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1 **Geometrical evolution of interlocked rough slip surfaces: The**
2 **role of normal stress**

3

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17 **Keywords: roughness evolution, fault geometry, direct shear, mechanical work, wear, surface**
18 **roughness**

19 **Abstract**

20 We study the evolution of slip surface topography using direct shear tests of perfectly mating
21 surfaces. The tests are performed under imposed constant normal stress and constant slip rate
22 conditions, to a sliding distance comparable to the roughness scale of the studied surfaces.
23 Prismatic limestone blocks are fractured in tension using four-point bending and the generated
24 surface topographies are measured using a laser profilometer. The initially rough fracture interfaces
25 are tested in direct shear while ensuring a perfectly mating configuration at the beginning of each
26 test. The predetermined sliding distance in all tests is 10 mm and the sliding velocity is 0.05 mm/s.
27 A constant normal stress is maintained throughout the tests using closed loop servo control. The
28 range of normal stresses applied is between 2 MPa and 15 MPa. After shearing, the surface
29 topographies are re-scanned and the geometrical evolution is analyzed. We find that surface
30 roughness increases with increasing normal stress: under normal stresses below 5 MPa the surfaces
31 become smoother compared to the original geometry, whereas under normal stresses between 7.5
32 MPa and 15 MPa the surfaces clearly become rougher following shear. Statistical spectral analyses
33 of the roughness profiles indicate that roughness increases with length-scale. Power spectral
34 density values parallel to the slip orientation are fitted by power-law with typical power value of
35 2.6, corresponding to a Hurst exponent of 0.8, assuming self-affine roughness. This power value is
36 consistent for the post-sheared surfaces and is obtained even when the original surface roughness
37 does not follow initially a power-law form. The value of the scaling-law prefactor however increases
38 with increasing normal stress. We find that the deformation associated with shearing initially rough
39 interlocked surfaces extends beyond the immediate tested surface, further into the intact rock
40 material. The intensity of the damage and its spatial distribution clearly increase with increasing
41 normal stress. Wear loss is measured by subtracting the post-shear surface from the pre-shear
42 surface matrices using known reference points. Our measurements indicate that wear loss and

43 roughness evolution are both positively correlated with the mechanical shear work applied during
44 the experiments. We argue, therefore, that normal stress plays a significant role in the evolution of
45 interlocked surfaces, such as geological faults, and strongly affects the energy partitioning during
46 slip.

47

48 **1. Introduction**

49 Faults in the upper crust are characterized by complex zones of deformed rock that shear during
50 repeated faulting events (Chester & Logan., 1986; Ben-Zion & Sammis, 2003; Wibberley et al., 2008;
51 Faulkner et al., 2010). Most of the displacement along faults is localized at principal slip surfaces
52 exhibiting geometrical irregularity at all measurable scales (Power et al., 1988; Siman-Tov et al.,
53 2013; Candela et al., 2012) and as in other material interfaces the roughness is critical to the
54 understanding of shear and frictional processes (e.g. Bowden & Tabor, 1950; Dieterich & Kilgore;
55 1994). The presence of gouge and cataclasite zones in natural faults indicates that the fault surface
56 itself evolves through wear production (Power et al., 1988; Wang & Scholz, 1994). In each slip event
57 wear is generated and the initial geometry of the slip surface is continuously modified, a process
58 that has been referred to as “roughness evolution” (Sagy et al., 2007).

59 Previous roughness evolution studies in the field by means of geometrical measurements of natural
60 fault surfaces suggest that faults smooth with accumulated slip. Wesnousky (1988) observed strike-
61 slip fault traces at geological map scales and discovered that the number of steps along the trace
62 reduces with increased offset on the faults. By comparing profiles along slip surfaces that
63 accommodated dozens to hundreds of meters of displacement to these which sheared less than a
64 meter, Sagy et al. (2007) concluded that roughness parallel to slip orientation reduced due to slip at
65 all measured scales. Brodsky et al. (2011) increased the sampling population and demonstrated that
66 roughness of profiles at lengths of 0.5 to 1 m decreased very gradually as function of the slip
67 amount. Bistacchi et al. (2011) studied paleo-seismic fault surfaces exhumed from seismogenic
68 depths and demonstrated that similar geometrical evolution occurs at these depths.

69 Surface roughness of fractures was intensively investigated in laboratory experiments as an integral
70 component of contact and shear mechanics (e.g. Bowden & Tabor, 1950; Archard, 1953). Many
71 pioneering works in rock mechanics investigated roughness of faults and fractures in relation to

72 mechanical strength and shear resistance (Patton, 1966; Barton, 1976; Byerlee, 1978). In the last
73 decades, quantitative statistical analysis methods to describe surface geometry were proposed (e.g.
74 Mandelbrot, 1983; Bouchaud et al., 1990; Grasselli et al., 2002) and some were applied to describe
75 rock discontinuities. Amitrano & Schmittbuhl (2002) for example measured the geometry of shear
76 fractures formed by triaxial shear tests and suggested that they exhibited self-affine power-law
77 geometry with Hurst exponents H of 0.8 and 0.74 for profiles normal and parallel to the slip
78 direction, respectively. Results obtained with rotary shear tests demonstrated slip rate effects on
79 surface roughness (Fondriest et al., 2013; Boneh et al. 2014; Siman-Tov et al., 2015). These studies
80 focused solely on the roughness characteristics after slip and therefore the actual roughness
81 evolution through shear remained unresolved.

82 Roughness evolution studies require measuring the surface geometry before and after shear
83 displacement. Renard et al. (2012) slid smooth halite surfaces on a coarse sandpaper substrate
84 under constant normal stress and characterized the roughness exponent evolution. Davidesko et al.
85 (2014) demonstrated that when shearing under relatively low normal stress (2 MPa) surface
86 roughness decreased with displacement; they sheared initially rough tensile fracture surfaces
87 produced by three-point bending to increasing slip distances, up to 15 mm.

88 Normal stress is fundamental in the theory of friction and wear (Bowden & Tabor, 1950; Archard,
89 1953; Byerlee, 1978) and therefore it is reasonable to assume that it also strongly affects damage
90 and deformation in natural faults which typically yield under tectonic stresses of significant
91 magnitudes. In the present study the effect of normal stress on roughness evolution of rock
92 surfaces is examined by means of direct shear experiments coupled with laser profilometer
93 measurements before and after shear. The advantage of the combined mechanical-tribological
94 methodology adopted here is that multi-scale mating surfaces are sheared relative to each other as
95 in natural faults, and are mapped with high precision. Moreover, the direct shear system used here

96 allows great control and measuring capabilities during shear displacement. The acquired roughness
97 data is examined both statistically, using spectral analyses, and morphologically, using cross-
98 sections and height maps of the surfaces.

99 **2. Experimental Procedure**

100 The experiments consist of several consequent stages: 1) rough tensile surfaces are created using
101 four point bending; 2) both surfaces are scanned with a laser profilometer; 3) direct shear
102 experiments under constant normal stress to target displacement of 10 mm are performed while
103 ensuring the sheared surfaces are perfectly mating ; 4) re-scanning of both surfaces; 5) roughness
104 analysis.

105 The experimental surfaces are generated from prismatic limestone beams. The starting material is a
106 fine-grained limestone with an average grain diameter of ~ 0.4 mm known locally as “Hebron
107 Marble”. The elastic parameters of the intact rock are Young’s modulus of 57 GPa and Poisson’s
108 ratio of 0.29 (Davidesko, 2013).

109 The four-point bending tests utilized the direct shear system with the shear load frame removed
110 and the normal piston used to deliver the axial load (Fig. 1a). A vertical notch approximately 5 cm
111 long was pre-cut to direct the propagation direction of the induced tensile fracture (see Fig. 1a).

112 The produced surfaces were typically 8 cm wide and approximately 11 cm long.

113 The uniqueness of the generated surfaces in this procedure is that the roughness of one surface
114 matches exactly the roughness of the other, thus enabling the surfaces to slide relative to one
115 another from a completely mating configuration. Furthermore, the roughness of each set (two
116 mating surfaces) is neither predetermined nor reproducible, which better simulates natural fault
117 surfaces. The experimental fault surfaces in the present study, therefore, differ substantially from

118 the usual surfaces used in friction studies, because they allow examining of a multi-scale asperity
119 interlocking contact (Fig. 2).

120 The experimental fault surfaces are sheared in a hydraulic, servo-controlled, direct-shear system
121 (Fig. 1c) to a constant distance of 10 mm at a rate of 0.05 mm/s, under imposed constant normal
122 stress so that the tested interface is allowed to dilate vertically during shear. Normal load is
123 delivered from the axial piston which connects to the top of the shear load frame using a centering
124 pin. The lower shear box rolls on frictionless rollers that are placed between the shear box and the
125 base platen (Fig. 1d).

126 The fractured interfaces are cast in the shear boxes using cement in a completely mating
127 configuration so that when initially loaded the interlocking contacts are fully preserved. The shear
128 boxes are placed in the shear load frame which is connected to the horizontal shear piston (Fig. 1c).
129 Six linear variable displacement transducers (LVDTs) are attached to metal plates on both flanks of
130 the steel frames (Fig. 1d); four vertical transducers are used to measure dilation during shear, and
131 two horizontal transducers are used to measure shear displacement. The LVDTs monitor the
132 displacements very close to the sliding interface, thus allowing excellent control capabilities during
133 testing because the shear displacement feedback to the closed-loop system is obtained from the
134 outputs of the two horizontal shear transducers.

135 The before and after topography of the tested interfaces is obtained by means of laser profilometer
136 (Fig.1b) and the data are used for roughness analysis. Both top and bottom surfaces are scanned
137 before and after shear. Prior to scanning, the surfaces are cleaned of dust and moisture. Wear
138 particles are removed from the post-shear surfaces using a soft brush and air pressure. The scans
139 are performed parallel to the direction of shear (longitudinal direction of the samples) using a 75
140 mm lens with a sampling frequency of 0.02 mm^{-1} and 34.34 mm^{-1} in the longitudinal and transverse
141 directions, respectively. The scans are used to map the entire surface in four parallel strips from

142 which roughness analysis is performed. By comparing the results to higher resolution
143 measurements in the same samples it is concluded that the accuracy of the measurements is robust
144 in our samples for detecting power spectral density values for wavelengths above 0.2 mm. All pre-
145 shear scans had post-shear counterpart scans that covered the same area for later roughness
146 comparison. The acquired scans data are presented using surface matrices of heights.

147

148

149 **Figure 1. Experimental methods in use: (a) Prismatic limestone beam in four-point bending**
150 **configuration, the length of the beam is 50 cm long. (b) Profilometer scanning a surface, note that**
151 **the surface is fixed to a steel shear box which links the sample to the direct shear system. (c) The**
152 **direct shear system: the normal piston (delineated by n arrow) and the shear piston and load**
153 **frame (delineated by s arrow). (d) Side view of the shear load frame with the vertical and**
154 **horizontal LVDTs (delineated by v and h arrows, respectively).**

155

156

157 **Figure 2. Schematic illustration of tested surface configuration in typical rock friction and wear**
158 **experiments (top) and the multi-scale, interlocking roughness in the present study (bottom).**

159 **3. Mechanical Results**

160 The mechanical results obtained from six direct shear experiments conducted in the present study
161 and data from one experiment conducted by Davidesko et al. (2014) are presented in Table 1
162 (Supplementary Material). All tests were sheared to a constant displacement of 10 mm at a rate of
163 0.05 mm/s under constant normal stress conditions. During shear displacement, the sliding
164 interface was allowed to dilate under the imposed normal stress; an example of a typical stress-

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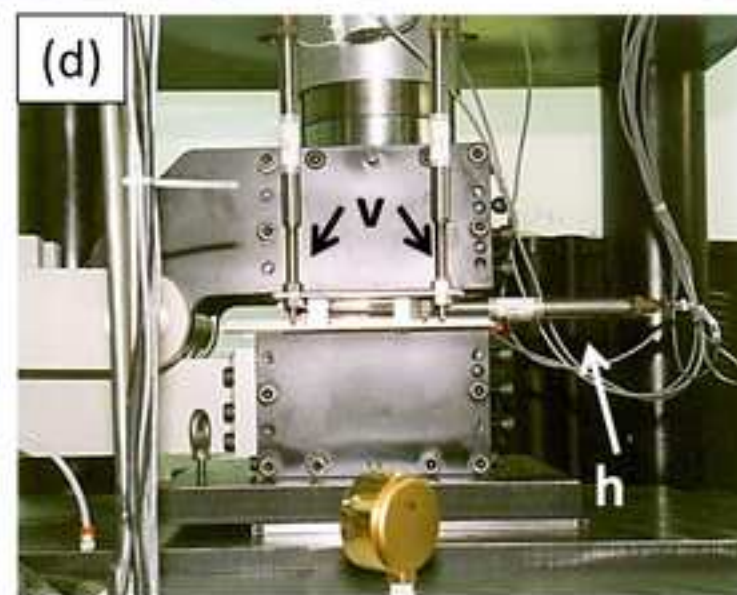
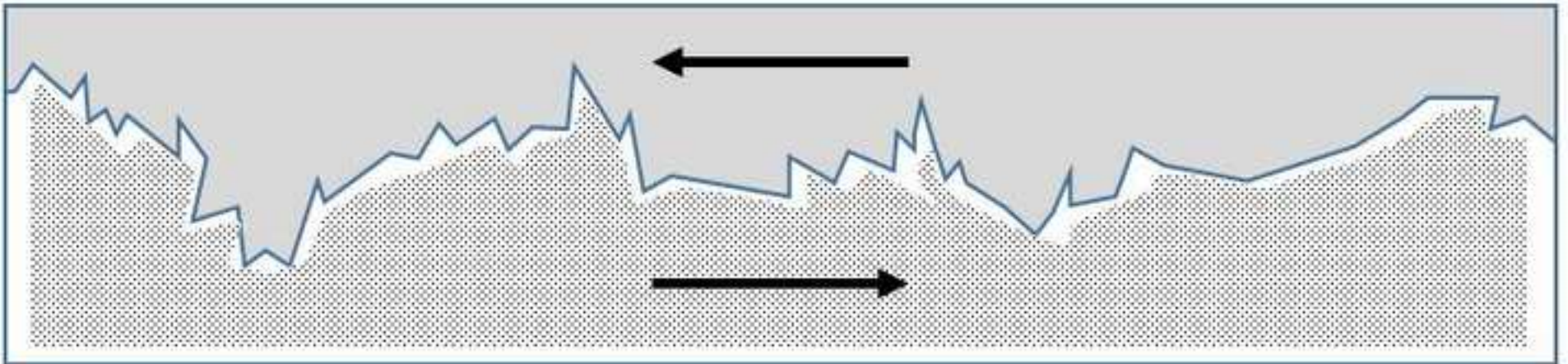
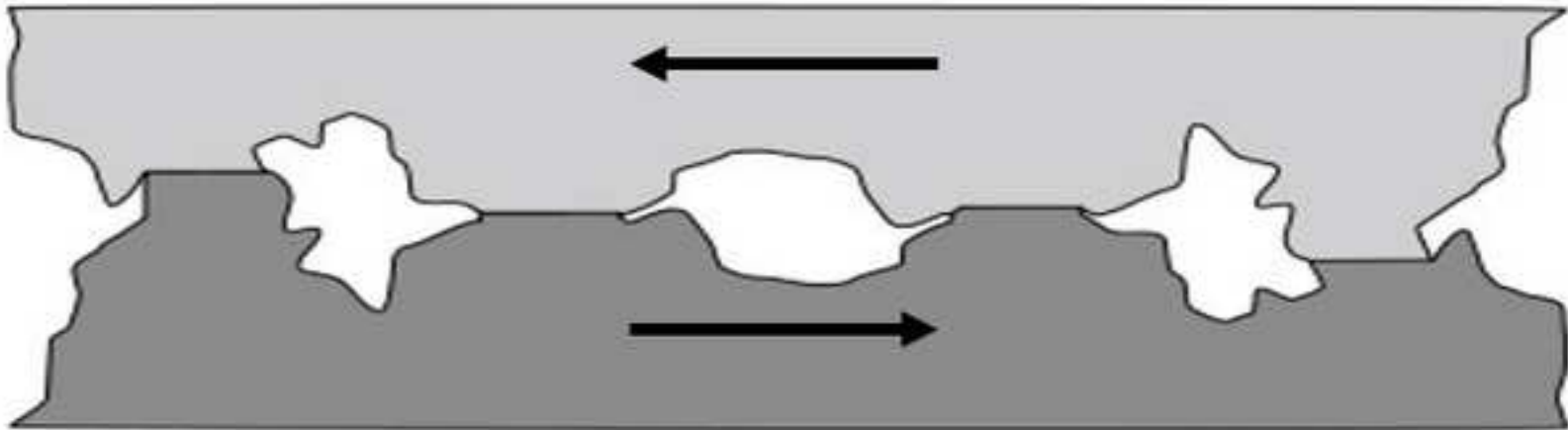


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165 displacement curve is shown in Figure 3. The results shown in Table 1 include measured shear
166 stress (τ) and normal stress (σ_n), calculated shear resistance (τ/σ_n), and calculated stress-drop ($\Delta\tau$)
167 results. Shear resistance, as used here, is the value of the measured shear stress divided by the
168 applied normal stress at any particular instance. Stress-drop refers to the change in shear stress
169 from peak to minimum residual stress. It should be noted that while peak shear stress was clearly
170 exhibited in all tests, a constant residual shear stress, elsewhere referred to as “steady state” (e.g.
171 Dieterich & Kilgore, 1994) was never reached for the pre-specified target displacement of 10 mm.
172 We therefore use the tail of the shear stress – shear displacement curve to assign a residual shear
173 stress value for each test, thus obtaining the calculated stress-drop values reported in Table 1.
174 Peak shear resistance was typically reached after a few millimeters (2-6) of displacement for each
175 experiment (Fig. 3a). Until that stage, the rough surfaces exhibited slip-hardening behavior
176 (Ohnaka, 2003) attributed to elastic deformation and yield of asperities before peak shear stress is
177 attained. As can be readily observed from inspection of figure 3b, this stage was coupled with
178 complex dilatational behavior, typically beginning with interface closure followed by interface
179 opening, before peak shear stress is reached.

180 Maximum values of shear resistance did not correlated with the imposed normal stress in our
181 experiments. The maximum shear resistance in the present study ($\tau/\sigma_n=1.25$) was obtained in an
182 experiment performed by Davidesko et al. (2014), which was performed under the lowest level of
183 normal stress in this suite of tests, $\sigma_n = 2$ MPa. The minimum shear resistance ($\tau/\sigma_n = 0.661$) was
184 measured in experiment LN6 performed under normal stress of $\sigma_n = 10$ MPa. This experiment is
185 different from the rest because a precursory slip event occurred before peak stress was attained.
186 The same phenomenon also occurred in experiment LN7 ($\sigma_n = 15$ MPa) where a significant stress-
187 drop (~ 0.54 MPa) was registered before peak strength was attained. These precursory stress-drop
188 events smoothed the stress-displacement curve, most likely dissipating some of the stored elastic

189 energy prior to peak stress and consequent plastic yield of the tested interfaces. Due to the initially
190 rough geometry of the surfaces, these precursory, uncontrolled events came as no surprise.

191

192

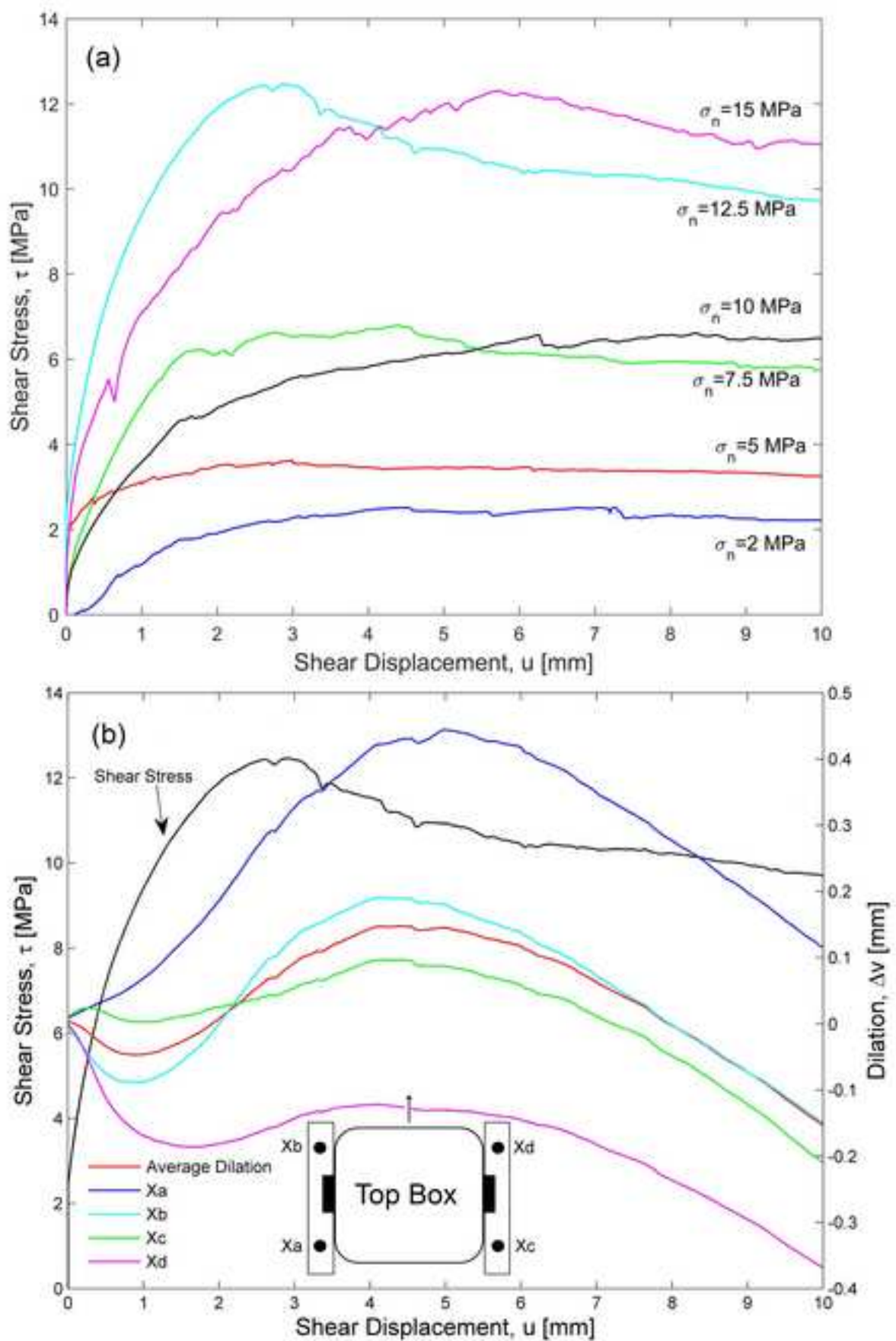
193

194 **Figure 3. (a) Shear stress – shear displacement curves for all experiments. (b) Experiment LN11,**
195 **sheared under a normal stress of 12.5 MPa. Shear stress denoted by the black curve. The colored**
196 **curves depict the dilation-displacement curves of all four vertical LVDTs (labeled Xa-Xd) and the**
197 **average dilation (red curve). Note that here dilation is positive and contraction is negative.**
198 **Schematic illustration of LVDT layout (horizontal, labeled Ya-Yb, and vertical, labeled Xa-Xd)**
199 **presented in inset, shear direction marked by arrow.**

200 **4. Geometrical Evolution**

201 Roughness topography of sheared surfaces typically evolves through wear production (Power et al.,
202 1988; Wang & Scholz, 1994; Brodsky et al., 2011). Here we first present direct observations of
203 geometrical variations followed by the statistical analysis of surface roughness. To prevent edge
204 effects due to irregular fracturing at the edges of the studied surfaces roughness analysis was
205 performed on selected zones in the center of the samples, few to dozens of centimeters long and
206 few centimeters wide. The geometrical analyses, therefore, represent these zones on the samples
207 only. The product for any given sample is a topographical map (expressed as a matrix) of any
208 particular domain before and after shear. Figure 4 displays topographical maps of surfaces before
209 and after slip, obtained from two different experiments. Both surfaces evolved through shear, but
210 under normal stress of $\sigma_n = 5$ MPa (Fig. 4a-b) the surface smoothed whereas under normal stress of
211 12.5 MPa (Fig. 4c) the surface roughened. Similar roughening is also clearly observed in other

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212 surface maps of samples sheared under 7.5 and 15 MPa (See supplementary material). The
213 topographical variations are demonstrated along two profiles parallel to the slip direction (Fig.
214 4b,d). It appears that the profiles in Figure 4b suggest that under normal stress of 5 MPa the
215 surfaces smoothed, most likely through asperity decapitation (Wang & Scholz, 1994), which
216 decreased the overall roughness of the surface (see also Davidesko et al., 2014).

217 In contrast to the smoothing mechanism observed up to normal stress of 5 MPa, the clearly
218 observed surface roughening under higher normal stresses is novel and not trivial to explain. We
219 believe that because the surfaces are initially rough and perfectly mating (Fig. 2) under higher
220 normal stresses shear must be associated with significant penetrative damage. This process is best
221 understood when the sheared surface morphology is carefully examined. Figure 5 presents the
222 surface of the sample that was sheared under normal stress of 12.5 MPa. Three main features can
223 be identified across the surface. First, there are undamaged zones where the original texture is
224 exposed. Other parts of the surface are covered by smooth grooves oriented in the slip direction,
225 similar to slip striations observed on natural faults. The third distinctive features are fractures that
226 penetrate the edges of the shear interface to a depth of a few millimeters. These fractures (Fig. 5b)
227 resemble Riedel shears and tensile fractures which typically develop along natural faults (Tchalenko,
228 1968; De Paola et al., 2008). Consider that in a given sample the fracture intensity varies across the
229 surface, with increasing density and penetration depth near geometrical irregularities. We find that
230 such penetrative damage is much more significant in surfaces sheared under relatively higher
231 normal stresses. Nonetheless, islands of striated polished zones (Fig. 5 a,c) suggest simultaneous
232 localization processes.

233

234 **Figure 4. Geometrical evolution of surfaces sheared under a normal stress of 5 MPa (a-b) and 12.5**
235 **MPa (c-d). (a,c) pre-shear (top) and post-shear (bottom) matrices for a surfaces sheared under**

236 $\sigma_n=5$ MPa and $\sigma_n=12.5$ MPa, respectively. (b,d) selected profiles in direction parallel to shear
237 (shear direction is to the left) for a surface sheared under $\sigma_n=5$ MPa and $\sigma_n=12.5$ MPa,
238 respectively. The pre and post shear surfaces are depicted by blue and red curves, respectively.
239 The matrices cover an area of 25×14.56 mm² and 69.9×14.56 mm² for the surface sheared under
240 5 MPa (a) and the surface sheared under 12.5 MPa (c), respectively.

241

242 **Figure 5. Picture of a surface sheared under 12.5 MPa (a). Three different zones are identified;**
243 **undamaged zones exhibiting the original texture of the rock, penetrative damage, exhibiting**
244 **multiple fracture traces (b), and scattered zones of fine white gouge with slip-striations. Some of**
245 **these contain highly polished patches (c).**

246

247 Statistical description of roughness evolution is performed using power spectral density (PSD)
248 analysis, which provides quantitative roughness values and variations as a function of length scale.
249 The analyses are performed on both pre - and post - shear matrices that contain the selected
250 damage zones, on profiles parallel to the slip direction. The analysis follows a procedure introduced
251 previously (Sagy & Brodsky, 2009; Brodsky et al., 2011; Candela et al., 2012; Davidesko et al., 2014);
252 namely, any profile is de-trended and the discrete Fourier transform is calculated. The power is the
253 square of the amplitudes of the coefficients and the PSD is the power spectrum normalized by the
254 profile length. The PSD value, presented here for any given wavelength (Fig. 6), is averaged from
255 the values calculated from several hundred profiles.

256 Figure 6 presents power spectral densities as function of the length scale of experimental surfaces
257 before (blue curves) and after (red curves) 10 mm of shear displacement under various normal
258 stress levels. Interestingly, the initial roughness in part of the samples does not fit well one power-

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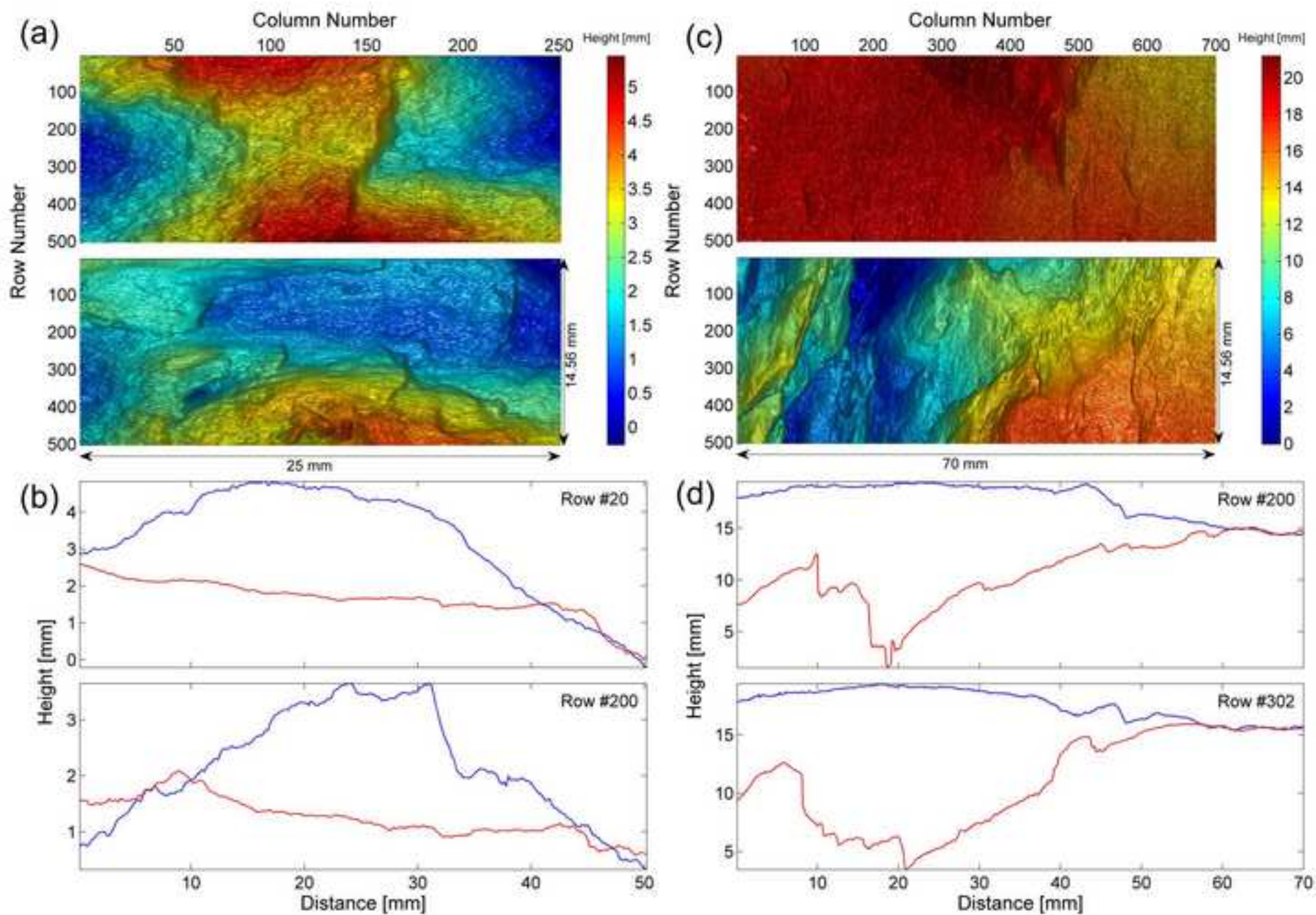
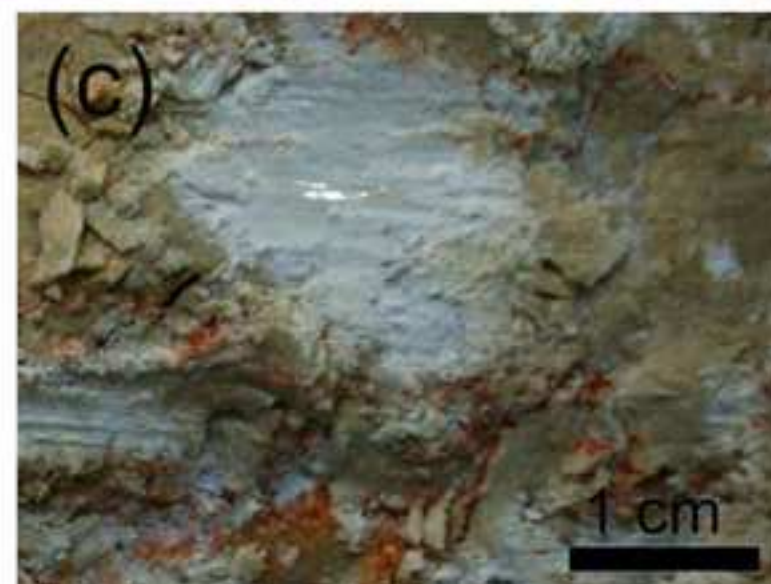
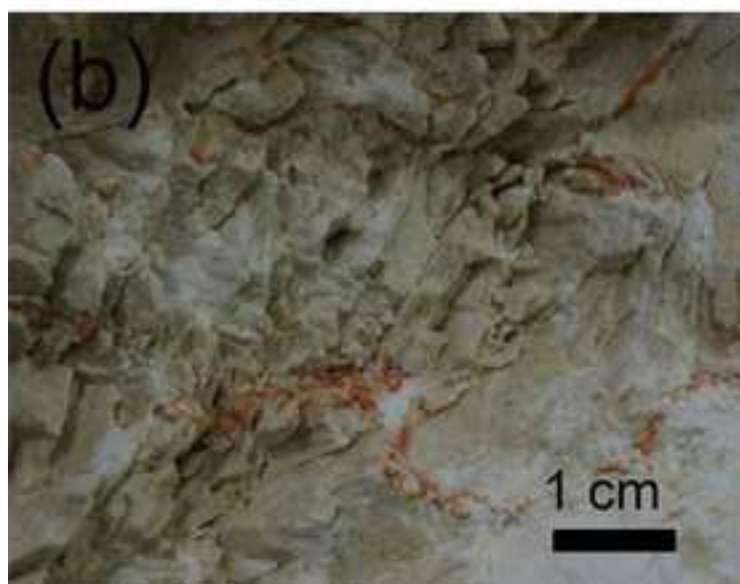


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259 law and at relatively short wavelengths becomes moderate when compared to longer wavelengths
260 (Fig. 6). However, the post-shear PSD curves closely fit a power of $\beta=2.6$, or $H=0.8$ (black lines).
261 Figure 6 also shows that when the surfaces are sheared under normal stresses greater than 5 MPa
262 the PSD increases at all measurable scales. The increase in PSD values corresponds to a mean
263 increase in roughness for all the profiles that make up the surface at the specified wavelength. This
264 behavior is clearly depicted in figure 7 where the PSD post to pre shear ratios are plotted as a
265 function of the tested wavelength (final PSD(λ)/initial PSD(λ)). There is a distinct separation
266 between samples sheared under normal stress levels greater than 5 MPa, all of which exhibit
267 roughness ratios greater than 1 (roughening), and samples sheared under equal or lower normal
268 stress levels than 5 MPa, all of which exhibit roughness ratios smaller than 1 (smoothing). The
269 above observations (Figs. 4-7) suggest that penetrative brittle fracturing is enhanced with
270 increasing normal stress. During shear sliding, fragmentation occurs in and near the fractured zone
271 and consequently rock fragments are detached from the host rock. Measurements of the surface
272 irregularities indicate that roughness evolution reflects this wear mechanism.

273

274 **Figure 6. Power spectral density roughness before (blue curves) and after (red curves) 10 mm**
275 **shear under varying normal stresses. The slope in this bilogarithmic plot is of $\beta=2.6$,**
276 **corresponding to a Hurst exponent: $H = (\beta - 1)/2=0.8$.**

277

278 **Figure 7. Roughness evolution (PSD Ratio) as a function of wavelength for surfaces sheared under**
279 **constant normal stress.**

Figure 6
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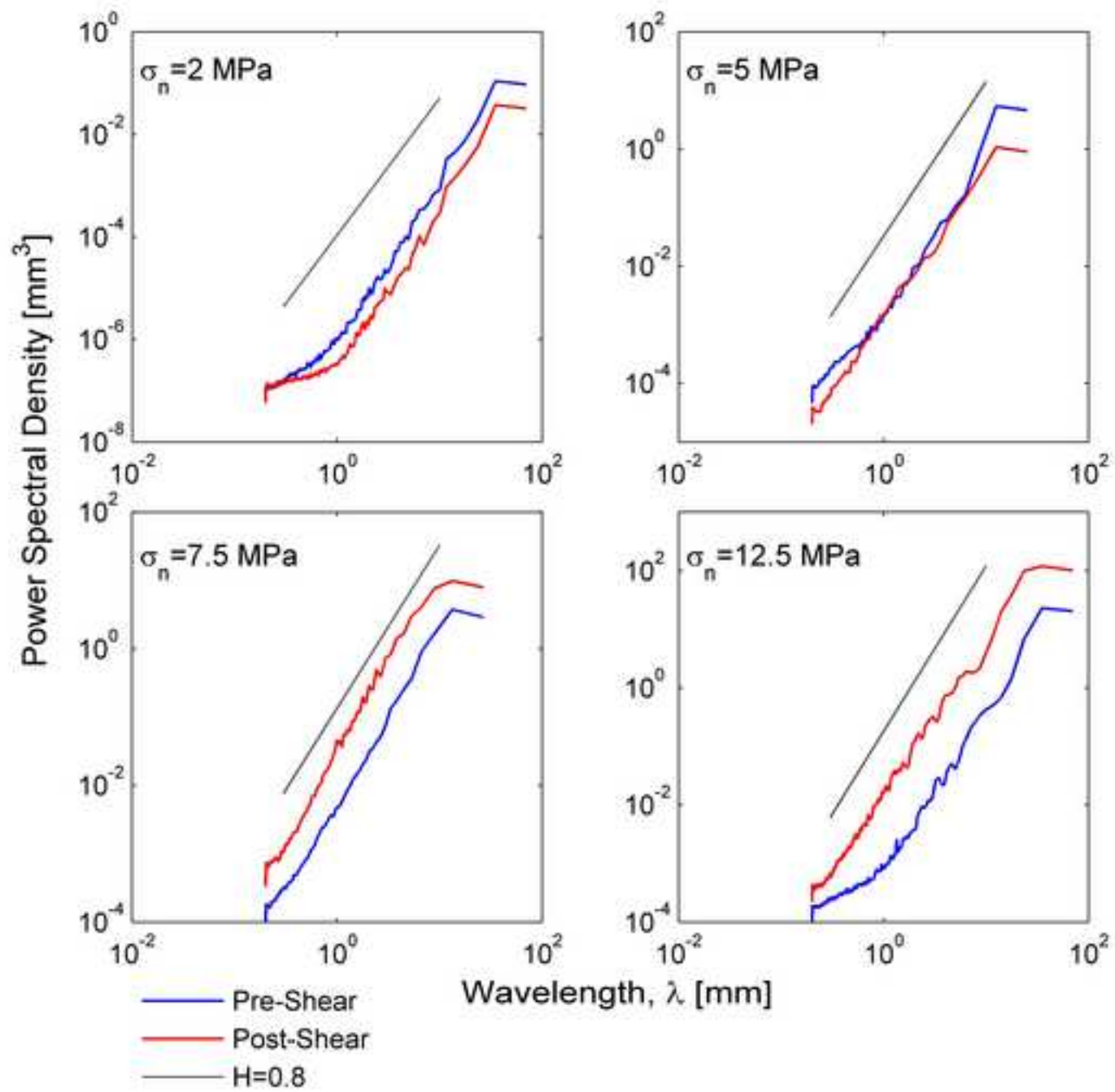
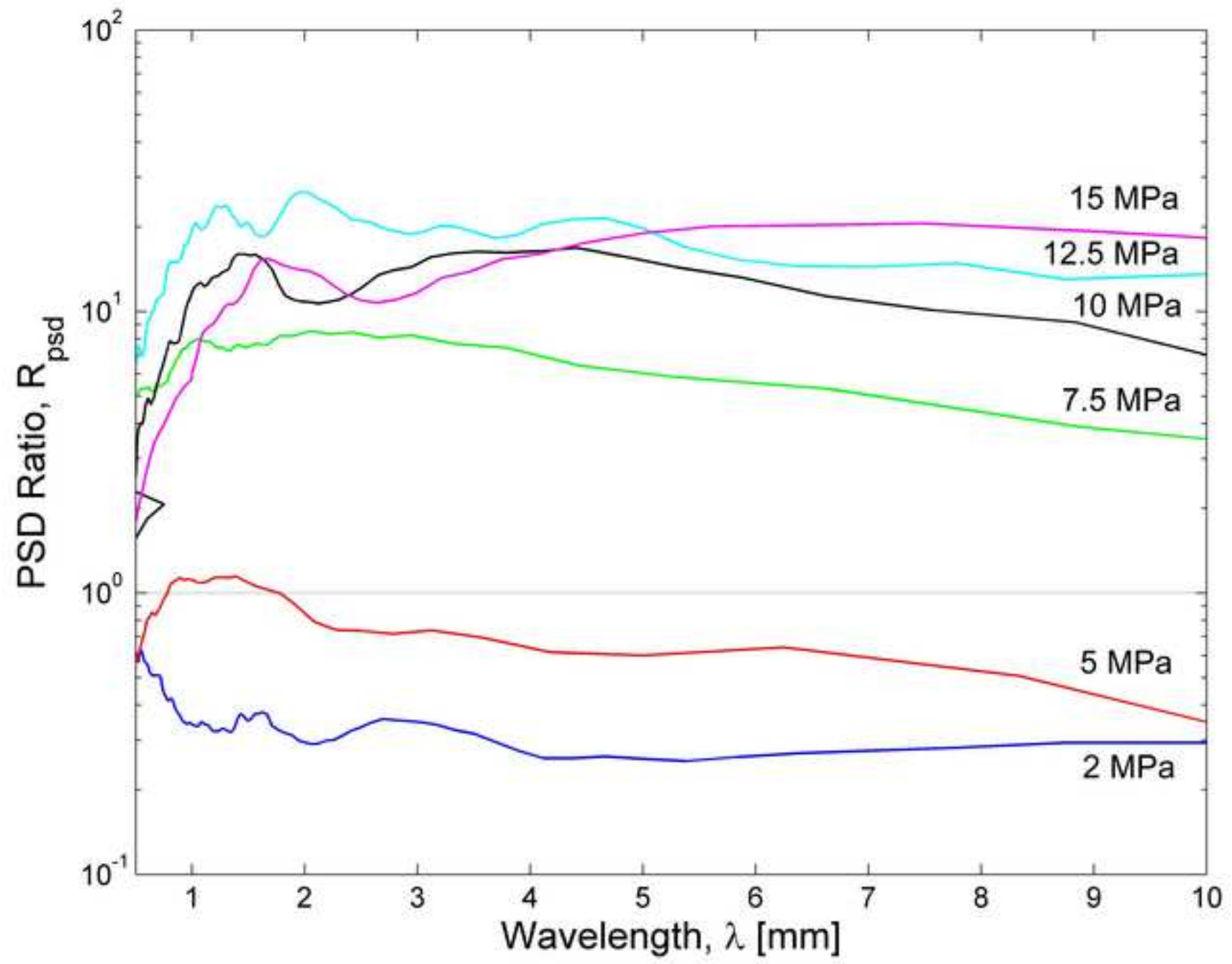


Figure 7
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280 5. Discussion

281 5.1 Geometrical-Mechanical Interactions

282 While this study focuses on roughness evolution, wear loss due to shear is a natural by-product of
283 the geometrical evolution and is therefore examined as well. Wear loss is measured by subtracting
284 the post-shear matrices from the pre-shear matrices, thus delineating the zones that experienced
285 significant damage in the resulting height-difference matrix, referred to here as the “damage
286 matrix” (Fig. 8). Such height subtraction was possible because some parts of the post-shear surface
287 remained intact and could therefore be used as a reference for “zeroing” the two matrices.

288 Quantitative wear analysis is done by calculating the height difference between each compatible
289 point in the pre- and post-shear matrices. Each point in the damage matrices represents a unit cell
290 area of $0.1 \times 0.0291 \text{ mm}^2$, corresponding to the resolution of the scan in both transverse and
291 longitudinal directions, so that for each cell area we could calculate the wear volume at good
292 approximation. A threshold height difference is set to 0.5 mm in order to minimize height
293 difference incompatibility of the pre- and post-shear matrices. The wear volume is normalized by
294 the area of the whole damage matrix (or damage zone) as follows:

$$h_{wear} = \frac{\sum V_{ij}}{nA} \quad (1)$$

295
296 Where $\sum V_{ij}$ is the total wear volume obtained from all the unit cells in the matrix (above threshold
297 value), n is the total number of cells in the entire matrix that entail a height difference value greater
298 than the set threshold, and A is the unit cell area. The calculated wear volume is normalized by the
299 area of the sampled zone. Combining measurements from both mated surfaces in a given
300 experiment provides the average wear, expressed here in terms of total wear loss volume per
301 damage area (Fig. 9a). The main parameter that changed between experiments was the normal

302 stress, but because the initial roughness of our samples although similar, was not identical, we plot
303 the wear loss against the total mechanical shear work spent during the shearing process (Fig. 9),
304 thus integrating the effects of normal stress, surface geometry, and material properties. The shear
305 work due to shear sliding is obtained directly from the shear stress - shear displacement curves (e.g.
306 Fig. 3):

$$W_t = \int_0^{10} \tau du \quad (2)$$

307 where W_t is the spent shear work during sliding to a pre-specified target distance of 10 mm, τ is the
308 shear stress and du is the displacement interval.

309 The relationships between mechanical shear work (normalized to the surface area) and wear loss,
310 normal stress and roughness ratio are plotted in figure 9. The roughness ratio is defined as the
311 value of the PSD ratio along the range of 1mm to 1cm. As would be intuitively expected, shear
312 induced wear generation and surface roughening are energy sinks, which require increasing
313 amounts of mechanical energy to be provided by the loading system.

314

315 **Figure 3. Damage matrices for surfaces that were sheared under 5 MPa (top) and 12.5 MPa**
316 **(bottom). The matrices depict zones that underwent significant damage (red areas) and**
317 **undamaged zones (blue areas) that were used as reference for “zeroing” the pre and post shear**
318 **matrices.**

319

320 **Figure 9. Wear loss and roughness ratio presented against the total shear work. The average**
321 **width of the wear volume in any given sample is presented in Fig. 9a. Red dots represent values**
322 **calculated using measurements from both mating surfaces, while the grey diamond represents a**

Figure 8
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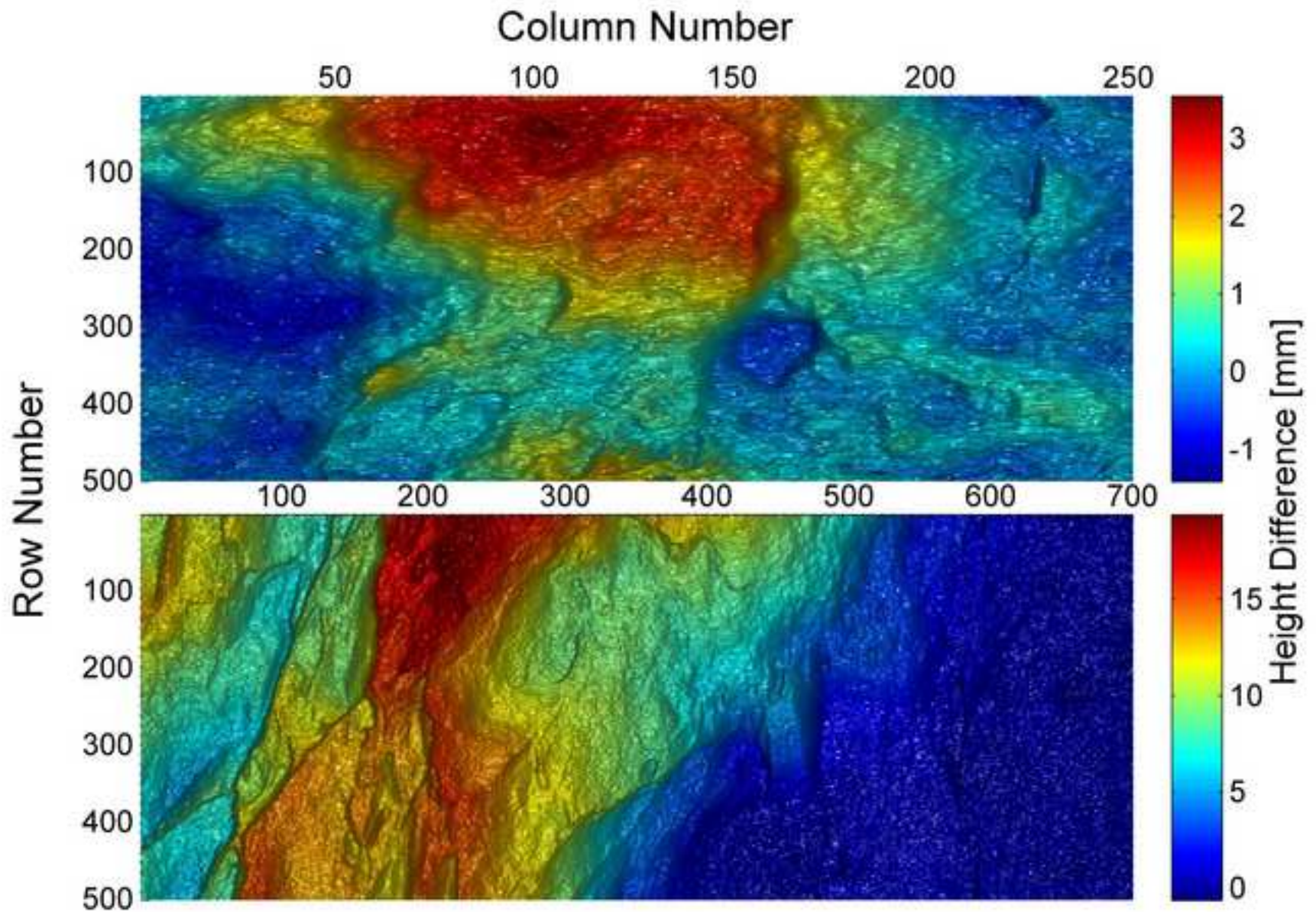
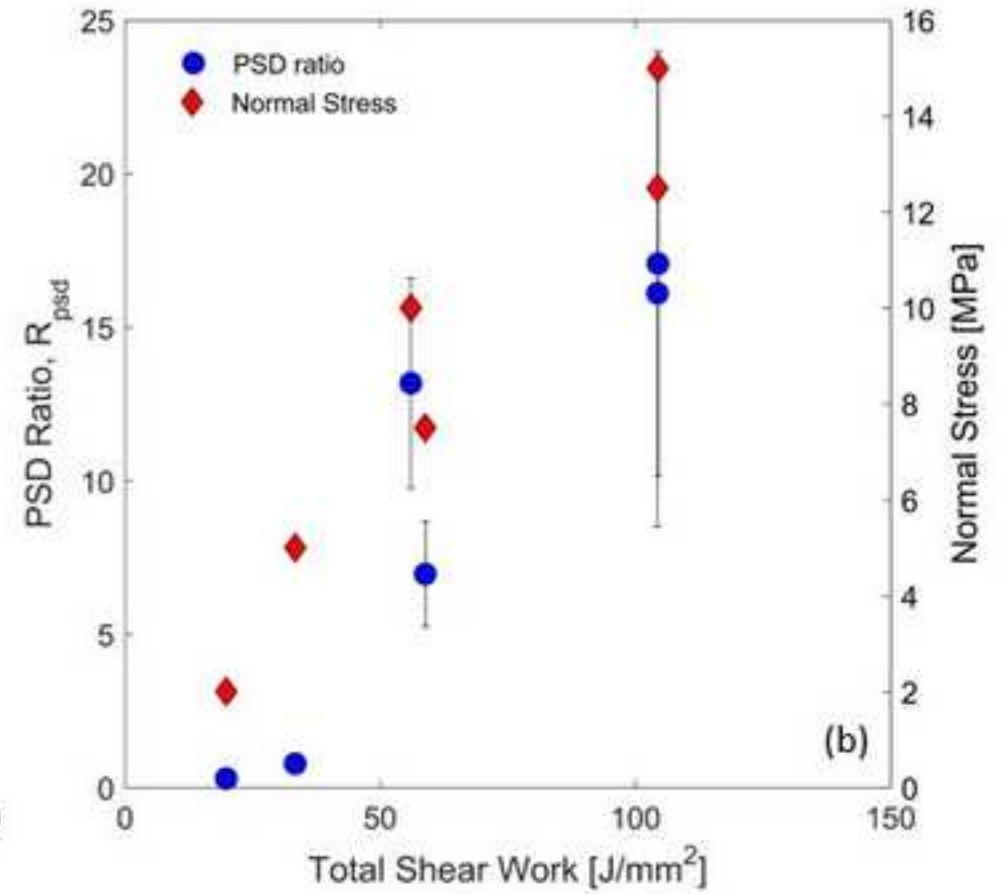
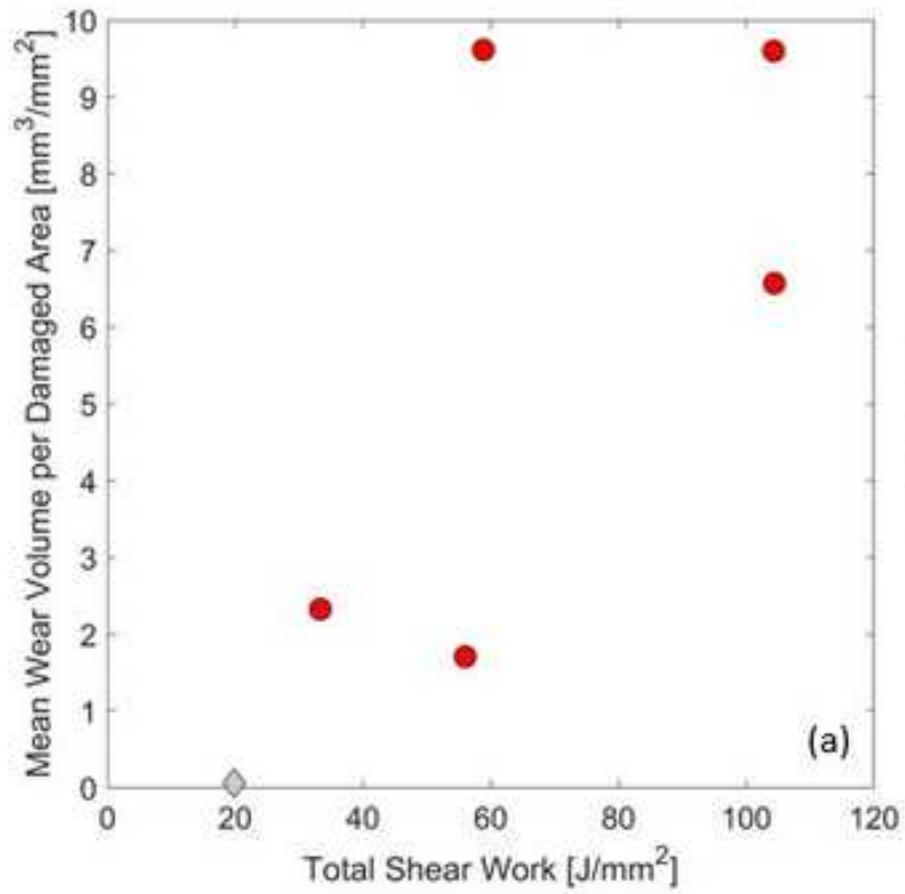


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323 value obtained from a single surface and multiplied by two. PSD ratio and normal stress values
324 are presented in Fig. 9b. The error bars (right) depict one standard deviation.

325 5.2 Roughness evolution

326 The PSD analyses performed on the experimental slip surfaces portray the geometrical modification
327 of the surfaces through shear. The overall picture suggests that surface roughness increases
328 through shear under relatively high normal stresses (≥ 7.5 MPa) and decreases under relatively low
329 stresses (≤ 5 MPa). Previous experimental observations demonstrated that surface roughness
330 smooths as function of slip distance (Davidesko et al., 2014). In those experiments, surface
331 roughness of tensile fracture were fitted well by a similar power-law, before and after shear,
332 suggesting that when constant normal stress is applied during shear displacement the power
333 spectral density of the surface can be described by:

$$p(\lambda) = k_{(d)}\lambda^\beta \quad (3)$$

334 Where β is the slope of the PSD lines (in logarithmic space) and $k_{(d)}$ is the slip dependent coefficient
335 of the smoothing process. It is demonstrated here that when the displacement is fixed and the
336 normal stress is variable, the PSD can be described by:

$$p(\lambda) = k_{(N)}\lambda^\beta \quad (4)$$

337 where $k_{(N)}$ is the normal stress dependent coefficient of the roughening process. The prefactor k is
338 therefore the parameter that chiefly varies during our shear experiments. Interestingly, computer
339 simulations demonstrated that the prefactor of the self-affine surface roughness is the main
340 component of roughness that affects energy dissipation during faulting (Newman & Griffith, 2014).
341 On the other hand, In most sheared surfaces of both sets of experiments, the power β exhibits a
342 typical value of 2.6, in direction of slip along the measured scales, which in self-affine surfaces
343 corresponds to a roughness (or Hurst) exponent of $H=0.8$, as measured in previous studies

344 (Bouchaud, 1997), where $\beta=1+2H$ (Barabasi & Stanley, 1995). It is therefore suggested that this
345 roughness exponent might represent a more general multiscale self-affine roughness as suggested
346 previously both for tensile and shear fractures (e.g. Bouchaud et al., 1990; Amitrano and
347 Schmittbuhl, 2002; Renard et al., 2006).

348 Examination of the experimental surfaces more locally reveals that the tested surfaces undergo
349 smoothing and roughening at different localities (Figure 10a). The pre- and post-shear curves
350 display an overall increase in surface roughness; however, when different zones in the same post-
351 shear surface matrix are examined areas of different roughness are evident. The rough zone
352 (magenta colored curve) exhibits the maximum PSD values for each wavelength. In contrast, the
353 smooth zone showing striations with no intensive penetrative damage, exhibits PSD values that are
354 much closer to the initial values before slip has occurred. When two PSD functions with equal
355 power ($\beta=2.6$) but different prefactor values are plotted along with the surface data, it can be
356 concluded that while some variations in the power exist in the data, the predominant change in
357 roughness is manifested mathematically as an increase or decrease in the prefactor (k) value.

358 Following our observation that the prefactor is normal-stress-dependent, and its value increases
359 with normal stress (Figs. 6-7), we conclude that the same process also occurs locally. The striation
360 zones have presumably experienced a lower local normal stress than the rough ones. These local
361 variations of the normal stress are mostly influenced by the initial geometry of the fault, as evident
362 by direct observations (Fig. 5) and suggested by models of stress distribution near rough fault
363 surfaces (Chester & Chester, 2000; Sagy & Brodsky, 2009; Griffith et al., 2010). We thus conclude
364 that initial roughness strongly influences post slip damage intensity and surface geometry.

365 Figures 6 and 10a also demonstrate that at short length scales ($< 1\text{mm}$) some of the initial tensile
366 fracture surfaces display a kink in the PSD values. Examination of thin sections reveals that the
367 average grain size of the tested rock before shear is 0.4 mm, and therefore the bend in the PSD

368 values is best interpreted as associated with the typical grain scale of the samples ($\sim 1-0.1$ mm).
369 Such small-scale cutoff is commonly observed in tensile fractures for numerous materials
370 (Bouchaud, 1997). Interestingly, this cutoff remains in post-shear PSD curves for the surface
371 sheared under 2 MPa (Fig. 6), but diminishes in surfaces sheared under higher normal stresses (Figs.
372 6, 10a). Figure 10b presents the most extreme case of deviation of initial roughness from a power-
373 law. The plot includes measurements from the high resolution lens of 50 mm, which enlarges the
374 scanning resolution down to less than 0.05 mm. The kink in the pre-shearing roughness is reduced
375 in the post-shear roughness and “moves” around smaller wavelength. This is attributed to higher
376 efficiency of fragmentation in the grain scale during shear, as the grains themselves are fractured.
377 The typical grain size in the gouge becomes smaller as shear progresses, as observed in figure 5 and
378 discussed by Amitrano & Schmittbuhl (2002).

379

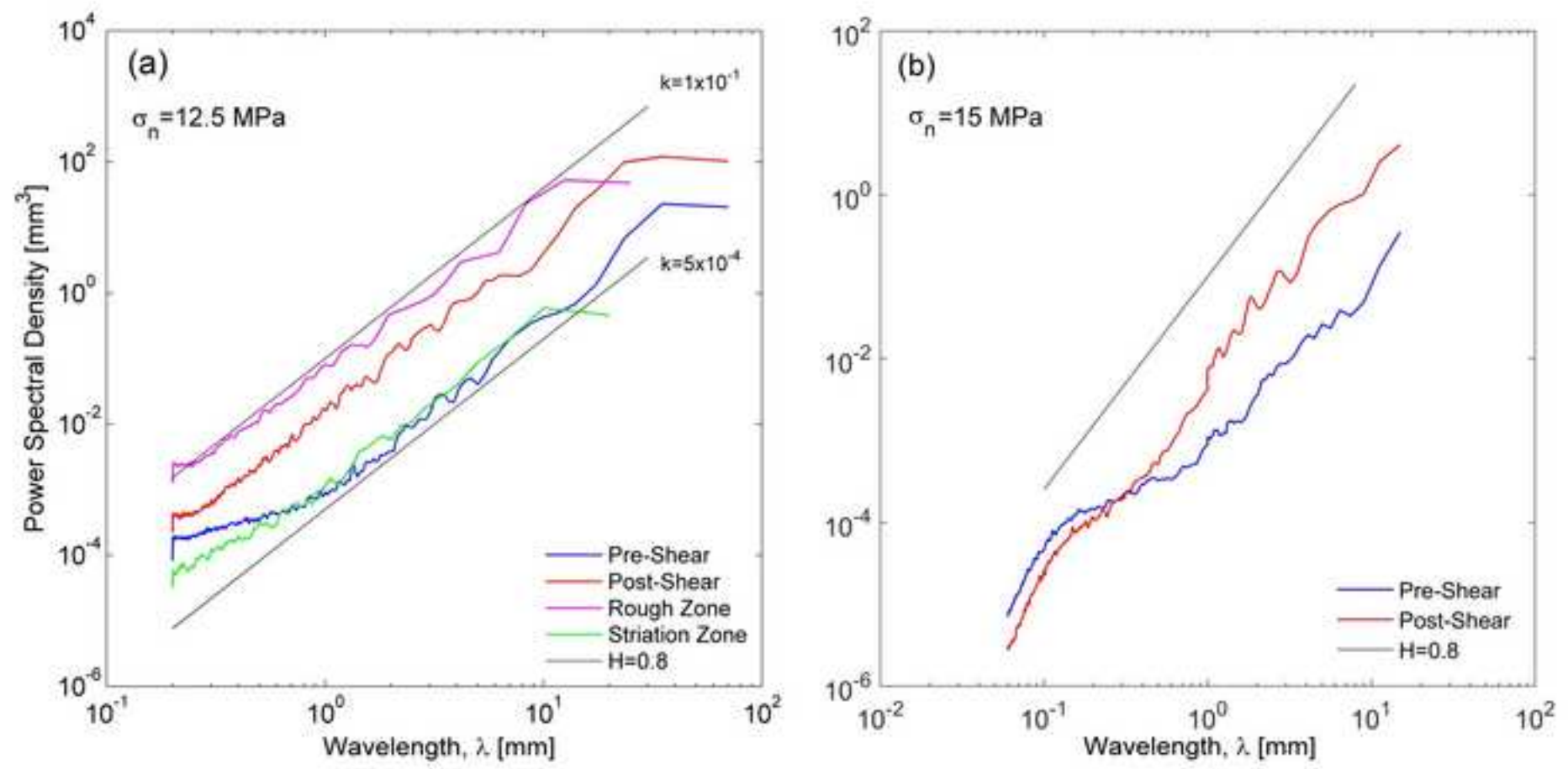
380 **Figure 10. (a) PSD curves for different zones of unequal roughness for a surface sheared under**
381 **12.5 MPa. The pre and post shear curves refer to the whole surface before and after shear,**
382 **respectively. The rough and striation zone curves refer to two distinct zones in the post-shear**
383 **surface that underwent roughening and smoothing, respectively. The two black solid lines are**
384 **upper and lower bounds to the data featuring different values of k . (b) Power spectrum curves for**
385 **a surface sheared under 15 MPa. Note the cross-over between the pre shear (blue) and post**
386 **shear (red) curves around a wavelength of 0.4 mm.**

387

388 **5.3 Applications for natural faulting**

389 The initial setup presented here is of a tensile fracture that is reactivated by shear. Such a slip mode
390 is common in natural environments (Segall & Pollard, 1983; Martel et al., 1988; Di Toro &
391 Pennacchioni, 2004). Moreover, field and experimental observations as well as theoretical analyses

Figure 10
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392 demonstrate that the initial inelastic deformation of brittle rocks, even under compression, usually
393 includes tensile mode fracturing, while shear occurs only when these fractures interact (Segall &
394 Pollard, 1983; Ashby & Sammis, 1990; Reches & Lockner, 1994). More broadly, one can interpret
395 the presented configuration as a simplification of the shear of a multiscale interlocked rough fault,
396 as is the case for faults along the entire range of length scales. At large scales, even mature faults
397 can express significant roughness (Wang & Bilek, 2011).

398 Friction experiments under constant loading conditions display in some configurations strain
399 hardening and strain weakening stages, followed by low resistance to shear (e.g. Ohnaka, 2003).
400 Considering previous (Davidesko et al., 2014) and current results we suggest that the evolution of
401 roughness in sheared interlocked surfaces exhibits a roughening stage during strain hardening while
402 gradual localization and smoothing occurs during strain, or slip, weakening. Our samples which
403 contained initially rough surfaces never experienced the entire transient stage because the
404 displacement length required for crossing the entire transient stage is strongly dependent upon the
405 initial roughness and the normal stress (Queener et al., 1965; Wang & Scholz., 1994). Figure 10b
406 demonstrates surface roughness in an experiment that was terminated during the slip weakening
407 stage after 10 mm of slip. Although in average the surface roughened, smooth striated zones were
408 observed (Fig. 5) indicating that some localization had already occurred. We therefore suggest that
409 our experiments best simulate the deformation of a fault patch with roughness larger or
410 comparable to the slip displacement of the event.

411 Contrary to this, many experimental works adopted the shearing of relatively smooth surfaces in
412 order to study the friction properties of rocks. Unsurprisingly, the transient stage in these
413 experiments is relatively short. Beyond this stage, under constant applied velocity and normal
414 stress, roughness, wear rate and resistance to shear remain statistically stable, (Archard, 1953;
415 Boneh et al., 2014; Lyakhovsky et al., 2014). We therefore assume that these experiments best

416 simulate fault patches which absorbed slip amounts larger than their length. We also note that slip
417 velocity and normal stress further affect surface roughness at this stage (Boneh et al., 2013; Chen et
418 al., 2013; Fondriest et al., 2013; Siman-Tov et al., 2015).

419 Finally, natural fault roughness values decrease with net slip (Sagy et al., 2007; Bistacchi et al.
420 2011), albeit very gradually (Brodsky et al., 2011). Normal stress variations, as presented here,
421 could be important to this evolution. Roughness and wear loss in the present testing configuration
422 evolve throughout brittle damage and increase with the mechanical shear work (Fig. 9). Following
423 these results and previous theoretical analysis (Newman & Griffith., 2014) we speculate that the
424 energy dissipation during natural slip is affected both by the level of normal stress and by the initial
425 fault surface roughness. Further experimental and theoretical research focused on the transient
426 wear stage is necessary for better simulating dissipation and partitioning of energy during
427 earthquake.

428

429 **6. Summary and conclusions**

430 Our experimental configuration in which the surfaces are: a) initially rough, b) include multiscale
431 geometrical irregularities, c) initially interlocked, and d) sheared to distances that are comparable
432 to the roughness amplitude of the surface, is well suited to simulate natural faulting. Such a testing
433 configuration has never been attempted in previous experimental shear and roughness evolution
434 studies. While it is generally assumed that shearing surfaces one against the other is closely
435 associated with polishing and smoothing of surface asperities, we find that deformation associated
436 with shearing extends beyond the immediate zone of the asperities and that this deformation
437 becomes more intensive with increasing normal stress. We demonstrate here that roughness
438 evolution is a complex mechanism that consists of simultaneous roughening and smoothing in a

439 given surface. Roughening occurs as part of damage development during strain hardening stage
440 while gradual localization and smoothing occur during strain weakening. Under constant stress, the
441 final roughness value depends on the slip amount (Davidesko et al., 2014). When the slip distance
442 and the loading velocity are constant, the surface becomes rougher with increasing normal stress.
443 Consequently, the roughness of the surface after shear can be higher than the initial roughness, an
444 experimental finding never reported before.

445 We show that roughness, as function of measured wavelength, fits a power-law with power value
446 of $\beta \sim 2.6$, or Hurst exponent of $H \sim 0.8$, assuming characteristic self-affine topography parallel to the
447 slip direction (Figs. 6 and 10). Interestingly, this power is stable in the sheared surfaces even when
448 the initial roughness does not fit a power-law, indicating that this characteristic roughness is an
449 attractor for the morphology developed under brittle shear. Therefore, continuous shear can
450 enlarge the range of length scales which statistically obey power-law roughness. The final
451 roughness of the surface, which depends on the initial geometry, the level of normal stress, and the
452 imposed sliding distance, is expressed by the evolution of the scaling-law prefactor. This value
453 increases with normal stress but decreases with continuous slip.

454

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459

460 7. References

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553

Geometrical evolution of interlocked rough slip surfaces: The role of normal stress

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Supplementary Material

Table 1. Results from direct shear experiments

Experiment	Normal Stress, σ_n [MPa]	Peak Shear Resistance, τ/σ_n	Peak Shear Stress, τ [MPa]	Stress-Drop, $\Delta\tau$ [MPa]
L10 *	2	1.25	2.5	0.224
LN1	5	0.724	3.622	0.369
LN10	7.5	0.905	6.787	0.989
LN6	10	0.661	6.61	0.142
LN11	12.5	0.997	12.458	2.673
LN5	15	0.862	12.93	2.223
LN7	15	0.821	12.312	1.248

*Data from Davidesko et al. (2014)

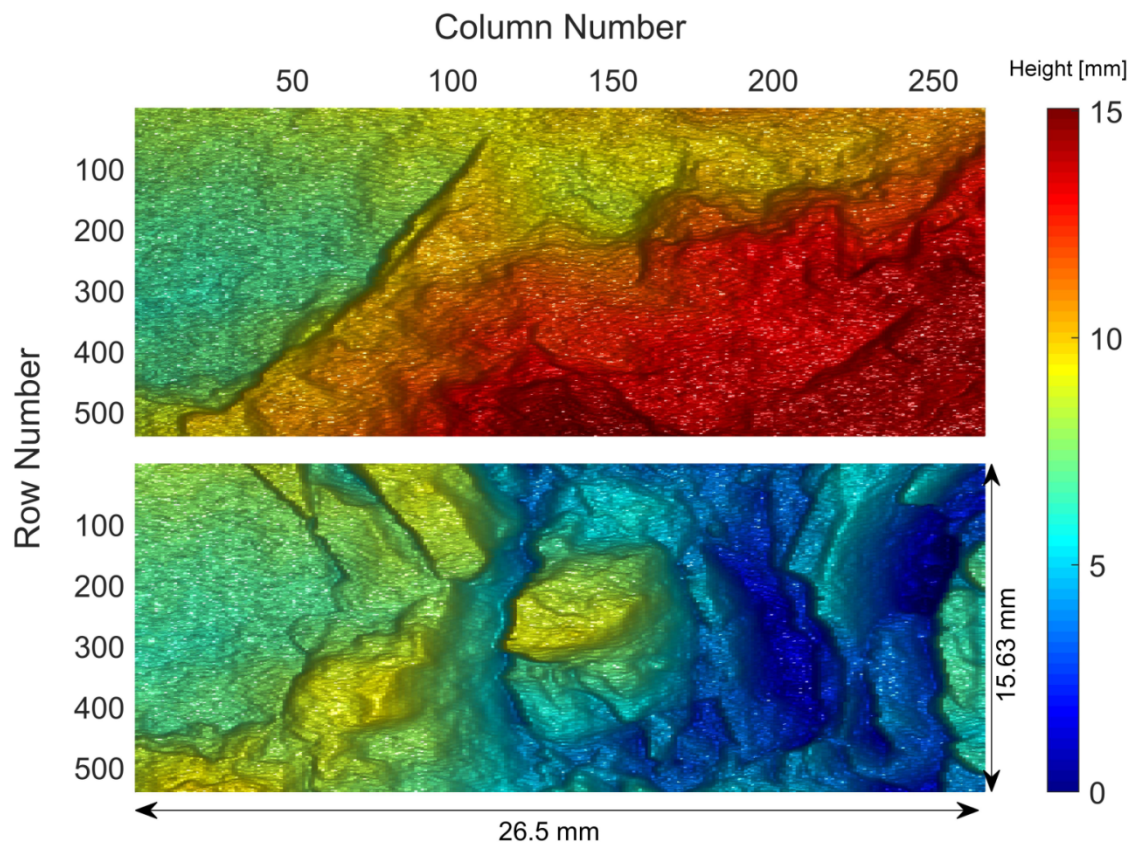


Figure 1. Surface matrices before (top) and after (bottom) shear for an experiment sheared under 7.5 MPa.

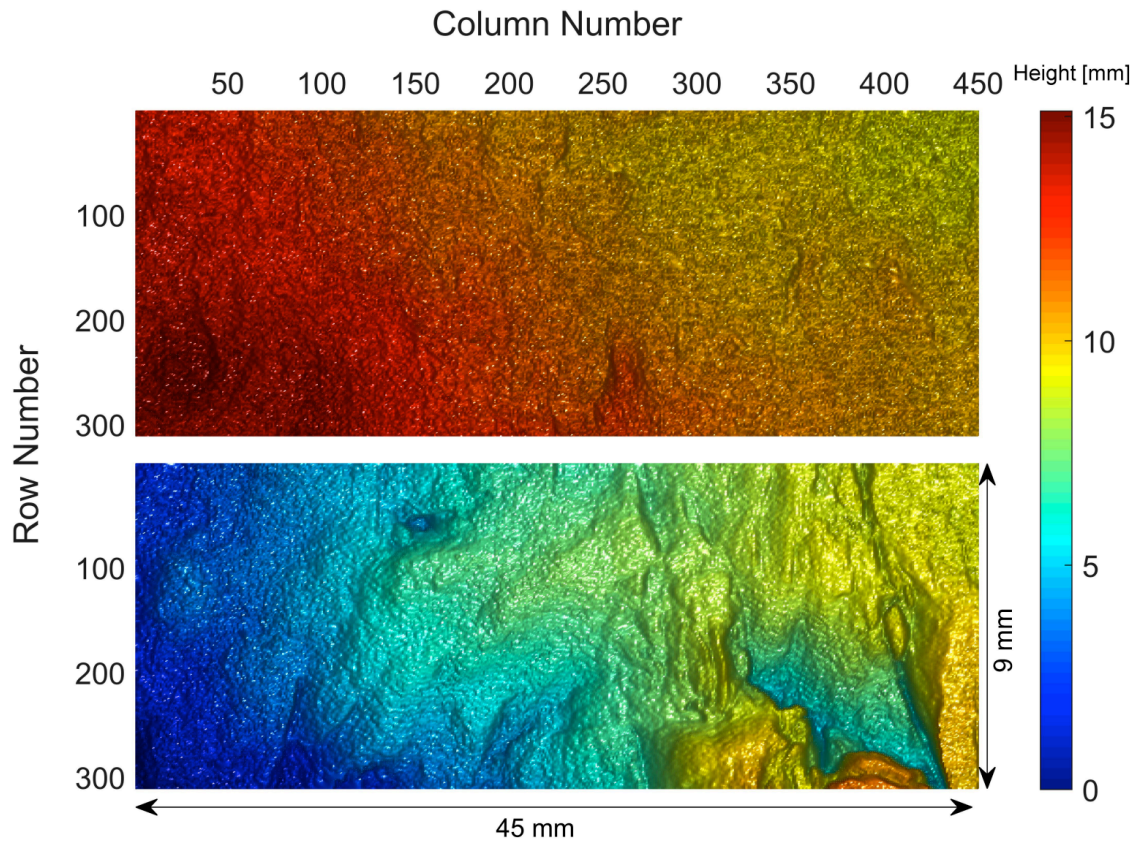


Figure 2. Surface matrices before (top) and after (bottom) shear for an experiment sheared under 15 MPa.