap. Within the small grain size range, the smallest grains are found embedded within the PSS matrix with a $d_{min}=30\ nm$.

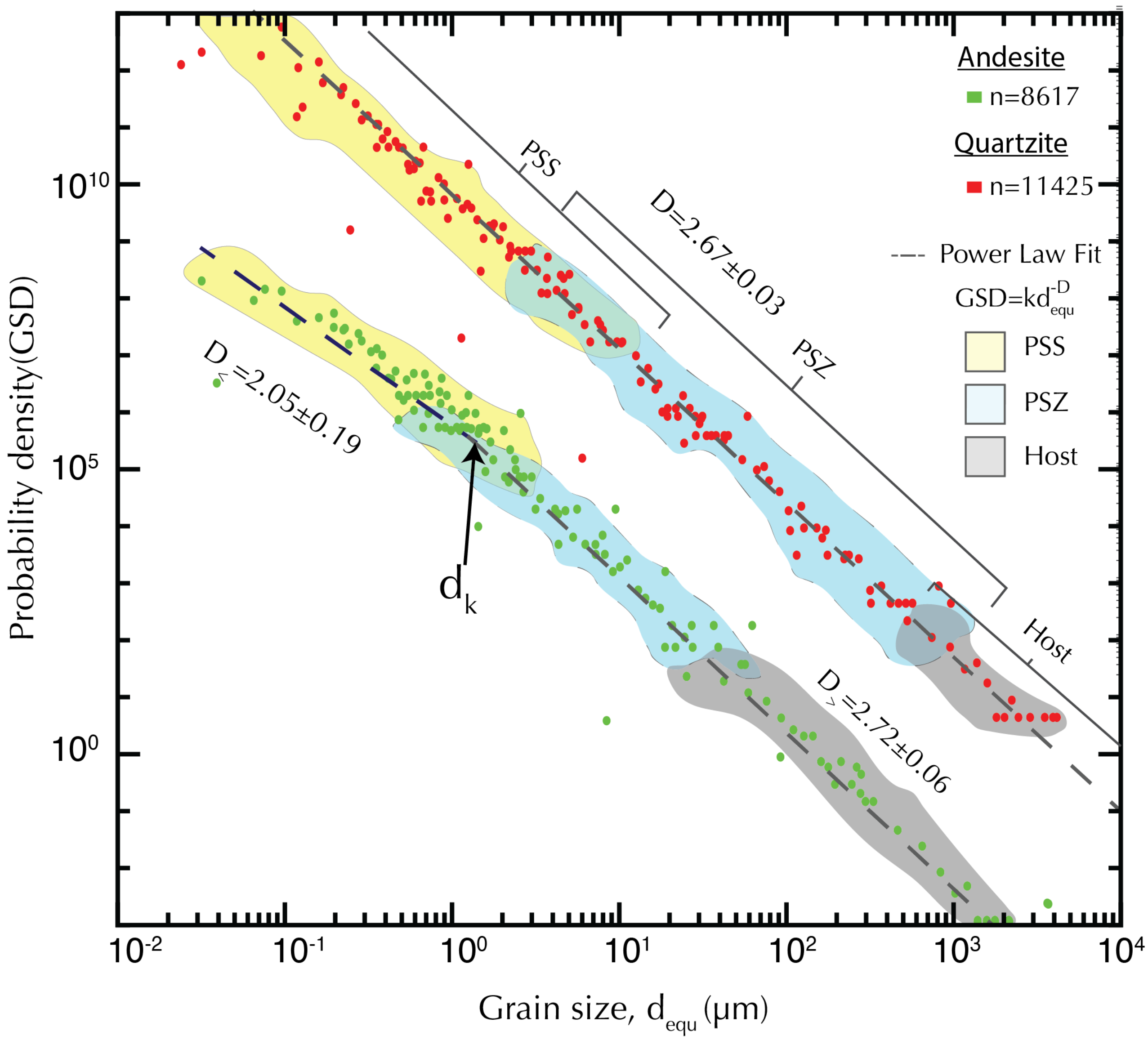

Andesite
n=8617
Quartzite
n=11425
Power Law Fit
$GSD=kd_{equ}^{-D}$
PSS
PSZ
Host
PSS
PSZ
Host
D=2.67±0.03
$D_<$=2.05±0.19
$D_>$=2.72±0.06
d_k
Probability density(GSD)
10^{10}
10^5
10^0
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
Grain size, d_{equ} (μm)

Figure 12. Grain Size Distributions of quartzite (red) and andesite (green) host rocks. Data has been displaced vertically for clarity. The GSD of quartzite samples can be described by a single $D = 2.67 \pm 0.03$, whereas GSD has two distinct slopes for $D_< = 2.05 \pm 0.19$ and $D_> = 2.72 \pm 0.06$ for grain size smaller or larger than $d_k \approx 2\ \mu$m, respectively. The different color envelopes indicate the range of grain sizes found within the PSS, PSZ, and the host rock. Data points outside the color envelopes correspond to artifacts due to the limited resolution in each measured image.

4 Discussion

This work provides a detailed study of surface roughness of slickensides and the associated microstructures in the surrounding fault rocks from three different fault zones hosted in various rock types that have experienced different deformation histories. The observations from both the surface and respective volume and their implications for our understanding of faulting processes are discussed below.

Fully characterizing a fault surface is of particular importance for better understanding fault processes. It has been shown that the stress distribution is affected by fault geometry, as the latter controls to a first degree the real contact area (e.g., Ben-Zion & Rice, 1997; Bruhat et al., 2020; Cattania & Segall, 2021; Harbord et al., 2017; Sagy & Lyakhovsky, 2019; Tal et al., 2020). Our current understanding of fault surface geometry is that it is self-affine and that it can be characterized by four parameters ($H_{per,}$ $H_{par,}$ $C_{par,}$ C_{per}) (Brodsky et al., 2016; Candela et al., 2009, 2012). In agreement with other reports, our studied fault surfaces further indicate that regardless of lithology or tectonic setting, the roughness of individual fault surfaces exhibits an anisotropic self-affine topography with Hurst exponents (H) and pre-factors (C) within the 0.4-0.8 range and 10^{-5} - 10^{-2}, respectively. The surface roughness of our samples, however, consistently exhibited smaller H-values and less anisotropy than most reported natural fault surfaces, i.e., the roughness measured perpendicular- and parallel to the slip lineations exhibited closely valued Hurst exponents with mean $H_{par}=0.53 \pm 0.07$ and. $H_{per}+0.60 \pm 0.10$ as opposed to the more commonly reported $H_{par}\approx0.6$ and $H_{per}\approx0.8,$ (Bistacchi et al., 2011; Candela et al., 2009, 2012; Power & Tullis, 1989; Renard et al., 2012; Sagy et al., 2007; Thom et al., 2017; Tisato et al., 2012). The smaller H values likely indicate that our surfaces appear smoother at larger scales and rougher at finer scales than other faults while the reduced anisotropy could be related to inherent heterogeneity within the fault surfaces. Similarly, this discrepancy could also be related to the conditions at which such surfaces were formed and/or altered. While intriguing, our current observations cannot explain this peculiarity.

In addition to describing fault surface geometry via fractal descriptors ($H_{per,}$ $H_{par,}$ $C_{par,}$ C_{per}), this work includes multiscale analyses (MSA) on the height distribution of fault surfaces. Our results suggest the kurtosis and skewness of such distributions deviate from Gaussian with a noticeable dependence on the scale of observation, which contrast to some of the models used in earthquake simulations that typically assume faults as Gaussian self-affine rough surfaces (e.g., (Cattania & Segall, 2021; Graves & Pitarka, 2016). The latter has important implications on our understanding of the role of geometry in faulting processes, as studies on the contact behavior of non-Gaussian surfaces have reported that roughness parameters skewness and kurtosis correlate to noticeable effects on tribological properties such as: friction, wear, mean asperity pressure, and contact area (Ghosh & Sadeghi, 2015; Gu et al., 2021; Kim et al., 2006; Kotwal & Bhushan, 1996; McCool, 1992; Sedlaček et al., 2012; Tayebi & Polycarpou, 2004; Tomota et al., 2019; W.-Z. Wang et al., 2006; Yan et al., 2014; S. Zhang et al., 2014) and fluid transport properties (M. Wang et al., 2016). Thus, further measurements of fault surfaces that also characterizes the distribution of their heights in addition to their fractality seem crucial for more accurate representations of fault roughness in models that explore the role of geometry on seismic slip.

While this simplification of fault zones into self-affine rough surfaces is useful for making educated predictions of fault surface geometry at scales and locations not accessible with the current technology (subsurface faults), it is worth noting that wear and therefore slip on a fault cannot be entirely explained by two rough surfaces sliding past each other. Firstly, microstructural observations near single fault surfaces have reported the presence of a discrete zone that concentrates strain and wear comprising extremely comminuted layers with an abundance of nanoparticles and/or other types of tribofilms, within the PSZ and PSS (Ault et al., 2019; De Paola, 2013; Dor & Reches, 2005; Goldberg et al., 2016; Heesakkers et al., 2011; Houser et al., 2021; Kuo et al., 2016; Ohl et al., 2020; Otsubo et al., 2013; Pec et al., 2016; Power & Tullis, 1989; Rowe et al., 2019; Shervais & Kirkpatrick, 2016; Siman-Tov et al., 2013, 2015; Taylor et al., 2021; Tisato et al., 2012; Verberne et al., 2014, 2019; Viti et al., 2016), suggesting that individual fault surface evolution and wear could be better modeled by what is known in tribology as third-body wear (Boneh et al., 2014; Boneh & Reches, 2018; Brodsky et al., 2020; Milanese et al., 2019). More importantly, however, geologic and experimental observations from the submillimeter to kilometers scale indicate that fault zones involve the interaction several structures, with multiple anastomosing fault strands occasionally crosscutting each other (Faulkner et al., 2003; Rowe et al., 2018; Shervais & Kirkpatrick, 2016; Swanson, 1988; Torabi et al., 2020, 2021). For instance, observations of individual natural slickensides and their respective host rocks reveal an intricate set of structures that document progressive localization of strain into what eventually become multiple principal slip surfaces on which subsequent sliding takes place. Specifically, most samples exhibited foliated cataclasites with S-C-like fabrics, with clasts progressively becoming finer toward the C-plane-parallel principal slip surfaces as documented in Fig.9, similar to the structures reported along the PSS of numerous other fault zones (Berthé et al., 1979; Hippertt, 1999; Jordan, 1987; Kirkpatrick & Brodsky, 2014; Y.-J. Lee, 1991; A. Lin, 2001; S. Lin et al., 2007; S. Lin & Williams, 1992; Nakamura & Nagahama, 2002; Ortega-Arroyo, 2017). Such observations suggest that development of the PSS is preceded by formation of progressively mechanically weaker zones along which strain is further localized. A simple sequential model is proposed in Fig. 13 based on the observations from natural slickenside samples, analogue experiments with no pre-cut fault surfaces (Will & Wilson, 1989; C. J. L. Wilson & Will, 1990) and numerical modeling (Finch et al., 2020). Therefore, in our interpretation the exposed slip surfaces are the end product of fault slip and wear on fault zone and not the initial conditions on which slip initiate.

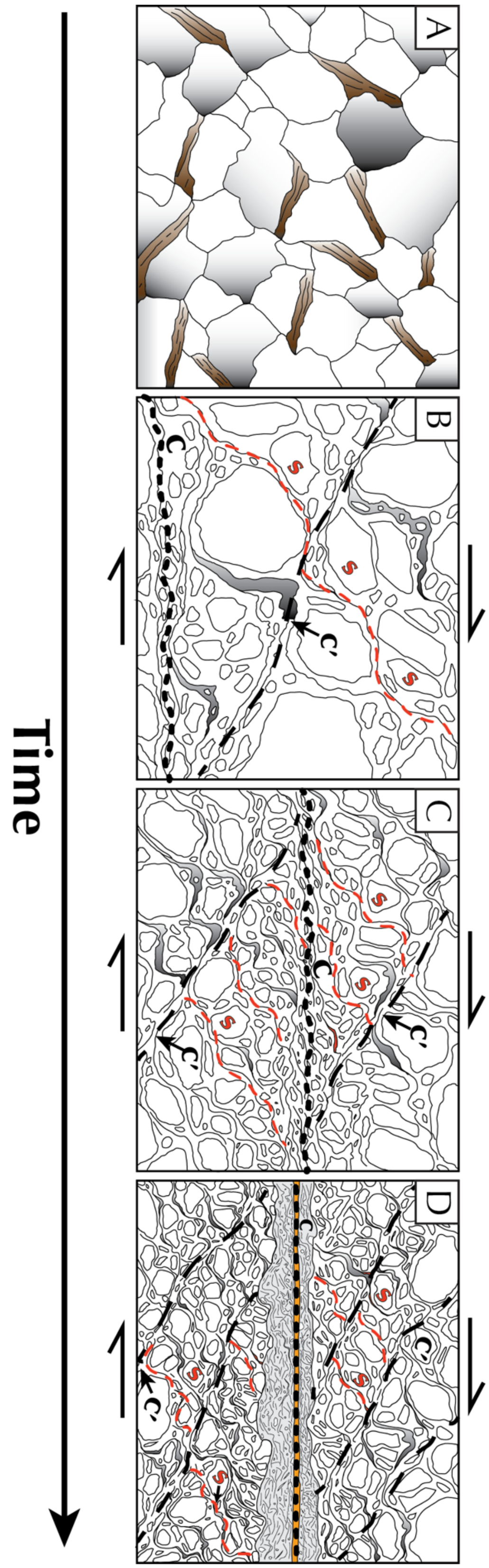

Time
A
B
C
D

Figure 13. Schematic sequential model of slickenside development. A) Initial undeformed rock. B) S-C-C' fabrics start developing at low -intermediate strain levels. Note S-foliation (red-dashed lines) is defined by asymmetrical clast and clast aggregates with their tails oriented at about 45º to the C-surface (black-dotted lines), whereas C'-shear bands appear oblique orientations (black-dashed lines). C) As shearing continues more S-C' fabrics propagate throughout the sample and create rheologically weaker regions via grain size reduction that preferentially rotate towards C-planes. D) Strain further localizes along the C-planes in the form of finely comminuted material observed in the PSZ (grey) and PSS (yellow)

At low to intermediate strain, deformation is accommodated via incremental development of oriented fabrics along S-C structures (Will & Wilson, 1989; C. J. L. Wilson & Will, 1990). At higher strains, passive rotation of S-planes into C-planes becomes a more efficient way to accommodate strain over creation of new planes, (Berthé et al., 1979; Finch et al., 2020; Hippertt, 1999; Jordan, 1987), which create rheologically weaker regions that accommodate higher strain rates (Finch et al., 2020) and can progressively link with each other to form through going shear zones (Finch et al., 2020; Pec et al., 2016; Will & Wilson, 1989; C. J. L. Wilson & Will, 1990), akin to the process zone suggested by (Cox & Scholz, 1988). The development of these localized shear zones also facilitates infiltration of fluids, as seen in the ubiquitous concentration of secondary minerals and/or alteration products (mainly Fe-ox) along the PSZ and PSS, Figs. 8-11, that likely cause further weakening and slip due to metasomatic reactions and pore pressure effects. The latter suggests an extreme degree of strain localization, where most of the deformation is accommodated by extreme comminution along thin kinematically favorable regions, generally a few tens of microns thick, as documented in Figs. 8-10.

To better characterize the extreme comminution processes affecting our samples we performed grain size analyses. Interestingly, the way the grain sizes are distributed appears to vary between the andesite and the quartzite sample. For instance, the slickenside within the quartzite shows a GSD that can be described with a single D value for over six orders of magnitude, whereas the andesite GSD has a break in slope near $d_k \approx 2\ \mu$m, Fig. 12. Grain size measurements from other polymineralic natural and experimental fault rocks have also reported a break in the slope of their GSD at similar critical grain sizes d_k that suggest a change in the dominant comminution mechanisms with attrition and shearing becoming more important at values lower than d_k, usually attributed to the grinding limit (Billi & Storti, 2004; F. M. Chester et al., 1993; J. S. Chester et al., 2005; Keulen et al., 2007). Our quartzite sample does not exhibit this transition and is in contrast to what Keulen et al., (2007) reported for quartz grains in other polymineralic gouges. There could be multiple explanations for the discrepancies at these scales. Firstly, the difference could be related to different breakage mechanisms at sub-micron scale associated to the parent mineralogy (Knieke et al., 2011), as the observations reported in 0Keulen et al., (2007) were done on granitoid lithologies and ours on quartzite and andesite. Moreover, the break in slope observed in the andesite GSD could be related to changes in material properties likely caused by mechanochemical and/or tribochemical reactions acting along the friction zone, PSS, as the d_k appears at the transition where their grain sizes overlap between the PSZ and PSS, (Knieke, 2012; Knieke et al., 2011; Romeis et al., 2016). It is possible that partial mechanical amorphization is among some of the reactions occurring within the PSS, which could help explain the distinct textures observed along the PSS and its GSD. For instance, the dense portion of the PSS, Fig 10B,E,F , exhibits similar textures to those observed along the silica layer within the slickensides studied by Taylor et al., (2021), wherein Fe-ox nanorods are embedded in a partially amorphous matrix, while the "wispy" microporous matrix, observed in Fig. 10A, resembles the textures reported from hydrothermally altered quenched frictional melts in (Fondriest et al., 2020) likely representing portions that have undergone more advanced hydrothermal alteration with formation of clay minerals, (e.g., Fe-smectite). Furthermore, observations of coeval amorphous and nanocrystalline material are not uncommon along high strain frictional interfaces and have been widely reported along natural fault surfaces (Ault et al., 2019; Houser et al., 2021; Kirkpatrick et al., 2013; Kuo et al., 2016; Ohl et al., 2020; Verberne et al., 2014, 2019; Viti et al., 2016), rock deformation experiments (Kaneki et al., 2020; Marti et al., 2020; Pec et al., 2012, 2016; Pec & Al Nasser, 2021; Toy et al., 2017), and deformation of engineering materials (Han et al., 2012; Viat et al., 2017; Y. S. Zhang et al., 2014;

Zhao et al., 2016), indicating that both nanocrystalline and amorphous material are common products during frictional wear processes regardless of the parent material, and an important component to consider when studying rheology of faults. Nanocrystalline fault rocks are inherently weaker than their microcrystalline counterparts and therefore can form in-situ weak layers along which strain further localizes (Sun and Pec 2021).

Alternatively, both GSD's could also represent different stages in the comminution process as recent studies in confined comminution of granular materials using a simple Discrete Element Models (DEM) and Apollonian gasket models suggest that the GSD continuously shifts as the porosity is reduced until it reaches an ultimate power law that also determines the ultimate contact force distribution (Ben-Nun et al., 2010). Based on the microstructure of each sample it is possible that the observed changes relate to different degrees of comminution. Similarly, Knieke et al. (2009) work on ultrafine particle (nm-range) production with stirred media mills on a variety of different materials shows that the ultimate size that a particle can be broken into, i.e., grinding limit, depends on a multitude of variables including stressing types, the material of the particles to be milled as well as the size and material of the milling particles, and solvents (e.g., hydrous fluids). Thus, the ultimate particle distribution observed along comminuted rocks could reflect the conditions during grinding.

5 Summary and Conclusions

We investigated the surface roughness and associated microstructures of natural slickenside samples from three different fault systems hosted in andesite, quartzite and mylonitic meta-sedimentary lithologies. We found that in addition to exhibiting the usually reported self-affine roughness, with mean $H_{par}=0.53 \pm 0.07$ and. $H_{per}+0.60 \pm 0.10$, all surfaces exhibited non-Gaussian height distributions with noticeable scale-dependence on their S_{kur} and S_{sk} roughness parameters. While our dataset is limited to the shorter length scales associated with fault surface roughness, further studies at a wider range of scales could help constrain the type of height distributions common to natural faults. Moreover, our microstructural analyses suggest such surfaces are likely the product of progressive strain localization and partitioning along regions with high degree of fabric development (S-C-C'- fabrics) that culminate in multiple principal slip zones throughout the samples identified by a sharp decrease in clast size and thin ($\leq$100 μm) principal slip surfaces wherein nanosized particles are abundant along with other tribofilms and reaction products. The prevalence of nanoparticles observed within fault zones regardless of lithology or tectonic setting urges the need to investigate the effect of nanogranular material on the rheological and frictional properties of faults. In this light, a re-visiting of the energy budget of faulting seems necessary to account for the interaction between various structures (present even along individual slip surfaces) and the work done to decrease the grain sizes to nanometers. Partitioning of energy between heat, grain breakage, intracrystalline deformation, amorphization, and seismic wave radiation will ultimately influence how much energy goes into heating (Bestmann et al., 2011; Knieke et al., 2011; Ranganathan et al., 2021; Rosakis et al., 2000; B. Wilson et al., 2005). Heating of fault zones and the associated microstructural changes present the best opportunity to distinguish between fault segments that underwent rapid slip form fault segments that crept at slow rates (Rowe & Griffith, 2015 and references therein).

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7 Appendix

The accuracy of the signal processing technique was assessed by recording the difference between the “input” Hurst exponents of randomly generated synthetic isotropic self-affine surfaces using the code provided in Candela et al. (2009) and the “output” recovered with our methods. For each value of the input Hurst exponent, we analyzed a set of 1000 synthetically generated surfaces as presented in Fig. A1. We further assessed our method by analyzing surface data from the Corona Heights fault surface samples from Thom et al. (2017). The average Hurst exponents of the Corona Heights Fault slickenside samples corresponded to 0.72 ±. 0.11 and 0.78 ± 0.09 for the parallel and perpendicular orientations, respectively. However, when the data in both directions are taken into account, we obtained 0.75 ± 0.10, which agrees with the value found by Thom et al. (2017).

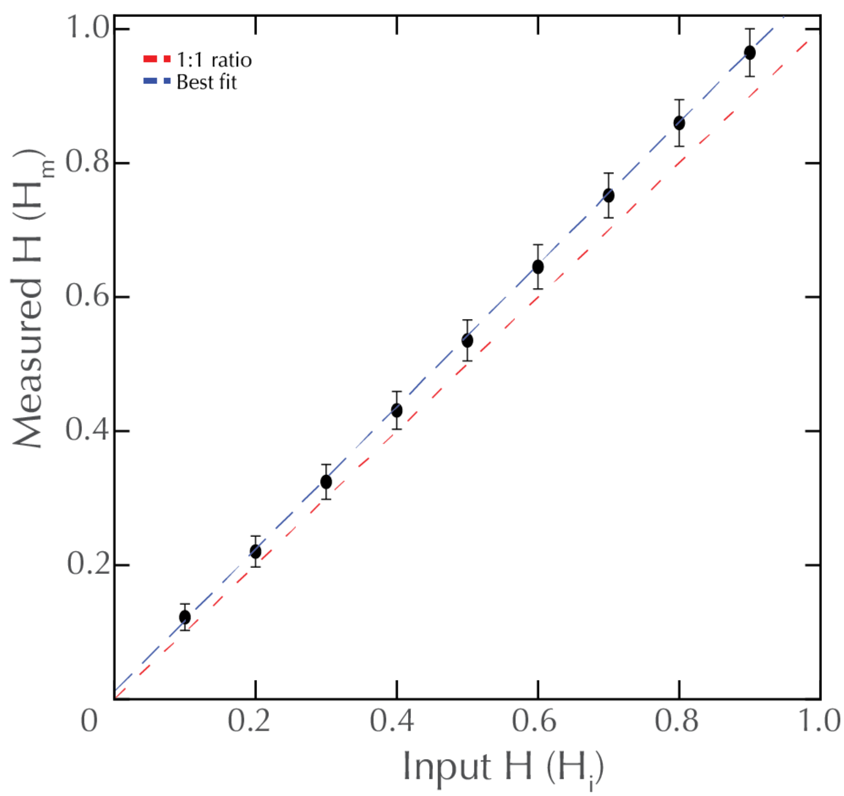

Figure A1. Calibration of PSD method for calculating the Hurst exponent (*H*). Note that the measured Hurst exponent (H_m) does not follow a one-to-one ratio (red). Instead, it has a linear best fit of the form $H_m=1.065\ H_i + 0.006$ with a coefficient of determination R^2=0.999.

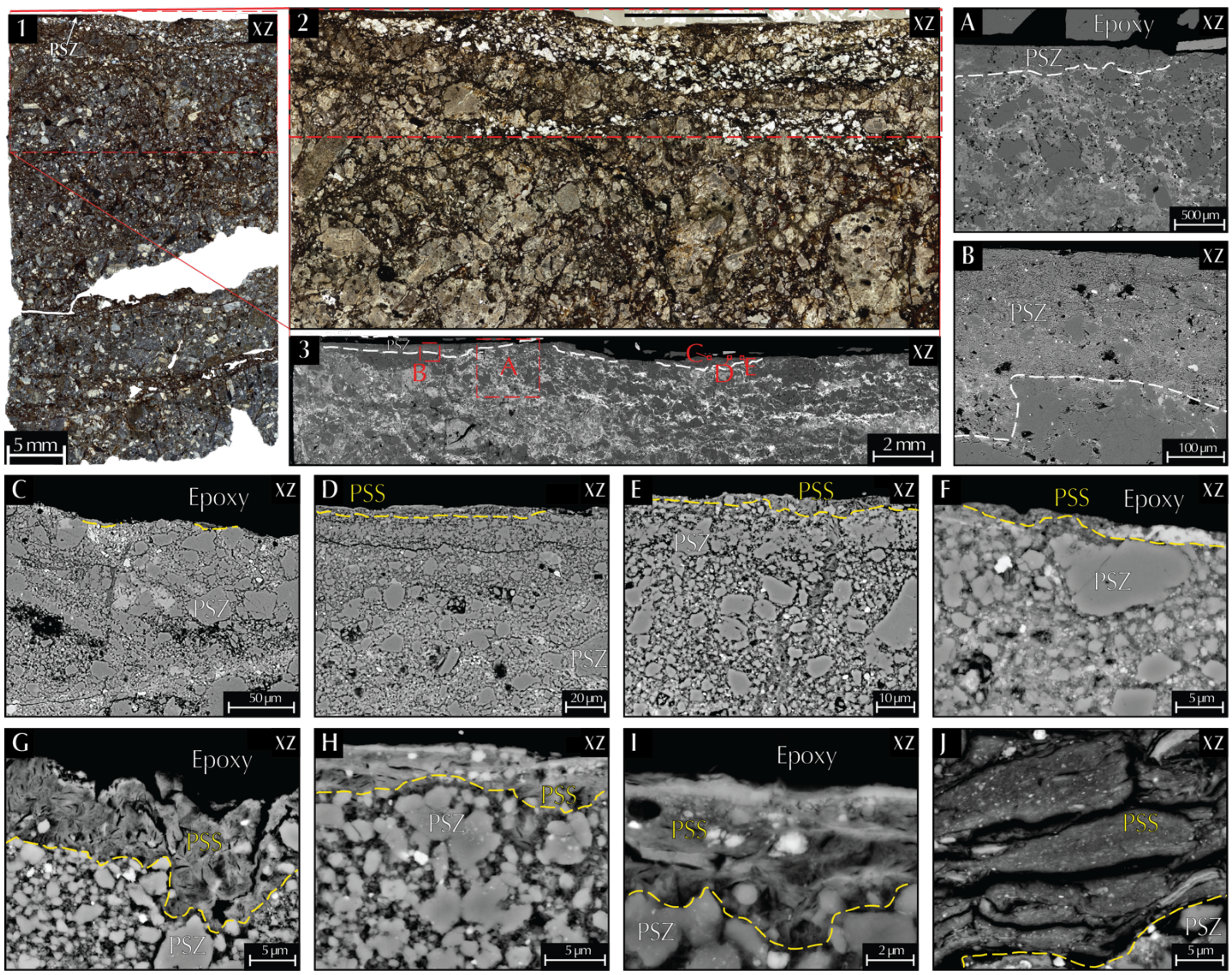

Figure A2. Set of images at progressively higher magnifications used in the GSD determination of andesite hosted slickenside. See text for details.

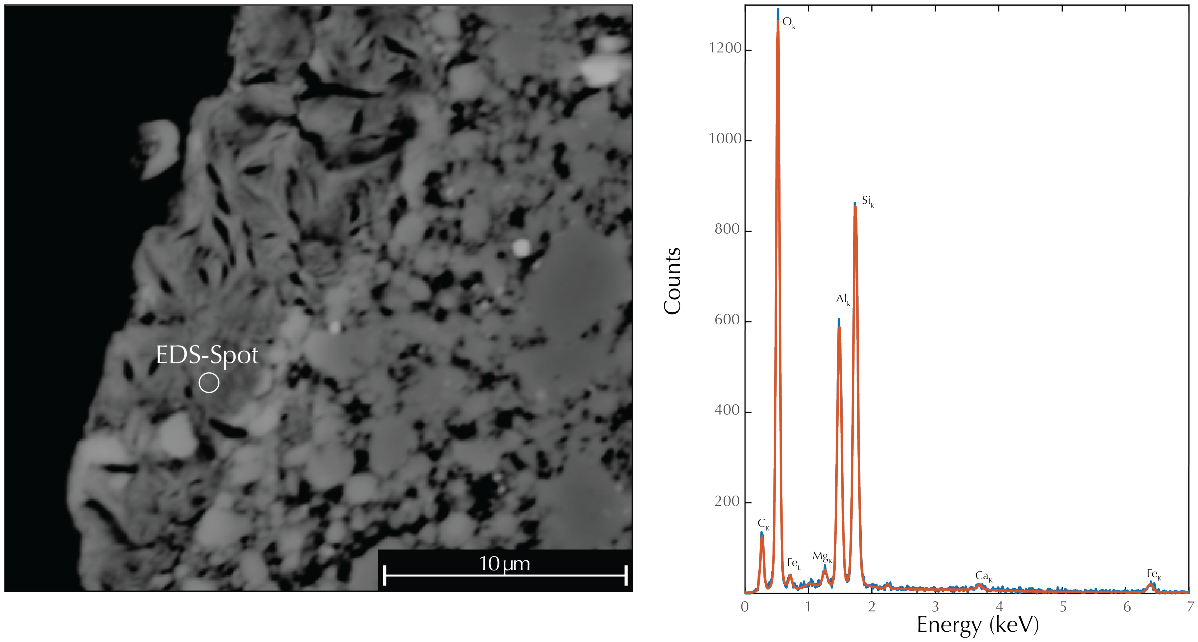

Figure A3. EDS-spectrum of "wispy" PSS from andesite hosted slickensides.

8 Data Availability Statement

Data reported here are publicly available at Zenodo Repository at: https://doi.org/10.5281/zenodo.6558132 (SEM and petrographic photomicrographs), https://doi.org/10.5281/zenodo.5167913 (surface roughness data), and https://doi.org/10.5281/zenodo.6558649 (grain size distribution data) under a Creative Commons Attribution 4.0 International Public License.

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